Predicting the spatial and temporal effects of landuse change using the CATSALT modelling framework

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Abstract: A system of water quality targets including salinity benchmarked at the outlet of each major river of the Murray Darling Basin has been adopted (DLWC, 2000; MDBMC, 2001). The CATSALT modelling framework (Tuteja et al., in press; Vaze et al., in press) has been developed to quantify the spatial and temporal effects of landuse changes on water and salt export from a catchment. Water balance is distributed within a catchment by taking into account the effects of topography, landuse and soils and temporal variability of the climate on runoff and recharge. The distributed water balance is then linked with the salt transport to predict salt export from the catchment. Landuse change scenarios are designed to: (a) increase the perennial content of the pastures and crop rotations and (b) increase the current remnant native woody vegetation with additional tree cover. These scenarios are investigated to determine the level of intervention required to develop ameliorative strategies. Implementation of the CATSALT model is demonstrated on the Boorowa River catchment located in the Lachlan Basin, New South Wales. Likely downstream impacts of the reduction in water flow and salt export are also estimated.

Keywords: *Landuse; Runoff; Topographic Wetness Index; Modelling; Dryland salinity; CATSALT*

1. INTRODUCTION

Dryland salinity is a major problem in Australia. It is generally accepted that the spread of dryland salinity in the upper parts of the Murray-Darling Basin has resulted from the clearing of native vegetation for European style agriculture (*Walker et al.*, 1992). The issue of vegetation effects on catchment water balance has been the subject of extensive observation and modeling across the world for many years (*Horton*, 1919; *Cornish*, 1993).

In recent times complex process modeling approaches have given way to more simplistic approaches due to issues of scale and data availability. Many authors (*Holmes and Sinclair*, 1986; *Zhang et al.*, 2001) have developed relationships between vegetation type and average annual evapotranspiration from a small number of readily available parameters. Although informative as to the relative efficiency of each vegetation type in affecting the water balance, on their own these coarse average annual relationships provide insufficient information on the temporal effects of tributary flow and salinity. Such relationships may only be useful in a steady state analysis.

Lumped parameter conceptual rainfall runoff models such as SMAR (*Kachroo*, 1992) are used around the world in river forecasting. They are particularly useful in estimating the major components of the water balance (evapotranspiration, surface runoff, baseflow and interflow) from daily rainfall, pan evaporation and gauged stream flow.

Water balance effects alone are insufficient to explain patterns of stream salinity. Salt stores in the landscape are required to be linked with water balance components to account for surface, sub-surface and groundwater processes whereby salt enters the stream. As such the water balance needs to be sufficiently distributed to capture the heterogeneity of the salt store and mobilisation processes.

Topography is one of the dominant physical drivers of flow in a watershed and is the primary determinant of catchment response (*Beven and Kirkby*, 1979). Several topographic indices relating position in the landscape to hydrologic behaviour have gained acceptance as predictors of surface, sub-surface and groundwater flow (*Tarboton,* 1997).

This paper describes the results from a study of the effects of landuse change on daily water and salt balances for Boorowa River catchment in New South Wales, Australia. Conceptual rainfall runoff modeling techniques are combined with landuse efficiency indices, topographic modeling, salinity hazard and salt outbreak mapping. Unlike conventional salinity studies that focus on groundwater alone, this study explores surface and groundwater interactions with salt stores and the stream.

2 MODELING METHODOLOGY

A quasi-physical model-CATSALT (for details see *Tuteja et al.*, in press; *Vaze et al.*, in press) was developed to couple landscape salinisation and stream salinity. The model operates on a daily time step and includes three modules:

(a) A lumped conceptual rainfall runoff model SMAR: The SMAR model consists of two components in sequence, namely, a water balance component and a routing component (*Kachroo*, 1992). The water balance component generates runoff which is transformed by the routing component into discharge at the catchment outlet through a Gamma Function Model. SMAR also provides estimates of baseflow separation.

(b) A runoff distribution component based on landuse and topography: To account for current landuse and incorporate the effects of landuse change, the lumped water balance needs to be distributed. The distribution methodology requires leakage rates (moisture draining the soil profile below the root zone) for all landscape positions and landuse combinations within the catchment. Vegetation efficiency indices for both surface and groundwater components were developed by reference to published data and modeling results from a nearby catchment with similar soils.

(c) A salt mobilisation and washoff component: The salt mobilisation and wash-off model links salt sources from within the catchment with the distributed surface runoff obtained using the procedure described above in (b). A surface salt store map (depth averaged salinity) was constructed by combining soil landscape mapping, soil profile data and salt outbreak mapping in a GIS. Water entering the river as surface runoff undergoes sorptive exchange with salts adsorbed to the soil matrix. The general form of the non-linear Freundlich isotherm is used to describe the exchange process.

3 CATCHMENT DESCRIPTION AND DATA USED IN THE STUDY

The modeling methodology described above was applied to the Boorowa River catchment, located in the Central West of New South Wales (NSW), Australia. The total area of the Boorowa River Catchment above Prossers Crossing (Gauging station number 412029) is 1550 km^2. The range in slope is 32.8 degrees with an average slope of about 4 degrees for the entire catchment.

3.1 Climate

Climate surfaces are available for the Australian continent using a widely accepted methodology (*Jeffrey et al*., 2001). Daily climate surfaces for rainfall and pan evaporation were drilled at a 5 km grid for the entire catchment and spatially averaged for the period 1975-1995. Streamflow at the catchment outlet (Boorowa River at Prossers Crossing, 412029) was measured continuously for the entire modeling period (1975-1995).

3.2 Landuse

Landuse data for the Boorowa River catchment was obtained from the following sources: NSW Department of Land and Water Conservation (DLWC) landuse maps for the Boorowa River catchment, and the Australian Landuse Classification System – ALCC (*Stewart et al.*, 2001). These data sets comprise six landuse categories (cropping, trees, pasture, urban, bare, and water). These are rationalised so that five categories are used in the modeling. Water bodies, bare and urban areas constitute a very small proportion of the total catchment and therefore have been classified as "Other". Pastures are further sub-divided into perennial and annual components based on land capability class and expert local knowledge.

The landuse change scenarios were developed in conjunction with the regional staff and farmers and are based on the land capability mapping and soil conservation guidelines of the DSNR. The developed landuse changes were spatially distributed by linking with the topographic wetness index (for details see *Vaze et al.*, in press). The following landuse change scenarios were used in the study.

- <u>Scenario 1.</u> All area under annual pasture was changed to perennial pasture and 30 % of the area under cropping was also changed to perennial pasture. This scenario is designed to increase the perenniality of the vegetation. This scenario represents the most acceptable option for change to the local community, as there are likely productivity benefits without major structural change.

- Scenario 2. Increase the tree cover to 20 % (Scenario 2.1), 30 % (Scenario 2.2) and 40 % (Scenario 2.3) of the catchment over and above the landuse changes in Scenario 1. Scenarios 2.1 to 2.3 are based on incorporating more stringent recharge control measures to mitigate landscape salinisation in the discharge areas.

3.3 Stream and soil salinity data

Continuous streamflow and salinity data at the catchment outlet was available for a period of one year. Additionally, 84 measured discrete flow and EC data points were also available (1968-1997). Salinity was measured as electrical conductivity (EC) where, 1 EC unit = 1 $\mu S.cm^{-1}$ or 0.64 $mg.L^{-1}$ at 25^oC. The continuous and discrete in-stream EC data was used for model calibration. The missing salinity data was constructed using the flow and EC/salt load relationships based on continuous and discrete data.

For the modeling exercise, terrain analysis based on toposequence was used to separate areas of individual soil types within soil landscapes. The salinity levels of the soils within the soil landscapes are variable with some being more saline and having a higher proportion of sodic soils. Additional soil salinity profile data (*SALIS*) corresponding to the mapping of saline discharge areas were combined with the soil landscape map salinity data to produce a depth averaged surface salt store map.

4 RESULTS AND DISCUSSION

4.1 Water and salt balance under current landuse

The entire Boorowa river catchment was modelled using the SMAR model as a single lumped catchment to estimate the partitioned water balance components for the period 1975-95. Model performance was evaluated using the R^2 efficiency criterion of *Nash and Sutcliffe* (1970).

Figure 1(a) shows the annual observed and estimated streamflow along with the routed surface and groundwater discharge for the entire modeling period (1975-1995). The model was able to simulate both the flow peaks and the low flow conditions consistently. When comparing the annual totals, the model under estimated most of the high flow years and over estimated most of the low flow years. Overall, the water balance model was able to simulate the daily (not shown here) and annual streamflow adequately (see Figure 1(a)). Given the scale of the problem and the objectives of assessing long-term impacts of landuse change, this was considered a reasonable representation of the water balance at the catchment scale.

Figure 1(b) shows the comparison of the annual observed and estimated salt loads. Similar to the water balance simulations, the model was able to estimate the daily salt load series during both high flow and low flow conditions adequately (not shown here). When comparing the simulated and observed annual salt loads, the model was able to reproduce the observed salt loads with an R^2 of 0.98 (see Figure 1(b)).

Figure 2(a) shows the areas under the current landuse. Estimated runoff from each landuse is obtained using landuse efficiency parameters and the respective areas under current landuse using the methodology described in *Vaze et al.*, in press. Runoff contribution from areas under perennial pasture is more than runoff from areas under annual pasture because of larger areas of the former, even though they are less efficient in runoff generation.

The flow and salt contribution at the catchment outlet from individual landuse is shown in Figure 2(b). Perennial pastures, which cover 47% of the catchment area, contribute 45% of the total flow and 50% of the total salt at the catchment outlet. Annual pastures contribute about 35% of the total flow and 25% of the total salt whereas the contribution from cropping areas is about 18% to flow and 23 % to total salts. The total contribution to flow and salts from trees and Other landuses is less than 2%.

4.2 Effect of landuse change on water and salt balance

Figure 2(c) to (j) shows the areas under different landuse and the respective flow and salt contributions at the catchment outlet from individual landuses for the four landuse change scenarios. Figure 2(k) and (l) show the total flow and salt load at the catchment outlet under current landuse and all the four landuse change scenarios. In landuse change Scenario 1, all the area under annual pastures and 30% of area under cropping was converted to perennial pastures without specifically targeting the saline discharge areas. As such, the reduction in salt load produced by Scenario 1 (about 5%) is almost linear with reduction in flow (about 7%). For landuse change scenario 2.1, high recharge and the saline discharge areas in the catchment (although very small proportion of the total catchment area, about 16 km^2) were targeted first by simulating the introduction of salt tolerant plantation along the fringes of the saline discharge areas. Hence, the reduction in salt load (about 40%) is not linear with reduction in runoff (about 18%). Almost all of the 16 km^2 of saline discharge areas are targeted in Scenario 2.1 and so for Scenarios 2.2 and 2.3, the reductions in salt loads are less dramatic and are almost linear with reductions in flow. Implementation of landuse change Scenario 2.3 resulted in a reduction of total runoff at the catchment outlet by 33% and total salt load by 49%.

In landuse change Scenario 1 (see Figure 2(c)), the area under perennial pastures increases to about 86% of the catchment, with about 5% under trees and 9% under cropping. Overall flows and salt load are lower. Areas under perennial pastures now contribute to about 86% of the total flow and 90% of the total salt at the catchment outlet. The contribution from cropping areas reduces to 13% for flow and 8% for salts whereas the woody area contribution remains the same as under no landuse change scenario (see Figure 2(d)).

In scenario 2.1, 2.2 and 2.3, the woody (tree) cover in the catchment is increased to 20%, 30% and 40% respectively, with 15%, 25% and 35% of the total catchment simulated as perennial pastures in Scenario 1 changed to woody. The area under cropping stays the same as for landuse change Scenario 1. The relative changes to the contribution from individual landuses to flow and salt load at the catchment outlet vary for each landuse change scenario (see Figure 2(e) to (j)). Although the area under woody/trees is increased from 5% (current landuse) to 40% (landuse change Scenario 2.3) of the total catchment area, the contribution to flow and salt load at the catchment outlet from this landuse increases from 1% to 11% and 25% respectively. This is basically because of the higher water use efficiency for trees.

For the Boorowa River at Prossers Crossing, estimated reductions in average annual salinity from its base level of 681 μS.cm^{-1} are 10 μS.cm^{-1} corresponding to the landuse change Scenarios 1, 150 μS.cm^{-1} for landuse change Scenario 2.1, 170 μS.cm^{-1} for landuse change Scenario 2.2 and 180 μS.cm^{-1} for landuse change Scenario 2.3.

The results here suggest that simply increasing perennial pasture content of the vegetation is unlikely to produce substantial benefits with regard to salinity (Scenario 1). Tree plantation over and above 20 percent tree cover (Scenario 2.1) does not produce any additional benefit with regards to stream salinity, while reducing runoff from the catchment. But this is mainly due to the fact that the Boorowa catchment has only 16 km^2 of saline discharge area which was almost all targeted in landuse change Scenario 2.1. As such, the results are sensitive to the actual area of saline discharge in the catchment. This also suggests that a much smaller increase in tree cover than that proposed in Scenario 2.1 is responsible for the non linear reduction in salt load with flow.

Downstream impact assessment of the landuse change Scenarios in the Lachlan River after the confluence of the Boorowa River (Lachlan River at Cowra, 412002) indicate 2% reduction in flow and 7% reduction in salt load (Scenario 2.1). Estimated reductions in salinity in the Lachlan River are 2, 18, 20 and 21 μS.cm^{-1} corresponding to the landuse change Scenarios 1, 2.1, 2.2 and 2.3 respectively.

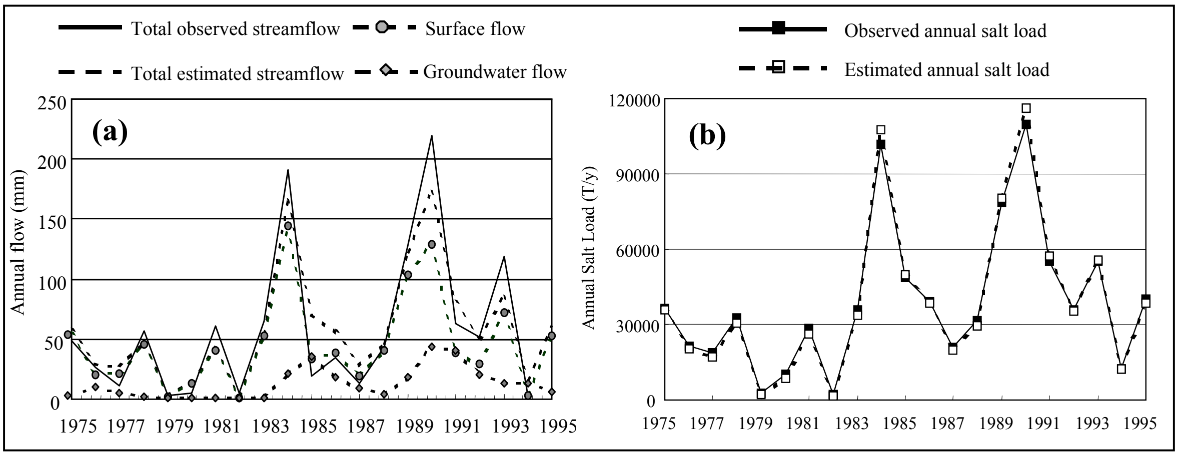

Figure 1. Observed and estimated annual streamflow (a), and observed and estimated annual salt load (b) at the catchment outlet (1975-1995)

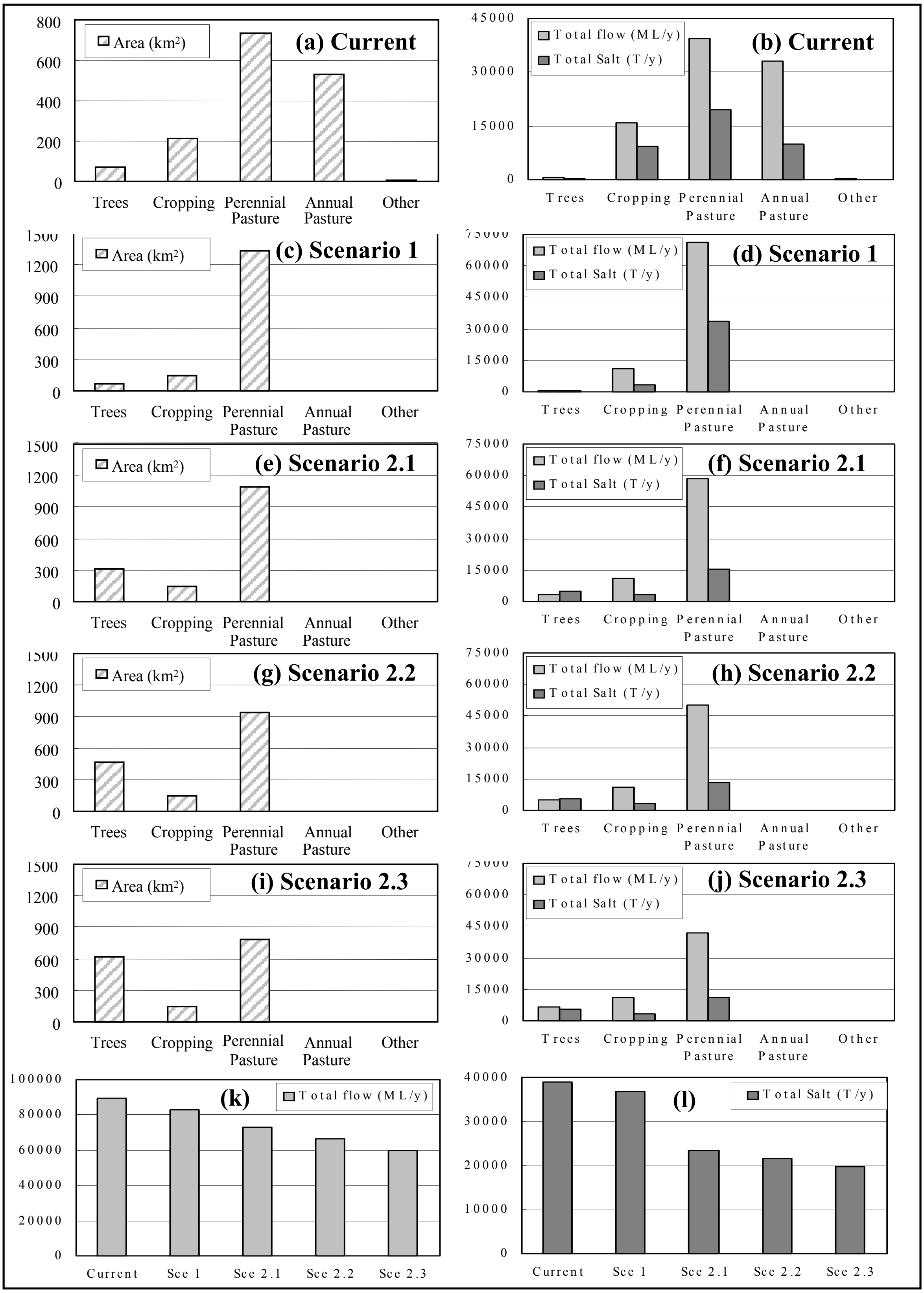

Figure 2. Flow and salt load at the catchment outlet from individual landuses for current landuse (a) – (b), all the four landuse change scenarios (c) to (j) and total flow and total salt load from all the landuses for current and all landuse change scenarios (k) – (l).

5 CONCLUSIONS

The processes of water movement and salt delivery from the Boorowa River catchment are conceptualised using detailed data sets and modelled using CATSALT.

The water balance model was able to simulate both the daily observed stream flow and salt load at the catchment outlet for high and low flow conditions satisfactorily. The model estimated mean annual leakage rate under current landuse for the Boorowa catchment was 23.2 $mm.y^{-1}$. The corresponding total runoff and the salt export from the catchment were 89382 $ML.y^{-1}$ and 38900 $t.y^{-1}$, respectively.

Investigation of various landuse change scenarios indicates that changing annual pastures and cropping areas to perennial pastures is not likely to result in substantial improvement of water quality in the Boorowa River. A landuse change to 20% tree-cover, specifically targeting high recharge and the saline discharge areas, would be needed to decrease stream salinity by 150 $\mu S.cm^{-1}$ from its current level. Estimated stream salinity reductions in the main Lachlan River downstream of the confluence of the Boorowa River would be about 20 $\mu S.cm^{-1}$.

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