Catchment Scale Biophysical Modelling to Support Auctions for Multiple Nnvironmental Outcomes

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EXTENDED ABSTRACT

This paper is an extension of previous work completed in the development and application of an evidence-based approach to the procurement of environmental improvement (Eigenraam et al 2007). Additional modelling results are presented supporting the economic principle of joint production as well as demonstrating environmental outcomes are both spatially and temporally correlated.

The modelling framework, known as the Catchment Modelling Framework (CMF), explicitly links biophysical and catchment scale processes and was used to estimate multiple environmental outcomes.

The CMF model was used to support a project piloting a market-based approach to procure multiple environmental outcomes. Whereas market-based approaches have been used in the past to distribute environmental funds, this is the first time a market-based policy has been fully integrated from desk to field with a biophysical modelling framework for the purchase of multiple outcomes.

This paper reports on the application of the CMF to the Avon-Richardson sub-catchment (371,000 ha) in north central Victoria. The catchment model was used to undertake an *a priori* assessment of environmental outcomes. The CMF operates at both the farm scale (< 1 ha) and the catchment scale; explicitly links surface and groundwater interactions; accounts for land management and practice; and estimates water balance, erosion, carbon and vegetation dynamics on a daily basis.

The paper concludes that spatially explicit, physically-based biophysical models are capable of providing robust and transparent information to support evidence-based approaches to the procurement of environmental outcomes.

INTRODUCTION

Auctions for the procurement of multiple environmental benefit outcomes have been used in the past to distribute environmental funds. BushTender, a single dimension auction (one environmental outcome) demonstrated that significant cost savings are achieved when compared to other grant-based approaches (Stoneham *et al* 2003). In general, auctions aim to provide private landholders with the incentive to truthfully reveal their cost of undertaking specified actions that produce environmental outcomes. If correctly applied auctions can help to overcome common problems involving *asymmetric information* – where landholders have information about the cost of undertaking an action but this information is hidden from the agency who is providing the funds. The agency needs both cost information from landholders and information about the environmental outcomes (*missing information*) provided by the proposed land use change, to make choices between both environmental management options and the allocation of funds. It follows then that markets should be able to be created by addressing these information problems. By attending to a) mechanisms that reveal information from landholders (auction format and design); and b) disclosure of scientific information to inform purchasers about the quantum of services provided by bidders, Stoneham *et al* (2003) showed it was possible to create a market. The pilot auction (BushTender) demonstrated that cost savings of up to seven times are achievable when compared with previous grant based systems in the same area. BushTender focused on one environmental outcome, terrestrial biodiversity, for which the "*habitat hectare*" approach was applied along with other biodiversity-related information to help solve the missing information problem (Parkes *et al* 2003).

This paper reports on the next advance in the application of market-based instruments to environmental problems associated with private land use (Eigenraam *et al* 2005). It reports on the information needed to conduct a pilot multiple-outcome auction (EcoTender) where the purchaser is provided with information about the impact of land use change from four environmental dimensions (carbon sequestration; aquatic function [defined as the sum of quickflow and baseflow]; dryland salinity impacts; and terrestrial biodiversity). The CMF was developed to estimate the environmental impacts of these multiple environmental outcomes and to spatially represent these impacts to potential bidders and the purchaser (Victorian Government) of these services. This approach offers the prospect of improving the cost-effectiveness of the single dimension auction, possibly beyond that achieved by BushTender. It also reduces the costs of providing information about the impact of land use change thereby decreasing transaction costs.

The auction approach explicitly recognises the heterogeneous nature of landholders' opportunity costs to undertake alternative land management. The auction allows landholders to determine the payment required to undertake the agreed management. The environmental outcomes vary between landholders for the same management. Past modelling approaches have adopted large homogenous land areas assuming the environmental outcomes within the area are the same for all landholders. The CMF models land management at farm/paddock scale to explicitly account for the heterogeneous nature of the environmental outcomes. When heterogeneity exists it is possible to generate more environmental outcomes for a given environmental budget.

There is growing recognition that environmental outcomes are correlated: benefits are jointly produced by the same action. For instance, revegetation may jointly produce carbon, improvements to water quality and wildlife benefits. Wu and Boggess (1999) refer to this as an ecosystem-based approach that recognises the interaction between alternative environmental benefits. They show that an efficient fund allocation must account for both physical production relationships between environmental outcomes and the value of those outcomes. Ribaudo (1986) relied upon qualitative empirical analysis of one environmental benefit (erosion and water quality) to demonstrate that conservation programs have been inefficient because they have focused on on-site information rather than environmental outcomes. Wu and Boggess (1999) used theoretical models to demonstrate their point but highlighted the need for empirical models to inform investment decisions. In both cases there was very limited empirical scientific data to support their findings.

The CMF presented in this paper focuses on providing the missing information that links environmental outcomes with actions on private land. The framework provides empirical estimates of correlations between environmental outcomes and explicitly links on-site land use changes with off-site environmental outcomes. The framework has been designed to explicitly model and report the joint production of environmental outcomes enabling policymakers to more efficiently allocate conservation funds.

CONTEMPORARY MODELS

In order to address the missing information issues, a review of contemporary catchment scale models was undertaken to identify a potential framework/s capable of assessing the site specific and off-site environmental outcomes arising from alternative land management. The framework needed to operate at the appropriate resolution to link farm scale land use change to off-site catchment scale impacts. In the past, physically based, one-dimensional simulation models have been used to evaluate the production and environmental aspects of farming systems, including the amount of deep drainage lost below the plant root zone (Coram and Beverly 2003). The amount of excess water available (defined as rainfall less soil evaporation and plant water use) includes: deep drainage; sub-surface lateral flows and surface runoff (which is partitioned into recharge to the deeper groundwater); and lateral flow to stream. This partitioning is important because the vertically dominated recharge pathway results in very different environmental outcomes to the laterally dominated flow pathway.

Past studies using one-dimensional farming systems models have assumed deep drainage contributes only to, and is analogous to, groundwater recharge. For instance, the Liverpool Plains study (Paydar *et al* 1999; Ringrose-Voase and Cresswell 2000) identified large anomalies between recharge estimates based predominantly on deep drainage predictions derived from one-dimensional models, and those derived from groundwater hydrograph responses. These anomalies are directly attributable to the lack of partitioning and accounting for lateral flow processes.

Contemporary catchment models such as the USDA soil and water assessment tool (SWAT) and MIKE-SHE typically use a generalised vegetation algorithm to simulate all forms of land use. Often such models do not preserve spatial resolution and in some cases do not explicitly model distributed groundwater dynamics, but rather adopt both parameter approach (Neitsch *et al* 2001).

In contrast to the physically-based catchment models described above, generalised approaches based on average annual relationships between evapo-transpiration demand and rainfall have been developed (Holmes and Sinclair 1986; Zhang *et al* 1999). Recent studies have adopted these empirical relationships to assess the impact of land use change on mean annual runoff for grassland and forest catchments. However these models have limited temporal and spatial resolution to assess the impact of landscape intervention at the farm/paddock scale. Furthermore, they are not explicitly linked to a distributed groundwater model, which is essential to estimate the groundwater balance and off-site water table impacts.

The CMF was developed because none of the above approaches provided farming systems models that operated at the catchment scale and wee explicitly linked to groundwater. Furthermore, they did not provide transparent estimates of environmental outcomes nor the ability to combine biophysical information into environmental outcomes in a systematic manner.

CATCHMENT MODELLING FRAMEWORK (CMF)

The CMF is an enhancement of the Catchment Analysis Tool (DSE 2007; Beverly *et al* 2005) which incorporates a suite of one-dimensional farming systems models into a catchment modelling framework with modification to account for lateral flow/recharge partitioning. The CMF consists of an interface and a simulation environment. The interface is used to assemble time series and spatial data sets for use by simulation models, visualisation and interpretation of data, and the interrogation of simulation outputs. The interface was designed to assist in both the pre- and post-processing of spatial and temporal data sets.

The interface is also used to apply rule-based methods to analyse landscape features. The interface was developed using the mathematical programming environment MATLAB® and can be distributed as an executable to non-technical users and stakeholders.

The simulation environment is an assemblage of one-dimensional farming systems models capable of simulating pasture, crop, trees and livestock enterprises. The soil/water/plant zone is linked to a deeper groundwater system which is simulated using, in this instance, the fully distributed multi-layered groundwater model MODFLOW (McDonald and Harbaugh 1988). The CMF simulates daily soil/water/plant interactions; overland water flow processes; soil loss; carbon sequestration; and water contribution to streamflow from both lateral flow (overland flow and interflow) and groundwater discharge (base flow to stream). The agronomic models can be applied to any combination of soil type, climate, topography and land practice. Using the interface, outputs from these simulations can be compiled for visualisation, interpretation and interrogation.

APPLICATION

The pilot auction was conducted in two sub-catchments in Victoria, namely the Avon-Richardson (371,000ha) and Cornella (47,000ha) (Figure 1) located in the North-Central and Goulburn-Broken Catchment Management Authority regions respectively. However this paper will only report on the Avon Richardson application. Catchment selection was based on data availability; the areal extent of any proposed land use change; the type of management considered by land managers; and a requirement that the focus catchment be a priority region as identified by the appropriate state authorities. The landscape needed to be topographically and climatically variable and the catchment unregulated (not significantly controlled by in-stream structures and diversions for other uses such as irrigation) and monitored in order to provide continuous streamflow and water quality data to underpin model calibration and validation. Additionally, catchment selection was based on the presence and quality of time series groundwater observation data, which was used to conceptualise and validate the groundwater dynamics.

The current land use in the Avon-Richardson comprises 52% cropping, 37% grazing, 6% trees and the remaining 5% constituting urban infrastructure and water bodies. Rainfall ranges from 350 to 765 mm/year.

For each spatial vegetation coverage, discrete land units across the catchment were defined based on soil, slope, climate, land use, land management and elevation. Each land unit varied in size ranging between several hectares to tens of hectares and was connected to an underlying three layer MODFLOW groundwater model (McDonald and Harbaugh 1988). A biophysical farming system model simulating daily soil/water/plant interactions was assigned to each land unit.

The calibration procedure adopted a split sample test with non-overlapping calibration and verification periods. The calibration strategy applied to pre-scenario conditions between 1957 and 1995 whereas model verification was assessed on data measured between 1996 and 2000 inclusive.

Figure 1: Locality of catchments in which the pilot auction was conducted.

Calibration of the framework was based on matching measured catchment yield and salt export, stream dynamics, selected groundwater hydrograph responses, depth-to-water table information, and mapped groundwater discharge areas. Streamflow analysis techniques were applied to measure stream gauge data to estimate quickflow (overland, sub-surface and groundwater surface discharge) and groundwater baseflow (groundwater flow into stream). The calibration criterion compared these quickflow and baseflow time series data sets with predicted volumes to calculate goodness of fit based on 44 years of historical climate data.

RESULTS

In the case of the Avon-Richardson catchment, the simulated area of groundwater discharge was 16,200 ha which correlated with the mapped 15,500 ha. Groundwater mean annual baseflow was simulated to be in the order 250-300 ML/year, which also correlated with gauged streamflow data (Hocking 2007).

Figures 2, 3, and 4 illustrate the environmental impacts of systematic changes in units of the landscape from current back to pre-European landscapes as described by the ecological estimation techniques developed by Parkes *et al.* (2003). The results presented in these figures were generated by systematically changing 25 ha units from current land use to pre-European vegetation, whilst maintaining current condition on the remaining landscape. Figure 2 shows the impact on mean annual carbon (kg/m2/yr); Figure 3 shows the impact on streamflow (mm/yr); and Figure 4 the impact on saturated area (< 2m depth-to-water table) of changing the land use from current to the pre-European landscape. These predictions were used to inform the auction process.

Table 1 summarises the catchment response under pre-European and current condition. Based on these results and the spatial patterning of likely catchment impacts, the correlation matrix for the five key metrics are summarised in Table 2.

Figure 5 shows the location and extent of five spatially separated regions within the study catchment broadly describing different land use by soil by slope and rainfall intercepts. Figure 6 shows the estimated groundwater response times arising from the replacement of current land use to native vegetation within each of the five landscape zones. The groundwater response time describes the time and trajectory of the groundwater system to reach the new equilibrium (or steady-state condition) following a change in recharge (due to the land use change).

DISCUSSION

The figures below show that there are heterogeneous environmental impacts on all domains of the environment. Figure 3 indicates that changing vegetation from predominately annual systems (crops) to deep-rooted perennial pre-European vegetation in some locations causes significant reduction in expected streamflow, while in other locations there is little detectable impact on streamflow. The results demonstrate that the location of interventions in the landscape significantly affect the environmental goods and services generated.

As shown in Figure 4, a similar conclusion can be drawn with respect to the area of land subject to shallow water tables and water logging. Figure 4 shows that intervention in different locations (each intervention being a 25 ha change to native vegetation) causes variable changes in the area of land subject to shallow water tables (less than 2m depth to water table). Intervention/revegetation in some locations causes a reduction in the current shallow water table area by only 1 hectare of land, whereas, while in other locations, the same 25 ha intervention causes the area of land subject to a shallow water table to drop by up to 46 ha.

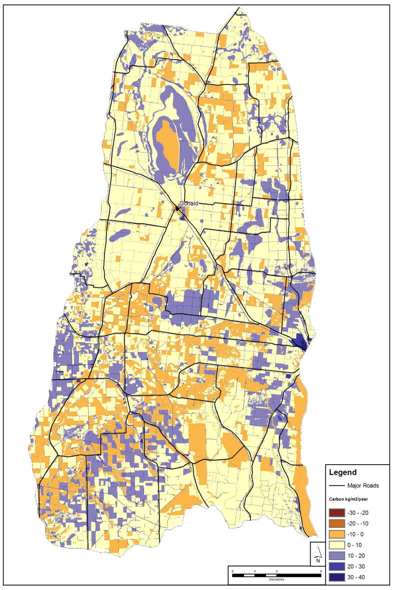

Figure 2: Impact on mean annual carbon (kg/m2/yr) of changing land use from current to pre-European land use

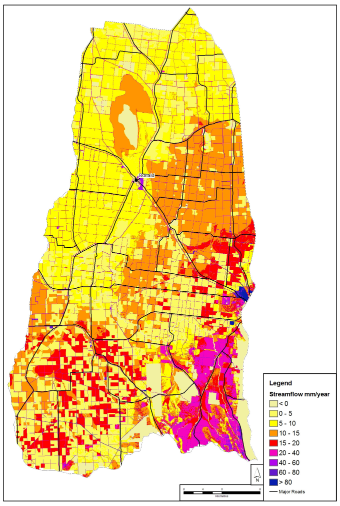

Figure 3: Impact on mean annual streamflow of changing land use from current to pre-European land use

Additionally, the groundwater response results illustrated in Figure 5 show that different parts of the catchment have different response times, ranging from approximately 100 to 180 years in this instance. These variations reflect the non-homogenous nature of the groundwater systems and the varying interactions that are dominant in different regions of the landscape.

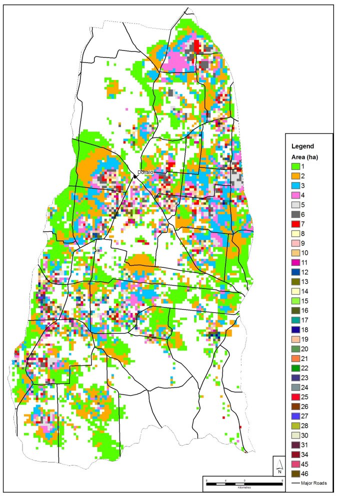

Figure 4: Impact on saturated area (< 2m depth-to-water table) of changing the land use from current to the pre-European landscape

Table 1: Pre-European and current landscape condition

	Pre-European landscape	Current landscape
Mean annual streamflow (GL), *(Standard error)*	18.9 GL *(62%)*	66.8 GL *(71%)*
Area of land with groundwater > 0.8m	370,938 ha	370,215 ha
Habitat (habitat hectares)	370,000	14,000
Carbon sequestered (million tonnes) Mean, *(Standard error)*	103.9 Mt *(17%)*	78.2 Mt *(33%)*
Water quality – export of salt to streams (tonnes/annum)	2,190	53,460

Table 2: Correlation matrix for catchment

	SF	C	SL	WQ	TB
SF	1				
C	0.17	1			
SL	0.16	0.06	1		
WQ	0.03	-0.07	-0.09	1	
TB	0.09	-0.06	-0.17	0.64	1

SF=Streamflow C=Carbon SL=Saline land
WQ=Water quality TB=Terrestrial biodiversity

The auction process involved government advertising the auction followed by landholders submitting an expression of interest. Subsequently each landholder was visited by a field officer that collected site specific data and discussed alternative land management actions. The field officer then enters site details and management actions into the CMF to calculate the total environmental impact.

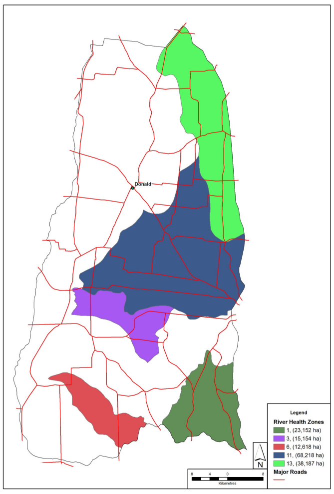

Figure 5: Location of different landscape units used to estimate groundwater response times.

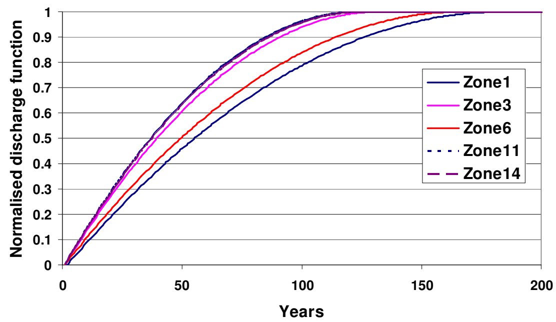

Figure 6: Groundwater response times for different landscape units

The total environment impact of all landholders sites is combined with their bid and used to determine the best value for money - bids are ranked from least cost upwards based on their environmental impact and total cost.

Within the pilots budget constraint a total of 357,186 environmental benefit index (the environmental benefit of each proposed contract was determined as the sum of the percentage movements for all public good domains) units were procured, consisting of 277,595 units of habitat improvement, 25,056 units of water quality improvement and 5,755 units of salinity control. These units are additive representing the relative movement from the current environmental status toward a pristine state (as defined by the pre-European landscape). A total of 32 contracts were secured, representing management agreements over 257 hectares of land. Additionally, analysis of the simulation results derived for all sites within the pilot study suggests that 73% generate two or more environmental goods supporting the hypothesis that environmental outcomes are jointly produced from a single land use change. Given outcomes are jointly produced there may be scope to reduce total costs if outcomes are correlated.

CONCLUSION

The CMF has significantly reduced the transaction costs associated with accurately determining environmental outcomes for any site within the landscape. The CMF can be calibrated to any catchment, providing there is sufficient data. Furthermore, the framework can be readily updated as new data becomes available. The correlation results presented in Table 2 suggest that the CMF is capable of exploring the trade-offs between metrics.

The CMF provides policy makers with a new tool to analyse landscape intervention and make informed decisions about the outcomes resulting from investment at paddock scale. The framework is practical and feasible for application in the field and provides a cost effective, replicable and transparent method for the assessment of environmental outcomes to support programs for the allocation of environmental funds.

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