Spatial Water Balance Modelling for Targeted Perennial Planting in South Western Australia

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EXTENDED ABSTRACT

A common strategy in mitigating secondary salinity in southern Australia is the planting of trees and other deep-rooted perennial vegetation. Planting needs to target areas where perennials will provide the most benefit by minimising runoff and groundwater recharge. A number of one-dimensional (1D) water balance models have been developed in Australia that predict water balance components (evapotranspiration, runoff, soil water storage and deep flow), based on climate data and soil/land use at a location. In Western Australia (WA), the Department of Agriculture (DAWA) has developed a simple model, AgET, that is tailored to the local soils and land uses (based on field-measured hydrological parameters), and is easily customisable.

This paper describes how a modified version of AgET was coupled with the ArcGIS 9.0 geographic information system (GIS) to map estimated recharge across the Lake Warden Recovery Catchment (LWRC) on the south coast of WA. The GIS automates the process of bringing input datasets together, running their parameters through the model and mapping the results. It was also used to implement an algorithm that incorporates slope information to partition deep flow into sub-surface lateral flow and recharge.

The soil water storage parameters required by AgET were determined from the DAWA soils database, field trials and trial and error calibration.

The datasets (rainfall, pan evaporation, soils, land use and digital elevation model) required for the exercise are available for most of the south west agricultural zone, so the approach may be applied to other areas.

Areas close to the Lake Warden Wetland System (LWWS) exhibited the highest recharge rates. This is due to the abundance of permeable, sandy soils and proximity to the coast where rainfall is highest. This result was expected but the exercise allowed quantification of the relative recharge rates of different areas of the LWRC. The predicted reduction in annual recharge under farmer-proposed perennial plantings was mapped and estimated to total 2.2 GL (gigalitres) of water.

The scale and proportional nature of some of the soil and land use mapping means the results are inappropriate for paddock scale planning. However, the method is supplying catchment managers with a useful tool in the rapid identification of areas amenable to recharge control as a groundwater management option through the ability to produce maps of expected recharge reduction resulting from specific planting strategies.

Priority areas for perennial planting will depend not just on recharge, but other factors such as the degree of connection with assets like the LWWS. Isotope and chloride analysis to define surface water and groundwater interactions within the LWRC are being conducted to gain the further understanding required to make effective management decisions. Water quality criterion, as well as volume criterion, must be met to maintain ecological thresholds of the LWWS. More complicated modelling techniques are required if the lateral flow of water, both above and below the surface, is to be fully accounted for. Future work to incorporate lateral flows may follow the FLUSH and/or LUOS approaches developed in NSW.

1. INTRODUCTION

One option to combat rising watertables and the associated dryland salinity problem in much of Australia's agricultural lands is to switch land use to higher water use crops (trees and other perennials). At a particular location, the change in the hydrological balance, resulting from a change in land use, will depend on the soil, climate and landscape position. It is impossible to conduct field studies across a whole region or catchment, but modelling allows us to extrapolate the results of limited experiments.

A number of 1D water balance models have been developed in Australia, including APSIM (Hammer et al., 1993), PERFECT (Littleboy et. al., 1989) and AgET (Argent 1999). These predict water balance components (evapotranspiration, runoff, soil water storage and deep flow), based on daily climate data and soil/land use at a single location. AgET is tailored to WA datasets and comes with tables of hydrological parameters for 16 WA soils (more detailed tables are being prepared, including the one used in this study) and land use, as well as Bureau of Meteorology rainfall records (1954-1993) for 103 weather stations and regional pan evaporation data.

GIS can provide a spatial component to water balance modelling. Some simple water balance models have been coded directly into GIS for catchments in the south east of Australia (Dowling et al. 2004, Zhang et al. 2003), but have only considered simple land use scenarios at a broad scale. The simplest method to integrate the power of both GIS and existing 1D water balance models is to use the GIS to determine the combinations of input parameters, pass them to the model and spatially represent the results. Ringrose-Voase et al. (2003) ran APSIM in this way for 1,960 soil/climate/land use combinations in the Liverpool Plains catchment of NSW. Littleboy et al. (2003) applied the PERFECT model to the NSW portion of the Murray-Darling Basin. They used only five land use categories and a 1km grid cell.

This paper presents a similar coupling approach using the AgET water balance model in south WA. The study area is the Lake Warden Recovery Catchment (LWRC) for which the Department of Conservation and Land Management (CALM) is the lead agency. It contains the Lake Warden Wetland System (LWWS) which is threatened by rising water levels. Short et al. (2000) conducted APSIM modelling in conjunction with MODFLOW transect modelling for the catchment, but only considered five soil/rainfall combinations and land use was only mapped proportionally (i.e. they reviewed the amount and type of land use change required, but not where). There is now scope for more detailed analysis using recent GIS datasets.

There seems to be little similar work completed in WA with a couple of exceptions. Harper et al. (in press) also used AgET, to map recharge in the 283,000ha Collie catchment. They performed a series of simulations for native vegetation and annual pasture, then plotted the predicted deep drainage against mean annual rainfall and fitted cubic polynomial expressions to extrapolate the results. Pracilio et al. (2003) used APSIM across the 25,000ha Elashgin Creek catchment, but only evaluated one land use.

A noted problem with 1D water balance models is over-estimating recharge, because they fail to take into account sub-surface lateral flow (Short et al. 2000, Ringrose-Voase et al. 2003, Tuteja et al. 2003). They all make the simple assumption that water that goes below the root zone (deep flow) becomes groundwater recharge. Rassam and Littleboy (2003) have developed a technique for partitioning deep flow into sub-surface lateral flow and recharge, based on the two key parameters of slope and the ratio of the soil hydraulic conductivity (K) of the upper soil layer to that of the lower soil layer. Their technique was used in this study.

2. SPATIAL DATA SOURCES AND PREPARATION

2.1. Rainfall

To represent the spatial variation in rainfall an interpolated grid of mean annual rainfall (based on the period 1961 to 1990) was obtained from the Bureau of Meteorology. The grid was generated using:

- the ANU (Australian National University) 3-D Spline surface fitting algorithm;
- 6,000 rainfall stations across Australia; and
- a 0.025 degree (2.5km) resolution digital elevation model (DEM) to take into account the topographic effect on rainfall.

Daily rainfall estimates for each cell were then determined by multiplying the Esperance daily records by a scaling factor (the cell's mean annual rainfall divided by the Esperance station mean annual rainfall). Esperance rainfall for the period 1973 to 1993 was selected to represent the decline in rainfall the Esperance region has experienced over the past 100 years.

2.2. Soils

Soil information was obtained from DAWA's soil-landscape mapping (Schoknecht et al. 2004). This mapping is proportional, because within a soil-landscape mapping unit there can be more than one soil group and land unit. The dominant group (highest proportion) within each mapping unit was assigned to the whole unit for this analysis. The "phase" level soil-landscape mapping available (Overheu et al. 1993) does not cover the entire catchment. An initial trial of the AgET simulation using broader scale "subsystem" level soil-landscape mapping indicated low recharge in these areas, so its was considered acceptable to omit them from analysis until the phase mapping is updated. A total of 13 soil groups were mapped (4 to be excluded from analysis).

2.3. Land use

The following data sources were used to map land use (their order indicates priority in the case of overlapping information):

- Farmer land use surveys undertaken by the LWRC officer in 1999 and 2003 indicating the location of perennial pastures, farm tree revegetation, native revegetation and agriforestry
- Plantations from the Forest Products Commission's annual report 2003/2004
- DAWA's Vegetation Extent (remnant vegetation) September 2004 (Hopkins et al. in press)
- Farmer surveys undertaken by the LWRC officer in 2003/2004 indicating annual farming systems

The annual farming system dataset is the least accurate, because only areas under different crops were recorded, not the location of those crops within land parcels. The dominant crop was chosen and assigned to each land parcel identified for that farmer in the Department of Land Information's (DLI) Spatial Cadastral Database (SCDB) 2001. After this process some areas in the catchment remained without land use information. Some data gaps were addressed using local knowledge and the remainder were assumed to be volunteer pasture. The land uses were rationalised to 14 categories to match AgET's crop file.

2.4. Slope

Percentage slope was calculated from the Land Monitor (Allen and Beetson 1999) digital elevation model (DEM). The 10m cell size was used in all subsequent grid-based analyses.

2.5. Salinity and Water

AgET is not designed for cases where the root zone intersects the watertable. Therefore, areas of waterlogging, shallow groundwater and salinity were excluded from the analysis. The Land Monitor "Salinity" and "Water Mask" datasets (Meston 2001) and farmer surveys undertaken by CALM in 1999 and 2004 were used to identify the affected areas.

3. MODELLING METHODOLOGY

3.1. Unioning data

All GIS analyses were performed using ArcGIS 9.0 (ArcInfo seat) software with the Spatial Analyst Extension installed. The rainfall, soils and land use data sources were all converted to ArcInfo coverage format and unioned together. The attribute table in the unioned coverage was rationalised so there were three main fields (one for each of the three inputs).

3.2. AgET modifications

The AgET code (V 2.1) was stripped back to the water balance component and modified to run in a batch mode. It reads a file containing any number of input combinations (mean annual rainfall, soil, land use), runs these through the water balance simulation and writes an output file of the mean annual values of evapotranspiration, runoff and deep flow. The program was simplified by removing the option for crop rotations, so that it assumes static land use over the period of simulation.

The standard AgET crop and soil files were modified. An entry for Kikuyu was added to the crop file. The soil file was substituted with one specifically for the Esperance soil survey region. Soil water retention parameters, estimated from field texture and structure, were extracted from the DAWA soils database (Schoknecht et al. 2004) and adjusted where field data was available. Permeability parameters were calibrated by trial-and-error to produce recharge values commensurate with average, regional rates of groundwater rise and expert best guess.

3.3. Arc Macro Language (AML)

An AML program was written to:

- determine all unique combinations of input parameters from the unioned coverage;
- run the AgET batch mode executable; and
- join the output back to the coverage.

3.4. Excluding areas from analysis

The unioned coverage then had the datasets from section 2.5 erased from it, as well as "Saline Wet Soil", "Salt Lake Soil", "Wet Soil" and "Bare Rock" soil groups from section 2.2. Also roads from the SCDB (2001) were erased.

3.5. Sub-surface lateral flow partitioning

Deep flow was partitioned into lateral flow and recharge using a variation of the algorithm of Rassam and Littleboy (2003). The ratio of the AgET parameters describing the maximum rate of flux of water from the A to B and from B to deep soil horizons was used in place of the ratio of the hydraulic conductivities of the A and B horizons as described by Rassam and Littleboy (2003).

3.6. New land use scenarios

To estimate the change in recharge resulting from a change in land use, the above process was run for the new land uses. The resulting grid was then subtracted from the current recharge grid to produce a map of the predicted change in recharge.

4. RESULTS AND DISCUSSION

4.1. Results

Figure 1 represents the recharge over the LWRC predicted by AgET. The white areas were not modelled (for the reasons outlined above), but this does not imply low recharge. As expected, the higher recharge rates are closest to the coast, where rainfall is highest and permeable sandy soils are common. These higher recharge areas can be prioritised for recharge reduction strategies. Care should be taken not to use the information at too fine a scale given the spatial accuracy of the input datasets. The results are probably best viewed at what Harper et al. (in press) refer to as catchment scale (1:100,000) and certainly not below 1:50,000, the published scale of the soil-landscape mapping.

The predicted change in recharge was mapped for a series of farmer proposed plantings. The proposals included sugar gum, oil mallee, maritime pine, yate, tagasaste, veldt, lucerne, kikuyu, salt land pastures, farm tree revegetation and native revegetation. The plantings that will provide the greatest reduction in recharge will be given priority for assistance. By multiplying each recharge change value by its spatial area, an estimate of volumes can be calculated. A 2.2 GL reduction in annual recharge was calculated should all the proposed plantings be undertaken. This volume is similar to the ground and surface water annual inflows to Lake Warden estimated by Marimuthu et al. (submitted). However, only a fraction of the recharge reduction will be passed on to the LWWS, depending on the flow paths involved.

4.2. Data limitations

An important assumption in this analysis is the daily rainfall at a location can be represented by the daily records from a rain gauge, scaled by the ratio of the mean annual rainfall of the location to that of the gauge. The further the location is from the gauge the less valid this assumption. Mean annual values do not account for the daily and seasonal patterns that may influence recharge. The study presented here extends about 35km from the gauge used. No other rain gauges, that have data built into AgET, fall within the catchment. However, there are other gauges further north in the catchment, for which the Bureau of Meteorology holds data. To make use of this information would either require sub-dividing the catchment and running separate simulations for each gauge, or interpolating daily rainfall directly.

An alternative approach to dealing with the proportional soil-landscape mapping is to average the soil hydrological properties across a map unit, based on the typical relative proportions of the soil groups within it. Ringrose-Voase et al. (2003) used this approach in the eastern states. Harper et al. (in press) used it in their Collie catchment AgET modelling. This approach is most appropriate if there is not a clearly dominant soil group within each soil-landscape unit. However, in this study one soil group usually was dominant. There is a growing body of literature on the use of other environmental variables to predict the spatial distribution of soil properties (Summerell et al. 2004, Pracilio et al. 2003). Further work is required to combine such information with existing soil mapping.

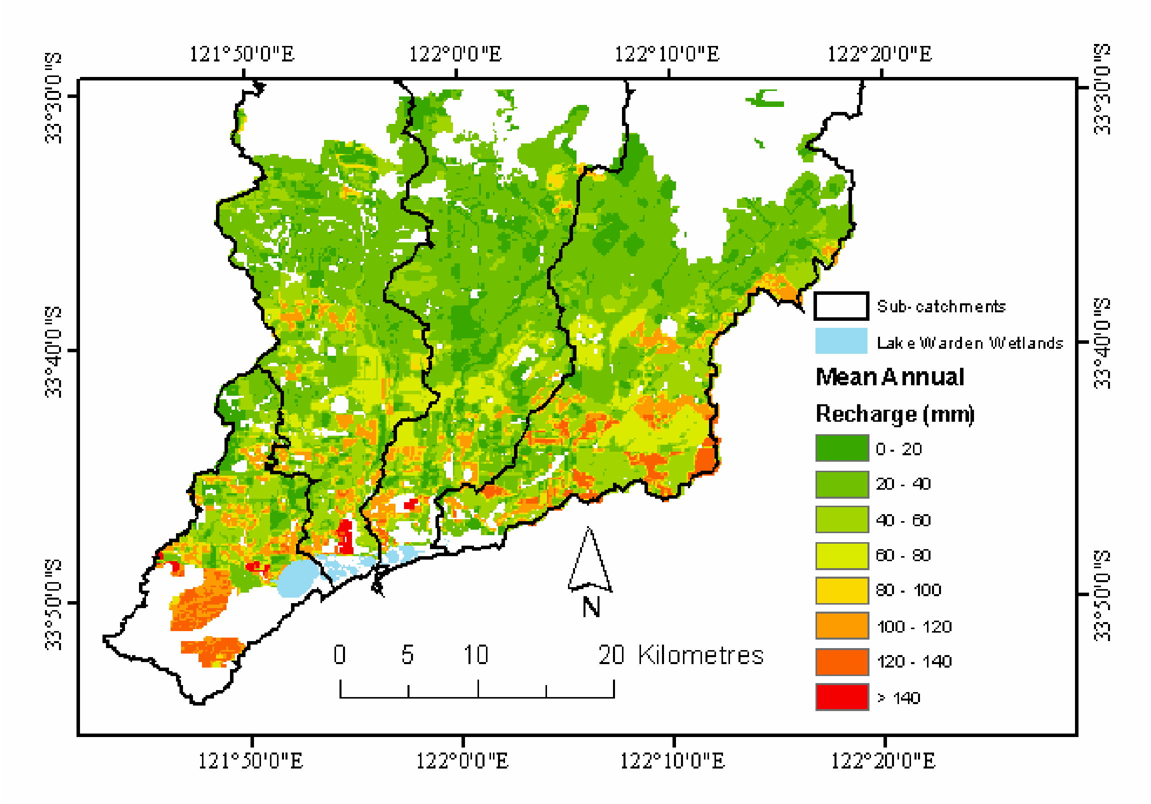

Figure 1. Estimated Mean Annual Recharge (mm) for the Lake Warden Recovery Catchment

4.3. Modelling limitations

A limitation of spatially distributing the results of a one-dimensional model is that lateral flows (both surface and sub-surface) are ignored. The influence of landscape position is partially addressed via its correlation with soils, but groundwater flow paths and discharge points are not determined, and the interactions between depth to groundwater and recharge rate are ignored (Short et al. 2000).

The application of the Rassam and Littleboy (2003) sub-surface lateral flow partitioning algorithm addresses these issues to some degree but it has not been validated for WA conditions. Short et al (2000) predicted that sub-surface lateral flow would be minimal in the LWRC due to the generally low slopes. The algorithm results are consistent with this with an average sub-surface lateral flow of 5% and very few values above 20%.

Paydar and Gallant (2003) have developed a framework for incorporating 1D hydrological models with lateral connections between adjacent land units. A DEM derivative is used to delineate upper, lower and valley floor land units, and APSIM modified for lateral connections to pass water between the units. Soil and land use parameters are spatially averaged within the units. Wang et al. (2004) refer to this framework as FLUSH (Framework for Land Use and Spatial Hydrology).

Another approach adopted in NSW, incorporates topography and matches the water balance values across a catchment with mean annual stream flow estimated at the catchment outlet (Tuteja et al. 2003). A catchment is divided into grid cells and each cell is given a weighting that represents its relative contribution to the mean annual stream flow. A decision support tool, the Land Use Options Simulator (LUOS), facilitates running different land use scenarios through the model (Herron and Peterson 2003).

There is scope to pursue more complicated modelling in the LWRC. The DEM data and programming code is available for the two approaches described above, however multi-dimensional models are not as easy to parameterise as 1D models (Rassam and Littleboy 2003). With the need for management decisions in the catchment, this 1D approach provides a rapid assessment of the higher recharging areas in the landscape and estimates of recharge benefit from land use change. The approach would be complemented by effective monitoring and evaluation programs to validate the modelling in conjunction with management strategies.

4.4. The bigger picture

Recharge is not the only factor affecting suitability for perennial planting. Recent research has suggested valley floors should be targeted first for recharge reduction (George et al. 2004, Wang et al. 2004). The perennial species chosen for a location will depend on environmental and economic factors. Plantings in the LWRC are being encouraged by cost sharing agreements between government agencies, private industry and land holders.

Priority for plantings will also depend on the degree of connection with threatened assets, such as the Lake Warden Wetland System (LWWS). Isotope and chloride analysis are being used to further define surface water and groundwater interactions between the LWRC and the LWWS (Marimuthu et al. submitted). High recharge in the Mid-Neridup Creek sub-catchment has minimal impact on the LWWS due to an underlying palaeochannel that drains to the Southern Ocean. Furthermore, water quality, as well as quantity, criteria need to be addressed to maintain ecological thresholds for the LWWS

Once developed for the LWRC, this approach will be applicable to other south coast catchments, because most input datasets, with the exception of detailed spatial agricultural land use, are readily available for the agricultural area of south western W.A. Although the process is quick to run, the program does not have a Graphic User Interface and still needs GIS technical expertise.

5. CONCLUSIONS

Mapping of recharge by this method is a useful tool to identify the areas contributing the greatest volumes of water to the LWWS. Areas amenable to recharge reduction strategies with perennial plants can also be identified. The interpretation of AgET output must be incorporated with an understanding of defined and constraining hydraulic processes linking the LWRC to the LWWS. Such a process will provide a strong decision support base for targeting public or private funds into revegetation strategies that maximise the benefits for a public asset such as the LWWS.

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