A Simplified GIS-Based Approach to Prioritise Salinity Investment at the Property-Scale

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Abstract: The New South Wales Salinity Strategy is developing ways to establish new income opportunities for landholders through the creation of an environmental services market. These services include reducing the mobilisation of salts, nutrients and acid sulfate soil products, reducing soil loss, reducing greenhouse gases and enhancing biodiversity. As part of a pilot scheme established in 2002 to support the development of markets for environmental services, a methodology was developed for comparing the salinity benefits arising from land use change scenarios at the property scale.

This paper describes a GIS-based modelling tool, the Land Use Options Simulator (LUOS), which predicts the impacts of land use changes on the export of salt and water from a catchment. Within a catchment, each pixel is assigned a weighting reflecting its contribution to mean annual streamflow and saltload, measured at the catchment outlet, under current land use conditions. The weighted runoff source-area surfaces take account of the distributed effects of land use, topography and soils. Weighted salt source area surfaces reflect the influences of groundwater flow systems, salt outbreaks and catchment position.

A change in land use or management modifies the salt and water contributions from the affected pixels, resulting in revised mean annual streamflow and salt load totals at the catchment outlet. The relative changes in salt and water exports under a land use change form the basis of a salinity benefits index (SBI). The SBI enables competing salinity management actions to be ranked and serves as a guide to public investment.

Keywords: *salinity management; GIS; salinity benefits index*

1. INTRODUCTION

The New South Wales Salinity Strategy is developing ways to establish new income opportunities for landholders through the creation of an environmental services market. Services include reducing the mobilisation of salts, nutrients and acid sulfate soil products, reducing soil loss, reducing greenhouse gases and enhancing biodiversity. As part of a scheme established in 2002 to support the development of markets for environmental services, toolkits were developed for each environmental service to assess the potential benefits, in the form of an index, that a range of land use changes would produce. These indices enable comparisons between different land use options at the property level, within and between different catchments, and serve as a guide to public investment.

This paper describes the GIS-based modelling behind the salinity benefits index (SBI) toolkit. The SBI is a relative measure of the changes in salt and water exports from a catchment under a land use change. It enables competing salinity management actions to be ranked and serves as a guide to public investment. It has its origins in CATSALT (Tuteja et al., 2002), a catchment water and salt balance model, developed by NSW Department of Land and Water Conservation.

2. MODELLING THE IMPACTS OF LAND USE CHANGE ON CATCHMENT SALT AND WATER YIELDS

Widespread land use changes were undertaken in Australia following European settlement, to convert native grassland, woodland and forests to agricultural production. The resultant changes to catchment water balances, including decreases in evapotranspiration and increases in runoff and recharge, have increased the mobilisation of salts stored within the regolith. In many areas, the development of dryland salinity is now threatening the productivity of important agricultural lands.

2.1. Catchment Scale Models

Catchment-scale efforts to model the impacts of land use change on catchment water yields have focussed on modifying the terms of the water balance to reflect different vegetation water use patterns. Typically only generic land use changes have been considered, such as from annual, shallow-rooted systems to perennial, deeper-rooted systems (Dawes et al., 2001; Herron et al., 2002).

With the growing salinity problem, models are being developed within Australia which link catchment runoff to salt exports. Vaze *et al.* (in press) and Tuteja *et al.* (submitted) describe the application of the CATSALT model to the prediction of land use impacts on catchment salt and water yields in two NSW catchments. They combine lumped, conceptual rainfall-runoff modelling with land use efficiency indices, topographic indices and salinity hazard and salt outbreak mapping to spatially apportion daily catchment water and salt yields across the contributing catchment in a physically meaningful way. The range of land use changes considered is currently very limited.

More simple approaches such as the Land Use Options Simulator (LUOS) and the Biophysical Capacity to Change (BC2C) model are currently under-development. Both of these models consider mean annual responses. BC2C (Dawes et al., 2001) is intended to rank areas at a regional scale in terms of the impact whole-of-catchment land use changes may have on stream salinity at a target site. Only generic tree and non-tree land uses are considered.

2.2. Land Use Options Simulator

The LUOS combines catchment- and property-scale information to assess impacts of property-scale land use changes on catchment runoff and salt load exports. A wider range of land use changes are considered than have previously been modelled, and the emphasis is on prioritizing salinity management at the sub-catchment scale, although catchment and state-scale analyses are possible.

The LUOS is a GIS based tool, designed to

- permit recording, updating and correcting of spatial information;
- store different land use scenarios; and
- quantify salt load and streamflow impacts of different land use scenarios.

It includes simple decision rules and models to assist in locating key areas for salinity management, and as such is a useful tool for on-site property planning. Computations are performed on raster surfaces for quick performance.

3. DISTRIBUTING STREAMFLOW

The approach involves the apportionment of mean annual streamflow, estimated at the catchment outlet across the catchment based on hydrologic principles. Thus, every pixel is weighted in terms of its contribution to streamflow under current land use conditions. When a land use change is made, the affected pixels take on a new weighting, and a new mean annual streamflow can be estimated. The starting point for any simulation is an estimate of mean annual streamflow.

3.1. Mean Annual Streamflow

A catchment is defined by a gauging station with long-term continuous flow data, and some salinity data. The period 1975-2000 serves as the standard reference period for all catchment salinity assessments in the Murray-Darling Basin Salinity Audit, and is therefore recommended for estimating mean annual streamflow and salt load estimates in each catchment.

Where streamflow data are available, they can be separated into different flow components reflecting the pathways of flow across or through the catchment. The pathways differ in terms of quantity of water moving through them, salinity and travel times. We have chosen to separate the daily streamflow record into two components, quickflow and baseflow, using a digital filter approach.

Quickflow includes surface runoff and rapid subsurface flow. It is often referred to as stormflow, as it dominates the stream hydrograph during storm (runoff) events. Baseflow is delayed runoff, sourced from rainfall that has infiltrated deep into the soil profile to recharge groundwater. Baseflow dominates the stream hydrograph between runoff events, although it can be a significant component of a small flood hydrograph.

3.2. Quickflow

The LUOS approach assumes that saturation-excess runoff dominates quickflow. Saturation-excess runoff occurs on areas that are saturated and hence unable to infiltrate rainfall or runoff from upslope. This assumption is reasonable when doing analyses in temperate areas on a mean annual basis.

LUOS also assumes the partial area model of quickflow runoff generation (Betson, 1964). This model assumes that not all parts of a catchment generate surface runoff because saturation conditions are not met uniformly across a catchment.

Topography - CTI_w

The compound topographic index (CTI) of Beven and Kirkby (1979) is an indicator of soil moisture distribution within a catchment. The CTI is a function of upslope contributing area and local slope. High values are produced for areas with large contributing areas and/or low slopes and correspond to areas where soil moisture is likely to be high, due to the accumulation of slow moving catchment runoff between rainfall events. These areas are predisposed to generating quickflow during a rainfall event because they saturate quickly.

A quickflow source area can be defined using a CTI threshold, CTI_{crit}. Setting a threshold is a somewhat arbitrary approach, given the dynamic nature of the hydrologic system, but for long-term average conditions it represents a simple means of separating hillslope areas from dominant quickflow source areas. A value of 10 assumes about 10% of a catchment contributes quickflow and gives a reasonable starting split, but we must recognise that CTI_{crit} will vary with catchment conditions, reflecting different climate and geomorphic controls.

Within the quickflow zone ($CTI > CTI_{\mathrm{crit}}$), a variable source area model of runoff generation is assumed. This means the extent of saturation in a catchment varies with rainfall distribution as well as with topography. We attempt to capture the spatial variation in runoff frequency within the quickflow zone using a simple function of CTI:

$$CTI_w = 0.1 * CTI - 0.9 \qquad (1).$$

Eqn (1) gives greater weight to CTI values close to CTI_{crit} than higher CTI values. For CTI>19, the maximum weighting of 1 is adopted, as these areas tend to coincide with the drainage network. While the precise form of the function describing the temporal pattern of runoff generation within this zone is not known, the concept of a variable source area is captured.

Rainfall - RF

In general, areas of high average rainfall shed more runoff than areas of low average rainfall, other things being equal. The spatial pattern of average annual rainfall across a catchment can be used directly to weight areas in terms of their contribution to quickflow.

Land Use - RO_{LU}

Land use influences the evapotranspiration term of the catchment water balance. It is well established that perennial vegetation types use more water through a year via evapotranspiration than annual vegetation types, which are active for only part of the year (Zhang et al., 2001). In general, trees use more water than perennial grass systems because they tend to have deeper root networks, and can access water stored deeper in the soil profile. Where there is no vegetation cover, the transfer of rainfall back to the atmosphere is by evaporation from the soil and this is restricted to a fairly shallow depth. These differences between vegetation types and cover influence the quantity of rainfall which is available for drainage deep into the soil profile and for runoff over or near the surface.

Results from water balance modelling across the Murray-Darling Basin within New South Wales using PERFECT (Littleboy et al., this issue) provide permit comparisons between the recharge and runoff components of a limited number of land uses. Relative differences in runoff between crops, pastures, trees and bare soil were calculated, using pasture as the reference land use, and are used here to weight the land use coverage in terms of runoff contributions. More modelling runs are required to expand the list to include a wider range of land uses and management options. Table 1 gives an example prepared for the upper Goulburn catchment in the Hunter Valley, in which runoff weightings, RO_{LU}, have been estimated based on different proportions of bare soil, pasture and trees.

Weighted Quickflow Index- QF_w

A weighted quickflow surface is generated in the land use options simulator by combining the CTI weighted surface with rainfall and land use:

$$QF_w = RF * RO_{LU} * CTI_w \qquad (2).$$

RO_{LU} refers to land use weightings for runoff (Table 1). The magnitude of QF_w in a cell reflects its contribution to catchment quickflow.

3.3. Baseflow

The baseflow contribution to catchment streamflow is a function of recharge, which varies with land use, soil type and rainfall. The whole catchment is assumed to contribute baseflow to the catchment outlet, except where the CTI_w value for quickflow is equal to 1. In this case, no recharge occurs because the profile is saturated and cannot infiltrate rainfall.

Table 1. Runoff and recharge weightings for a range of land uses.

Land Use	Runoff weighting	Recharge weighting	Remarks
Pasture	1.00	1.00	
Crops; Horticulture	1.10	1.05	
Forest; Remnant Vegetation;	0.95	0.70	
Moderate Pasture	0.99	0.95	20% bare
Fair Pasture	0.97	0.91	40% bare
Degraded Pasture	1.72	1.51	60% bare
Sparse Woodland - Degraded Pasture	1.34	1.11	
Open Woodland - Moderate Pasture	1.00	0.95	
Open Woodland	0.93	0.77	
Sparse Woodland	0.40	0.33	
Mine	2.20	1.85	Assume bare soil

Topography - CTI_{mod}

In areas defined as quickflow source areas (CTI>CTI_{crit}), recharge is a function of CTI_w as follows:

$$CTI_{mod} = 1 - CTI_w \qquad (3).$$

Where CTI<CTI_{crit}, baseflow is directly dependent on the magnitude of recharge and the topographic weighting, CTI_{mod}, is 1.

Soil Type and Rainfall – Re_{soilCZ}

The relative differences in recharge due to soil type and rainfall can be determined from the recharge modelling outputs of Littleboy et al. (this issue). The magnitude of recharge for each soil type-rainfall combination can be used directly to weight different areas on their propensity to recharge groundwater. To contain the number of unique soil type-rainfall combinations, the rainfall grid is re-classed into 50 mm bands.

Land Use - Re_{LU}

Table 1 lists the recharge weightings for different land uses in the upper Goulburn. They are based on the relative differences in recharge calculated using PERFECT.

Weighted Baseflow Index- BF_w

A weighted baseflow surface is generated in the land use options simulator as follows:

$$BF_w = RF * \mathrm{Re}_{LU} * CTI_{mod} \qquad (4).$$

Every pixel in the catchment is weighted according to its contribution to average baseflow.

4. DISTRIBUTING SALT LOAD

Where sufficient flow-EC data are available at a gauging station, mean annual salt load can be estimated. There are various ways of doing this, but they are not discussed here. The approach assumes that the mean annual salt load for a catchment is known and that the source areas of salt can be weighted based on salt storage patterns.

4.1. Quickflow Salt Loads

Quickflow salt is derived from the quickflow source area. Ideally soil salinity data should be used to differentiate between different parts of the quickflow zone, but these are rarely available. Instead, groundwater salinity data is used as a surrogate, although the dependence of soil salinity on groundwater salinity is not tested.

Quickflow salt source areas

Groundwater salinity is used to directly weight the salt source area coverage. Areas with highly saline groundwaters are assumed to be more significant sources of salt than those characterised by low groundwater salinity.

Where salt outbreaks are evident at the surface, we assume salt accumulation and concentration is high. These areas are weighted more strongly than non-outbreak areas, reflecting the greater availability of salt for mobilisation to the stream during runoff events. A multiplier of 5 is used to increase the weighting of outbreak areas relative to the background groundwater salinity. This factor is only weakly-based on field data and should be viewed as preliminary.

To reflect the accumulation of salts along a flow path, each cell in the salinity grid is weighted to reflect the number of cells and the salinity of each cell in the its flowpath, $GWEC_{QFw}$. Flowlength is calculated using the salinity grid to weight each cell, and the stream network to define the endpoint of each flowpath. Thus, the effect of a land use change on salt export from a cell will effectively encompass a downslope impact.

Weighted Quickflow Salt Load Index- S_{QFw}

The salt source area coverage for quickflow will not vary with a change in land use, until it is linked to the weighted quickflow surface as follows:

$$S_{QFW} = GWEC_{QFw} * QF_w \quad (5).$$

This equation says simply that the flow-weighted salt source area pattern for quickflow is a function of the quickflow and salt load weightings across the catchment.

4.2. Baseflow Salt Loads

Baseflow salt loads are derived from all parts of the catchment where baseflow is generated. Groundwater salinity, $GWEC_{BF}$, is the only property used to weight the source area distribution. Salt outbreaks do not influence the baseflow salt loads.

Weighted Baseflow Salt Load Index- S_{BFw}

The flow-weighted source area of baseflow salt surface is calculated as:

$$S_{BFW} = GWEC_{BF} * BF_w \quad (6).$$

5. LAND USE CHANGE IMPACTS ON CATCHMENT EXPORTS

Once the distribution of catchment exports is defined for current land use conditions, different land use changes can be modelled and the change in mean annual salt loads and streamflow estimated. The LUOS is designed such that the user can digitise the proposed land use changes on screen or import a coverage containing the land use changes. The new exports are calculated as follows:

Quickflow

$$\Delta QF = \frac{\sum QF_w^{new}}{\sum QF_w} * QF_{ann} \quad (7)$$

Baseflow

$$\Delta BF = \frac{\sum BF_w^{new}}{\sum BF_w} * BF_{ann} \quad (8)$$

Quickflow Salt Load

$$\Delta S_{QF} = \frac{\sum S_{QFw}^{new}}{\sum S_{QFw}} * S_{QF}^{ann} \quad (9)$$

Baseflow Salt Load

$$\Delta S_{BFw} = \frac{\sum S_{BFw}^{new}}{\sum S_{BFw}} * S_{BF}^{ann} \quad (10)$$

These equations compare the sum of all the cells in the weighted grid for the new land use scenario to that of the current land use for each flow and salt component and multiply the ratio by the current mean annual quickflow, QF_{ann}, baseflow, BF_{ann}, quickflow salt load, S_{QF}^{ann} and baseflow salt load, S_{BF}^{ann}, respectively. Thus, using information about current exports and the best available hydrologic and salt storage data, estimates of the impacts of land use changes on streamflow and salt loads are possible.

It is important to note, however, that the method is designed to compare land use options based on the best available data, rather than to compute absolute changes in each of the flow and salt components. Therefore, we use the model outputs to compute a salinity benefits index, which is a measure of the relative changes in flow and salt for a land use scenario.

6. SALINITY BENEFITS INDEX

In 2002, as part of the NSW Salinity Strategy, the Environmental Services Scheme was launched, which has its aim the establishment of markets for the provision of environmental services. Under this scheme, landholders were invited to apply for funding to undertake a range of land use changes on their properties which provide environmental services. A means of objectively assessing each of the applications for their salinity, biodiversity, soil retention, nutrient retention, carbon storage and acid sulfate soils benefits were required. The Salinity Benefits Index (SBI) was developed, using an earlier version of the methods described above, to enable comparisons between the salinity benefits of each of the land use change proposals.

The SBI is calculated as:

$$SBI = \frac{\frac{S_{current}}{Q_{current}} - \frac{S_{new}}{Q_{new}}}{\frac{S_{current}}{Q_{current}}} \quad (11)$$

where S is mean annual salt load and Q is mean annual streamflow. Eqn (11) is a measure of the change in stream salinity resulting from a land use change relative to the initial stream salinity. A negative value indicates that the reduction in salt exports from the land use change is proportionately smaller than the reduction in water exports, and points to an increase in the salinity of the draining stream at the catchment outlet. Conversely, a positive SBI indicates a reduction in stream salinity.

When comparing SBI values from different areas, caution is advised as the SBI is influenced by the choice of reference point at which it is calculated. First, the magnitude of the SBI is affected by the area of the land use change relative to the area of the catchment for which it is calculated. For a given land use change, the SBI will have a larger value when calculated at the outlet of a small catchment than a larger one. This means that SBI values calculated at different reference points are not directly comparable.

Secondly, the choice of reference point can affect whether the SBI is positive or negative. Sample calculations for land use changes at selected ESS sites at local catchment, valley and state scales show that the sign of the SBI can change with a change in reference point. An increase in stream salinity in a small local catchment does not necessarily mean an increase in salinity in the higher order stream to which it drains.

Given the influence of choice of reference point on the magnitude and sign of the raw SBI results, it would be prudent to select a reference point that reflects the scale at which prioritisation decisions are required. For prioritisation of funding at the state scale, the reference point needs to reflect the combined streamflow and salt load totals across all the basins in the State. For sub-basin scale prioritisation, a site on the mainstream upstream of major diversions or tidal influences provides a more suitable reference point. By estimating the SBI at different reference points, the impacts of a land use change can be evaluated at a range of scales.

7. CONCLUSIONS

A simple method for assessing the impacts of land use change on catchment salt and water exports is demonstrated, which can be easily implemented within a GIS framework. The method uses hydrologic principles and spatial salt store information to define flow and salt source area coverages which are dependent on land use. A change in land use changes the weighting of the source area coverages, and the relative differences are used to estimate new average salt and flow amounts.

A salinity benefits index provides a useful means of comparing land use options within and between catchments. Consideration of the scale of prioritisation is needed to pick an appropriate reference point for SBI calculations.

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