Model Building : Process and Practicality

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Abstract Dryland salinity is an accelerating problem that threatens some of Australia's most productive agricultural land. The problem with using models for developing management options in dryland areas is the general lack of data: there is no shortage of complex physical models, but we have little data with which to calibrate them. Not only is there the problem of having confidence in the equations and parameters used in the models, but it is difficult to follow the information trail that leads to the conclusions. This is emphasised when the outputs of one model are used as inputs to another. In the case of dryland salinity, the catchment is first broken into so-called homogeneous areas to drive a surface water balance model, which drives a groundwater model, which in turn drives an economics model, the results of which influence management decisions. What confidence do we have in the model outputs, at any of these stages, upon which decisions worth millions of dollars are made? This work presents an examination of field data leading from a conceptual model to a simple numerical model of groundwater flows in the Liverpool Plains. We maintain the critical process interactions and derive a simple flow model, whose output can be coupled with production and economic models. The Liverpool Plains is a National Dryland Salinity Program focus catchment. As such there has been more work done and more data available than for most catchments in Australia. Given a need to link physical and economic models and follow the information trails, we require conceptual and numerical models that include the critical processes and interactions, described by the simplest equations and fewest parameters. With these models in place, we present common management scenarios, and draw conclusions about the current and prospective state of the system, and the modelling exercise.

1. INTRODUCTION

The salinisation, and subsequent loss of production, of dryland farming areas of southern and eastern Australia is a result of rising groundwater tables. Bradd and Gates [1995] estimate that this recent, but accelerating, phenomenon already affects 2,000 km^2 of New South Wales alone, and is expected to cover 50,000 km^2 of the Murray-Darling Basin within 20 years. There is a need to develop and implement whole catchment plans that address a range of management and land degradation issues including dryland salinity. Poor choice of, or poor implementation of, land management schemes can alienate land-holders, waste valuable time and money, and even make the situation worse.

To help minimise poor management decisions and implementations, a technical basis for whole catchment plans is required. Does computer modelling provide this technical basis? The main objective of catchment modelling is to provide a predictive capability, and this constrains the type of model we can use. Firstly, the model must be process-based. Secondly, it can require extensive data sets to separately calibrate and test the model with, and are often not available at the catchment scale. Thirdly, management decisions based on technical grounds require economic analysis, *ie.* the outputs of the biophysical models are used as inputs into economic models. Finally, the land management options are implemented at the farm level, which is usually a very different scale from that of modelling and data collection. Not surprisingly, many are sceptical of the role that modelling can play, and are not confident in the predictions from models. This is complicated by the marketing and availability of a range of models of varying complexity.

We use the field site of the Liverpool Plains, a 12,000 km^2 catchment in north-eastern NSW., to explore the modelling process. This is a National Dryland Salinity Program focus catchment, which means there has been considerable investigative work done within the catchment, and a large amount of data collected over many years for calibration and testing of models. The aim of the modelling exercise is to predict the impact of land use change on groundwater levels, and present the results in a form useable for economic analyses. This work is part of NRMS Project D6026 the aim of which is to critically review the usefulness of models in catchment management, from land mapping, to recharge estimation, and through biophysical and economic modelling to provide land management options. Within the groundwater modelling component of this project, two models are being compared with contrasting levels of complexity. In this work we endeavour to use the simplest possible model that captures the key processes and interactions of the system. The aim of this paper is to examine the value that is added to management decisions by mathematical modelling of existing field data.

2. SITE DESCRIPTION

The Liverpool Plains (Figure 1) consist of extensive alluvial black soil plains (40%), partly surrounded by the forested Liverpool Ranges (20%), and intruded with sandstone hills and ridges (40%). The hills and ranges were partially cleared in the 1800s for grazing. The alluvial black soils were originally covered by tall native grass, and were only cleared for cropping in the 1950s when technology and agricultural practices allowed economic large scale tillage. These plains are a rich agricultural area, which Greiner [1994] estimates have an annual production value of AUS$150 million.

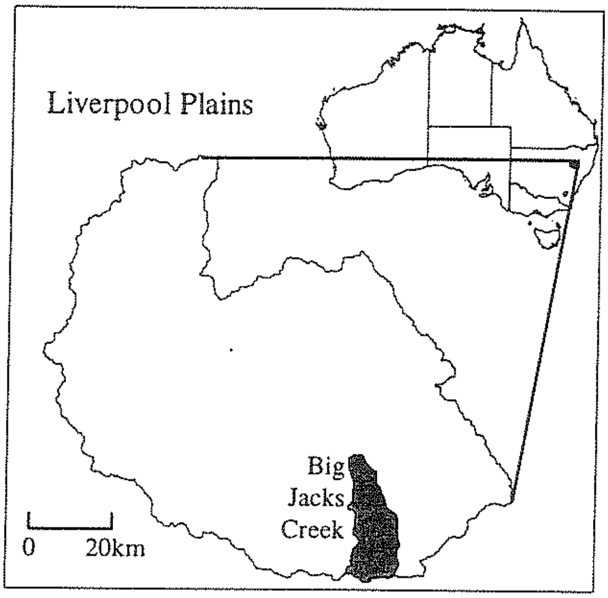

Figure 1: Locality map of the Liverpool Plains and modelled sub-catchment.

Annual rainfall grades from 1200mm in the ranges to around 500mm in the western part of the plains. The high rainfall and relatively shallow red-brown earth soils of the Liverpool Ranges contribute a large amount of water to the plains in the form of surface runoff and stream flow. Zhang *et al.* [1997], following Holmes and Sinclair [1986], have estimated the amounts of total discharge from the Liverpool Ranges under native cover and all agriculture conditions.

The key groundwater features related to dryland salinity problems on the plains are the unconsolidated alluvial formations overlying the bedrock. The upper formation is a deposited clay layer up to 50 m thick, named the Narrabri Formation. This overlies a highly conductive aquifer between 5 and 100 m thick consisting of boulder, gravel, and sand beds, named the Gunnedah Formation. This aquifer is partly exposed at the land surface at the contact zone between the basaltic highland ranges and the alluvial plains. Basalt lies beneath the hills and extends partly under the plains. At the outlets of each of the surface water sub-catchments the underlying material is comprised of sandstone and conglomerates, and this forms hills and ridges within the plains.

Despite the large annual volumes of water coming from the Liverpool Ranges, permanent streams do not exist across those catchments affected by dryland salinity. Direct infiltration of runoff water through exposed gravel beds at the contact with the plains provides an important mechanism of recharge to the Gunnedah Formation. The other recharge mechanism of interest is deep drainage below the root zone of crops on the black soil plains. It is the relativity of these two components that will determine the choice of management options to control dryland salinity.

In the lower parts of the catchments, groundwater flow within the Gunnedah Formation is restricted by the intruded sandstone hills, which reduce the width of the valleys and aquifers. In addition the aquifers generally become thinner, and consist of finer material toward the outlets. This combination places restrictions on outflow both laterally and vertically, and contributes to high groundwater levels. Increased recharge from runoff and below crops, and groundwater constrictions, combine to produce rising water tables in the Liverpool Plains. Broughton [1994] found widespread evidence of rising water tables and salinity, and estimated that 1,200 km^2, or 25% of the productive area, could be lost to dryland salinity within 20 years unless water levels are stabilised. Dryland salinity occurs in parts of the Liverpool Plains while, ironically, in other areas groundwater levels are dropping due to irrigation pumping.

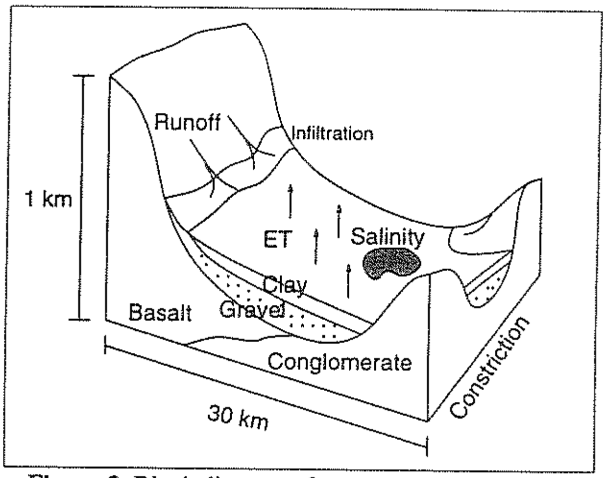

Figure 2: Block diagram of conceptual groundwater system.

3. ASSUMPTIONS AND KEY PROCESSES

The conceptual model used here has been described in detail by Stauffacher *et al.* [1997], and a summary of the principal features follows; see also Figure 2.

- The Liverpool Plains groundwater system can be broken into a number of independent sub-systems due to the low permeability of the underlying basement aquifer and geological constrictions. This allows sub-systems to be modelled and managed separately.
- Dryland salinity occurs because of a lack of surface water drainage and the presence of groundwater constrictions. This means the aquifer cannot carry

sufficient amounts of groundwater and therefore some must be lost through evapotranspiration.

- The alluvial system has two layers: the upper low permeability Narrabri Formation, and lower high conductivity Gunnedah Formation.
- There is reasonable hydraulic connection between the layers, and on the temporal and spatial scale of interest, heads in the confining layer are in equilibrium with the heads in the conducting aquifer.
- All lateral fluxes occur within the Gunnedah Formation, which is assumed to always be under pressure.
- Conditions that contribute to dryland salinity are narrowing of the catchment, thinning of the aquifer, decrease in mean permeability, and decrease in groundwater gradient (due to reduction in mean surface slope).
- In many dryland situations, the loss of groundwater by evapotranspiration is limited by vertical permeability and this leads to groundwater pressures higher than the land surface. Field data suggests that few areas in the Liverpool Plains have artesian groundwater.

4. CONCEPTUAL AND NUMERICAL MODEL

The conceptual model used here has one-dimensional flow along a tube, and can be easily modelled with the groundwater equivalent of a diffusion equation. We use a standard water balance approach, by equating change in water storage with time, to the change in flux with length, and assuming incompressible media, and no thermal or solute effects on properties. Taking into account the features of the conceptual model, the differential equation solved for this work is:

$$\rho_2 \frac{\partial A_2}{\partial t} = \frac{\partial}{\partial x}\left(-A_1 K_1 \frac{\partial h}{\partial x}\right) + R \qquad (1)$$

where ρ is porosity ($L^3\ L^{-3}$), A is cross-section area (L^2), K is hydraulic conductivity ($L\ T^{-1}$), h is hydraulic head (L), R is diffuse recharge per unit length ($L^3\ T^{-1}\ L^{-1}$), t is time (T), x is distance positive downslope (L), and subscripts *1* and *2* refer to the conducting and confining layers respectively. The formulation of flux on the right-hand side of (1) allows for all forms of constriction of groundwater flows important in the aquifer systems of interest. Analytical and numerical solutions of diffusion equations have been widely studied in hydrological and chemistry literature, and the behaviour of solutions of (1) are well understood; see Crank [1975], for example.

Equation (1) has been written in finite difference form, and solved explicitly. The boundary condition used at each end of the tube is a flux; at the top end it is a flux of water directly infiltrating into the conducting aquifer, and at the lower end it is a flux calculated from the last head to a fixed regional head further downstream. Diffuse recharge through the confining layer is allowed along the length of the tube at a fixed rate. The discharge process is controlled by setting a maximum discharge rate. By setting this rate to a large number all water that exceeds the storage will be removed, and by setting it to a small number or zero, some or no water will discharge and heads in the conducting aquifer become artesian. In this work, all water in excess of storage is considered to be discharge.

A single tube is the simplest case of an alluvial groundwater system. There are also tree-like structures of high permeability, which follow the original paleo-stream network. A model has been developed that treats these networks. In this paper we will consider a single sub-catchment of the Liverpool Plains which is well represented by the single flow tube. Big Jacks Creek is a 280 km^2 sub-catchment of which the lower 113 km^2 is downslope of the alluvial contact zone and included in the model.

5. CALIBRATION

The parameters in the numerical model include the physical size of the conducting aquifer, the properties of the aquifer, and the temporal distribution of runoff and recharge fluxes. There are approximately 6,000 bores available in the Liverpool Plains database. Of these, 95% are in the two largest sub-catchments which show little evidence of salinisation, do not fit well with the conceptual model, and are not included in the current work. Of the remaining bores only 25% have both useable lithological and water depth information. Further these bores were drilled for water supply and tend to be distributed in clusters, away from the boundaries of groundwater systems, and measurements of the physical properties were not make. This data source is therefore not optimal to provide information in cross- and long- sections required to comprehensively parameterise a groundwater model. There was little bore hydrograph data to test the dynamic aspects of the model, *ie.* increased groundwater recharge over time, or seasonal dynamics, and we therefore present long-time steady-state results.

The thickness and extent of the Gunnedah Formation has been estimated for Big Jacks Creek. There are no estimates of porosity or hydraulic conductivity available. Broughton [1994] estimated on the basis of material descriptions from lithological logs, that hydraulic conductivity ranged from 10 to 100 m d^{-1}, and we have used a porosity value of 0.2. To estimate the conductivity in the upper parts of the catchment, we assumed that flux and heads were in equilibrium, and inverted Darcy's Law thus:

$$K_1 A_1 = q \,/\, \frac{\partial h}{\partial x} \qquad (2)$$

where q is the average annual input from the Liverpool Ranges ($L^3\ T^{-1}$). This estimate can be redone for any subsequent re-estimation of q. Dividing the lumped parameter K_1A_1 by the cross-sectional area of the aquifer as estimated from lithological logs, we were able to compare the conductivity values with those in Freeze and Cherry [1979] for appropriate aquifer material. For the discharge area, we assume the conductivity is the same or lower, according to the common paradigm that conductivity decreases down gradient with increasing clay content.

Annual runoff from the Liverpool Ranges was estimated by Zhang *et al.* [1997], and diffuse recharge was based on a figure of 20 mm yr^{-1}, consistent with the work of Greiner and Hall [1997] and Abbs and Littleboy [1997]. Greiner and Hall [1997] used a "hydrological connection" value of 60-80% for runoff as input to the plains, where we have assumed that 100% of runoff infiltrates through the contact zone.

The model was run with the average annual conditions until an equilibrium condition was reached, and initial groundwater heads set as the estimated current condition. The catchment was set to discharge as much water to the surface as necessary to maintain heads in the Gunnedah Formation at the land surface only in these initial runs. With a perfectly calibrated system in equilibrium that exactly fits the conceptual model, the heads would remain the same from the start of the simulation. The differences between modelled and estimated heads will be the result of some combination of the inadequacy of the conceptual model, how far out of equilibrium the system is, how poor the estimation of parameters is given the sparse data, and the lack of calibration of the physical properties of the aquifer.

6. RESULTS AND DISCUSSION

Zhang *et al.* [1997] estimated runoff from the Liverpool Ranges into Big Jacks Creek as 28.7 M m^3 yr^{-1}, and diffuse recharge, based on 20 mm yr^{-1}, as 2.2 M m^3 yr^{-1}. On first examination it is obvious that the runoff input greatly exceeds the recharge, in this case by an order of magnitude. If the greater proportion of runoff becomes infiltration, then this leads to three simple conclusions about this, and other similar, systems. Firstly, the commonly held theory that changes in diffuse recharge of the order of 40 mm yr^{-1} are responsible for widespread dryland salinisation does not apply in these catchments. Secondly, and closely related, is that the common management emphasis on reduction of water lost past the root zone of agricultural crops will have local effect only. Finally, a meaningful reduction in gross inputs will involve the capture, or reuse, of a large volume of water.

To understand the results of the modelling we introduce the concept of aquifer carrying capacity, defined as:

$$q_{cap} = K_1 A_1 \frac{\partial h_s}{\partial x} \qquad (3)$$

where q_{cap} is the aquifer carrying capacity (L^3 T^{-1}), and h_s is the land surface elevation (L). While this is not strictly true in all cases, it is a useful simplification for our purposes.

This represents the maximum flux of water through the aquifer when it is full. When the total input of water exceeds the carrying capacity, discharge occurs. We define the hinge line as the point where the input flux equals the carrying capacity. Within the discharge area, the difference between input flux and carrying capacity equals the water discharged. The impact of changing recharge on the position of the hinge line is depicted in the graph of carrying capacity, see Figure 3. If we assume that 100% of runoff becomes recharge and use the figures from Zhang *et al.* [1997] for native cover and all agricultural conditions, then the effects are illustrated in Figure 4.

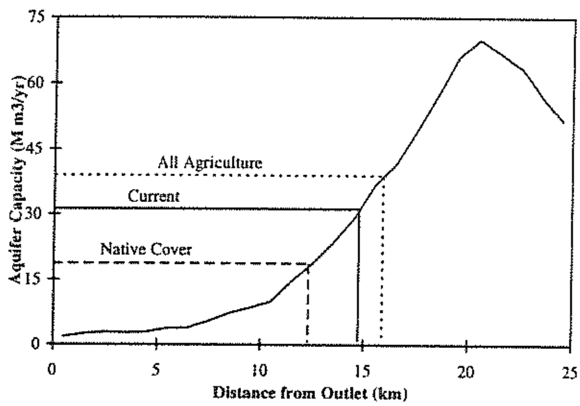

Figure 3: Big Jacks Creek aquifer carrying capacity with distance from outlet. Note lines indicating current, native cover, and all agricultural land use.

The most important point to note is that current inputs are at the steepest part of the curve. This means that for a unit decrease in aquifer inputs, there is the smallest decrease in distance from the outlet. This implies that even a large reduction in the inputs, from either runoff or diffuse recharge, will result in only a small amount of land being reclaimed, or receiving lower water levels.

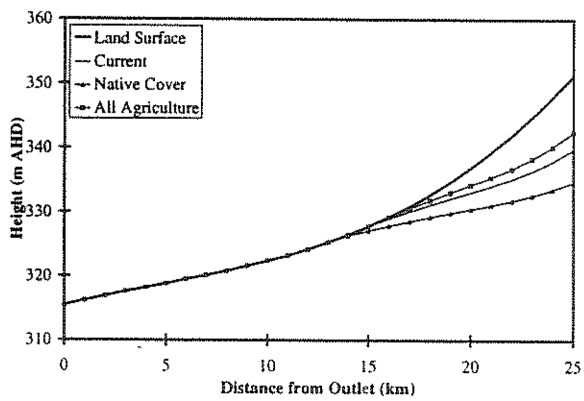

Figure 4: Modelled long term heads for Big Jacks Creek assuming current inputs, and those under native cover, and all agricultural land use.

If we again assume that 100% of runoff input becomes infiltration, then the modelled heads at steady-state are shown in Figure 4. Long-term modelled heads have a root mean square error of 3.4 m compared to estimated current water levels; this result is encouraging given the lack of calibration and simplicity of the model. The land surface becomes steeper at the location of the hinge line, and this is why the discharge area is relatively insensitive to changes in water inputs. It shows that most of the differences in treatments are storage changes in the recharge area. It can be further seen that full reforestation causes little change to the discharge area; the system is full and it will take a very long time for heads to lower. Further evidence of this is that the discharge areas account for a large fraction of the alluvial system.

The discharge rate has been calculated from the difference between aquifer carrying capacity and input flux along the flow path. These rates based on 100% runoff input are not physically reasonable, being of the order of 100 to 700 mm yr^{-1}. Also when one looks at the fitted lumped conductivity values from (2) of 100 to 500 m d^{-1}, these are also not consistent with similar Australian depositional landscapes (W. R. Evans, pers. comm.). Therefore we suggest that less than 20% of runoff can infiltrate into the Gunnedah Formation. Where does the other 80% of the runoff go?

An examination of the field data suggests that it does not enter the basement rock. And while there are no permanent streams in this catchment, the area is subject to flooding, and recent data suggest that 25% of the runoff may exit the catchment in this way. We believe that the other 55% must be lost through evapotranspiration as it spreads over the contact zone and onto the plains. This result has significant implications for modelling, and land management on the plains. It brings fitted conductivities into the range of 20 to 100 m d^{-1}, and discharge rates to less than 100 mm yr^{-1}. This further suggests that runoff infiltration recharge is only twice as large as diffuse recharge, and hence brings back into consideration recharge reduction below crops.

While this result is preliminary, it does show the importance of using a simple water balance to ensure inputs are in a reasonable range. None of the work here uses complex models and procedures, allowing the information trail to be easily followed from data analysis, through the model, and to the results. While these results are inputs to economic models, the head values themselves will not be taken simply at face value, but interpreted according to the understanding of the system and the relativity of fluxes and parameter values we have gained through the modelling process.

The iteration between calibration and application is rapidly converging on an acceptable range of values for parameters and outputs. Firstly we have clarified the relative importance of recharge from runoff and diffuse sources, and this determines possible land management options. Secondly we have estimates of groundwater fluxes useful for the design of groundwater pumping schemes. For example it may be feasible to pump relatively fresh Gunnedah Formation water from dryland salinity affected catchments to nearby catchments with large irrigation drawdowns. Thirdly the results show there is an imbalance between runoff from the ranges and input to the Gunnedah Formation, resulting in a large additional water balance term on the plains. Finally the modelling has shown the importance of catchment geometry on the dryland salinity process. It would be relatively easy to identify catchments with similar geometry, from elevation data alone, to help identify others at risk of salinity in the region, without the need for detailed data collection and modelling.

In principle, we could have performed the same exercise with a more complex model, such as MODFLOW (McDonald and Harbaugh, 1988) or SHE (Abbott *et al.*, 1986). In practice it is much more cumbersome to perform the basic data handling and problem definition tasks. Further, the model complexity can hide the information trail and make it difficult to relate results back to input data and parameter values.

There is often the tendency with complex models to enter a calibration exercise without thinking through the important questions and processes. It can be difficult to suppress the temptation to fit all possible model parameters without recourse to the data available to fit them. A system with more parameters to be fitted than the number of degrees of freedom in the data, or the number of independent data sources, is described as over-determined. Without careful control on the spatial distribution and possible range of fitted parameters, there theoretically exists an infinite number of solutions of the parameter values. We suggest that analysis using an under-determined system can provide insight into the processes and range of input and state parameters, and point to further needs in terms of data collection and analyses.

7. CONCLUSIONS

While the model itself may not supply the important conclusions or management options directly, the process of generating a conceptual model and fitting field data into the numerical model critically challenges our thinking and understanding about the system, and this provides insights into management requirements. As a corollary, a complex model may mask or obfuscate the key interactions and information trail that challenge us to rethink and re-examine our understanding of the processes and interactions.

We suggest that significant value has been added to our understanding of Big Jacks Creek through the fitting of a conceptual model, and analysis of data through our simple numerical model. The conclusions reached have significant management impacts, as well as being useful for later economic analyses. We also suggest that such value can be added to similar catchments in the region.

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