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Separating the impact of climate change from land use change in local and regional groundwater systems

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Abstract: This paper considers the problem of integrating projected future climate change predictions into a catchment modelling framework to determine future impacts on the groundwater resource. Catchment hydrology will also be altered as land managers alter management and land use regimes in response to a changing climate. The response of the groundwater system is further complicated in water-limited environments as plant systems will not respond linearly to changing rainfall, temperature and CO_2 inputs. There is a need to separate the effects on hydrology due to land use change, and those resulting from climate change, to enable adaptation strategies to be proposed that help best manage our groundwater resource.

Presented are results from the Catchment Analysis Tool (CAT), a modelling framework which links the daily surface water balance from actual land use management to a calibrated fully-distributed MODFLOW groundwater model. The MODFLOW model, calibrated against historical climate conditions, has been used to assess the groundwater impact under projected changes in rainfall, temperature and solar radiation due to climate change, for the Corangamite catchment in Victoria. Monthly climate change projections provided by the CSIRO climate change model for regional Australia have been converted to daily data using a modified downscaling method. The historic and projected climate data have been used as inputs to a suite of daily biophysical simulation models (CAT) that account for multiple agricultural landscapes, generating mean-annual groundwater recharge estimates which are fed into a steady-state MODFLOW groundwater model. A method proposed to separate the localised groundwater impact of changing land use from the more regional impacts due to climate change is also presented.

The following conclusions are drawn from our modelling analyses:

- The A1F1 climate change scenario resulted in mean annual rainfall for the catchment decreasing by 73 mm and average annual temperature increasing by 1.6°C. Using the current practice scenario, the model predicted that mean annual evapotranspiration would decrease by 7% (39 mm/year) and recharge by 21% (24 mm/year) under climate change;
- The groundwater resource will be affected by the impact of climate change in Corangamite, especially in the upper reaches;
- Based on the results shown, a 100 ha tree plantation had a decreased impact on potentiometric head, within 5 km of the plantation due to climate change. The impact, however, was greater between 5 and 10 km;
- The potential impact of climate change on potentiometric surface can exceed the impact on a tree plantation; and
- The combined effect of land use and climate change will be large although the response across the landscape is variable.

Keywords: *Catchment Analysis Tool (CAT), climate change, recharge, groundwater, MODFLOW*

1. INTRODUCTION

Land management practices are evolving as landholders respond to changing climates, markets and new knowledge. This change has a lag, and is influenced by past events, such as the recent run of dry years in southern Australia. Although climate change predictions imply that future hydrological conditions will be drastically altered, land mangers still tend to adapt their systems based on current conditions. Recent climatic conditions at a global scale have led to a change in thinking about our current land use and management in regional Australia; carbon trading schemes have led to increased viability of tree plantations, water scarcity has led to reallocation of land use options and there has been much debate over the allocation of groundwater extractions and rerouting of stream flow. Clearly, there is a need to understand the local and regional impacts of climate change and how this integrates with existing and future land use and management.

There is an increasing recognition that recharge across the whole landscape can impact specific assets, such as rivers or lakes, due to interconnected groundwater aquifers. The difficulty to date has been in assessing the magnitude and scale of the impact that land use change has on groundwater systems and separating this from the more dominant regional impacts expected under climate change. To determine if planning processes are adequate for dealing with potential climate change impacts on groundwater resources, there is a need to identify how future land use change will influence groundwater resources and conversely how land use is likely to be altered as groundwater responds to a changing climate.

To address some of these issues, this paper explores some methods and techniques used to investigate the potential impacts of land use change on groundwater resources within a climate changed environment.

2. THE STUDY AREA

The study area shown in Figure 1 represents the area managed by the Corangamite Catchment Management Authority (CCMA) of south-west Victoria, Australia. The area includes both privately owned land (10,852 km^2, 82% of catchment area) and publicly owned native vegetation areas covered by State and National Parks (2,430 km^2, 18% of catchment area). The catchment supports a diverse mix of land uses ranging from cropping to grazing, including dairy farming where rainfall is sufficient or where irrigation water is available, such as around Lake Corangamite. Soil types within this region are predominantly derived from basalts leading to heavy clay soils prone to waterlogging when wet and cracking when dry. The potential for farm forestry within the region is high with many commercial ‘farm forestry’ companies actively purchasing land on suitable soil types to grow high quality sawlogs.

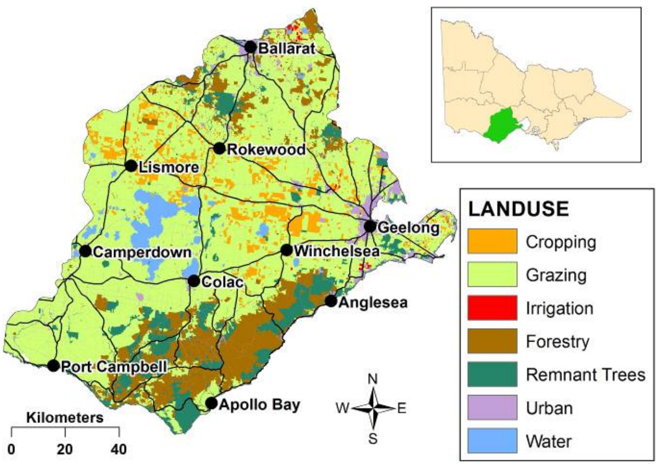

Figure 1. The CCMA study area in south-west Victoria showing dominant current practice land use.

3. MODELLING METHODOLOGY

3.1. Overview of Climate Change Data Generation

Daily climate change projections were generated using de-trending methods described in Hennessy et al. (2006) and Anwar et al. (2007). This approach uses annual climate prediction estimates from the Inter-governmental Panel on Climate Change (IPCC) scaled by pattern-of-change maps developed by CSIRO (Hennessy et al., 2006). The IPCC estimates are available at the global scale and predict increasing mean temperatures as well as elevated atmospheric CO_2 concentrations for a range of future scenarios (SRES, 2000). To date, the actual atmospheric measurements of global temperatures and CO_2 concentrations have been tracking at the upper boundary of the extreme case IPCC projections (A1FI) used in this paper. The pattern-of-change maps provide a spatial distribution of climate change impact across regional Australia on a mean-monthly basis. Within Victoria, the mean change in temperature and CO_2 concentration is expected to be small, while a significant reduction in rainfall is expected across the western half of the State.

To obtain climate data in a form suitable for running daily biophysical simulation models, a CSIRO downscaling technique was used (Anwar et al., 2007). The daily historical data was de-trended, referenced to the base year (1990), then scaled by the mean-monthly pattern of change data from the Mk 2 model (Hennessy et al. 2006) and the 'extreme' A1FI IPCC global warming factor for the particular year of interest (2050). This resulted in a sequence of climate data having the same period and variation as the historical data, allowing the impact of climate change to be analysed over a range of years including dry and wet periods. The pattern was applied to 46 years (1957–2002) of historic daily data (from SILO patch-point, http://plum.nre.vic.gov.au/silo/), generating climate projections for maximum and minimum temperature, rainfall and solar radiation for each of the 79 climate stations in the study area.

In this analysis, the historical sequence is the basis for the climate change sequence and the two data sequences are fully correlated. The method of Suppiah et al. (2001), as applied by Anwar et al. (2007), differs from this in that an incremental global warming factor is applied to each year resulting in a complete smooth weather sequence from the historic data to the projected end year. The disadvantage of this technique is that it is difficult to separate at a given point in time the impacts due to climate change and those just due to stochastic variability in the climate data.

The climate model is limited in that variations expected under specific climate change scenarios are not considered. As such, the model tends to over-predict certain events, such as the number of rainy days, and under-predict extreme temperature and rainfall events. Alternate climate change prediction models could alter the daily recharge estimates used for the groundwater modelling; however, they would not alter the trend of deceasing water availability due to climate change. As other climate change models are developed, new projected climate sequences can be readily incorporated into this modelling framework.

3.2. Recharge Generation

The Catchment Analysis Tool (CAT) landscape modelling toolkit (Weeks et al., 2008) was employed to study alternative land use and climate change scenarios. The advantage of CAT is that it can explicitly model surface and groundwater processes within the landscape (Beverly et al., 2005) and link drainage from the root-zone to groundwater and surface water interactions. This connectivity of CAT offers more realistic responses from daily time-step land use modelling and water table related management options than single enterprise models.

Daily catchment recharge estimates were derived for current land use (Figure 1) and "100% tree coverage" for both historic and climate change predictions for 46 years. The recharge response of each of these four scenarios was converted to a mean annual basis then was used as an input to the fully-distributed groundwater model as described in Section 3.4.

3.3. Groundwater Conceptualisation and Calibration

A seven-layer MODFLOW groundwater model was developed based on available stratigraphical delineation. Details of the conceptualisation, attribution and calibration are reported in Hocking et al. (2007). The groundwater model adopted a uniform grid (842 columns by 795 rows) of 200 m resolution.

Steady-state model calibration was made using observed groundwater levels, as well as mapped salinity and river base flow estimates for the year 1995. The daily recharge estimates from CAT for 1995 were converted to an average annual basis. Representative bores totalling 697 in number were selected based on duration, frequency of monitoring, screen depth and location in catchment. Comparison of the average annual 1995 water level data and the steady state results demonstrated that on a 1:1 basis 97% (scale RMS 2.69%) of the measured catchment variation could be accounted for by the calibrated groundwater model.

3.4. Modelling Approach

3.4.1. Climate change impact on groundwater

To determine the impact of climate change on groundwater resources, the steady-state calibrated MODFLOW model (Figure 2a) was run using two different recharge estimates to determine the potentiometric surface:

1) current practice recharge estimates based on the historic daily climate data (1935-2002) (Figure 2b); and
2) current practice recharge estimates based on the climate change (2050) predictions (Figure 2c) described in Section 3.1

The difference between the potentiometric surface outputs from both these MODFLOW model runs were then calculated to represent the predicted impact of climate change on the groundwater surface (Figure 2d).

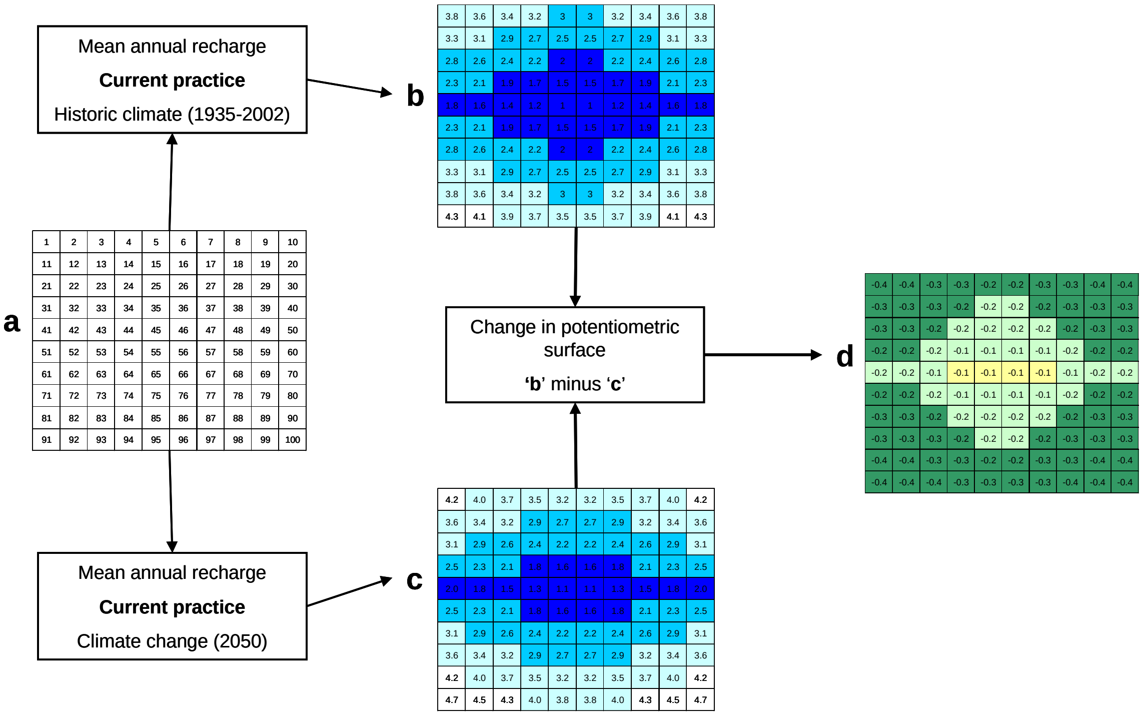

Figure 2. **(a)** Example of MODFLOW model (10 by 10 grid); **(b)** Potentiometric surface generated from groundwater model using historic climate to generate recharge map; **(c)** As for (b) but using climate change data to generate recharge map; and **(d)** The change in potentiometric surface due to climate change.

3.4.2. Land use change impact on groundwater in a climate changed environment

To determine the impact of changing land use on the groundwater surface, the recharge layer was systematically changed from current practice to 100% trees for each MODFLOW grid cell whilst maintaining the current practice recharge for the rest of the catchment. A simplified example is shown in Figure 3**a** where the land use in 'grid-cell' **34** was changed to reflect 100% tree cover in that cell. For each new recharge layer, the groundwater model was run to identify the location of groundwater cells impacted by that recharge change (Figure 3**b**). For the example shown in Figure 3, this systematic approach would lead to 100 separate MODFLOW runs. The impact on groundwater represented by a change in the potentiometric surface in all grid-cells resulting from each MODFLOW run is captured in an output data array for post-processing display.

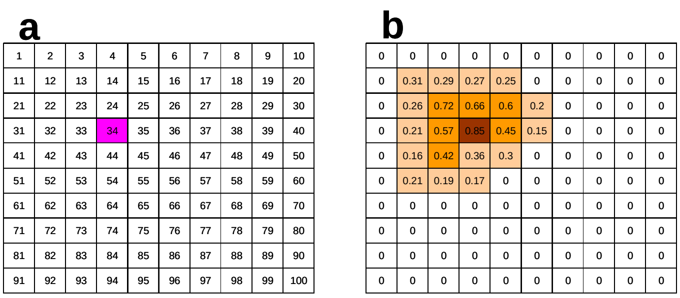

Figure 3. Replace recharge in 'grid-cell' **34** due to altered land use (**a**). The recharge in the other 99 grid-cells remains unchanged. Run MODFLOW model to determine grid-cells impacted by land use change (**b**).

To consider the impact of changing land use with and without climate change, two systematic MODFLOW runs were modelled.

1) Using the method shown in Figure 3, recharge based on the historic climate data for current practice land use and 100% trees was run; and
2) The procedure was repeated for current practice land use and 100% trees using the climate data altered to represent a predicted climate future at the year 2050.

The difference between each of these systematic model runs illustrates the differing impact of a single land use change in a climate changed environment.

4. RESULTS AND DISCUSSION

4.1. Climate Change Impact on Groundwater – Current Practice Scenario

The A1F1 climate change scenario resulted in mean annual rainfall for the catchment decreasing by 73 mm and average annual temperature increasing by 1.6°C (**Error! Reference source not found.**). Using the current practice scenario, the model predicted that mean annual evapotranspiration would decrease by 7% (39 mm/year) and recharge by 21% (24 mm/year) under climate change (**Error! Reference source not found.**).

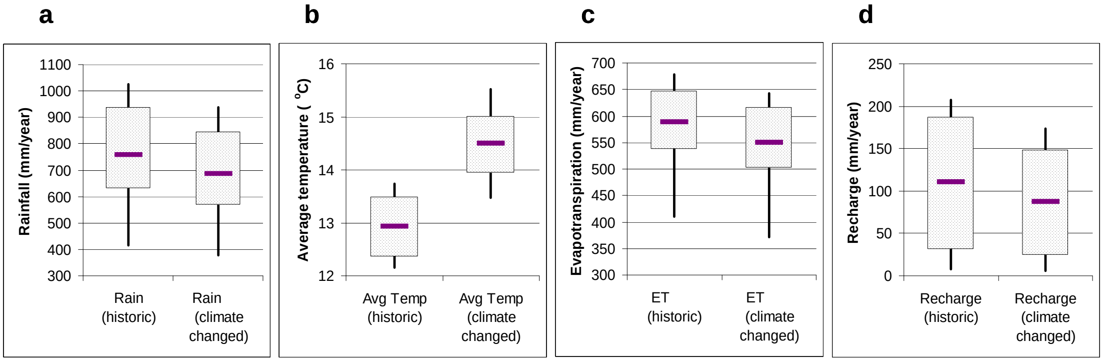

Figure 4. Catchment annual averaged results (46 years) showing maximum, 90 percentile, mean, 10 percentile and minimum values for **(a)** rainfall, **(b)** average daily minimum temperature, **(c)** evapotranspiration (current practice) and **(d)** recharge (current practice).

The impact of climate change on the groundwater resource was assessed using the difference between the potentiometric surface for the historic and climate change climates (**Error! Reference source not found.**). Across the CCMA, the average potentiometric head decreased by 4.1 m due to the reduction in recharge under climate change (Figure 4d). There was only a small change in potentiometric head due to climate change in the lower reaches of the catchment which is dominated by the lakes region in the centre. In contrast, a significant drop in potentiometric head was predicted under climate change for the upland reaches of the Corangamite catchment, due to the high hydraulic gradient in this steep terrain.

Importantly, the pattern of response is consistent with the observed changes in potentiometric head within this catchment resulting from below average rainfall over the last 10 years.

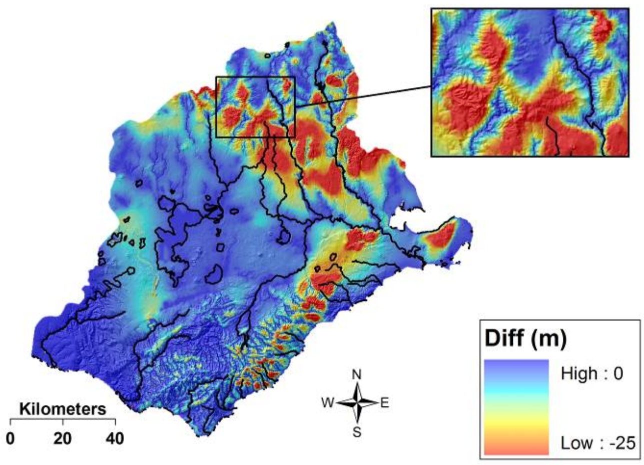

Figure 5 Difference in potentiometric surface under current practice (historic climate data minus predicted climate change data (2050))

4.2. Land Use Impact on Groundwater

Land use and management evolves as landholders respond to changing climates, markets and new knowledge. Land use change to a defined area alters recharge within that area, but groundwater resources will be more broadly impacted. For example, if 100 ha of pasture in the Corangamite Catchment was converted to plantation forestry (Figure 6), this would lead to a decrease in the potentiometric surface across more than 17,000 ha under historic climate conditions (**Error! Reference source not found.a**), and 16,400 ha under climate change conditions (**Error! Reference source not found.b**). The relative volume change for the groundwater resource was 10,998 ML under historic conditions (**Error! Reference source not found.a**) compared to 7,242 ML under a climate change sequence (**Error! Reference source not found.b**). The reduced impact on the groundwater resource of converting 100 ha of pasture to trees under a climate change sequence is the result of water table surface which has already been reduced by climate change; hence, there is less groundwater available for tree water use. Interestingly, different areas of the potentiometric surface were affected by the land use change under historic climate and climate change sequences (**Error! Reference source not found.c**), with the 100 ha tree plantation having a decreased impact on potentiometric head, within 5 km of the plantation due to climate change and a greater impact between 5 and 10 km. The example, presented of a plantation change, is located within the most responsive groundwater area of the CCMA. In other areas of the catchment, the response is consistent with this prediction, although the impact zone is smaller.

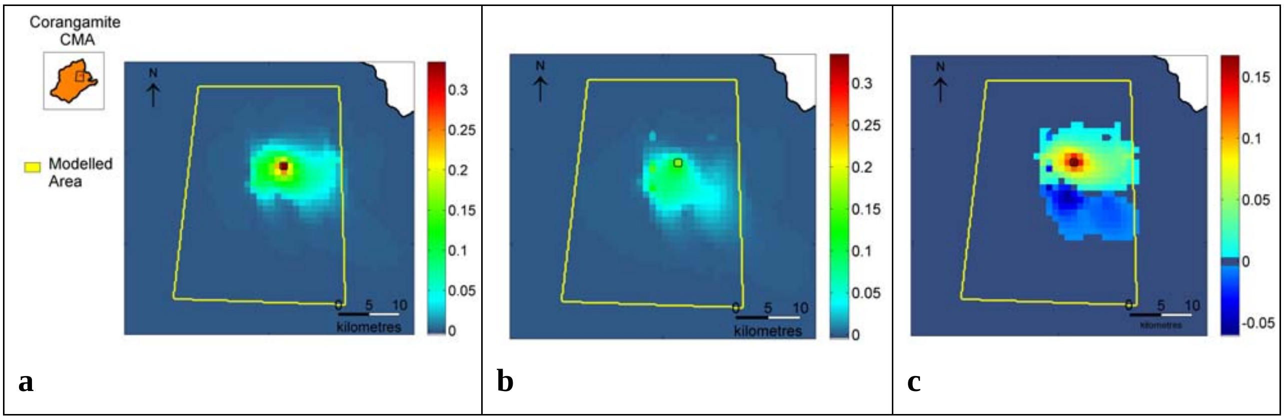

Figure 6. The drop in **potentiometric head** (m) of surrounding groundwater cells after planting 100 ha of land with trees under (**a**) the historic climate sequence and (**b**) projected climate change sequence. The difference between **a** and **b** is shown in **c**. Modelled area (91,300 ha) gives and indication of scale of impact.

4.3. Separating Tree and Climate Change Impact on Groundwater

By combining information on the effect of climate change and land use change on the potentiometric surface, the relative impact of land use and climate change can be separated.

For the example presented in **Error! Reference source not found.**, the potentiometric head directly under the 100 ha decreased by:

- 11 m in response to land use change under historic climate sequence (**Error! Reference source not found.**a);
- 14 m in response to climate change (Figure 5); and
- 7 m in response to land use change under a climate change sequence (**Error! Reference source not found.**b).

The results imply that at the 100 ha location selected for a tree plantation, the future impact on groundwater of climate change (**Error! Reference source not found.b**) will exceed any impact a tree plantation will have under current climate conditions (**Error! Reference source not found.a**).

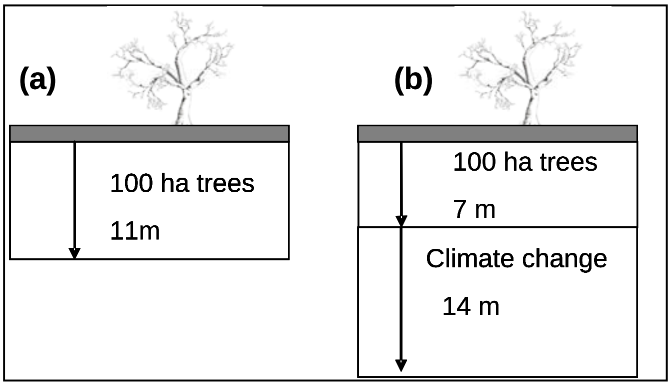

Figure 7 The reduction in potentiometric head for **(a)** the100 ha tree plantation from **Error! Reference source not found.**a and **(b)** the100 ha tree plantation from **Error! Reference source not found.**b plus the climate change impact under the 100 ha from

The impact of climate and land use change on the groundwater resource varies throughout the catchment. A 100 ha of tree plantation in another location within the Corangamite catchment would not necessarily have the same magnitude or pattern of influence on potentiometric surface.

This variability in response presents a challenge for catchment managers who are trying to manage water resources. The modelling approach presented in this paper presents a method to study the potential interactions of land use and climate change.

5. CONCLUSIONS

This study complements a broader study of modelling how agricultural land systems might adapt to cope with the impact of climate change in the south western Victorian region. The objective has been to separate how climate and land use interact to impact on the groundwater resource. The following conclusions are drawn from our modelling analyses:

- The A1F1 climate change scenario resulted in mean annual rainfall for the catchment decreasing by 73 mm and average annual temperature increasing by 1.6^{o}C. Using the current practice scenario, the model predicted that mean annual evapotranspiration would decrease by 7% (39 mm/year) and recharge by 21% (24 mm/year) under climate change;
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