Biophysical Approach To Predict Salt And Water Loads To Upland REALM Nodes Of Victorian Catchments

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EXTENDED ABSTRACT

The need for a consistent Statewide approach to the modelling of water and salt export across the Murray-Darling Basin has led to the conceptualisation of the 2CSalt model. The model was developed by State agencies and associated partners of the CRCCH and Murray-Darling Basin Commission. It provides consistent and transparent predictions of salt movement under current practice and is capable of predicting the likely impact of land-use change on catchment yield and salt export.

The 2CSalt model has been designed for application to upland catchments dominated by local-to-intermediate Groundwater Flow Systems (GFS). The model operates on monthly time-steps and builds on the existing understanding of the GFS (Coram et al., 2000) to estimate the partitioning of surface, lateral and groundwater pathways of water within a catchment. The surface hydrology and partitioned vertical to lateral water pathways are generated *a priori* and are required as an input to the 2CSalt model.

The 2CSalt model simulates end-of-catchment stream flow and salt export from catchments up to 200,000 ha in area. The catchment landscape must be topographically and climatically variable to meet criteria associated with GFS modelling approaches. The catchment must also be unregulated and gauged so as to provide continuous stream and salt load data to underpin model calibration and validation. Surface terrain modelling is used to define the catchment groundwater response units, and as such, the surface topographical features are reflected in the hydrological processes.

This paper presents results from the application of the 2CSalt model to the Bet Bet catchment that covers an area of 64342 ha within the south-west region of the North Central catchment of Victoria. The Bet Bet pilot region has an estimated mean annual salt export of 20,020 tonnes and has been targeted as a priority catchment by the North Central Catchment Management Authority (NCCMA, 2003). Results incorporate recent improvements to the modelled salt pathways and a discussion is included on the impact of these changes.

Four land-use scenarios were tested in the Bet Bet catchment to demonstrate the use of the 2CSalt model to determine the impact of land-use change on salt and water yield. These scenarios were:

- *Upland alluvial*: the planting of trees in upland alluvial areas.
- *Biodiversity:* biodiversity enhancement rules developed by Wilson et al (2003).
- *Break-of-slope:* connection between hillslope and alluvial areas buffered by trees.
- *Upland break-of-slope:* break-of-slope scenario applied to upland areas only.

The impact of each land-use change on stream flow and salt load per hectare of trees planted is summarised in Table 1. The results show that the 2CSalt model can predict differences in streamflow and salt load between different configurations of planted trees. The optimum outcome in terms of salinity management is to decrease salt load while maintaining stream flow for potential use downstream. Of the four scenarios tested the biodiversity scenario had the greatest impact in terms of reducing end-of-catchment stream salt concentration.

Table 1. Impact of land-use scenario on stream flow and salt export per hectare of tree planted

	Upland Alluvial	BOS	Bio-diversity	Upland BOS
Decrease in stream flow (ML/ha of tree)	21	14	15	25
Decrease in salt load (tonnes/ha of tree)	13	8	10	14

Results presented in this paper show that the 2CSalt model is capable of representing the primary pathways of the end-of-catchment water and salt export. As such, this model is capable of providing stakeholders with information on the optimum land-use implementation strategy to mitigate the impact of stream salinity in upland catchments.

1. INTRODUCTION

A series of spatial and temporal inputs are required to run the 2CSalt model. A digital elevation model (DEM) is used to define the groundwater response units (GRUs) and their attributes such as height, major and minor axes and length. Spatial groundwater attributes are required including depth-to-bedrock (m), water height relative to bedrock (m), hydraulic conductivity (m/day), specific yield and groundwater salinity (mg/l). Additionally, a hydrological response unit (HRU) layer representing the suface hydrology must be generated by unioning climate (temperature, rainfall, aspect and climate station) and soil/slope layers. Temporal inputs, including estimates of surface runoff, subsurface lateral flow, recharge and potential evaporation, have been generated for each HRU using the Catchment Analysis Tool (CAT) (PIRVIC, 2005).

The functional unit at which the 2CSalt model operates is the Groundwater Response Unit (GRU). Groundwater response units are derived from the DEM by dividing the catchment into a series of stream-node based sub-catchments. Each sub-catchment is split into hillslope and alluvial areas using a Multi Resolution Valley Bottom Flatness (MrVBF) terrain analysis model. While GRUs are not explicitly connected to route water and salt within a catchment, the output from each GRU is used to spatially apportion end-of-catchment monthly stream flow and salt export. The 2CSalt model uses physical and non-physical coefficients to define water and salt movement within the catchment. These coefficients are typically calibrated using monitored stream gauge information and as such the model is not recommended for application to ungauged catchments.

The hillslope and alluvial zones are partitioned into unsaturated and aquifer stores as shown in Figure 1. The hydrology of the unsaturated zone is calculated by spatially averaging the HRU monthly time series of surface runoff, lateral flow and recharge over each GRU,

$$H_{GRU,t} = \frac{\sum_{i=1}^{HRU} H_{i,t} Area_i}{Area_{GRU}} \qquad (1)$$

where $H_{i,t}$ is the monthly HRU time-series, $Area_i$ is the HRU area, $Area_{GRU}$ is the GRU area and $H_{GRU,t}$ is the monthly time-series, spatially averaged over the GRU.

The hillslope aquifer store is based on a simple mass balance of water. Conceptually, packets of recharge ($Recharge_{HS,t}$) enter the aquifer on a monthly basis. If the hillslope store exceeds a user defined threshold volume ($HS_{Threshold}$), water is released as groundwater discharge ($Discharge_{HS,t}$). If the store fills beyond capacity (HS_{max}), the excess water ($Excess_{HS,t}$) flows directly to stream.

$$\begin{aligned} &HS_{t+\Delta} = HS_t + Recharge_{HS,t} - Discharge_{HS,t} \\ &\quad if\ HS_{t+\Delta} > HS_{\max}, \\ &\qquad then\ \ Excess_{HS,t} = HS_{t+\Delta} - HS_{\max} \\ &\qquad and\ \ HS_{t+\Delta} = HS_{\max} \end{aligned} \qquad (2)$$

Here HS_t is the water stored in the hillslope aquifer at time t and HS_{max} is the maximum hillslope storage derived from the groundwater attribution layers.

The alluvial aquifer is filled through recharge from the unsaturated zone ($Recharge_{AS,t}$) and discharge from the hillslope aquifer store ($Discharge_{HS,t}$). Water leaves the alluvial aquifer as baseflow to stream ($Baseflow_{AS,t}$) and evaporation ($Evap_{AS,t}$) each occurring when the store is above a user defined threshold ($AS_{Threshold}$, $Evap_{Threshold}$). Excess water ($Excess_{HS,t}$) flows directly to stream.

$$\begin{aligned} &AS_{t+\Delta} = AS_t + Recharge_{AS,t} + Discharge_{HS,t} \\ &\qquad - Evap_{AS,t} - Baseflow_t \\ &\quad if\ AS_{t+\Delta} > AS_{\max}, \\ &\qquad then\ \ Excess_{AS,t} = AS_{t+\Delta} - AS_{\max} \\ &\qquad and\ \ AS_{t+\Delta} = AS_{\max} \end{aligned} \qquad (3)$$

Here AS_t is the water stored in the alluvial aquifer at time t and AS_{max} is the maximum alluvial storage. The hillslope discharge, evaporation and baseflow fluxes are derived using a simple storage-discharge relationship,

$$Flux = \alpha \left(\frac{S - S_{Threshold}}{S_{\max} - S_{Threshold}} \right)^{\beta} \qquad (4)$$

where α is the maximum flux, β is a fitted shape parameter, S is the volumetric store, $S_{Threshold}$ is the volumetric store threshold and S_{max} is the maximum storage.

The end-of-catchment stream flow ($Flow_t$) is calculated as the sum over all GRU's of the surface and excess stream components plus the baseflow contribution from alluvial GRU's only.

$$\begin{aligned} Flow_t = &\sum_{n=1}^{GRU} Runoff_{n,t} + Lateral_{n,t} + Excess_{n,t} \\ &+ \sum_{n \in GRU_{AS}}^{GRU} Baseflow_{n,t} \end{aligned} \qquad (5)$$

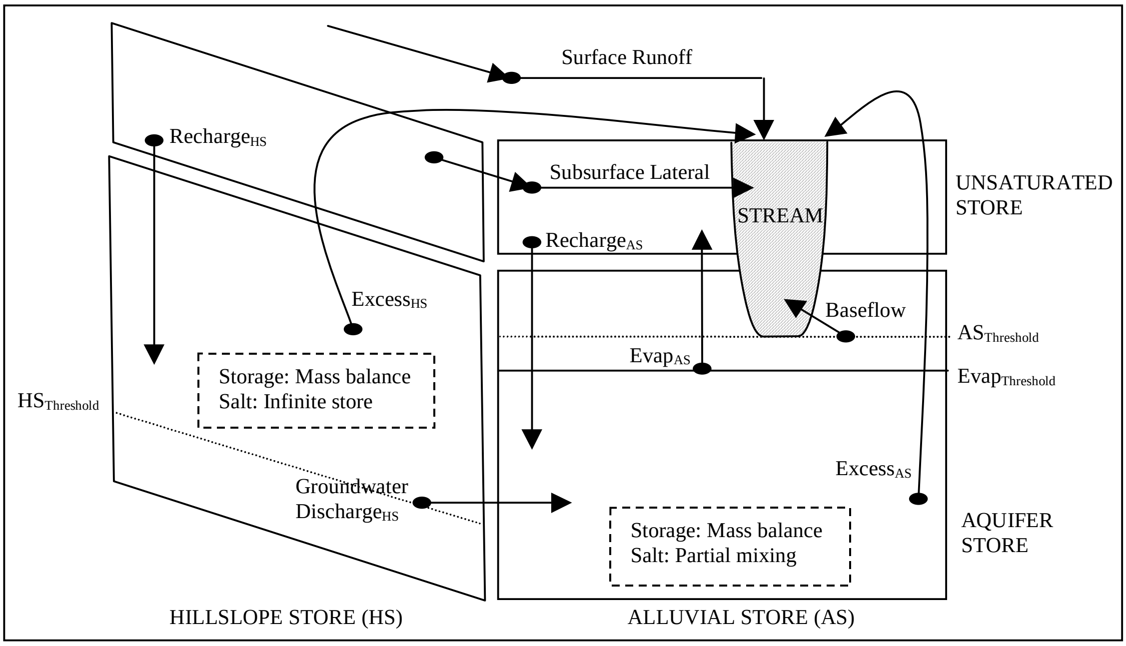

Figure 1. Pathways of water and salt movement in the 2CSalt model

The description of salt pathways is still being explored. This paper briefly compares the current conceptualisation with a developmental salt model. Under the current conceptualisation the hillslope aquifer is considered an infinite source of salt. Excess, hillslope discharge and baseflow have a salt concentration proportional to their respective aquifer salinities. Salt accumulates in hillslope and alluvial surface stores through evapotranspiration and rainfall salinity and is then released to stream through surface runoff. The hillslope lateral subsurface flow carries a salt concentration that increases proportionally with the hillslope store water level. The alluvial lateral subsurface flow is discharged at the alluvial aquifer salinity multiplied by a mixing coefficient.

In contrast, the developmental model effectively creates a salt mass balance in the unsaturated zone. The hillslope aquifer is still considered an infinite source of salt and contributes to the mass balance of salt in the alluvial aquifer. Surface runoff enters the stream at rainfall salinity and the recharge and subsurface lateral stream components have salt contributions proportional to the unsaturated zone salinity. The alluvial evaporation carries an additional amount of salt from the aquifer to the unsaturated store to account for salt accumulation in the near surface zone. Results presented in this paper are derived from the developmental salt pathway model.

2. MODEL CALIBRATION

The 2CSalt model is typically calibrated using 'end-of-catchment' gauge information. Bet Bet has three gauged sites within the catchment giving scope to not only calibrate the model against end-of-catchment stream data but to validate the calibrated model at the internal gauged locations. At each gauge location daily monitored stream flow, groundwater baseflow and stream salinity data has been extrapolated over the period 1975-2000 using methods described in the REALM-Loddon model (Sinclair Knight Merz, 2004).

Measured and predicted mean annual streamflow, baseflow and salt export have been summarised in Table 2, with the location of the REALM gauges illustrated in Figure 2. In general, the 2CSalt model captures the end-of-catchment stream data, predicting a mean annual streamflow of 57 mm compared with the REALM prediction of 56 mm.

Table 2 Mean annual streamflow, baseflow, and salt export for gauged areas in Bet Bet

	Gauged Area	REALM	2CSalt
Mean annual streamflow (mm)	Above 407288	86	86
	407220 → 407288	46	68
	407211 → 407220	54	34
	End-of-catchment	56	57
Mean annual baseflow (mm)	Above 407288	29	22
	407220 → 407288	11	13
	407211 → 407220	9	10
	End-of-catchment	13	14
Mean annual salt (tonnes/ha)	Above 407288	0.76	0.50
	407220 → 407288	0.23	0.44
	407211 → 407220	0.28	0.19
	End-of-catchment	0.34	0.34

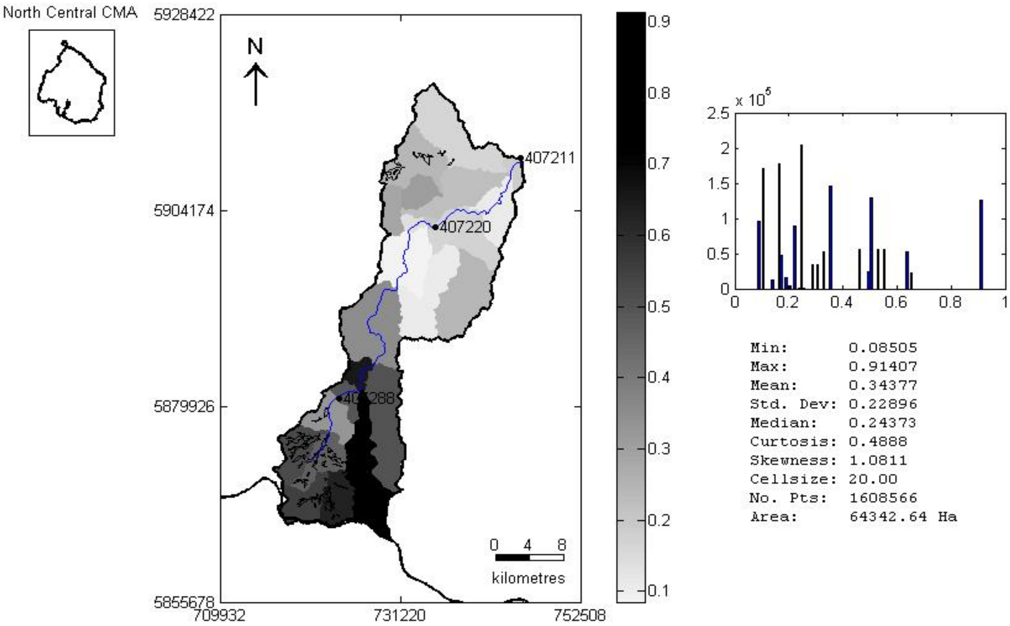

Figure 2. Spatial distribution of mean annual salt export (tonnes/ha) from Bet Bet sub-catchments. Mapped discharge regions and REALM stream gauges 407211, 407220 and 407286 shown.

A comparison of the modelled and observed stream flow at the three gauged points show that while the model accurately predicts a streamflow contribution of 86 mm from the high rainfall upland areas, there is a significant difference between the modelled and observed streamflow for the other gauged regions of the catchment. This discrepancy could be due to a number of factors. Firstly, attribution of the 2CSalt model is sourced from spatial data often based on the GFS approach that provides a relatively coarse representation of catchment attributes. Additionally the 2CSalt model adopts a single parameter set across the whole of catchment, and as such, the fitted parameters are weighted towards regions of high rainfall and subsequent streamflow contribution. The spatial distribution of mean annual salt export (Figure 2) highlights the regions of high salt contribution to stream. Taking into account the variation between the measured and simulated salt export at the internal gauges of Bet Bet, the 2CSalt model still provides a reasonable spatial apportionment of saline regions across the catchment. The 2CSalt model predicts high salt loads from the upland areas of Bet Bet which is consistent with the mapped saline discharge regions within the study area (Clark, 2005).

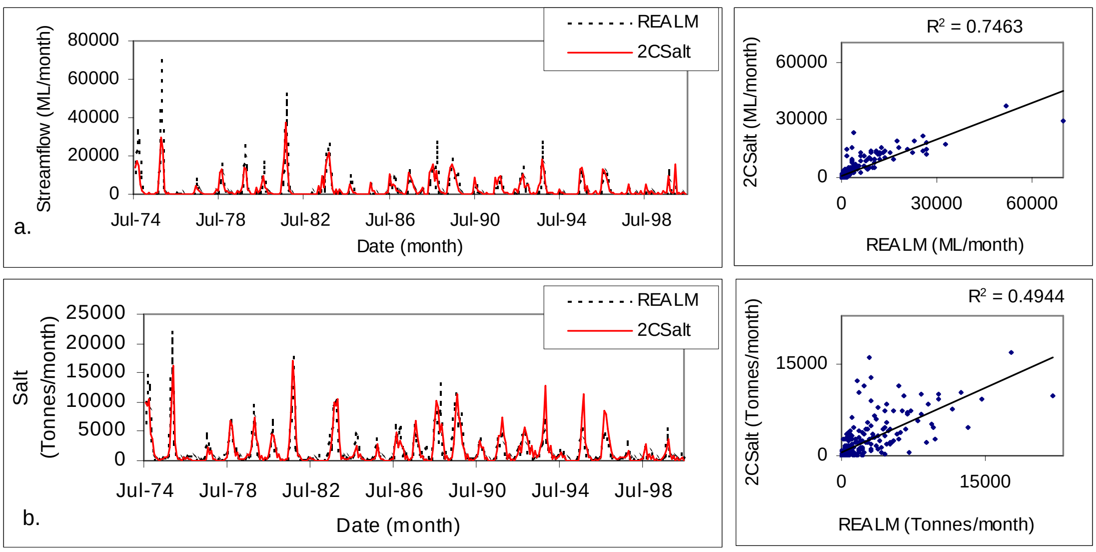

Figure 3. Comparison of REALM and 2CSalt end-of-catchment a) stream flow (ML/month) and b) salt export (tonnes/month).

The temporal end-of-catchment stream flow and salt export for the measured REALM and modelled 2CSalt data is shown in Figure 3. The 2CSalt model is shown to consistently provide a good temporal fit to end-of-catchment stream flow and salt export with minimal calibration of model parameters. Results suggest that the model underestimated large events, which could potentially be attributed to the smoothing effect caused by averaging HRU inputs such as rainfall and recharge on a monthly basis.

An observation was the models capacity to reflect plausible hydrological and salt pathways. A baseflow separation algorithm (Arnold et al. 1999) was employed to identify the base-flow and quick-flow components of the measured REALM data. This model estimated a mean annual base-flow contribution of 23% of the total stream flow under current-practice land-use. The hydrological pathways predicted by the 2CSalt model are shown in Figure 4. The bulk of the predicted total streamflow (41%) was generated by lateral subsurface flow, with a 21% contribution from surface runoff, 14% from overtopping of alluvial stores and 24% from baseflow. Notably the stream baseflow matched the baseflow-separated REALM data to within 1%. These pathways are consistent with current knowledge of local groundwater systems and hydrological processes.

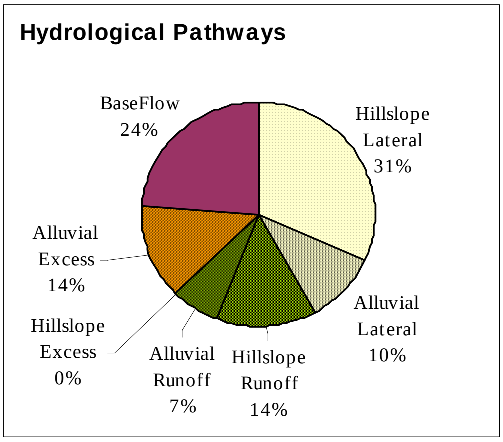

Figure 4. Hydrological pathways for calibrated 2CSalt model for Bet Bet catchment.

Figure 5 compares the salt pathways and flow-concentration graphs that were generated using the current and developmental conceptualisations of the salt pathways within the 2CSalt model. Figure 5a highlights the inconsistencies of the current model, showing the bulk of the predicted salt load coming from lateral pathways. At low stream flows where base flow was considered dominant, the predicted salt concentration was generally lower than the measured REALM data (Figure 5a). The developmental model predicted a significantly higher baseflow salt concentration and as such, there was less deviation in the flow concentration graph at low flows (Figure 5b). This result better describes observations and is more consistent with previous studies.

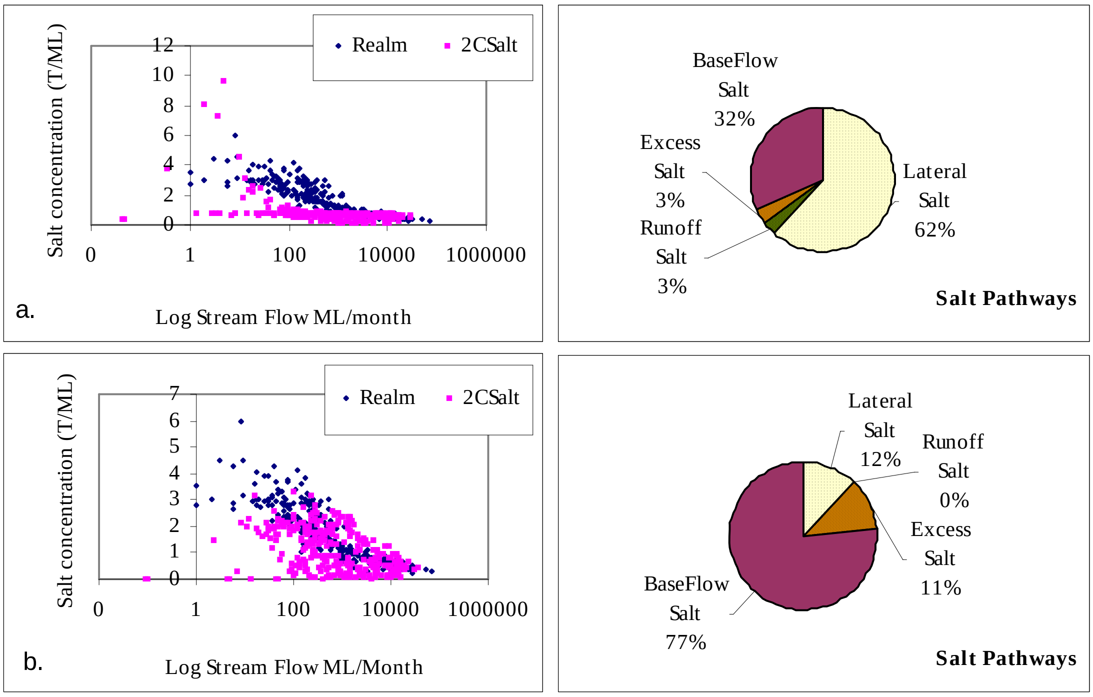

Figure 5. Comparison of flow-concentration and salt pathways for a) current b) developmental salt pathways of 2CSalt model

3. THE IMPACT OF LANDUSE CHANGE ON STREAM FLOW AND SALT YIELD

Four land-use change scenarios were applied to the Bet Bet catchment. Upland regions were targeted because of their higher salt contribution to stream.

1. *Upland alluvial scenario:* remnant vegetation was planted in upland alluvial areas.
2. *Break-of-slope (BOS) scenario:* remnant vegetation was planted along the interface connecting hillslope and alluvial areas.
3. *Biodiversity scenario:* of the five priorities outlined in the biodiversity plan (NCCMA, 2003) only the remnant priorities were implemented based on the biodiversity rules developed by Wilson et al. (2003). The first priority was to protect existing and most viable remnants by analysing vegetation extent, remnant size and connectivity. The second, to enhance existing remnants by buffering.
4. *Upland break-of-slope scenario:* the break-of-slope scenario was applied to the upland areas of the Bet Bet catchment.

A summary of the impacts of the four land-use scenarios over a 26-year simulation period from 1974 to 2000 is presented in Table 3. Figure 6 shows the impact of each land-use scenario on cumulative stream flow, salt export and respective pathways. Results are relative to the current practice land-use.

Table 3. Impact of scenarios on streamflow and salt load over a 26-year simulation period.

	Current Practice	Upland Alluvial	BOS	Biodiversity	Upland BOS
Total stream flow (ML)	951,899	870,437	871,675	703,325	825,045
Total Salt Load (T)	575,778	525,866	531,779	415,083	503,488
Reduction in stream (ML)		81,461	80,224	248,574	126,854
Reduction in Salt (T)		49,913	43,999	160,695	72,291
Increase in treed area (ha)		3,970	5,746	16,652	5,115
Total treed area (ha)	10,353	14,323	16,099	27,005	15,468
Decrease in stream flow (ML/ha trees)		21	14	15	25
Decrease in salt load (T/ha trees)		13	8	10	14

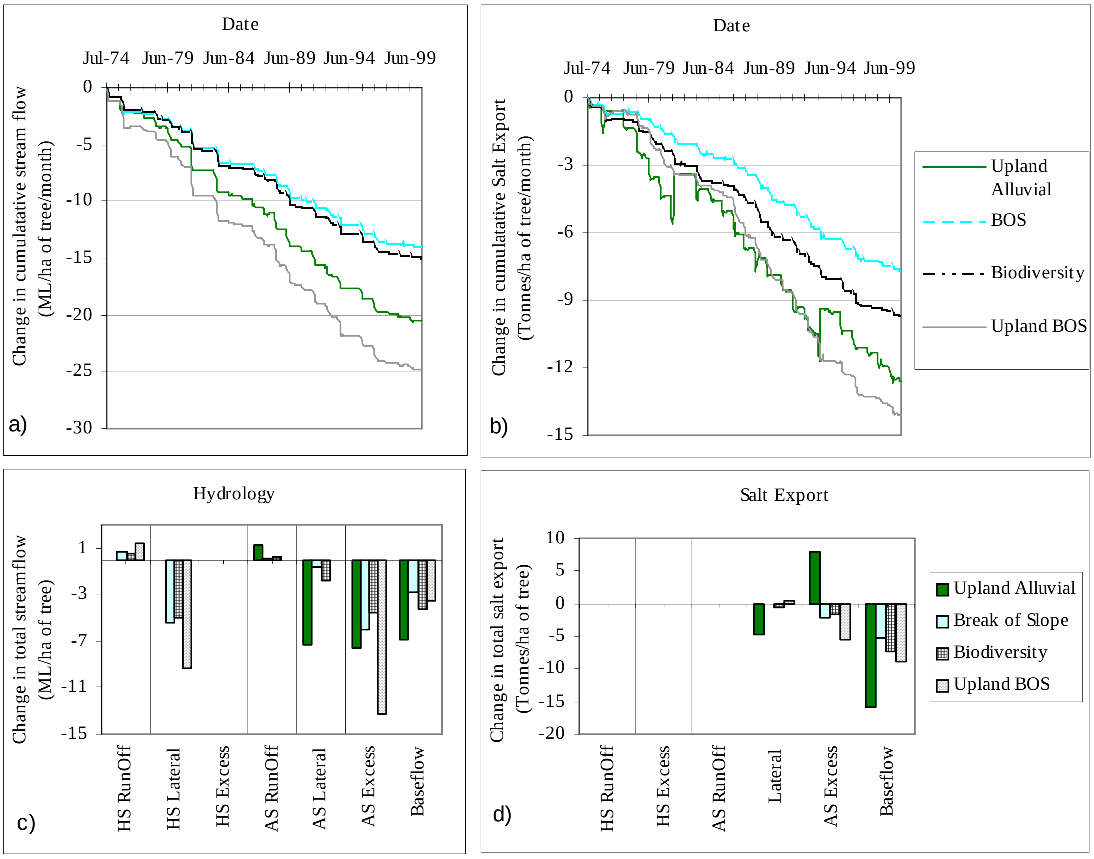

Figure 6. Change in a) cumulative flow and b) salt export per ha of tree planted, relative to current practice. Change in c) hydrological d) and salt export pathways under the four land-use scenarios.

To compare scenarios, streamflow and salt load were calculated against the change in treed area (ha). Results showed that while planting trees in the upland areas had the greatest impact on salt export to stream, a significant reduction in stream flow was also observed. From the scenarios run the biodiversity model generated the greatest reduction in end-of-catchment salt concentration.

Under the upland alluvial scenario, there was no impact on the hillslope hydrological or salt pathways. The alluvial store lateral, excess and baseflow hydrological components were each reduced by about 7 ML/ha trees. In terms of salt, the upland alluvial scenario made the greatest impact on baseflow salt export however this was countered by an increase in the salinity of the alluvial excess. The reduced baseflow salt load caused salt to accumulate in the alluvial aquifer. When a high rainfall event occurred, the aquifer overtopped, resulting in a surge of salt to enter the stream through excess. This can be observed in Figure 6b in June 1979 and June 1994. The break-of-slope scenario had the smallest overall impact on stream flow and salt export. The surface runoff and lateral flow were generally fairly fresh and acted to reduce stream salt concentration. As such, the reduction in hillslope lateral flow seen in the biodiversity and break-of-slope scenarios tended to increase the end-of-catchment salt concentration. The biodiversity scenario, had a fairly consistent reduction of about 5 ML/ha trees across lateral, alluvial excess and baseflow pathways. There was a decrease in salt export from each of these pathways but the decrease in baseflow salt was not as significant as for the upland alluvial and break-of-slope scenarios. The upland break-of-slope scenario had the biggest impact on salt export (Figure 6b) although this was countered by a large reduction in stream flow (Figure 6a).

The presented results suggest that the upland break-of-slope scenario had the greatest impact on salt export while the biodiversity scenario resulted in the greatest reduction in stream salt concentration. The results shown in Figure 6 demonstrate the ability of the 2CSalt model to reasonably predict the impact of various land-use implementation strategies on end-of-catchment streamflow and salt export.

4. CONCLUSIONS

Across Eastern Australia, salinity management planning is focussed on meeting end-of-catchment salinity targets. Intervention techniques such as targetted land-use change provide the means to meet salinity targets where there is a need to better quantify the impact of such strategies to support investment decisions. This paper demonstrates that the 2CSalt model, while still under development, has the capability to predict the impacts of land-use change on end-of-catchment stream flow and salt export. In addition, it can be used to identify priority areas and determine where the salt is stored in the landscape and how much is mobilised by groundwater discharge, surface runoff and subsurface flow. This model will assist natural resource managers in making consistent predictions of salt movement across the Murray Darling Basin and assess the likely impact of land-use change across a broad management scale. Further development of the 2CSalt model will focus on strengthening the definition of hydrological and salt pathways and broadening the model scope to include nutrient and other constituent delivery.

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