Biophysical Modelling of Catchment-Scale Surface Water and Groundwater Response to Land-use Change

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Abstract: The effect of land-use change on salt and water balances of catchments in Australia has been significant. Impacts of these changes are often masked by large time lags between the changes and their subsequent expression. Successful management relies on information that allows these changes to be understood and predicted. In the absence of detailed hydrogeological and hydrographic data, a simple approach is required. A logistic function model is introduced, which weights changes in recharge to changes in discharge according to a characteristic time-scale and a rate of change. This response function approach has been used to estimate the time lags for individual groundwater flow systems. These temporal responses can be aggregated to estimate whole catchment behaviour. Using this model, the predicted future effect of a range of afforestation strategies on catchment salt load has been simulated for sub-catchments of the mid-Macquarie (New South Wales, Australia).

Keyword: Groundwater flow system; Groundwater response; Land-use change; Catchment salt load

1. INTRODUCTION

Predicting and managing salinity at a regional scale is becoming increasingly important, especially considering recent political processes. Answers are needed to questions such as how to set salinity targets, what is the cost of salinity, and how will options vary according to landscape and catchment land-use. Understanding the groundwater processes that drive salinity is an essential component of this. The overall combined responses from the range of groundwater flow systems within a catchment to these land-use changes needs to be determined. However, in going to this regional scale, data scarcity becomes more acute while a predictive capability is still needed. Groundwater models already exist to predict the outcomes of land use changes, although at this scale their data requirements can not be satisfactorily met, even for more intensively studied catchments. As a result, there is a need for simple methods.

This study has adopted a classification approach in disaggregating a catchment into component groundwater flow systems, which account for most of the variation in processes and properties that lead to different responses to changed land use. The study has used relationships between catchment yield and land-use, together with a two-parameter groundwater discharge function for each flow system type, to estimate the changing groundwater response over time.

The overall objective of this work is to predict the time scales of salinity changes, as well as the magnitude of the changes (and hence costs). This work is part of a larger project which is looking at how adoption, policy and planning react to accommodate these changes.

The aim of this paper is to discuss the rationale behind the catchment classification approach to landscape disaggregation, present the predictive methodology, and apply it to part of the Macquarie catchment (NSW, Australia) as an example.

2. LANDSCAPE DISAGGREGATION

Groundwater discharge occurs via two pathways, to land and to streams. Suitable landscape disaggregation that addresses both these pathways is needed, and is an important first step towards the successful prediction of salinity at a regional scale [Gilfedder and Walker, 2001]. A range of landscape disaggregation techniques have been used by previous catchment scale salinity studies [see Salama et al. 1997, 1999; Sinclair Knight Merz, 1999]. These studies have attempted to separate catchments into hydro-geomorphic units (HGU) based on slope and elevation. These units were used to identify areas of recharge and discharge, construct groundwater head surfaces, and analyse catchment response. These HGUs are contiguous units, but they are discontinuous within sub-catchments. A constant rate of water-table rise has been used in some of this work, which avoids the need to specify water movement to streams. In our view, this approach needs further work to examine how these systems connect to streams. If entire Groundwater Flow Systems (GFS) are used when modelling temporal changes in recharge due to land-use change, it is not necessary to estimate groundwater movement to streams separately, because GFS are continuous within sub-catchments.

The Australian Groundwater Flow Systems (GFS), developed by Coram et al. [2000], have been used as the basis for the spatial disaggregation described in this paper. This national framework was developed to classify the groundwater systems across Australia in a consistent manner for comparing data sets and experiences in land degradation. The classification has two levels: (i) the scale of the GFS, and (ii) the specific landscape characteristics that lead to dryland salinity.

There are three types of GFS in the classification, each representing a different scale of operation. The first are *Local Systems*, which have shallow depths, with recharge and discharge areas close together (in the order of 1 to 5 km). They tend to occur in areas of high relief, are generally coincident with topographic catchments and are usually unconfined. The second are *Intermediate Systems* that occur in foothills and valleys, are not coincident with topographic catchments, have a scale of 5 to 50 km, and may be overlain by local flow systems. The third type are *Regional Systems* having relatively deep circulation depths (c. >100 m), and tending to be confined and with very long groundwater flow paths and consequent residence times. The typical scale of a regional flow system is 50 km or more. These systems can be overlain by local and intermediate flow systems.

Conceptually, the GFS have been defined as integral units of flow in that they encompass both the recharge and discharge areas. They also have been defined by a response function (see §4.1). The GFS approach adopted for this study was based on the methods developed for the national approach, but was applied to detailed local data. The primary attribute to distinguish between the three flow systems was a combination of slope and geology.

Given the scale of the modelling in this study when compared to the scale of local groundwater flow systems, it was necessary to define regions within which numerous local flow systems occurred. It was assumed that a single response function could be used to predict the cumulative effects of a distribution of responses from multiple groundwater systems.

3. RAINFALL PARTITIONING

A second important step in regional scale salinity predictions is to develop a response variable that captures the main elements of change within the natural system being modelled. As the salinity problem is driven by changes in recharge due to land use change, this would be the most efficient response variable to model. In previous work [Sinclair Knight Merz, 1999], the response variable modelled was the change in water-table level. This produced immediate inefficiencies, because to predict future salinity extent, translation functions were needed to determine water-table response from a given land use change.

The ability to partition rainfall into evaporation, runoff and recharge for a given catchment scale land use distribution is of paramount importance for salinity prediction. There are many complex models at a range of spatial and temporal scales available to perform water-balance studies, although many are constrained by data availability and hence are not suitable for this study.

The model described in this paper imposes a three-component water-balance, partitioning rainfall into evaporation, runoff, and recharge. The work presented in the following sections is based on Zhang et al. [2001] and Petheram et al. [2000].

3.1 Rainfall - Evapotranspiration Relationship

The two largest components of water-balances in Australia are rainfall and evapotranspiration. There are many processes that could be considered to estimate evaporation and plant transpiration at a point. Zhang et al. [2001] reviewed nearly 300 catchment experiments worldwide (96 of these in Australia), and developed a two-parameter model that described the difference in evaporated rainfall between fully forested and fully cleared catchments. Their model is:

$$ET = P\left(\frac{1 + wEo/P}{1 + wEo/P + P/Eo}\right) \qquad (1)$$

where *ET* is annual evapotranspiration in mm, *P* is annual rainfall in mm, *Eo* is potential ET calculated from Priestley and Taylor [1972], and *w* is a plant available water parameter. *Eo* is assumed to be a constant (*Ez*), and for forested catchments *Ez*=1410 mm and *w*=2.0, and for cleared catchments *Ez*=1100 mm and *w*=0.5. Equation (1) provided very good correlations (r^2=0.93 in forested, and r^2=0.90 in cleared catchments) between annual evaporation and measured rainfall minus streamflow [Zhang et al., 2001]. Figure 1 shows the envelope produced by (1).

Where a catchment has mixed vegetation, the catchment average annual evapotranspiration will be somewhere between the curves in Figure 1. Zhang et al. [2001], proposed a simple linear model, where the proportions of forest cover and cleared area in a catchment are multiplied by the respective evapotranspiration values and summed to get a combined total, and therefore excess water amount. Table 1 was used as a first estimate of how different land cover types may respond relative to native vegetation.

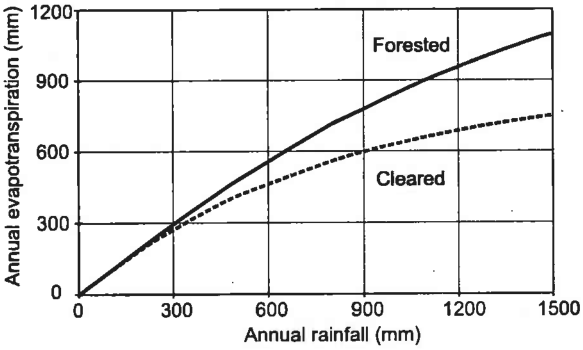

Figure 1. Curves for forested and cleared catchments [Zhang et al., 2001].

Table 1. Vegetation types as a proportion of the difference between fully forested and cleared.

Vegetation Cover Type	Proportion 'Forest'
Native vegetation	1.0
Forestry	0.5 - 1.0
Woodland or Lucerne	0.5
Opportunity or Improved Cropping	0.25 - 0.50
Perennial Pastures or Grazing	0.00 - 0.25
Annual Pastures or Cropping	0.0

Source: Zhang et al. [2001].

3.2 Rainfall – Recharge Relationships

After partitioning rainfall into evapotranspiration and excess water components, a far more difficult task is to separate this excess water into groundwater recharge and surface water runoff components. Vertessy and Bessard [1999] used Zhang curves to examine the negative impacts of the expansion of forestry in the upper Murrumbidgee Catchment at equilibrium. However, to look at temporal changes in groundwater systems under changing management, the break-up between fast (surface water runoff) and slow (groundwater discharge) components of catchment stream flow is needed.

Petheram et al. [2000] reviewed published recharge studies from across Australia. Figure 2 shows the scatter of data from all reviewed recharge measurement studies, and includes the Zhang curves of excess water (i.e. annual rainfall minus estimated annual evapotranspiration). Petheram et al. [2000] also stratified the data by broad soil types to gain further insight into the recharge process, and found that a satisfactory relationship could be established between rainfall and recharge for annuals on sandy soils (r^2=0.60).

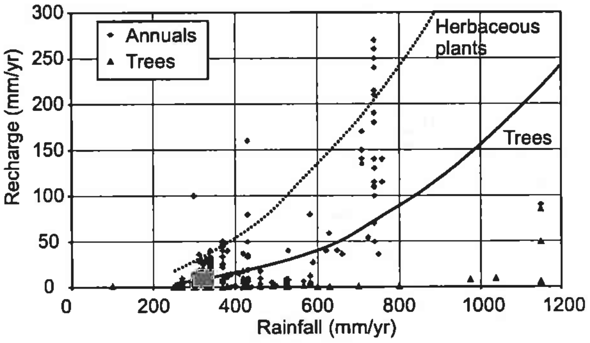

Figure 2. Measured recharge from southern Australia for different vegetation types. Zhang curves for expected non-transpired water are also shown. [from Petheram et al. 2000].

The data presented by Petheram et al. [2000] are consistent with the Zhang curves, which provides more confidence in the use of these curves at the catchment scale, and as a starting point for runoff-recharge partitioning. Based on broad soil types, values were used to estimate the fraction of non-evaporated rainfall from Equation (1), that becomes recharge (Table 2).

Table 2. Recharge fraction of non-evaporated rainfall for generic soil type descriptors.

Soil Type/Texture	Recharge Fraction
Sand	0.90
Sandy-loam	0.75
Loam	0.50
Clay-loam	0.25
Heavy Clay or Duplex	0.10

The values presented in Tables 1 and 2 are crude estimates. In practice, these values become fitting parameters so that both water and salt balances can be attained in each catchment. For example, a catchment may have a clay-loam soil type, which Table 2 suggests has annual recharge equal to 25% of excess water. If equilibrium salt loads indicate that there is a greater proportion of surface runoff, then this value may be changed to 20% without violating either the general soil type description or the relative values in Table 2. If the required value was closer to 10% then this may indicate a problem with the scale and accuracy of input data, the form of relationships used in the model, or a change in the dominant processes occurring in a specific catchment. If it is not a question of input data, then this will provide valuable insight into the sub-catchment of interest.

3.3 Rainfall Partitioning Discussion

This approach relies on there being a unique value of each component. The greatest variation of data around the Zhang curves occurs when the two lines become close, at low rainfall. This is explained by the fact that more subtle local factors influence the amount of excess water and its partitioning in these zones. In such cases, it may be desirable to impose a fixed average water balance not based on the gross parameters that apply at higher rainfalls. For example, recharge may be zero under native vegetation with 300 mm annual rainfall, and 20 mm per year under any other land-use.

A second issue is that of flood recharge. In many parts of south-eastern Australia, floods occur regularly and are an important mechanism for groundwater recharge, usually associated with regional groundwater systems. In a real annual sequence, recharge might be zero for nine years then 100 mm in the 10th year due to a flood event. To include such details in an annual model, knowledge of the flooding frequency and recharge volumes is required to apply a fixed minimum annual recharge to the annual estimates. Without this "adjustment", the simulated water and salt balances may be impossible to reconcile with observed fluxes.

4. GROUNDWATER RESPONSE

As mentioned above, a key attribute of any groundwater system is the length of time taken to reach an equilibrium state when the long-term recharge pattern is changed – the equilibrium response time. This attribute is conceptually based on a groundwater system's capacity to accommodate variations in inputs by allowing additions to storage as a buffer before discharge has balanced the new recharge regime. The concept relies on there being a distribution of annual recharge in response to long term climatic variability and that this distribution may change significantly with land use. Thus, a recharge event of a certain magnitude has a probability of occurring in any one year, and the response of the system to this time series of recharge relies on the aquifer's ability to allow the net water to pass through the system.

The use of unit response functions to reproduce the behaviour of streamflow and groundwater responses to discrete rainfall or recharge events is well established in hydrological literature – for instance, see Sherman [1932] as reported in a review by Moussa [1997]. In more recent work, Yu et al. [1999] examined and developed methods as an approach to avoid more complex approaches, for calculating parameters for a solution for breakthrough curves subject to step and impulse changes in input. These cases are exactly those used in the recharge response curve approach in this paper.

Wittenburg [1999] looked specifically at the partitioning of the water pathways of rapid surface runoff and slower groundwater discharge, and aimed at separating these two components on a storm hydrograph scale. This is relevant to the model used in this paper as it also distinguishes between surface runoff and groundwater components, albeit on an annual time-scale.

Luther and Haitjema [1998] examined the residence time distribution of recharge water in a groundwater system with varying degrees of spatial heterogeneity. They used MODFLOW [McDonald and Harbaugh, 1988] and found that where aquifers: (i) are uniform and homogenous, (ii) have properties which vary in a systematic manner that maintains a relatively constant value of recharge per unit thickness of aquifer, or (iii) have properties which are randomly distributed, that the residence time of water in the groundwater system is predictable, and that all three cases result in the same distribution.

We therefore conclude that it is reasonable to select a simple response function without regard for the internal variability within a larger catchment.

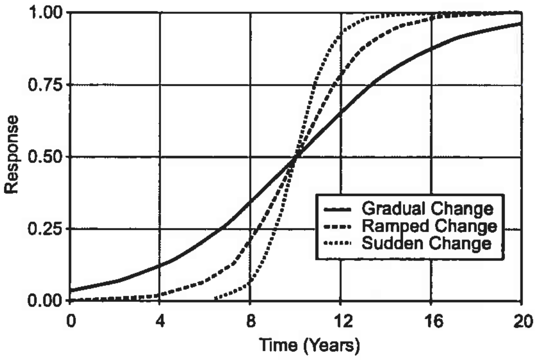

Figure 3. Discharge response function examples.

4.1 Discharge Response Function

A simple model of response to change has been used that weights changes in recharge to changes in discharge, according to a time scale and rate of change. The model is a logistic function and assumes independent annual recharge pulses, that the response is linear and additive, that recharge from year to year is not correlated, and that the discharge response is not hysteretic.

$$D(t) = \frac{1}{1 + exp\{(t_{half} - t)/t_{slope}\}} \qquad (2)$$

Equation (2) is the adopted function for discharge response to a time varying recharge input. t_{half} is the time until 50% of the recharge has passed through the system, and t_{slope} defines how steep the central portion of the curve is. Figure 3 shows the form of the function with values of t_{half}=10 years and t_{slope}=0.75 (sudden), 1.5 (ramped) and 3 (gradual). These values may be representative of small unconfined flow systems where recharge passes relatively rapidly through the aquifer material, and a new equilibrium in discharge is reached after only 20 to 30 years. For intermediate and regional systems, the time scale increases to many hundreds of years, while the slope parameter provides scope for controlling the rate of change of discharge area.

Equation (3) represents the response of the groundwater system to a single unit step change in recharge. With the assumptions stated earlier, the discharge response can be summed for each annual increment or decrement in recharge as follows.

$$G(t) = R_0 + \sum_{i=1}^{t} (R_i - R_{i-1})\, D(t-i) \qquad (3)$$

where $G(t)$ is the total groundwater discharge, R_0 is the historical equilibrium recharge rate, R_i is the recharge in year i, and $D(t-i)$ is the discharge response function of Eq. (2). In many applications it is necessary to consider continuous land use change, so it is very useful to have set of equations that are linear in changes to recharge, which allow a variety of changes to be superimposed.

4.2 Discharge Partitioning

This model allows for water to be discharged from a groundwater system: by direct discharge to a stream, and as shallow water-tables leading to land salinisation. The style of the partitioning used maintains the philosophy of the modelling approach by capturing the net effects in a meaningful manner, rather than attempting to follow individual processes. The break-up between these was determined using a simple threshold, where groundwater discharges to the stream until a maximum rate is achieved, then shallow water-tables develop and land-based discharge starts occurring. Ultimately this threshold was fitted using historical evidence of the onset and spread of stream and land salinisation, in concert with the shape of the groundwater discharge function. By altering the threshold, a catchment could be made to mimic degradation from land salinisation only, or conversely, by stream salinisation only.

In some cases a regional system may have a component that flows past/beneath a river and outside of the model domain. This flux is set within the model. This situation is expected to occur in some of the Victorian deep lead systems flowing beneath the River Murray.

5. MID-MACQUARIE CATCHMENT

This method was applied to the mid-Macquarie catchment (New South Wales, Australia), as an example of the method (Figure 4). Catchment salt and water balance information was obtained from Jolly et al. [1997]. This confirmed the partitioning of rainfall into evaporated and non-evaporated components. The median stream salinity and salt load from Jolly et al. [1997] allowed the partitioning of non-evaporated water into either recharge or runoff.

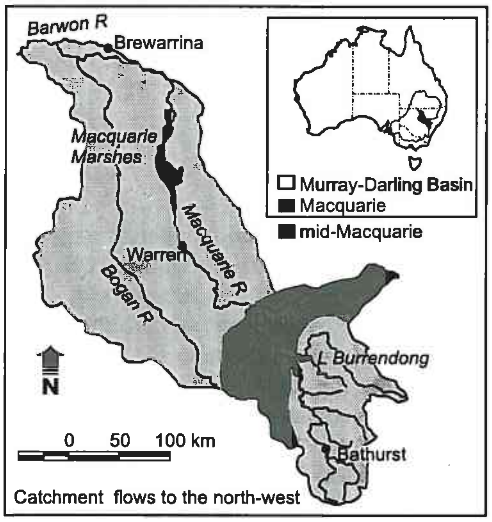

Figure 4. Macquarie catchment. Mid-Macquarie study area shown (Lake Burrendong to Dubbo).

Initially, the discharge parameters of Bell and Heaney [2000] were used. However, improved parameters have been developed and applied to the five selected sub-catchments of the mid-Macquarie. The targeted areas made up 22% of the catchment, being local-scale systems with elevated stream salinities.

Total salt yield from the mid-Macquarie was simulated 200 years into the future for three scenarios: a) no change to current forest cover, b) targeted replanting of 22% of catchment between 2000 and 2015, and c) blanket reafforestation of entire catchment over the same time (Figure 5). The model suggests that impacts of last century's clearing will not reach an equilibrium for almost another 100 years, while it predicts that the effects of the 3 current scenarios will not begin to reduce stream salt loads for at least 50 years.

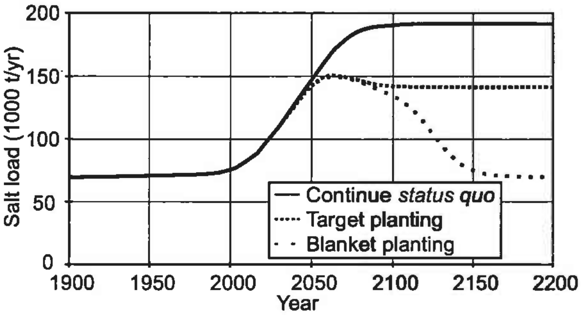

Figure 5. Modelled salt load from mid-Macquarie.

6. DISCUSSION

This approach shows the success of keeping things simple. With limited available hydrogeological data at the catchment scale, methods such as has been described in this paper are useful for building in the time lags in response to land-use changes. As more information becomes available there will be greater confidence in how groundwater systems behave. Improved response functions are being developed which use more complex groundwater system attributes [Gilfedder et al. 2001].

7. SUMMARY

A simple method has been developed to provide a useful temporal link between land-use change and subsequent changes in catchment salt balance, which is suitable for the level of currently available data. An underlying assumption for this conclusion is that given the current data availability and conceptual understanding, simple models are the only ones that can be realistically applied at this scale. This method estimates the time lags involved in the effects of land-use changes, makes them clear to policy planners, and hence allows them to be built into policy target frameworks.

8. ACKNOWLEDGEMENTS

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