Predicting Upland Stream Salinity After Reforestation

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EXTENDED ABSTRACT

Native vegetation clearing has created salinity problems in many parts of Australia. Reforestation has the potential to reduce salinity, but also reduces stream flow and this is a cause of concern. Spatial predictions of the stream flow and salinity impacts of reforestation are needed to assess the ability to achieve salinity and water resource targets. Unfortunately, our ability to predict salinity changes after reforestation is limited. Direct measurements at the catchment level are few, and the processes of salt mobilisation and delivery to the stream in upland catchments are poorly understood.

Several feasible distributed or "bottom-up" models have been developed, by combining existing surface water balance and groundwater models. Their validity is compromised to a largely unknown extent by the assumptions and scaling methods used, whereas broad-scale application is hindered by lack of input data. Nonetheless, these models are valuable research tools and are necessary to predict spatial patterns within catchments. Emergent or "top-down" model approaches consider the behaviour of the catchment as a whole. This approach has been fruitful for predicting land use impacts on catchment stream flow, and has also been applied to salinity in the BC2C model. This approach can avoid some problems specific to distributed modelling, although it cannot compensate the lack of empirical knowledge.

The real and urgent need for upland salinity predictions to guide land and water management and compare alternative options means that significant uncertainty needs to be accepted. The purpose of upland salinity modelling can be two-fold. Firstly, regional planning requires identification of catchments that contribute most to stream salinity. This is arguably achieved most effectively and efficiently using top-down approaches. Secondly, models are required to predict whether salinity reductions can be achieved more effectively (in terms of the area of land use change and/or accompanying stream flow reduction) by further finetuning location or design within a catchment, e.g. as hill-top or break-of-slope tree plantings. (Semi-) distributed models have a role in predicting the likelihood and magnitude of these spatial differences.

Both purposes and modelling approaches are represented in the Commercial and Environmental Forestry project, which aims to help increase the efficiency of public investment in the environmental benefits of tree planting. Regional BC2C predictions were developed for the Southwest Goulburn region, north of Melbourne, Victoria. The results suggest that reforestation in the sedimentary rock catchments within the area will indeed reduce stream salinity downstream, but in the higher rainfall granite catchments will actually increase stream salinity. Stream salinity can be reduced several times more effectively by focusing land use change in the most responsive catchments.

To examine within-catchment patterns, the forest growth and water use model 3PG+ was linked to a two-store groundwater model within the hillslope modelling framework FLUSH (Framework for Land Use and Hydrology). The framework allows the redistribution of water within a catchment to be simulated. It was used to evaluate the water and salinity impacts of focusing reforestation on different parts of the hillslope. The results suggest that the effectiveness of tree planting can indeed be further increased within the catchment by taking into account spatial patterns in soil properties and the redistribution of water.

The predicted spatial variability in salinity impacts between and within catchments stresses the value of improving our predictive capacity. Ongoing development of spatial soil and hydrogeology data sets should help improve predictions, although the lack of process understanding and field validation remains the ultimate constraint and should have research priority.

1. INTRODUCTION

Native vegetation clearing has created dryland and stream salinity problems in many parts of Australia. Returning trees to the landscape has the potential to reduce salinity, as well as having other potential economic and environmental benefits (Hairsine and Van Dijk, 2005). An important dis-benefit of reforestation is the associated reduction in stream flows. This can be a significant issue in regions with a high water use. Stream salinity can be thought of as the ratio of catchment salt yield over water yield. If reforestation is to produce a net reduction in stream salt concentrations, the relative reduction in catchment salt export will have to exceed the relative reduction in water export.

2. LAND USE AND STREAM SALINITY – CAN WE PREDICT IT?

2.1. Evidence for impact of land use on stream salinity

Salinity problems are readily observed in much of Australia's uplands: waterlogged areas, bare soils and salt crusts, gullies in dispersive soils, spiny rush and other salt-tolerant vegetation, increased salt concentrations in upland streams. These problems are rarely encountered where natural vegetation still persists, and there is real evidence that large scale reforestation can reduce stream salinity in catchments, if not without reducing stream flow (Figure 1). The reduction in stream flow after tree planting has been observed and measured in many catchments in Australia and abroad, and at catchment level the impact on long-term annual flow and on flow distribution can be predicted with reasonable accuracy (Zhang *et al.*, 2001; Lane *et al.*, 2005).

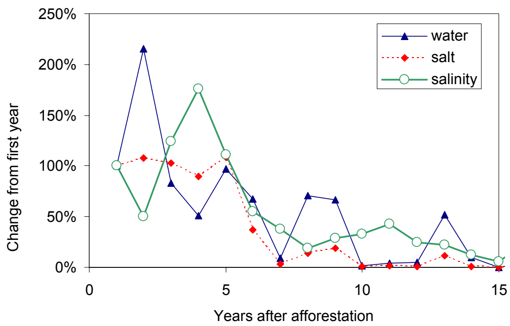

Figure 1. Relative changes in annual water and salt yield, and flow-weighted stream salinity after reforestation of a 3 km^2 Pine Creek catchment located in the Southwest Goulburn region (Van Dijk *et al.*, 2004).

The impact of reforestation on stream salinity is not nearly as well understood. In fact, the Pine Creek catchment in Victoria appears the only catchment to date where an unambiguous data set of stream flow and salinity response to full afforestation has been collected. Together with few other equally small catchments with observations on stream salinity change to partial afforestation and salinity increase after clearing, this forms our entire database on upland catchment salinity response.

2.2. Do we understand the processes?

The processes that link stream salinity and land use are less clear than sometimes assumed. It is evident that increased salt mobilisation after clearing is related to the lesser water use of vegetation with shallow root systems, such as pasture, which increases water leakage from the soil. Less clear is where and how the excess water mobilises salt and how this salt gets delivered to the surface and into the stream. The 'conventional' concept is that of vertical recharge feeding a saline groundwater body, which progressively rises closer to the surface and discharges increasingly large volumes of saline water directly into the stream. This may accurately describe the main mechanism of salt delivery in low relief areas with unconsolidated aquifers, but the process appears much more complex in many upland catchments (e.g. Cheng *et al.*, 2003; Van Dijk *et al.*, 2004). The conventional concept requires that salt has accumulated over a long period and resides in a slow responding groundwater body. Yet, stream salinity measurements indicate that the export of salt from upland catchments does not occur at a constant rate, as would be expected from a slow groundwater system, but increases during and after storm events. This phenomenon has also been observed in nutrient and tracer studies, and was described as the 'old water paradox' by Kirchner (2003). Different mechanisms can be conceptualised to explain this behaviour, including matrix-macropore exchanges, piston flow and wash-off of surface salt left at the surface during storms. Despite some field process studies, as yet there is no generally accepted explanation.

2.3. Bottom-up models

Despite the scarcity of field measurements, several salinity process models have been developed. These models consist of a combination of existing surface water balance and groundwater models. The surface water balance models are typically derived from tree or crop growth and water use models or surface parameterisations from climate models that, in turn, are a composite of process equations (e.g. soil hydrology, root water uptake, transpiration) developed in separate laboratory or field experiments. The groundwater models vary in complexity from a single linear reservoir, to fully distributed finite element networks with equations describing Darcian flow. Salt transport in the calculated flows is simulated in different ways, arguably reflecting model developers' experience or preference rather than experimental evidence. These distributed models can be labelled "bottom-up" models, as they consist of component models developed at smaller scales. Common problems associated with distributed models are well documented:

1. assumptions that need to be made about processes, parameters that control them, and interactions between them (leading to alternative models that can be calibrated equally well, but produce divergent predictions);

2. scaling of models to a space or time scale where they are not necessarily valid;

3. lack of distributed input data required to make profitable use of distributed models; and

4. effort in setting up and running the model.

The required process assumptions in bottom-up salinity models were mentioned earlier. Scaling and input data problems also occur. Darcian groundwater models can only be expected to accurately predict flows if the unit of modelling is fully homogeneous and connected. This assumption can work well in unconsolidated sediments, but can be problematic in the fractured aquifers often found in upland catchments. Dealing with this heterogeneity requires a level of hydrogeological understanding and data that is only available for a few small research catchments. Combined with the large but unknown spatial variability in groundwater salinity (potentially in three dimensions), it may be questioned whether the complexity of fully distributed groundwater models is commensurate with the data available to parameterise them for larger areas. A similar argument can be made for the spatial variability in soil properties.

Methods for deriving better spatial information on hydrogeology, groundwater salinity and soils from topography, airborne geophysics, and remote sensing are under development (e.g. Spies and Woodgate, 2005) and may help to constrain distributed models in future. Distributed process models, of course, have an important role as research tools to develop and test alternative hypotheses, and can be useful where the protection of valuable assets makes detailed data collection worthwhile.

2.4. Top-down models

"Top-down" models avoid some of the above problems by looking at the behaviour of the system as a whole. In this case the system is the catchment, as this is the level where stream flow and salinity can be, and routinely are, measured and therefore models can be developed and validated. It would be wrong to label these models as inherently less 'physically-based' than bottom-up models, as they may use the laws of conservation and thermodynamics, but operate at a different scale. A widely used top-down model in Australian catchment hydrology is the set of so-called 'Zhang curves' that links catchment runoff to mean rainfall, potential evaporation, and vegetation cover (Zhang *et al.*, 2001). The model has a sound physical interpretation and the additional benefit of being developed at the appropriate scale. Thanks to the considerable number of catchments where flow is measured, it is becoming increasingly well tested and used.

A top-down approach to catchment salinity is the Biophysical Capacity to Change (BC2C) model developed by Dawes *et al.* (2004ab). The model is intended to identify catchments in which land use change would have the greatest impact on stream salinity. It uses the Zhang curves and a simple coupled water-salt mass balance to estimate the initial and ultimate steady state catchment salt exports. The change between the two states is estimated from catchment and aquifer characteristics based on dimensional analysis. The approach is based on physical principles, but like other salinity models relies on assumptions about salt mobilisation and groundwater behaviour. An advantage of the BC2C model is that it uses information on climate and terrain that is widely available across Australia: spatial data on long-term average climate, tree cover, salt precipitation in rainfall, and relief; and groundwater flow system (GFS) maps. GFS maps have been generated at varying levels of spatial detail across Australia, based on geology and topography using a classification approach described in Coram *et al.* (2000). The model is intended for use in upland catchments, and application is limited to catchments for which surface and groundwater hydrological boundaries can be assumed identical and subterranean 'leakage' can be ignored.

2.5. The need for modelling

Despite the described uncertainties in salinity modelling, the salinity problem is urgent and therefore 'present best estimate' predictions are needed while research continues. Spatial predictions of upland salinity change can occur at two spatial levels (Van Dijk *et al.*, 2004). Firstly, large scale models (in particular BC2C) can be been used regionally, to identify catchments that contribute more to stream salinity than others. Secondly, more detailed models have been used to identify locations *within* catchments where land use change is most effective in reducing catchment salinity.

To introduce some consistency in the way in which upland salinity is modelled in Australia, the CRC for Catchment Hydrology has developed a model that (as much as possible) reflects consensus on an appropriate modelling approach among a number of key salinity research centres. The result of this effort is the semi-distributed 2CSalt model (e.g. Stenson *et al.*, 2005). The model aims to make optimum use of available data on topography, hydrogeology, soils and land use, without becoming fully distributed. The model was designed in such a way that several surface water balance models can be linked in. The one-dimensional surface water models used in 2CSalt will predict differences in the impact of land use change between locations if these differ in climate or soil properties. It has been suggested more than once that the lateral redistribution of water in catchments can cause further differences in water use and recharge reduction (e.g. Silberstein *et al.*, 2002). This lateral redistribution can occur as overland flow, lateral flows in the unsaturated zone, or groundwater flow. If it can effectively add to the soil water available to vegetation in lower hillslope positions, then this may lead to increased water use and growth, as well as in a greater reduction in groundwater recharge overall. It has been used as a rationale for the concept of tree belt plantings in break-of-slope positions. Indeed better tree growth, and sometimes higher water use, has been measured in lower slope positions and at forest edges, although differences in soil depth and the access of tree roots to water in the adjacent cropland soil may also explain many of these observations (Hairsine and Van Dijk, 2005). Direct measurements of changes in the water balance caused by overland or subsurface flows are scarce, and its impact on groundwater recharge has never been measured. Therefore inferences need to be made from model studies. Recently, Gallant *et al.* (2005) developed a modelling framework (FLUSH, for Framework for Land Use and Hydrology) that can help to predict the possible differences in growth, water use and salinity impacts arising from the lateral redistribution of water. To avoid adding another model to the already extensive range, it merely links existing models. Combinations tested so far are that of the one-dimensional tree growth and water use model 3PG+ (J. Morris, Melbourne University) linked to a two-store groundwater model (a precursor of 2CSalt; Gallant *et al.*, 2004, 2005). Below we refer to this FLUSH configuration.

3. MODELLING CONTEXT

3.1. Modelling purpose

We applied BC2C and FLUSH as part of the Commercial Environmental Forestry (CEF) project, a joint project between CSIRO and the Natural Heritage Trust. The aim of this project is to increase the effectiveness of public investment in the environmental services provided by trees in medium rainfall areas (approx. 500-800 mm annual rainfall). This rainfall zone was chosen because the options for reducing stream salinity through land use change are greatest, and because tree growth rates approach commercial rates. The scope of the project has broadened beyond commercial forestry, to include non-commercial tree plantings for environmental benefits. The initial project focus is on the Southwest Goulburn region in Victoria, north of Melbourne.

3.2. Study catchment

The Southwest Goulburn region covers a total area of ~24,000 km^2. It is the middle part of the Goulburn River catchment, which together with the adjacent Broken River forms an important part of the Murray-Darling River system, producing 11% of the total stream flow even though covering only 2% of its area. The two rivers also contribute an estimated 5% to average Murray River salinity near the basin outlet. The Southwest Goulburn region has intermediate altitude (mostly 200-1000 m ASL) and relief (average slope ~7º) and annual rainfall within the catchment increases from about 500 mm in the flatter northern part to up to 1100 mm in the higher parts. The main land use is dryland grazing with scattered patches of remnant native vegetation.

The Southwest Goulburn region is the most important source of salt in the Goulburn catchment. The area may be divided into three zones on the basis of hydrology and salinity (Cheng *et al.*, 2003; Van Dijk *et al.*, 2004). The granite catchments in the higher areas have greater rainfall and an incised relief, and produce relatively fresh water. The sedimentary rock catchments in the middle of the region have a rolling topography, and Quaternary basalt outflows and alluvium filling some of the valley bottoms. These catchments have the most severe salinity problems. The relatively flat alluvial plains of the Goulburn River extend into some of the side valleys and contain larger, slower responding aquifers.

4. MODELLING METHODS

4.1. Introduction

Below we briefly describe the parameterisation of the respective models. Full descriptions can be found in Van Dijk *et al.* (2004) for the BC2C model and in Gallant *et al.* (2005) for FLUSH.

4.2. BC2C modelling

The spatial data layers used in parameterising the BC2C model included: mean annual rainfall (2.5 km resolution), potential evaporation (5 km resolution), percentage tree cover (100 m resolution), rainfall salt concentration gradient, elevation (100 m resolution), and a groundwater flow systems (GFS) map (based on 1:250,000 geological mapping) with several geohydrological attributes estimated through regional expert consultation. The model was further constrained using about 2000 borehole salinity measurements from across the Goulburn-Broken catchment, and stream flow and salinity data from five catchments within the region. For each GFS class, an empirical relationship between groundwater salinity and annual rainfall was established and used in the model (Figure 2).

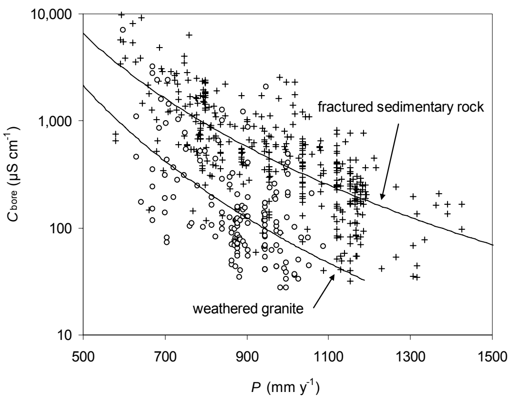

Figure 2. Examples relationships between mean annual rainfall (P) and borehole salinity (C_{bore}) (from Van Dijk *et al.*, 2004)

Long-term average water and salt export rates from the five catchments were used to calculate the apparent recharge fraction through inversion of the model; that is, by calculating the fraction of measured stream flow that needed to have recharged the groundwater store to explain measured salt exports. The resulting recharge values were interpreted and used to parameterise the model. Predictions were made for 5, 15 and 30 years after afforestation.

4.3. FLUSH modelling

We used the FLUSH to examine the likely effects of differences in soil characteristics, lateral redistribution of overland and sub-surface flow and groundwater uptake in different parts of the hillslope, on tree growth, stream flow and salinity. We did this for a 2.4 km^2 subcatchment of Whiteheads Creek, just east of Seymour in the centre of the Southwest Goulburn region. A 20-year climate time series from Seymour was used (rainfall was linearly scaled to produce the 725 mm of mean average rainfall). We used the framework in a semi-distributed fashion by splitting the catchment into three components (Figure 3). The values for soil water holding capacity, depth and the partitioning of excess soil water into recharge and lateral flow were varied for these three units. The 3PG+ parameterisation for *Eucalyptus globulus* (J. Morris, pers. comm.) was used. Systematic relationships between climate and topography were not accounted for in this small-scale analysis, although methods are available to do this (Gallant *et al.*, 2005).

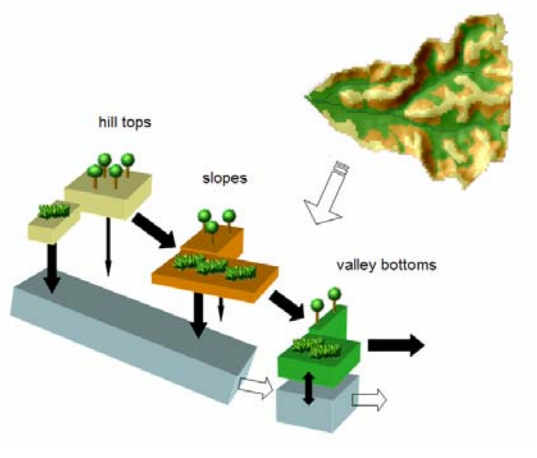

Figure 3. Mapped landscape units in Whiteheads Creek, and a conceptual illustration of the way in which 3PG+ (coloured boxes corresponding to landscape units) and the two-store groundwater model (blue cubes and white arrows) are linked in the FLUSH (represented by the black arrows).

5. RESULTS AND DISCUSSION

5.1. Regional predictions

The BC2C modelling suggested considerable differences in catchment salinity response to land use change. On 60% of the catchment's non-forested area, reforestation is expected to reduce stream salinity within 15 years (the blue areas in Figure 4). The remaining 40%, mainly in granite catchments, is expected to lead to increases in stream salinity because they have relatively fresh groundwater. The area with stream salinity benefits increases somewhat when the time horizon is stretched and the slower responding systems start to have an impact.

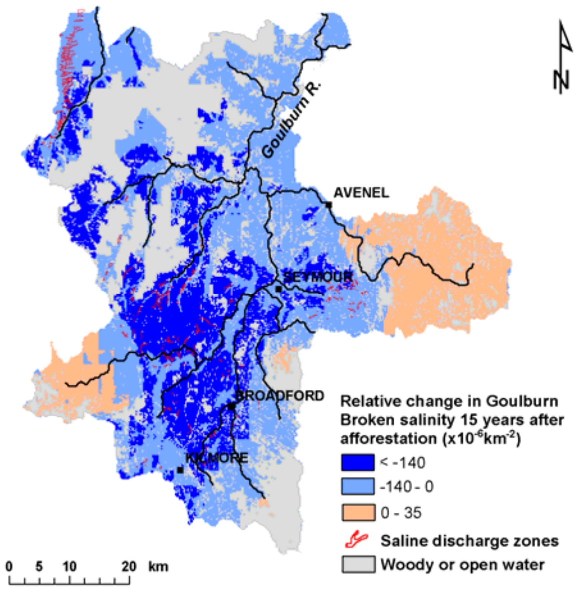

Figure 4. Map of the predicted change in stream salinity 15 years after reforestation of any 1 km^2 area across the catchment. Numbers represent the relative change in salinity of streamflow from the Goulburn and Broken Rivers combined, for an average year (e.g., -100×10^{-6} km^{-2} indicates that a 1 km^2 plantation would reduce combined stream salinity by 1 hundredth of a percent).

Within the 'suitable' (blue) area, the analysis provides guidance to where the greatest reductions in stream salinity can be achieved, thus enhancing the overall effectiveness of revegetation. Half of the maximum achievable reduction in stream salinity (estimated at 12% of overall Goulburn River salinity) can be realised by planting only the most suitable 17% of the region (the two darkest blue colours in Figure 4). The effectiveness of reforestation is predicted to be increased by 2 to 3 times through catchment prioritisation, depending on the total area to be planted. Saline discharge areas have been mapped previously for part of the region (Figure 4) and correspond rather well with catchments predicted to show a favourable response. There is not necessarily a direct link between saline surface discharge and stream salinity, but this agreement does increase our confidence in model results.

5.2. Hillslope analysis

Trees were predicted to grow better and use more water in the lower parts of the landscape. This appeared to be related primarily to the deeper soils assigned to these locations. Groundwater use was predicted to occur in the lowest landscape unit and led to greater water use. Inputs from upslope in the form of overland and unsaturated flow contributed less to increased growth and water use, because they were simulated to occur mostly during periods when soil water content was already close to capacity (results not shown here). The reduction in recharge was predicted to be up to three times greater on higher hillslope positions than in the valley bottom, and therefore reduced salt export more effectively.

Soil characteristics appeared to exert the greatest control over model results. Opportunities for planting designs to 'harvest' lateral flows through the unsaturated zone (e.g. break-of-slope) in this environment appeared limited to a rather specific pattern of soil characteristics along a hillslope. The effectiveness of this type of plantings may be more limited than previously thought (e.g. Silberstein *et al.*, 2002), although we consider the range of topography, climate and soil conditions tested insufficient to draw strong conclusions. Research is underway to increase the confidence in spatial surface water balance estimates, and to provide some degree of validation through field measurements. Ultimately, however, the ability to provide spatial estimates of stream salinity impact is fundamentally constrained by our lack of knowledge about the key salt transporting processes and the unknown spatial variation in hydrogeology and salt concentrations.

6. CONCLUSIONS

The contribution of upland catchments to stream salinity varies in intensity depending on climate, soils, topography and hydrogeology. Spatial predictions of the reduction in stream flow and salinity after land use change (such as reforestation) are needed at different scales. Unfortunately, models tend to require more data than is actually available. Predictions of the impact of reforestation on stream flow at a catchment level are reasonably robust, but the impact on catchment salt exports and the effectiveness of land use planning within catchments is predicted with considerable uncertainty. The main reasons for this is the lack of knowledge about the processes involved, the lack of spatial data on hydrogeology and soils, and several scaling issues. Nonetheless, best estimates are required here and now. The model predictions reported here suggest that the effectiveness of trees in reducing stream salinity varies significantly between catchments with different climate and hydrogeology, as well as between landscape locations with different soil properties and lateral inputs of water from upslope. Besides their direct use in catchment planning, these results also reiterate the value of investing in more reliable spatial predictions. Rather than further model building or parameterisation, perhaps the priority to achieve this should be to improve our understanding through data collection. Catchment experiments, whether designed or opportunistic such as the Pine Creek 'experiment', can greatly increase our understanding and confidence in models, and may produce results within years rather than decades. This quick return, combined with the availability of cheap monitoring technologies, should help to bring such experiments back into fashion.

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