18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009
http://mssanz.org.au/modsim09

Prioritising landscape investment using a process-based catchment model

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Abstract: This paper reports on the application and enhancement of a catchment-wide biophysical modelling framework to support an evidence-based approach for the procurement of environmental goods.

A biophysical modelling framework known as the Catchment Analysis Tool (CAT) is been used in this exercise to estimate on-site impacts of land management changes with off-site environmental outcomes. The framework comprises a suite of one-dimensional farming systems models capable of simulating a range of farming enterprises with modifications to account for lateral flow and groundwater recharge and is integrated into a fully distributed 3D-groundwater model.

This paper reports on the application to the Upper Wimmera catchment (310 326 ha) in western Victoria, Australia. The model is used to assess likely environmental outcomes due to farm scale revegetation. Additional information derived included the mapping of aquifer response times to land use/management change. This information is then used to prioritise catchment investment. The objectives of this paper are to;

(i) Describe the construct of the modelling framework,

(ii) Detail the modifications to the 3D-groundwater model to account for landuse, evapotranspiration and surface water/groundwater interactions, and

(iii) Present the application results. The paper concludes that spatially explicit, physically-based models can provide robust information to support evidence-based approaches to the procurement of environmental outcomes.

Keywords: *Catchment model, water balance, groundwater, surface water, salinity, Upper Wimmera, CAT, MBI, EBI*

1. INTRODUCTION

The aim of this investigation is to determine the locations in the landscape where revegetation has the greatest environmental benefit in the Upper Wimmera region of western Victoria, Australia. The outputs of this assessment are used to provide a measure of salinity contribution across the landscape, and rank salinity impact accordingly (refer to Hocking 2006). This project is funded by the National Action Pan for Salinity (NAP) and intended to provide hydrological economic analysis of the impacts of landuse change for salinity mitigation purposes.

Since the inception of revegetation programs for salinity control, the key question is where are the most effective locations to undertake on-ground works? In an attempt to answer this question, many prioritisation mapping frameworks have been developed (such as, Land Management Units (LMUs), Groundwater Flow Systems (GFS), etc), these frameworks consider a variety of landscape characteristics (such as soils, climate, hydrogeology, etc.). While some frameworks disaggregate the landscape into smaller zones, the question remains at paddock-point scale, where are the most effective locations to undertake on-ground works? Without doubt, there are locations in the landscape where revegetation has a greater impact for salinity control relative to others. Despite (in many instances) land managers and scientists having a detailed understanding of salinity-causing processes, it is not possible to distinguish the relative impact of revegetation on a point-to-point basis without the use of a spatially explicit numerical modelling application.

In the past, incentive grants were prescriptive and did not take into account the true costs of changing land use to achieve broader salinity benefits. The EcoTender project (Eigenraam *et al*., 2005) developed and applied a scientifically rigorous and transparent process to rank landscape outcomes arising from land use change. This information was subsequently used to inform the allocation of public funds to maximise environmental outcomes.

This paper extends the EcoTender approach by the application of an enhanced process-based catchment model to discriminate salinity impact across the landscape by assigning a market value for each modelled output to compare within a ranking system. Whereas the EcoTender approach assumed that a trend towards pre-European condition was positive, the current study explicitly considered the negative impacts associated with any landuse change (for example a reduction in runoff). Also, where the EcoTender process weighted all metrics equally (eg. a unit change in biodiversity was assumed equivalent to a unit change in streamflow), the approach adopted in this study used the market value of each metric evaluated in an attempt to account for community values and the trade-offs between environmental goods. As with the EcoTender project the process-based catchment modelling framework known as the Catchment Analysis Tool (CAT) (Beverly *et al*., 2005a, 2005b) was used ,but in the study the model was enhanced to provide evidence-based information to identify the most effective locations in the landscape to undertake on-ground works. In consultation with key stakeholders, three metrics were considered as the dominant factors which determine the priority of a location for revegetation activities, namely;

- change in land salinity area,
- change in surface water run-off, and
- change in saltload export.

Spatial model outputs generated through this study provides information for the Wimmera Market Based Instrument (MBI) project, known as Catchment Tender. Whitten and Shelton (2005) provided an implementation plan for establishing a MBI in the study area, and should be referred to for information of how the trial MBI trading operates on-ground. Modelling results derived using the developed methodologies are used by the Wimmera Catchment Management Authority (CMA) to guide and inform on-ground priority setting procedures.

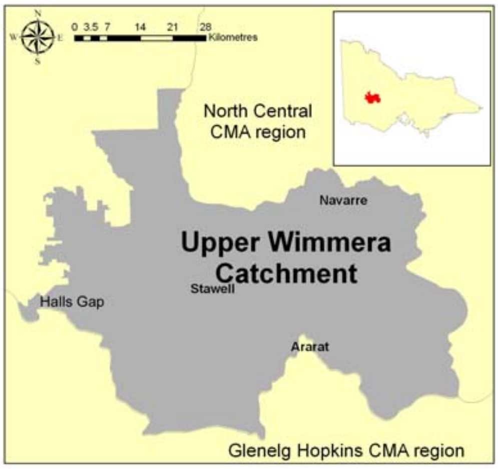

Figure 1. Upper Wimmera Catchment, within the Wimmera CMA region.

2. BACKGROUND

The Upper Wimmera Catchment (Figure 1) covers approximately 310 326 hectares. Mean annual rainfall varies between 430 to 1364 mm/year and averages 618 mm/year. The dominant land uses are native vegetation and public land (44%), grazing (42%), and cropping (12%), with intensive land uses such as viticulture occupying the remainder of the region. Major population centres located in the catchment are Stawell and Halls Gap, and Ararat is located just outside the catchment (Figure 1).

2.1. Topography & hydrology

Two perennial tributaries drain the catchment, Wimmera River and Mt William Creek (Figure 2). Topographic features define the catchment, they are the Great Dividing Range (including the Grampians Ranges) to the south south-west, the Pyrenees Range to the east and the lower Morrl Morrl range to the north. On average, 61,800 tonnes/year (200kg/hectare/year) of salt are exported from the catchment via surface water flow (WRSAP, 2003). In that area of salinity is 2,741 hectares.

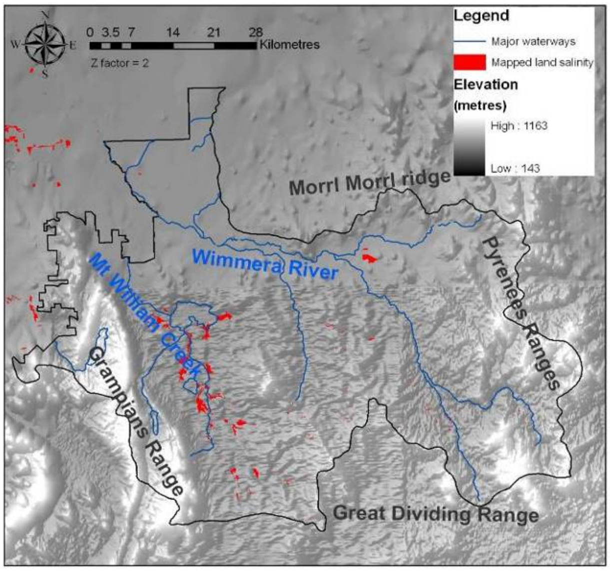

Figure 2. Topography, hydrology and salinity of the Upper Wimmera Catchment.

2.2. Geology & hydrogeology

The surface geology of the catchment is dominated by four geologies (Hocking, 2006). They are;

- Palaeozoic meta-sediments;
- Devonian granites;
- Tertiary weathering surfaces; and
- Quaternary alluvial sediments.

Four broad hydrogeological units have been identified that govern the movement of water in the landscape (Figure 3), they are;

- Quaternary alluvium-model layer 1;
- Deep leads (Calivil Fmt)-model layer 2;
- Devonian granite-model layer 3; and
- Palaeozoic basement-model layer 4.

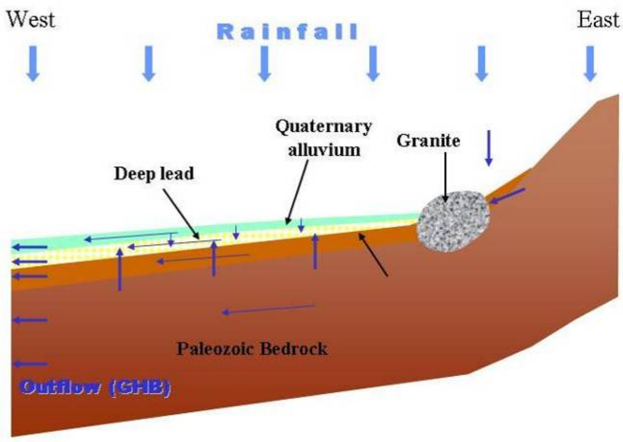

Figure 3 Simplified hydrogeological conceptualisation of the Upper Wimmera**.**

Groundwater movement generally flows to the north-west (with surface water flow). Hydraulic conductivity in the differing aquifers varies from ≈0.3 metres/day in Palaeozoic basement to >60 metres/day in deep leads. Approximate groundwater salinities for each model layer are presented below (Table 1).

Table 1 Estimated average groundwater salinity for each model layer

Model layer	Approximate EC (µS/cm)
1	8000
2	4000
3	5500
4	12000
5	7000

3. METHODOLOGY

3.1. Model framework

The CAT modelling approach used to estimate both the on-site and off-site impacts arising from landuse change uses a combination of a suite of farming system models that account for topography, soil type, climate and land use linked into a catchment framework with connection to a distributed, multi-layered groundwater model. The framework 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. Assigned to any landuse identified in the spatial landuse layer is a farming system model capable of simulating the soil-water-plant interactions for any combination of land management with allowance for time varying landuse, crop rotations, fertilizer and irrigation regimes. The climate data is reconstructed for each solution point to account for position in the landscape and is based on the meteorological data measured at the nearest climate station. Recharge estimates are based on the volume of water that leaves the root zone and soil characteristics such as total soil depth and slope. Simulation and calibration of the run-off and groundwater models enabled informed accounting of the total water balance at both point and catchment scale.

In this application, the daily recharge estimates were used as input into the distributed, multi-layered groundwater model MODFLOW (McDonald and Harbaugh, 1988). Modification to the MODFLOW model included the explicit incorporation of the landuse layer used in the surface hydrologic modelling such that evaporation depths and potential evaporation rates were spatially assigned to match the surface hydrologic model parameterization. Also, the 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. These modifications were necessary to ensure that total evapotranspiration did not exceed measured potential rates.

3.2. Model application

Input data layers required for the CAT include: mean annual rainfall, mean annual temperature, climate station proximity, aspect, slope, elevation, land use and soils mapping. All input data layers were created and/or resampled to a 20 metre cell size. Unsaturated landscape dynamic simulations were made between 1957 and 2005 at daily time-steps generating daily spatial outputs including:

- Crop and pasture yield
- Soil evaporation and vegetation transpiration
- Evapotranspiration (used by saturated model)
- Runoff, deep drainage, sub-surface lateral flow
- Recharge (used by saturated model)
- Soil loss, and
- Carbon

Groundwater simulations were based on a calibrated transient model developed during the project and operating on seven-day time-steps. Upon calibration, the model was converted to steady-state to estimate the likely equilibrium state arising from land use change scenarios. The groundwater model was composed of 584 rows and 789 columns operating 315 124 active cells in 4 model layers (eg. 1 260 496 solution points). Key groundwater estimates required for the assessment and subsequently generated spatially for each scenario at 100 metre cell size, included depth to watertable, groundwater discharge to stream/drains, and evaporation, extraction and outflow volumes.

3.3. Model calibration

Calibration of the catchment model involved the matching of simulated versus catchment stream gauge data, groundwater hydrograph trends, discharge area and crop yields where available. The farming system models used have had considerable review, validation and application (Weeks *et al*., 2007). The alternate land use considered was the restoration of pre-European vegetation as mapped by the Ecological Vegetation Class (EVC) land use based on an approach developed by Parkes *et al*. (2003). The change in runoff, shallow watertable area < 1.5 metres and groundwater baseflow volume were recorded on a cell-by-cell basis across the model domain.

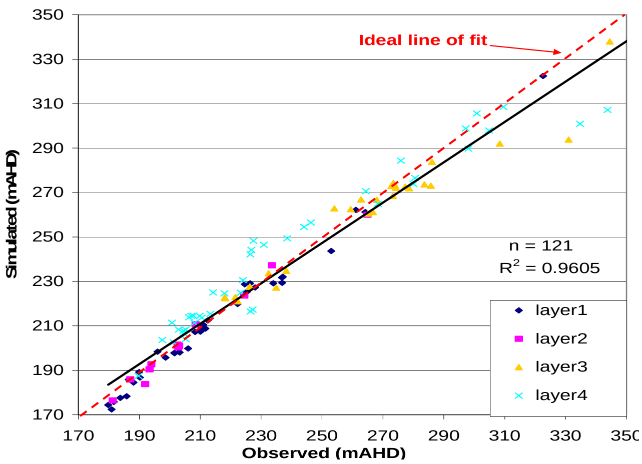

Figure 4. Calibrated simulation versus observed groundwater level.

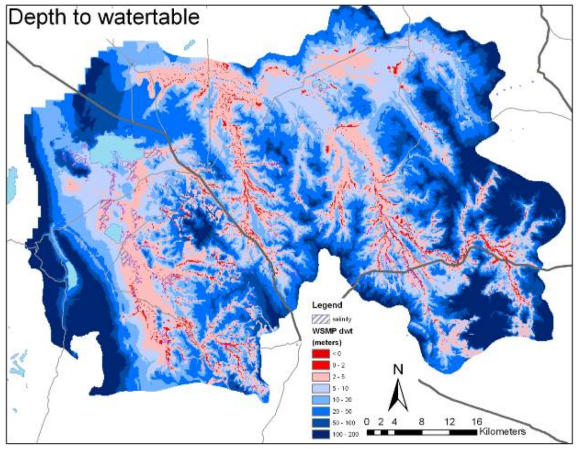

Figure 5. Calibrated depth to watertable layer.

4. RESULTS

4.1. Groundwater Model Calibration

Groundwater calibration was based on matching baseflow, saturated area and selected groundwater hydrographs. Figure 4 shows the observed versus simulated groundwater hydrograph results for 1995 for key observation bores. The year 1995 was identified as an "average" climatic year (Hocking, 2006). Table 2 summarises the calibration statistics derived from these results. In conjunction with stream gauge and bore hydrograph calibration, land salinity mapping was used for calibration. The mapping was used based upon the assumption that where mapped land salinity mapping occurred, the depth to watertable is less than 1.5 metres from ground surface. Figure 5 shows the predicted 1995 depth to watertable. The simulated discharge area was 2549 ha, which was in good agreement with the mapped area of 2741 ha.

Table 2. Calibration statistics of measured versus simulated bore hydrograph data

Scaled RMS	RMS error	Absolute residual error	Correlation coefficient (r^2)	Coefficient of determination	Number of bores used
4.77%	8.75 m	5.8 m	0.96	1.16	121

4.2. Scenario modelling

Results from the land use change scenario were recorded at each solution point. The three metrics considered for this application were 6a-change in run-off (mm/year), 6b- change in shallow watertable (<1.5 metres) area, and 6c-change in salt load (kg/year).

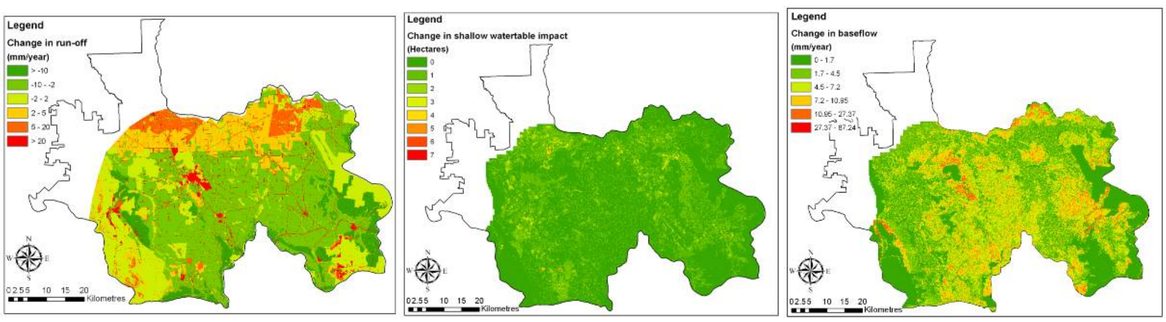

Figure 6a,b&c Difference between current landuse & EVC simulation outputs in the Upper Wimmera

4.2.1 Change in surface water flow

Change in surface water flow was determined by comparing simulated current land use overland flow with EVC land use overland flow data. The difference between the two layers is presented in Figure 6a. Results suggest there would be both increases and decreases in run-off across the catchment if current land use was replaced by pre-European conditions. The differences in run-off are associated with landuse variation. That is, under forestry plantation run-off was simulated to increase, whereas under grazing run-off was simulated to decrease.

4.2.2 Change in salinity area

Change in salinity area was assumed to represent any location where depth to watertable was less than 1.5 metres below ground surface. To determine the impact each cell had on shallow watertable area, groundwater recharge was modified upon each point (Figure 6b). Model outputs represent the total area of shallow watertable that individual cells would change (somewhere in the catchment) if land use was to change to EVC.

4.2.3 Change in saltload

Change in saltload was determined by summing surface water export via groundwater, namely drainage and river interaction nodes (Figure 6c). The model output represents the change in base flow each individual cell would have somewhere in the catchment, if land use was to change to EVC. The model layer where the change in volume occurred was considered where an average groundwater salinity was then assumed (refer to Table 1), resulting in a change in salt load layer.

4.3. Environmental benefit index

An environmental benefit index (EBI) was calculated to enable the comparison between the cost of intervention at different landscape positions. The EBI was assumed to be the summed cost of the total environmental outcome based on the economic value of each metric (Table 3).

Table 3 Economic values assigned to CMF model outputs

Model output	Economic description	Economic value ($)
Change in surface water flow	1 ML ≈ $20 in Upper Wimmera (GWMW pers. com.)	$20/ML
Change in salinity	1 ha carries ≈ 6 dse where 1 sheep gains ≈ $30/year	$180/hectare
Change in base flow to stream	1 EC unit ≈ $120,000 at Morgan (MDBC 2006)	$120,000/EC

Figure 7 presents the total cost of the three modelled outputs following the assignment of differing economic values for each output. Results estimate that the mean cost for revegetation per hectare is -$118, suggesting the overall impact of environmental work will be negative, principally due to the reduced surface flow contribution to streamflow associated with revegetation of deep-rooted perennials. Also shown in Figure 7 is the histogram of results shows the skewness of the distribution of the catchment EBI. However, it is recognised that the economic values assigned to the model outputs are generalised and may require further review in the future, but the overall methodology offers a transparent and robust approach to differentiating landscape intervention strategies. Also other environmental impacts may need to be considered in future applications (such as nutrients, carbon, biodiversity, etc.) which are available in the current modelling framework.

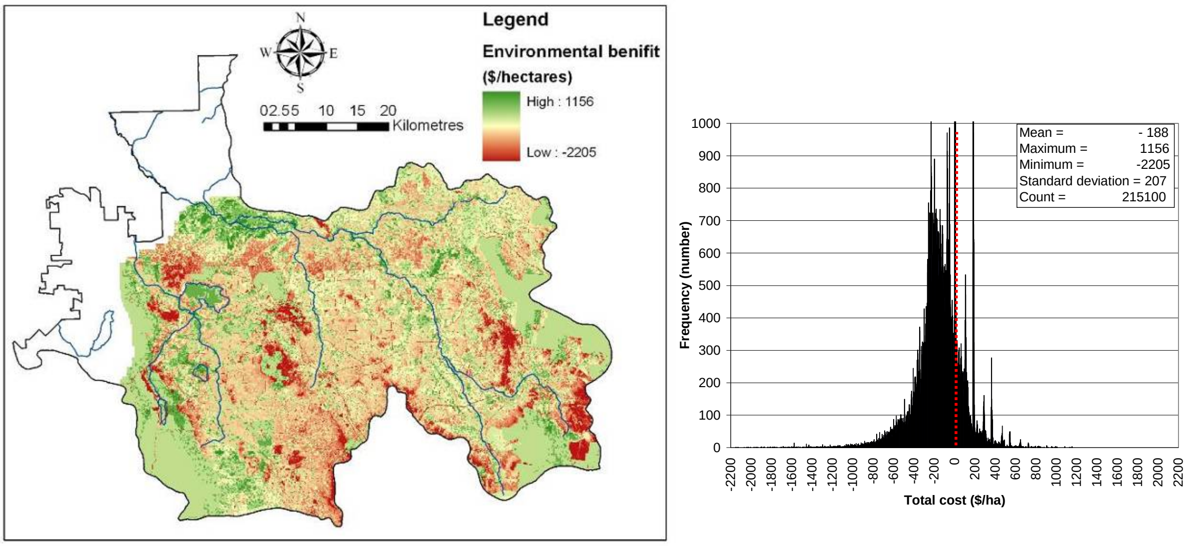

Figure 7 Spatial map of normalised environmental benefits of land use change (left) and associated histogram (right).

5. DISCUSSION

One driver for attempting to apply an economic context to the modelling results is to reveal the impact land use change/revegetation has on the catchment water balance. That is, catchment surface water flow yield is highly valued, and any loss in surface water flow is not desirable. The application of applying a value to the loss (or gain) in surface water flow needs consideration. Likewise, the value of salt affected land, compared to the decreases (or increases) in salt load, need to be accounted for.

The "change in base flow" scenario results generally agrees with the traditional salinity treatment concept that planting trees on top of hills will have the greatest benefit. However, contrary to expectations, the "change in land salinity area" scenario suggests the most beneficial locations for reducing salinity area are located in the mid-lower parts of the landscape. The "change in run-off" scenario confirmed the notion that cropping significantly reduces run-off relative to grazing and native vegetation.

6. CONCLUSIONS

The modelling approach presented in this paper has demonstrated an on-ground application linking spatially explicit biophysical modelling to policy and complex catchment management issues. The modelling has shown it is feasible to rank the relative catchment response of land use change at the paddock scale as a function of changes in the catchment scale water balance and exports including groundwater discharge, salt load and flow volumes. Within limits, the model has shown to be able to quantify within catchment processes at the land management scale. Economic values assigned to each model output may not necessarily reflect the exact monitory cost of landuse change adoption (Whitten and Moir, 2007); however, the approach has been applied elsewhere and reflects the likely range of costs based on the EBI estimates.

The EBI results identify locations in the landscape where the greatest environmental benefits can be achieved often aligns with floodplains and water bodies and as such differ from the traditional concept that "trees should be planted on top of hills to reduce salinity". The approach developed in this paper is shown to provide improved cost-effective and targeted intervention strategies and robust information to support evidence-based approaches to the procurement of environmental outcomes.

ACKNOWLEDGMENTS

This project was funded by the National Action Pan for Salinity on behalf of the Wimmera Catchment Management Authority and acknowledge the support from Robert Moir (Wimmera CMA) and Bernie Dunn (formerly of the Wimmera CMA).

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