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Predicting groundwater response times and catchment impacts to landuse change

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Abstract: Natural resource managers are becoming increasingly interested to incorporate into policy and investment frameworks the likely groundwater response time and spatial patterning of variable land management options. Until recently, predicting the response times of groundwater systems to a range of investment strategies (eg. agronomic changes and recharge management options) has relied on bounded analytical solutions or empirical observations from trials which rarely impact large areas. This paper describes and evaluates an approach to describe groundwater response times to changes in groundwater recharge from landuse and/or climate change. The approach is based on a derivation of the solution of the saturated flow equation and was applied to the upper Loddon catchment (6113 km^2) in south-western Victoria, Australia. It is demonstrated that the modeling approach is capable of representing the actual storage-discharge characteristics of sub-catchments. The objectives of this paper are to (i) estimate spatial variation in groundwater response times, (ii) identify locations in the landscape which have the greatest impact on watertable level and (iii) compare and evaluate the capacity of the modeling approach to account for landuse change. The modelling approach presented in this paper demonstrates the capacity to link a suite of farming system models into a catchment framework to derive spatially explicit recharge estimates which are integrated into a distributed groundwater model. In combination with the catchment depth to watertable impact mapping, the response time predictions derived using this modelling approach offer robust estimates of storage-discharge characteristics of catchments and can inform the development of transparent, cost-effective and targeted intervention strategies.

Keywords: *Groundwater, response time, distributed groundwater model, upper Loddon*

1. INTRODUCTION

Groundwater discharge to land surface and streams is a major process contributing to waterlogging and the delivery of nutrients and salt to streams. Understanding the time-lag between landuse change and groundwater response is fundamental to identifying where in a catchment to undertake mitigation programmes aimed at changing catchment condition within a specified timeframe. However predicting the timing of groundwater response to landuse change is difficult to estimate and subsequently not well understood, which is further compounded by limited data sets to quantify this process.

Previous studies have developed normalised relationships based on the saturated flow equation to develop generalized functions based on aquifer attributes (Glover and Balmer 1954, Kraijenhoff van de Leur 1958, Gelhar and Wilson 1974, Hookey 1987, Erskine and Papaioannou 1997, Manga 1999, Knight *et al*. 2005, Rassam *et al*. 2004). Gilfedder *et al*. (2003) derived a single similarity parameter describing the ratio of groundwater response to recharge and groundwater discharge.

A recent approach by CSIRO (2005) developed an idealized analogue of a sloping aquifer system for estimating the response of aquifers to changes in recharge and for predicting the time scale between changes in recharge and associated changes in discharge. This study developed two non-dimensional variables and used FLOWTUBE (Dawes *et al*. 1997, 2001) to compare results. However the idealised analytical solutions were based on strict boundary conditions such as the presence of groundwater divides across the upslope boundary, connection to stream across the bottom boundary and discharge only across the bottom boundary with no accounting for groundwater discharges to land surface. CSIRO (2006) extended this approach to account for groundwater discharge to land surface at a discrete location along the aquifer.

In contrast to analytical solutions, an alternate approach was the development of simplified numerical models such as FLOWTUBE (Dawes *et al*. 1997, 2001) which adopts a control volume construct of an aquifer flowline along which aquifer properties and recharge can vary. Whereas this model is based on Darcy's Law, Bidwell et al. (2007) developed and applied an eigenmodel approach derived from the partial differential equations of groundwater flow of the type embedded in distributed groundwater models and which was previously applied to the theory of groundwater discharge at catchment scale developed by Sloan (2000). Whereas the eigenmodel approach applies to any aquifer with linear behaviour (i.e. linear response of head to stress), regardless of its heterogeneity, geometry, or boundary conditions and can be analytically solved for homogeneous aquifers with simple geometry and boundary conditions, numerical methods with spatial discretisation of the aquifer domain are required for more complex conditions. This paper evaluates the effectiveness of applying a distributed groundwater model to estimate the groundwater response times to landuse change at a catchment scale. The objectives of this paper are to:

i. demonstrate a modeling approach that estimates the spatial variation in groundwater response times,
ii. identify locations in the landscape which have the greatest impact on watertable level, and
iii. compare and evaluate the capacity of the modelling approach to account for landuse and climate change.

2. THE UPPER LODDON REGION

The selected application catchment is the Loddon Catchment located in the North-Central region of Victoria. The upper Loddon catchment has been the focus of a recently completed data collation program (Wilford et al, 2007) and covers an area of approximately 611,316 ha. The catchment has a mean annual rainfall gradient between 410-1170 mm/yr, a mean annual surface water flow of 326,000 ML/y and a mean annual salt export of 111,000 tonnes. Dominant landuses are dryland grazing, production forestry and cropping respectively.

Surface geology in the upper Loddon Catchment varies, as does topography; elevation ranges from 105 mAHD in the north to 823 mAHD along the south-eastern boundary. Uplands geology is dominated by Palaeozoic meta-sediments, and to the north on the edge of the Riverine Plain surface geology is dominated by Quaternary alluvial sediments. Numerous Quaternary basalt eruption points and associated sheet flows cover much of the upland landscape. Buried sands and Miocene - Pliocene river gravels (known as 'deep leads' or Calivil/Renmark Group) meander beneath Quaternary geology as it extends north toward the Murray River.

3. MODELLING METHODOLOGY

The modelling approach used to derive recharge and groundwater response to landuse changes combines a suite of farming system models with a distributed, multi-layered groundwater model in a catchment framework. The farming system models account for topography, soil type, climate and land use. In this application the fully distributed multi-layer groundwater model MODFLOW (McDonald and Harbaugh, 1988) was adopted. The catchment framework is the CAT model (Beverly *et al.*, 2005; DSE 2007) which estimates the impact of various forms of intervention using a combination of paddock/farm scale models and a lateral flow model that are integrated into a regional catchment scale framework. This is achieved through the development of a surface element network that disaggregates the catchment into a series of connected units, each unit representing the paddock/farm scale. Each unit is evaluated using a modified one-dimensional farming systems model which simulates water balance, nutrient transport and production for a given combination of soil type, climate, topography and land practice. Connection to adjacent up-slope and down-slope elements enables the lateral redistribution of surface runoff and interflow (e.g. perched watertables) and facilitates the transport of water and nutrients from the top of the catchment to streams and end-of-valley. Underlying the surface element network is a three-dimensional representation of the groundwater system. Deep drainage from each surface element is spatially assigned to the underlying aquifer as recharge. The groundwater model laterally redistributes water and simulates time varying groundwater discharge to stream and land surface. The effectiveness of engineering options such as interception drains and groundwater pumps can also be assessed but this is not done in this study. This approach overcomes the need for the user to provide estimates of recharge *a priori* and enables the simulation of the impact of rising water tables on plant performance, production and extent of waterlogging.

3.1. Input data

Available spatial data layers were used. Land use and soil layers were based on 1:100,000 mapping, whereas slope, aspect and climate surfaces (specifically mean annual rainfall, temperature, solar radiation and potential evapotranspiration) were derived using 1:25000 scale digital elevation data. Climate data was available from 1957 to 2005. The climate surfaces were used to extrapolate and construct daily climate data files at every grid point within the modeled domain based on recorded meteorological data sets

3.2. MODFLOW enhancements

To meet the objectives of the study several modifications were incorporated into MODFLOW including:

- The landuse layer used in the surface hydrologic modeling was explicitly incorporated into the groundwater model. Evaporation depths and potential evaporation rates were spatially assigned to match the surface hydrologic model parameterization;
- Groundwater evaporation procedure was modified to match the root extraction algorithms adopted by each of the farming system models embedded in CAT as used to estimate surface hydrology and vegetation response;
- Incorporation of an optimisation approach based on Merrick (2002) to minimise the occurrence of dry cells and improve model calibration;
- Incorporation of an optimisation approach that is capable of modifying any attribute by layer by zone (in addition to river and general head boundary conductances) to minimize the error between predicted and observed baseflow, discharge zones and groundwater bore hydrographs;
- Incorporation of a well allocation scheme to account for poorly specified screen depths and miss assigned aquifer extraction volumes, and
- Incorporation of a sensitivity analysis routine that systematically reconstructs MODFLOW input data sets and reports modeled outputs. Information compiled can be used to assess the sensitivity of the model to variations in key input data sets.

3.3. Calibration strategy and sensitivity analysis

MODFLOW was calibrated based on matching 490 groundwater bore hydrograph levels, mapped salinity areas (assumed < 2 metre depth to watertable) and regional baseflow volumes. A comprehensive analysis was undertaken using the calibrated groundwater model to assess the sensitivity of key modelled outputs to variations in input data. Modelled outputs considered included baseflow volumes, saturated area and groundwater discharges (evapotranspiration, boundary fluxes and aquifer interflows). The objective of this analysis was to assess the robustness of the calibrated model and the uniqueness of the combination of input data variables with respect to modelled predictions and model attribution.

3.4. Impact of revegetation on watertable depth

An analysis was undertaken to estimate the impact of restoration/revegetation of native vegetation on watertable depth across the catchment. This approach identifies the area needed to be planted to trees in order to reduce the watertable beneath high-value assets within the catchment and was determined in the following way:

a) Catchment recharge estimates were derived using the suite of farming system models for (i) current land use and (ii) native vegetation.

b) Recharge data sets were generated by changing the landuse in the catchment in increments of 100 ha, from the current landuse to native vegetation. In this process, recharge estimates for current landuse, given by a)(i), were systematically replaced with recharge estimates for native vegetation, given by a)(ii). This generated approximately 6,120 recharge data sets.

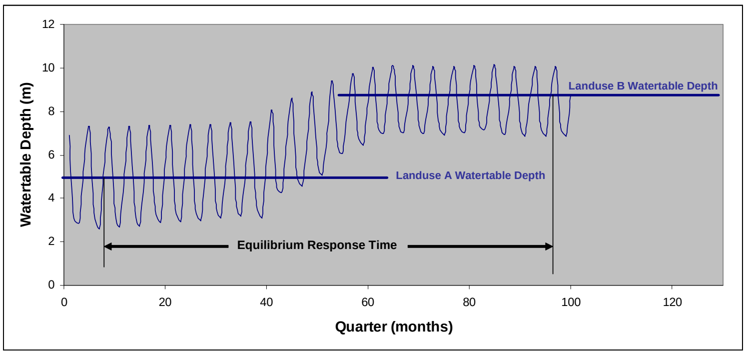

Figure 1. Conceptual representation of the response time derivation calculated as the time taken to reach a new equilibrium.

c) The MODFLOW model was run for each of the 6,120 recharge data sets and a single spatial map of groundwater response to revegetation was constructed. This map shows the area of altered shallow watertable (< 2 m) within the catchment relative to current condition as a result of landuse change within the zone of revegetation.

3.5. Response times

The groundwater response times were derived using the calibrated MODFLOW model. Extending the approach used to estimate the impact of revegetation on watertable depth, blocks of 960 ha were systematically replaced from recharge estimates of mean annual recharge derived for current land use with mean annual recharge estimates derived for native vegetation. The simulation period was 200 years using a fortnightly time step, with the first 10 years based on current recharge so as to minimize the impact of initial conditions on the response time predictions. To remove the impact of temporally varying boundary conditions all boundary conditions and recharge values were identical for each year of the simulation. For

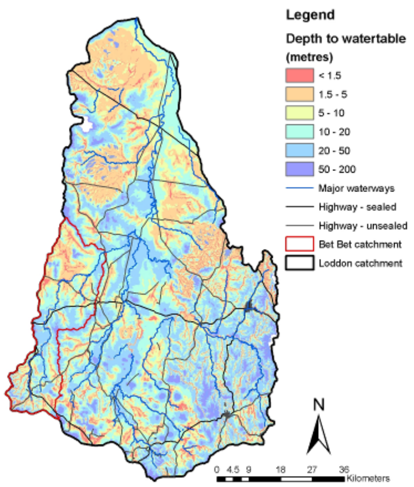

Figure 2. Simulated depth to watertable.

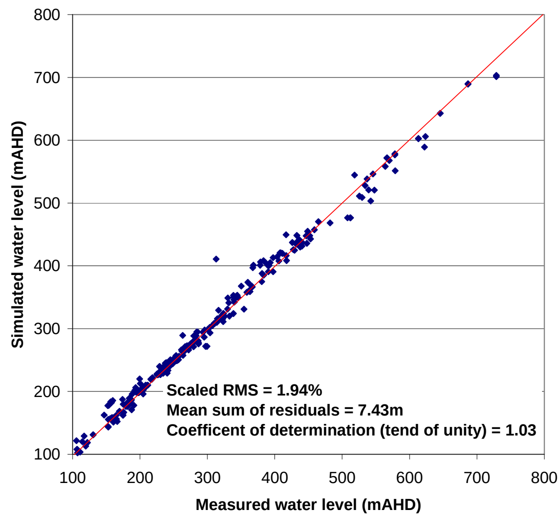

Figure 3. Predicted versus observed watertable elevation.

each simulation the time taken to reach a new equilibrium was calculated based on discharge fluxes and saturated area. Figure 1 shows a schematic response time derivation approach based on saturated area – the time to reach an asymptote between the initial state prior to the change in recharge and the altered state is assumed to represent the response time of that zone within which the recharge changed.

4. RESULTS

4.1. Calibration

Stream gauge
An evaluation of the calibrated MODFLOW model was based on the efficiency estimate developed by Nash and Sutcliffe (1970). The efficiency parameter ranges from minus infinity to one, with one representing calibration conformity. A coefficient of efficiency of 0.82 was calculated based on the comparison of monthly stream gauge and baseflow predictions against measured data.

Mapped salinity (depth to watertable)
The predicted depth to watertable at year 2000 is shown in Figure 2. Areas of mapped salinity were sampled and compared with simulated depth to watertable. Results suggest that the median depth to watertable in discharge zones was 1.71 m.

Groundwater Levels
The corresponding simulated verses observed watertable elevation for representative bores for the same period is shown in Figure 3. Analysis of the predictions show that the scaled RMS error to be 1.94%, the mean sum of residuals to be 7.4m and the coefficient of determination to be 1.03. This is considered within acceptable limits given the accuracy of the digital elevation data.

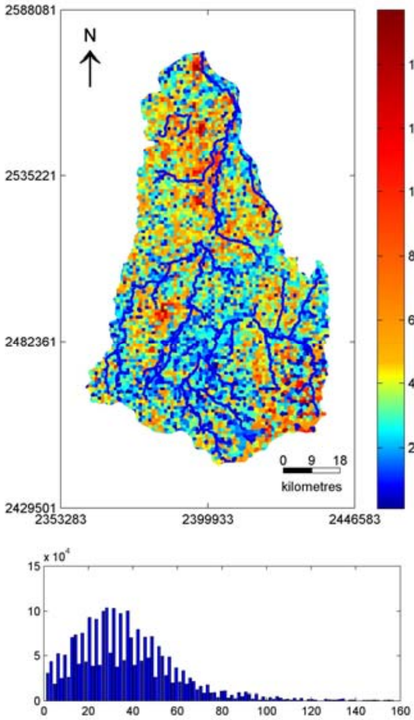

Figure 4. Impact on area of shallow watertable (ha) due to 1000 ha restoration/establishment of native vegetation.

4.2. Impact of revegetation on watertable depth

The predicted groundwater response to restoration/revegetation of native vegetation is shown in Figure 4. This figure shows both the spatial pattern and associated histogram. Results suggest that the minimum and maximum change in saturated area arising from a 1000 ha conversion from current landuse to native vegetation was 1 ha and 183 ha respectively, with the mean, median and standard deviation being 37 ha, 34 ha and 22 ha respectively. The zones of negligible impact are due to the presence of existing native vegetation in the landscape.

4.3. Response times

The predicted groundwater response times range from 40 to 103 years. Figure 5(b) summarises the histogram of the catchment response times (years) and shows that the mean is 70.4 years, median is 70.0 years and standard deviation is 6.2 years. Also shown in Figure 5(a) is the spatial mapping of the ratio of depth to watertable and response times. Included in Figure 5(a) are drainage features shown as solid blue lines and groundwater flow system (GFS) boundaries shown as thin lines. The GFS boundaries were derived based on an approach developed by Coram (1998) which summarises groundwater information in a simple but structured manner by using simple hydrogeological conceptual models (15 in total) to describe and map groundwater processes of salinisation across Australia.

5. DISCUSSION

The developed groundwater model is shown to give a reasonable prediction of the groundwater processes based on the calibration (matching water levels and discharge volumes) and sensitivity results. The sensitivity analysis (not reported) considered the impact of key input parameters on model predictions of discharge flux, evaporation, baseflow and saturated area. In all cases the model was shown to be sensitive to the combination of key input parameters from which it was concluded that the groundwater model represented a unique solution in contrast to a non-unique representation based on a range of possible input data combinations.

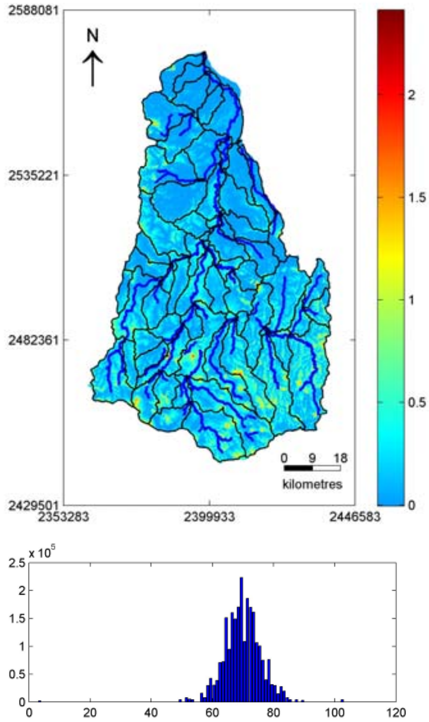

Figure 5. Spatial ratio of depth to watertable and response times and histograph of the catchment response times (years).

The estimates of response times are within the limits reported by Coram *et al*. (2001) for each broad scale groundwater flow unit present in the study domain. Whereas the GFS mapping is broad scale, the approach used in this paper explicitly accounts for the interaction between geological units, aquifers, groundwater uptake by vegetation and surface features including drainage lines and rivers. Examination of the response time mapping (Figure 5) shows delineation depending on landscape position and groundwater characteristics. For example quicker response times are predicted in zones of high groundwater gradients and close proximity to drainage features. Slower response times are shown in those areas in connection with intermediate and regional groundwater systems (for example the northern extent of the study domain) typically represented by large distances between recharge and associated discharge zones in combination with flatter groundwater gradients. Whereas this may be inferred from the idealised groundwater analogues, this approach provides finer resolution and is not constrained by strict boundary conditions and assumptions. In addition, analysis of the response times shows a 38% correlation with the lateral drainage analogy (=fn(S,T)) and only a 28% correlation with the time to fill analogy (=fn(∇ h,S,R)) as derived using a dimensionless similarity reduction of the saturated flow equation where S is the aquifer storativity, T is aquifer transmissivity, ∇ h is aquifer gradient and R is recharge. The correlation between the predicted response times and the ratio of the time to fill to time to drain is only 3%. This reinforces the notion that the idealised groundwater analogues do not adequately capture complex groundwater interactions and within-catchment dynamics as required to estimate groundwater response times arising from the land management scale interventions.

The spatial mapping of the impact of revegetation on depth to watertable (Figure 4) is a useful output to inform policy and land managers of the likely off-site impact of landuse change. In combination with the catchment response time estimates (Figure 5) transparent, robust and more cost-effective and targeted intervention strategies can be developed.

6. CONCLUSIONS

Idealised groundwater analogues simplify groundwater dynamics to a level that enables the basic underlying processes to be understood. However this simplification is based on strict boundary conditions and often heterogeneous aquifer properties with no allowance for complex groundwater interactions. In contrast to the analytical logistic functions that have been widely adopted to estimate groundwater response times to a change in recharge, the modelling approach adopted in this study explicitly accounts for position in the landscape, groundwater connection with drainage features and vegetation, existing and proposed extraction regimes, influences of adjacent boundaries and is fully distributed. In combination with the catchment depth to watertable impact mapping, the response time estimates derived using this approach offer the development of transparent, robust and more cost-effective and targeted intervention strategies.

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