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Spatially-explicit modelling for catchment-level salinity management

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Abstract: In this paper, a spatially-explicit model to undertake catchment-level analysis of dryland salinity is discussed. The model uses a raster-based approach where a catchment is represented as a grid of neighbouring cells. Each cell is defined by a set of seven attributes: land use, elevation, soil type, rainfall, aquifer thickness, groundwater-table depth and groundwater salinity. Cells receive and transmit groundwater information to and from neighbouring cells through a simplified hydrology model. The hydrology model is combined with an economic model and can be used to analyse the effect of alternative spatial patterns of land use. The model is implemented in the MATLAB programming environment and is designed to allow users to test any arbitrary pattern of land use and explore its long-term consequences. This facility permits the analysis of tradeoffs between financial (profit) and environmental (salt-affected area, water yield and water quality) outcomes. The model is illustrated in an application to a small agricultural catchment in central-west NSW, Australia. Attribute maps for elevation and soil type are read directly from ASCII grid files generated by GIS software. Rainfall is assumed to be uniform across the catchment, and monthly time steps ensure water movements between neighbouring cells in this small catchment are mimicked accurately. The model is initialised by reading a look-up table for land uses and their respective parameters, and a look-up table for soil types and their respective parameters. The user can change the number and types of land uses or soils and their associated parameters simply by changing the relevant look-up table in a spreadsheet. Three experiments were run where the catchment was entirely planted to a single land use, either tree belts, grazing on perennial pasture or annual cropping. Preliminary results demonstrate that the model responds to the different land-use scenarios in accordance with apriori expectations, with tree and pasture land uses generally resulting in lower groundwater tables. The model is in the process of being calibrated and validated using time-series data for groundwater-table depth for several piezometers located across the catchment and some issues are briefly discussed.

Keywords: *dryland salinity, catchment-level analysis, raster-based approach, bioeconomics*

1. INTRODUCTION

Dryland salinity is a serious land-management problem in Australia. It has been caused by replacing perennial native vegetation with annual crop and pasture species that allow a larger proportion of rain to recharge groundwater systems, and is evidenced by high and rising saline water tables in low-lying, discharge areas of catchments. Land-use decisions by upstream landholders can affect the depth of the water table in the lower catchment, and thereby impose externalities on downstream landholders through the negative effect of salinity on crop yields and profitability. Pannell (2001) provides an overview of the economic, scientific, social and policy dimensions of dryland salinity.

In this paper, a spatially-explicit approach is taken to modelling dryland-salinity management at the catchment level. This approach to resource-management problems is discussed by Hof and Bevers (1998). Two particular features characterise the approach. Firstly, the integrity of the spatial heterogeneity of the landscape is maintained; and secondly, the relationships that describe how adjacent parts of the catchment interact or are spatially connected are made explicit.

A spatially-explicit approach to modelling catchment-level salinity management differs from partial spatial approaches previously published in the literature. These approaches vary significantly in terms of the spatial detail of the landscape being modelled. Some approaches do not represent spatial heterogeneity and the landscape is assumed to be uniform. These approaches ignore how different parts of the catchment interact, which obviates their use for evaluating salinity externalities. Cacho and Hean (2004), Cacho (2001) and Cacho, Greiner and Fulloon (2001) use this approach. Other approaches represent some of the spatial heterogeneity in the landscape by dividing the catchment into at least two heterogeneous areas, and may take into account how these different parts of the catchment interact. Nordblom *et al*. (2006) use this approach in a model which represents a catchment by three spatially-independent sub-catchments, while Greiner (1996, 1998, 1999) and Greiner and Cacho (2001) divide a catchment into two recharge areas and two discharge areas, which are spatially connected through surface and groundwater flows.

These previous approaches are not directly compatible with spatial data sets provided by Geographical Information Systems (GIS), which come in cellular (raster) or geometric (vector) format. Pre-calculations or data manipulations are required before GIS data can be used. A spatially-explicit approach which represents the landscape in fine spatial detail consistent with available spatial data sets obviates this need.

In this paper, we describe the development of a modelling tool for land-management and policy analysis, which can be used to test any arbitrary spatial pattern of land use and explore its long-term consequences for a catchment. This facility permits the analysis of tradeoffs between financial (profit) and environmental (salt-affected area, water yield and water quality) outcomes. The model is designed to estimate salinity externalities as well as the costs imposed by government policies, such as end-of-valley salinity targets. We illustrate the model by applying it to a small agricultural catchment in central-west NSW, Australia. The model is in the process of being calibrated and validated and some issues are briefly discussed.

2. THE MODEL

The model uses a raster-based approach where a catchment is represented as a grid of neighbouring cells. Each cell is defined by a set of seven attributes: land use, elevation, soil type, rainfall, aquifer thickness, groundwater-table depth and groundwater salinity. Cells receive and transmit groundwater information to and from neighbouring cells through a simplified hydrology model. The hydrology model is combined with an economic model and can be used to analyse the effect of alternative spatial patterns of land use.

2.1. Economic Model

Consider a catchment comprising a total of I cells denoted by the subscript i ($i = 1,\ldots,I$), each of area a (ha). Catchment-level profit, measured by the net present value of output over a planning horizon of T years (NPV_T, \$), is given by:

$$NPV_T = \sum_{i=1}^{I} npv_{i,T}\{L_i, S_i, G_{i,1}, G_{i,2}, \ldots, G_{i,T}, gws_i\} \tag{1}$$

where $npv_{i,\mathrm{T}}$ is the net present value (\$) for each of the i cells in the catchment, which is a function of land use (L_i), soil type (S_i), groundwater-table depth (G_i) measured in m below the soil surface, and groundwater salinity (gws_i) measured in ppm (or mg/L). L_i, S_i and gws_i are constant for each cell, while G_i can vary over time from $t = 1,\ldots,T$. L_i can take a value that denotes one of J ($j = 1,\ldots,J$) possible land uses, and S_i can take a value that denotes one of K ($k = 1,\ldots,K$) possible soil types.

$npv_{i,T}$ is calculated as follows:

$$npv_{i,T} = \sum_{t=1}^{T} v_i\{L_i, S_i\} \cdot m_{i,t}\{L_i, G_{i,t}, gws_i\} \cdot \delta^t \qquad (2)$$

where v_i is the annual return ($/ha.y), which depends on land use and soil type; m_i is a multiplier with a value between zero and one, which captures the effects of waterlogging and groundwater salinity on annual returns; and δ is the discount factor given by $1/(1+r)$ for discount rate r; other variables are as previously defined.

m_i is given by:

$$m_{i,t} = \begin{cases} we_{i,t} & if\ we_{i,t} = 1 \\ we_{i,t} \cdot se_i & if\ we_{i,t} < 1 \end{cases} \qquad 0 \le m_{i,t} \le 1 \qquad (3)$$

where we_i is the waterlogging effect, which can vary over time depending on the depth of the water table, and se_i is the groundwater-salinity effect, which is constant. These effects are calculated as follows:

$$we_{i,t} = 1 - \beta_i\{L_i\} e^{\varphi_i\{L_i\} \cdot |G_{i,t}|} \qquad 0 \le we_{i,t} \le 1 \qquad (4)$$

$$se_i = 1 - \gamma_i\{L_i\} \cdot (gws_i - \phi_i\{L_i\}) \qquad 0 \le se_i \le 1 \qquad (5)$$

The functional form for we_i is taken from Cacho, Greiner and Fulloon (2001) and is represented in Figure 1. When the water table is sufficiently deep, we_i is unity and annual returns are not affected by waterlogging. As the water table rises towards the soil surface, above a critical depth (G_{crit}), the value of we_i falls and annual returns are correspondingly reduced. This effect becomes increasingly severe until a depth is reached (G_{min}) where we_i is zero and annual returns are dissipated. The values of β_i and φ_i vary with land use, so the shape of the function reflects the sensitivity of the land use to waterlogging.

The functional form for se_i is taken from Maas and Hoffman (1977) and Mass (1986) and is presented in Figure 2. When the groundwater is sufficiently fresh, se_i is unity and annual returns are not affected by salinity. As the salinity rises above a threshold level (gws_{crit}, which equals γ_i), the value of se_i falls at a constant rate (ϕ_i) and annual returns are correspondingly reduced. When gws_{max} is reached, se_i becomes zero and so do annual returns. The values of γ_i and ϕ_i vary with land use, so the shape of the function reflects the tolerance of the land use to salinity. It is assumed that if the water-table depth is G_{crit} or deeper (i.e., if we_i is unity), the salinity of the groundwater does not affect annual returns.

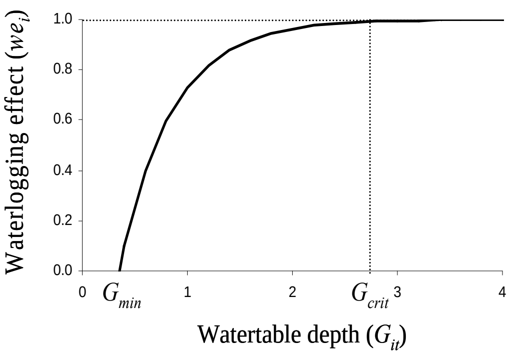


Figure 1. The waterlogging effect, given in eq (4).

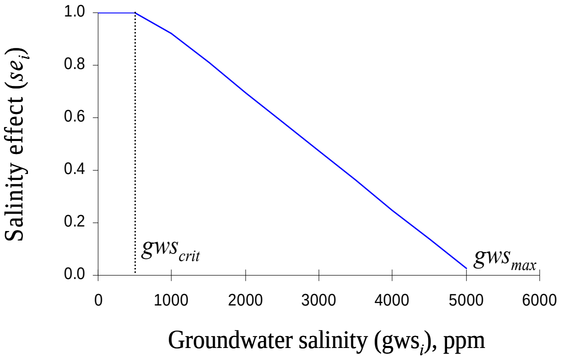


Figure 2. The salinity effect, given in eq (5).

2.2. Hydrology Model

The hydrology model comprises sub-models for water balance, groundwater dynamics, water yield and salt load.

The water balance for each cell i for each month m (m = 1,…,12) of the planning horizon of T years, is represented by:

$$P_{i,m} = ET_{i,m}\{L_i, S_i\} + D_{i,m}\{L_i, S_i\} + R_{i,m}\{L_i, S_i\} + \Delta SW_{i,m}\{L_i, S_i\} \tag{6}$$

where P_i is precipitation, ET_i is evapotranspiration, D_i is deep drainage to groundwater, R_i is surface runoff, and SW_i is soil water in the root zone; all rates are measured in m/month.

Evapotranspiration is estimated using the crop coefficient approach based on the FAO Penman-Monteith equation, and soil water is estimated based on the capacity of the soil to retain water available to plants, described by Allen *et al.* (1998). Deep drainage and surface runoff are calculated by partitioning the remaining rainfall as follows (Dawes *et al.*, 2000):

$$D_{i,m} = \left(P_{i,m} - ET_{i,m}\{L_i, S_i\} - \Delta SW_{i,m}\{L_i, S_i\}\right) \cdot \alpha_i\{S_i\} \tag{7}$$

$$R_{i,m} = \left(P_{i,m} - ET_{i,m}\{L_i, S_i\} - \Delta SW_{i,m}\{L_i, S_i\}\right) \cdot \left(1 - \alpha_i\{S_i\}\right) \tag{8}$$

where $(P_i - ET_i - \Delta SW_i)$ is "excess water", and α_i is the recharge fraction of excess water, which depends on soil type.

Groundwater in each cell in the catchment is recharged through deep drainage and groundwater flow from its neighbouring cells. Water flows are calculated using Darcy's Law (White, 1987; Hanks, 1992), which is based on the saturated hydraulic conductivity of the soils.

The annual water yield from the catchment consists of surface runoff plus any overflow of groundwater onto the soil surface and into streams. It is assumed that surface runoff and overflow reach streams in the year in which they occur. Overflow results when the water table of a cell rises above the soil surface due to deep drainage and the lateral flow of groundwater.

The annual salt load from the catchment for each year is calculated based on surface runoff, the salinity of rainwater, overflow and the salinity of groundwater.

This approach differs from other hydrology models used in economic analyses of dryland salinity by simulating the three-dimensional movement of groundwater through the catchment. It is conceptually similar to MODFLOW (McDonald and Harbaugh, 1988), which is a fully distributed groundwater model. MODFLOW and a range of other hydrology models are discussed by Beverly (2004) in the context of their application to economic and policy analysis of salinity management.

3. THE SIMULATION

The model is implemented in the MATLAB programming environment (The Mathsworks, 2002) and applied to the Boorowa River Catchment in central-west NSW, Australia, a 129-ha agricultural catchment. The model is initialised by reading parameters from tables in Microsoft Excel. The user can change the number and types of land uses or soils and their associated parameters simply by changing the relevant table and saving the spreadsheet.

The attribute maps used by the model are read directly from ASCII grid files generated by GIS software. Maps for digital elevation and soil type used in the simulations are shown in Figure 3. Digital elevations range from 523m to 569m, with the catchment outlet being to the north west in Figure 3A. There are two broad soil types that differ functionally: light sandy clay to the north west, and permeable sandy clay loam to the south east in Figure 3B.

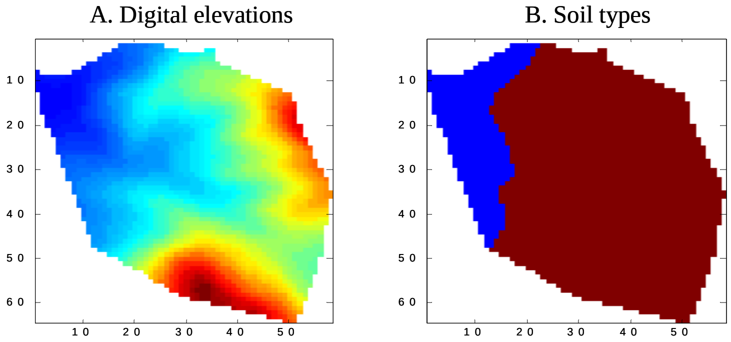


Figure 3. Maps of (A) digital elevations and (B) soil types.

Maps are represented as a matrix of dimensions $n_r \times n_c$ whose elements are square cells, each with a base and height of 25m. In the model, all maps are converted to column vectors of dimension $n \times 1$, where n is the number of valid rows and columns in the map. This speeds up execution and simplifies coding of numerical operations. These vectors can be easily mapped back to the original matrix (their elements are arranged vertically down the rows and then across the columns of the matrix).

Three experiments are run where the catchment is entirely planted to a single land use, either tree belts, grazing on perennial pasture or annual cropping. The total run time for these experiments is less than 2 minutes. The discount rate is assumed to be 6%, and the planning horizon is 18 years. Rainfall data used in the simulations is presented in Figure 4.

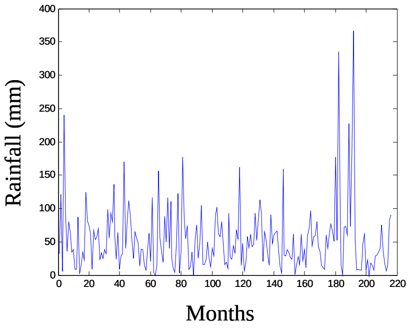


Figure 4. Rainfall.

4. RESULTS AND DISCUSSION

As the model runs, it draws groundwater-depth maps for each year in a simulation. A selection of these maps, for years 2, 6, 13 and 18, where the entire catchment is planted to trees, is presented in Figure 5. Changes in colours between the years reflect changes in water-table depth.

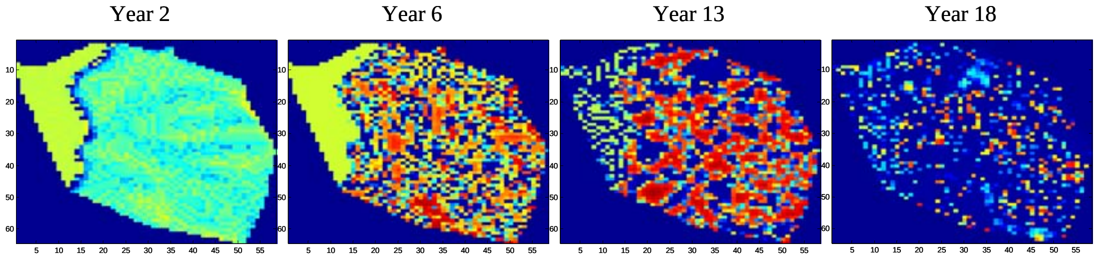


Figure 5. Groundwater-table depths, when the entire catchment is planted to trees.

Average results for the entire catchment are presented in Figure 6 for the three experiments. Cropping is clearly the most profitable land use throughout the simulation period, followed by grazing on perennial pasture, whereas trees are clearly unprofitable (Figure 6A). This conclusion is even more obvious when the annual returns presented in Figure 6A are discounted – net present values are $123,838 for cropping, $53,348 for pasture and -$35,810 for trees.

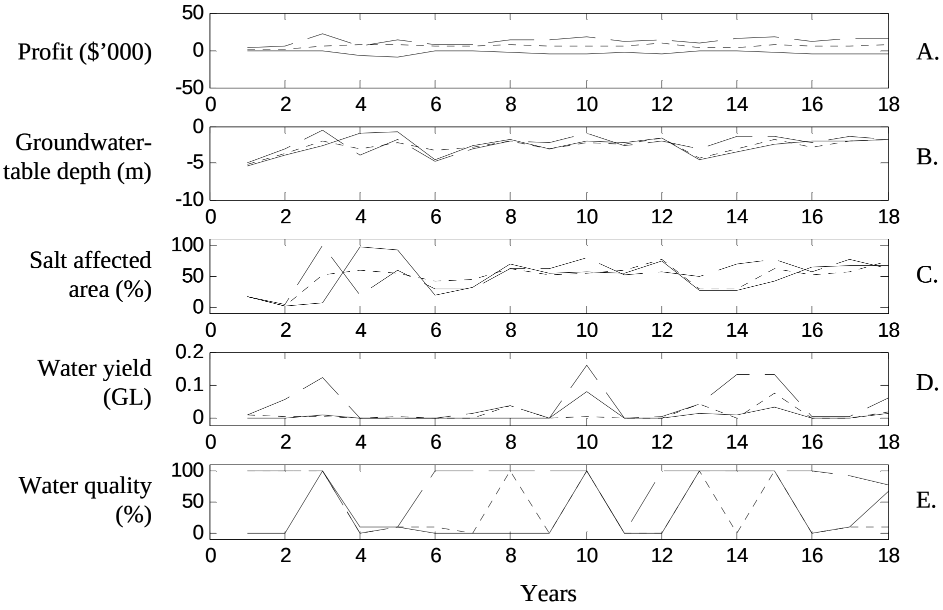


Figure 6. Average results for the entire catchment, for the three experiments: (1) tree belts (solid line), (2) grazing on perennial pastures (dotted line) and (3) annual cropping (dashed line).

Cropping generally results in the groundwater table being closer to the soil surface (Figure 6B) and more of the catchment being salt affected, which is measured here in terms of the water table being within 2m of the soil surface (Figure 6C). Water yield is also greater when the catchment is planted to crops (Figure 6D), which results in higher water quality, due to the dilution of groundwater flows (Figure 6E). In comparison, perennial pastures and trees generally result in a deeper groundwater table (Figure 6B) and less of the catchment being salt affected (Figure 6C). Water yield is less (Figure 6D) and this results in lower water quality (Figure 6E).

These preliminary results demonstrate that the model responds to the different land-use scenarios in accordance with apriori expectations, with tree and pasture land uses generally resulting in lower groundwater tables. These are average results for a catchment consisting of over 2000 cells. Analysis of spatial results is underway to identify differences in water and salinity outcomes in different areas of the landscape.

The model is currently being calibrated and validated using observed groundwater data recorded by several piezometers located across the catchment. The location of the piezometers is shown in Figure 7. Piezometers DDH2, 12 and 10 are on the light sandy clays to the north west, while the others are on the permeable sandy clay loams to the south east. Observed mean monthly groundwater data is presented in Figure 8 for two of these piezometers. The process consists of dividing the observed data into two samples, with the early data being used for calibration and the latter data for validation. Calibration is based on a binary-string genetic algorithm (Mayer, 2002), which minimises the sum of squared deviations between changes in observed groundwater-table elevations and changes in predicted values. So far, this process has demonstrated that predicted results are very sensitive to initial groundwater conditions, and to several of the soil parameters.

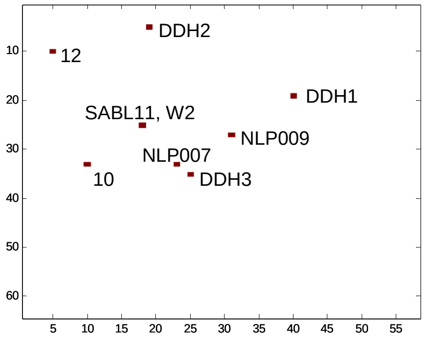
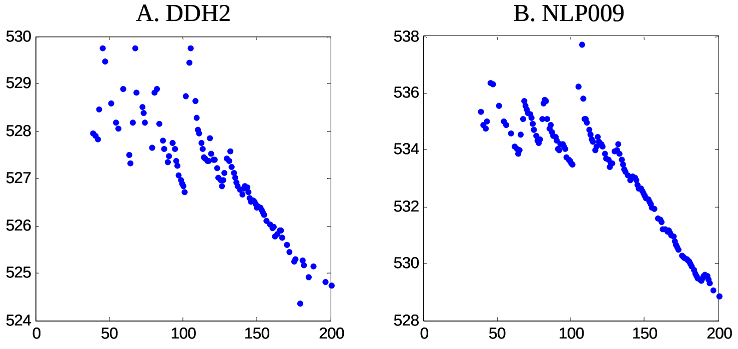


Figure 7. Piezometers in ASCII grid format.


A. DDH2

B. NLP009

Figure 8. Mean monthly observed groundwater table elevations (m) for two piezometers: (A) DDH2 and (B) NLP009

5. CONCLUSION

We developed a spatially-explicit model for analysing dryland-salinity management at the catchment level. A brief description of the model is presented, and we demonstrated how the model runs by applying it to a small agricultural catchment in NSW, Australia. The model is in the process of being calibrated and validated using data for observed groundwater-table depth recorded by several piezometers located across the catchment.

The model is implemented in the MATLAB programming environment and is designed to allow users to test any arbitrary pattern of land use and explore its long-term consequences. This facility permits analysis of tradeoffs between financial (profit) and environmental (salt-affected area, water yield and water quality) outcomes.

The model is designed to be very flexible in terms of the land uses and soils it accepts. It is initialised by reading look-up tables for land uses and their respective parameters, and soils and their respective parameters. The user can change the land uses, soils or parameters simply by changing the relevant look-up table in an Excel spreadsheet. The attribute maps used by the model are read directly from ASCII grid files generated by GIS software.

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