Applying a spatial modelling framework to assess land use effects on catchment hydrology

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Abstract: Sustainable land use and management requires an understanding of the processes of recharge, discharge and salt movement across the landscape. Evaluation of land use changes on different parts of the catchment requires the application of farming system models in a catchment context to assess the implications of different scenarios on water and salt balance of the catchment. In this study we have developed a spatial modelling framework capable of incorporating farming system models (1-D) applied to land units with hydrological (lateral) connections between adjacent units in a catchment. The framework was applied to Simmons Creek catchment, a sub-catchment of the Billabong Creek in southern NSW comprising gentle uplands and substantial low relief areas containing swamps. An integrated approach incorporating soil, hydrology, hydrogeology, and terrain analysis resulted in interpretation of landscape function and the necessary parameterisation of the modelling framework. APSIM was used as the farming system model in this study with SOILWAT2 as the soil water balance module, modified for lateral flow connections (surface and subsurface flows). Current land use (crop rotation and pasture) and an alternative land use (10% trees on uphill units and pasture in the lower lying lands) were simulated. The results of the modelling showed the relative contribution of parts of the catchment in total recharge. Comparison between current and alternative land use over 44 years of simulations indicated a decrease of mean annual drainage from 39 to 29 mm/yr and an average reduction of the groundwater level of about 0.4 m. More substantial decrease in water table depth would require targeted tree planting over larger areas. These can be investigated further with the spatial framework.

Keywords: *Spatial modelling; Farming systems; Catchment hydrology; Land use; Groundwater*

1. INTRODUCTION

With dryland salinity being a serious problem in many parts of Australia, including the Murray-Darling Basin, management of agricultural landscapes needs special attention. Well targeted land use change can help reverse the environmental impacts of dryland salinity such as increased stream salinity, loss of remnant vegetation and reduced land productivity. Accurate targeting for land use change requires detailed knowledge of recharge, discharge, and salt transport mechanism at catchment to property scale. Farming system models (1-D) can quantify drainage below the root zone for different crop rotations (Paydar et al., 1999). When applied to different parts of a catchment, the farming system models can identify areas in the landscape where changing land use might be effective in reducing deep drainage beyond the root zone of the crop (Ringrose-Voase and Cresswell, 2000, Ringrose-Voase et al.,1999). There is a need for a complete analysis of surface and groundwater responses to land use changes with explicit spatial references to land units with lateral hydrologic connections between them. Such a modeling tool can be used to study effects of different land use scenarios in the hydrology of the catchment. This study describes the application of a spatial modeling framework in Simmons Creek catchment, a sub-catchment of the Billabong Creek in southern NSW, Australia, Long term prediction of groundwater response to land use change from current practice are presented from simulations of both lateral and vertical flow in the catchment.

2. MODELLING FRAMEWORK

The model simulates fluxes by dividing the catchment into hydrological units (land units), invoking a farming system model on each land unit (multiple times to account for heterogeneity within the unit), delivering lateral fluxes of water to the down slope unit then invoking the model on the next land unit in sequence. Both surface and subsurface flow directions are topographically controlled. Runoff from a unit is discharged as both diffuse overland flow and channel flow with the proportions depending on the land unit geometry and the existence of channels. Water that moves vertically below the root-zone may end up as groundwater recharge if not being stored within the regolith. An explicit linkage is then made to a groundwater model.

Subcatchments are manually defined based primarily on constrictions in the valley floor areas. Within each subcatchment the landscape is further divided into three landscape position classes denoted upper, lower and valley floor. This delineation is completed using the multi-resolution valley bottom flatness (MRVBF) topographic index (Gallant and Dowling, submitted). The units used are large compared to many earlier approaches so that the essential elements of topographically driven lateral water movement are captured without intense spatial discretisation and the associated run times and data needs. Spatial variation (typically soil properties and land use) within a unit is permitted but is not spatially explicit so only the area fraction of each unique combination is required.

The framework is designed to be essentially independent of the details of any particular farming system model. The APSIM farming systems model (McCown et al., 1996) was used here. APSIM simulates plant growth, soil water and nutrient balances and has been verified against field measurements in previous studies (eg. Paydar et al., 1999). The model operates at a paddock scale (1-D) with a daily time step. Using climate data, the water balance part of the model simulates runoff, evaporation and deep drainage and provides water to the crop modules for transpiration. Here the 'cascading bucket' water balance model (SOILWAT2) was used. The hydraulic characteristics of the soil are specified by the lower limit (wilting point), drained upper limit (field capacity) and saturated volumetric water contents. Runoff from rainfall is calculated using the USDA curve number technique (USDA 1972).

3. APPLICATION IN THE SIMMONS CREEK CATCHMENT

3.1. Study area

The Simmons Creek catchment is located at the eastern edge of the Riverine Plain, immediately east of the Walbundrie Township in New south Wales, Australia. The mean annual rainfall is 546 mm (1956-2001), with most precipitation falling in the winter months. The catchment covers an area of 178 km^2 and is rimmed with low granite hills, with metasediments occurring in the upper part of the catchment. Valley-fill alluvium over weathered granite is highly variable in thickness (0-100 m). The Simmons Creek catchment can be divided into two roughly equal parts. The upper (northern) half has mostly gentle slopes (1 to 10%) drained by a partially connected channel network that discharges through a floodway into the lower catchment system. The lower (southern) half is dominated by a flat plain (slopes < 0.5%) with little channel development. A floodway carries runoff (including runoff delivered from the upper catchment) around the northern edge of the floodplain into Wiesner's Swamp, which overflows into Simmons Creek which in turn discharges into Billabong Creek.

Within the catchment, salt is stored in thick clay layers deposited over granite or metasediments. The mobilization of this salt is causing salinity problems. Based on the conceptual model of the groundwater system in Simmons Creek catchment (English *et al.*, 2002), there are two separate groundwater systems in the north and south part of the catchment, weakly connected because of basement highs constricting groundwater flow. The southern system has a larger role in waterlogging, salt remobilisation in the profile, and salt delivery to the Billabong Creek. It is shallow and covers the area where most of the salt store is located. The complete modelling framework was parameterised and applied to the Simmons Creek catchment for a simulation period from 1956 to 2001.

3.2. Model parameterization

Climate data was obtained for Walbundrie station from the Patched-point Meteorological Data (Queensland Department of Natural Resources, 1999). A 20 m resolution DEM covering the entire Billabong Creek catchment was constructed using ANUDEM from 1:50 000 contours and streamlines. This DEM was used to produce the MRVBF map needed for the land unit delineation and the catchment boundary for Simmons Creek and the subcatchments within (Figure 1).

Soil hydraulic properties needed for the modelling (water content at saturation, drained upper and lower limits, depth, bulk density, and saturated hydraulic conductivity) were mostly determined from field survey, laboratory measurements on selected soil samples in different land units and subsequent extrapolation (McKenzie, N.J. pers. comm.). For the land units with more than one soil type the simulation results were spatially averaged using the areal extent of each soil type within the unit. The curve number for partitioning daily rainfall into runoff and infiltration was estimated from surface condition and slope following Littleboy (1997).

A combination of previous land use mapping and local knowledge was used to define current land use and land management in the catchment. A currently typical rotation is: canola, wheat, triticale, canola, wheat, triticale, followed by three years of pasture. This crop rotation was simulated with APSIM using all the land management information required for crop simulation (time and depth of sowing, variety, time and amount of fertilizer application, etc.). For the areas not under crop rotation, an annual pasture system was simulated using a simple winter active grass. For each land unit the fraction of land under crop rotation and pasture were determined and used in the averaging of the water balance terms from the simulations (Figure 1). An alternative land use scenario was constructed to investigate one option for reducing recharge and consequent discharge of saline water to Billabong Creek. In this scenario the upland areas with sufficient soil depth were considered for tree planting, with a target of 10% tree cover similar to those described in catchment plans for the area. An increase of pasture area to about 20% in the low lying lands (valley bottoms receiving water from higher units) was also included.

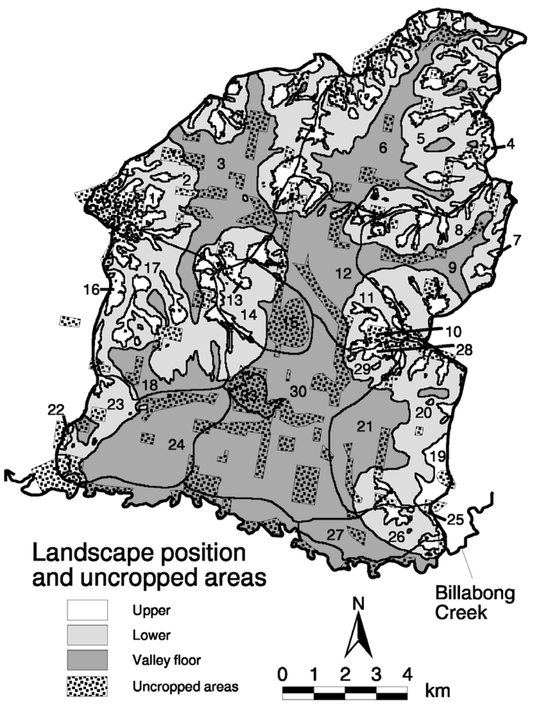

Figure 1. Land units with current land use.

In order to study the interaction between surface and the groundwater in the lower half of the catchment, a simple groundwater model was incorporated into the modelling framework. This bucket model receives the drainage water passed below the root zone as inflow (groundwater recharge) and discharges to the Billabong Creek as outflow (discharge). Discharge calculations are based on the piezometric heads of the groundwater. The recharge was obtained from the drainage term of the catchment farming systems model output (spatially averaged) since the groundwater is at shallow depth and there is not much storage between the bottom of the root zone (2 m) and the water table (<5 m). The model calculates the amount of discharge (m^3/month) to Billabong Creek and estimates the position of the water table in long term simulations using both the existing land use and the recharge reduction scenario.

4. RESULTS

The two gauging stations on the Billabong Creek, along the reach of the Simmons Creek catchment (Hillview-upstream and Walbundrie-downstream), show a substantial discharge from groundwater to the Billabong Creek (Figure 2) which is confirmed by the model. For the period 2001-2002 the model predicts a groundwater discharge of 1952 ML, close to the observed estimate of 2000 ML based on relative contributions of both sides of the creek. The model also shows the periods when the swamp has been filled and years when it has been dry, matching local observation. These comparisons give some confidence in applying the model to this catchment and using it to predict responses to alternative land use options to mitigate salinity and waterlogging.

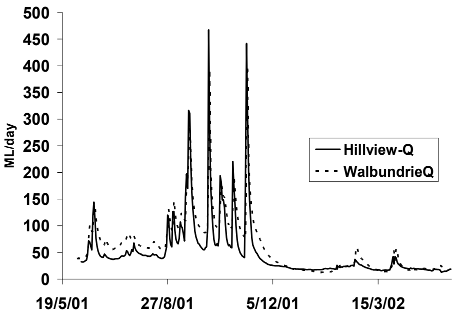

Figure 2. Observed flow of Billabong Creek at Hillview (immediately upstream of Simmons Creek catchment) and Walbundrie (below Simmons Creek).

The predicted median annual values (over 45 years) of water draining below the root zone, from each land unit under current land use is shown in Figure 3. The annual drainage under the current system ranges between 14 to 85 mm/yr with a mean of 39 mm/yr. More water (per unit area) is drained from those units that are receiving water from the up-slope units. Figure 3 also shows that in terms of drainage the upper part (units 1-12) and lower part (units 13-33) of the catchment behave similarly: the drainage depends mostly on the hydraulic properties of the soil and whether the unit is receiving water from other units. In terms of the relative magnitude of water balance terms, drainage is on the average 7% of the rainfall, while runoff is 1.7% and subsurface lateral flow is only 0.3% of total rainfall (mean value of 1.9 mm/yr; higher on upslope units). This indicates that subsurface flow is not a significant part of the water balance in this environment.

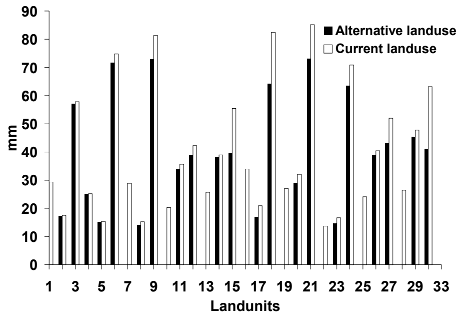

Figure 3. Median annual drainage values for each land unit under current and alternative land use

Using the drainage values averaged over the lower part of the catchment to recharge the groundwater system, the model predicted the long term trend in the groundwater head shown in Figure 4. The model predicts a substantial amount of monthly discharge to the Billabong Creek with a high effective hydraulic conductivity indicating the existence of permeable conduits in the groundwater system. The groundwater head predictions in Figure 4 were checked against piezometric observations where possible and they showed reasonable agreement with the measurements. The system does not show a long-term rising trend (other than some fluctuations in high rainfall years). The plain adjacent to Billabong Creek appears to be a self-draining system discharging to Billabong Creek and except for some isolated areas the general trend shows equilibrium between recharge and discharge.

The value of having an operational catchment scale model with the cropping system capability is that it can be used to study the effects of different land management options in different parts of the landscape on the hydrology of the catchment. For this study only one scenario was simulated with most of the uphill units planted to trees (~10% of the area) and increased permanent pasture in the lower lying lands. Figure 3 shows the comparison between the drainage predictions for the current and alternative land use. Drainage from the units planted to trees (every third unit from 7 to 28) is effectively zero. Although the mean annual drainage decreased from 39 to 29 mm/yr, its impact on groundwater rise is not substantial. Figure 4 shows a comparison between the groundwater trends for the current and alternative land use scenario. The groundwater level decrease with the recharge reduction scenario is on the average about 0.4 m. More substantial decreases in the water table would require tree planting over larger areas.

5. CONCLUSIONS

The simulation modelling showed substantial variation in drainage from different parts of the catchment indicating opportunities for well targeted land use change. It can also be used to quantify the catchment hydrology (e.g. groundwater discharge) as a basis for recommending salinity mitigation measures. A land use change of ~10% tree cover by area and an increase of pasture to ~20% of lower land units in the southern part of the catchment is not likely to significantly reduce recharge and water table levels here. However, extensive tree planting would likely decrease the flow of better quality water from the lower part of the catchment to the Billabong Creek. Given the requirement to balance good quality dilution flow and salt mobilization the best management option would appear to be targeted tree planting in those local recharge areas directly adjacent to Simmons Creek itself and the salinity outbreaks. Analysis to support management of salinisation and water yield, within the context of agricultural production, must clearly be spatial in nature and span from the farm to the scale of the key hydrological processes. The analysis outlined here provides a new means for linking farm management decisions on productivity to surface and groundwater hydrology at sub-catchment scale. Importantly production impacts (positive and negative) from any intervention can be assessed along with hydrological response to enable better evaluation of trade-offs and subsequent decision making. The catchment modelling framework could be usefully applied in other catchments in developing innovative new land use options that take advantage of spatial variation in both yield potential and hydrologic impact.

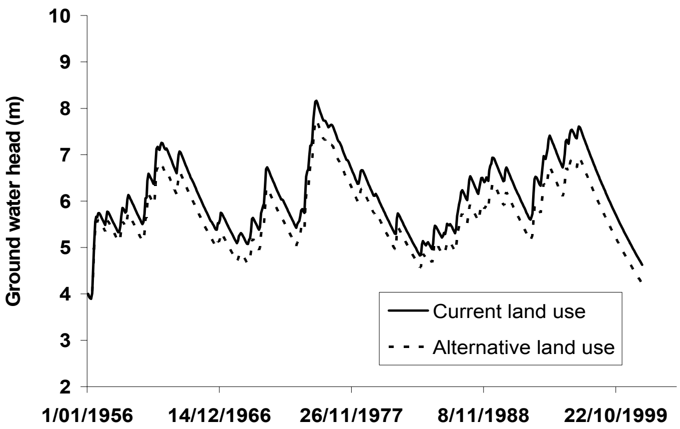

Figure 4. Predicted groundwater heads under current and alternative land use.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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