Linking Soil Water and Groundwater Models to Investigate Salinity Management Options

Carl C. Daamen[a] **and Greg P. Hoxley**[a]

[a]Sinclair Kight Merz, P.O.Box 2500, Malvern, VIC 3162, Australia.

Abstract: Salinisation of land and rivers is a problem of national importance in Australia. Appropriate land management options to alleviate salinisation should be chosen with knowledge of the effects of land management on stream flow, stream salinity, stream salt load and land productivity. The modelling approach described in this study links a one-dimensional soil water model with a groundwater model to investigate the effects of management options in study areas of approximately 50 km^2. The one dimensional model is used to characterise the annual soil water balance as a function of underlying aquifer pressure for all required combinations of soil, vegetation and groundwater salinity. It includes the effect of salt accumulation on plant water use. The groundwater model is then used to estimate the depth to watertable across the study area that reflects the topography, hydrogeology and the distribution of vegetation. Scenario modelling allows comparison of a range of distributions of vegetation including the introduction of new vegetation types with different water use characteristics. The approach is demonstrated in study areas within the Goulburn-Broken catchment in Victoria.

Keywords: *Salinity; Groundwater; Recharge; Land Management; Modelling*

1. INTRODUCTION

Salinisation of land and rivers is a problem of national importance in Australia. In dryland areas land management options can involve both vegetative and engineering options. Vegetative management may include use of perennial pasture, lucerne and trees at appropriate locations in the landscape. Engineering options may include pumping of groundwater for small-scale irrigation schemes in these environments. Land and catchment managers need information on how these management options affect stream flow, stream salinity, stream salt load and land/soil productivity so that informed choices between competing options can be made.

Assessment of a catchment salt and water balance must consider the effect on plant water use of the depth to any saline watertable and resultant salt accumulation in plant root zones. This paper presents a numerical modelling approach that is capable of estimating these effects and is able to estimate stream flow and salinity for different land use scenarios. It uses the groundwater model MODFLOW (McDonald & Harbaugh, 1988) within the Visual MODFLOW package (Waterloo Hydrogeologic, 1999) and a one-dimensional soil water and solute movement model, SoilFlux (Daamen et al., 2001). The modelling approach as a whole has already been described (Daamen et al., 2002), here we demonstrate the versatility of the approach by applying it to new study areas.

2. MODELLING APPROACH

2.1. Modelling Intent

The modelling approach was developed to allow comparison of the effects of land management options on catchment hydrology and salinisation. The clear intention is to provide land managers with information that allows differentiation of competing choices and approaches. The available input data sets for soil and groundwater models are often very limited in the areas targeted for investigation. Values for parameters are often subjectively estimated by the project team involved using the information available. Thus the models could be considered to be 'conceptual' in that they represent the catchment-wide water movement processes to our best understanding but conventional testing of model accuracy is often not possible.

However, for this study the most important model outputs are the stream flow and salt load out of the catchment (in the context of meeting end of valley targets for river salinity). Stream flow and salt load can be estimated using the stream gauge network in the surrounding area (see below). These independent estimates of catchment fluxes provide a test of the modelling approach that is appropriate to its objectives and application.

2.2. Overview

The modelling approach adopted in this study examines water and salt movement at two different scales. Daamen et al. (2002) describe the method and the details of this study are presented in a report (CLPR, 2003) therefore only brief descriptions are given in this paper.

Firstly, using daily climate inputs at the ‘plot’ scale, the vertical movement of water and solutes is modelled from the soil surface through unsaturated and saturated soil to a depth of 10 metres. Secondly, at the catchment scale (of order 10 000 ha) the lateral movement of groundwater is modelled using average annual fluxes. There are three stages in the combined approach:

1. Vertical soil water and solute movement is characterised using the SoilFlux model. For a range of vegetation types and soil types the primary outputs are the relationships between underlying groundwater pressure and: average annual groundwater recharge/ discharge; average annual runoff; and, average annual salt load carried in runoff.

2. Lateral groundwater movement is simulated with a steady-state MODFLOW model. The primary input is the relationship between [groundwater pressure] and [average annual groundwater recharge or discharge] calculated in Stage 1. The outputs include the groundwater pressure across the study area and the flow in the drainage lines.

3. Outputs from Stages 1 and 2 are processed to estimate average annual runoff and average annual salt load export across the study area as a function of groundwater pressure.

2.3. Stage 1 – Vertical soil water and solute movement

The first step is to establish how the water input (rainfall in the cases considered) moves through the soil profile and what fraction drains to the groundwater system. Different types of vegetation will affect this process in different ways and a change in vegetation may turn groundwater recharge into groundwater discharge.

The SoilFlux model is a one-dimensional model of water and solute movement developed by Sinclair Knight Merz (Daamen et al., 2001). It is used to characterise the average annual flow to or from groundwater and how it differs with vegetation type, soil type and depth to watertable. The SoilFlux model estimates soil water flow using the Richards equation, and solute flow using the advection-dispersion equation. Under test conditions, it compared well against the HYDRUS model (Simunek et al., 1998) and analytical solutions (Haverkamp et al., 1977).

SoilFlux requires daily inputs of rainfall and potential evaporation at the land surface, and underlying water pressure at the base of the simulated profile. The salinity of groundwater and rainfall are also inputs and assumed to be 1 000 mg/l and 10 mg/l respectively for the two catchments modelled in this paper. Daily rainfall and potential evaporation were estimated for the study areas using data from nearby Bureau of Meteorology climate stations.

Vegetation types are characterised by:

- a series of monthly evaporation partitioning coefficients; and
- root distribution with depth.

The partitioning coefficient is the fraction of potential evaporation that can be met by plant transpiration (i.e., root water uptake). It has a value between 0.0 and 1.0 and can be considered a measure of the fractional ground cover attained by a plant canopy. The maximum transpiration is equal to (partitioning coefficient)*(potential evaporation) and will occur when the soil water supply is not limiting. If the soil is dry or has high salt content, the transpiration will be reduced using an effective root zone soil potential, the combined effects of matric potential and osmotic potential (see Daamen et al., 2001).

The remaining fraction of potential evaporation is assigned to direct evaporation from the soil surface. Typically, in a drying cycle, evaporation from the soil surface will meet potential demand until the soil dries to a minimum matric potential. Thereafter, evaporation from the soil surface is controlled by the upward movement of water to the surface and the surface remains at the minimum matric potential until it is wetted by the next rain event.

Four different vegetation types are described in Figures 1 and 2. The simulated perennial pasture is winter-active representing a phalaris- or cocksfoot-based pasture. The vegetation labelled ‘trees’ simulates a dense plantation of pine or eucalypt.

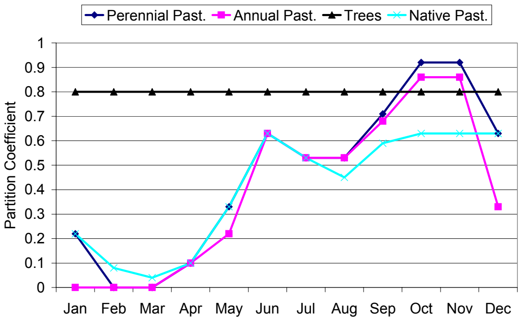

Figure 1. Monthly partitioning coefficients for potential evaporation for 4 vegetation types.

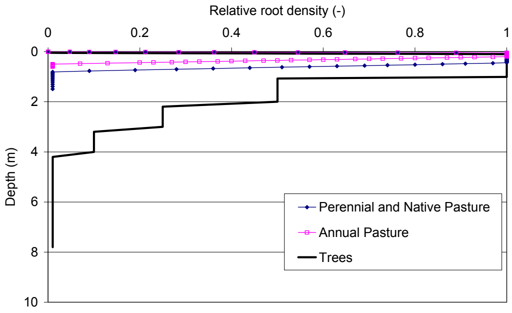

Figure 2. Relative root density over a depth of 10 m for four vegetation types.

In this study three different soil profiles were identified within each of the two study catchments (described below). The lower boundary condition was a constant groundwater potential. Each of ten model runs considered a different groundwater potential equivalent to depths to watertable between 0 m (the land surface) and 10 m.

The SoilFlux model was run for two consecutive 50-year periods; the first to establish the 'current' soil profile conditions in 2000 and the second to test the response to different management options through to 2050.

The annual flow to groundwater was averaged over 20 years (equivalent to the years 2030 to 2050) for each soil, crop, and groundwater pressure combination. Figure 3 shows the average annual flow to groundwater over the range of groundwater potentials for four vegetation types growing on a soil within Catchment 1. The line for annual pasture shows a net recharge of groundwater when the underlying groundwater pressure is equivalent to a depth to watertable greater than 0.7 m (i.e., some rainfall drains to the watertable). In contrast trees show a net discharge from groundwater for all depths to watertable down to 10 m. Soil salinisation reduces root water uptake by trees and discharge from groundwater when the depth to watertable is 2 m or shallower. Under non-saline conditions the uptake of groundwater by trees would be much higher (200 – 300 mm/year) when the watertable is shallow.

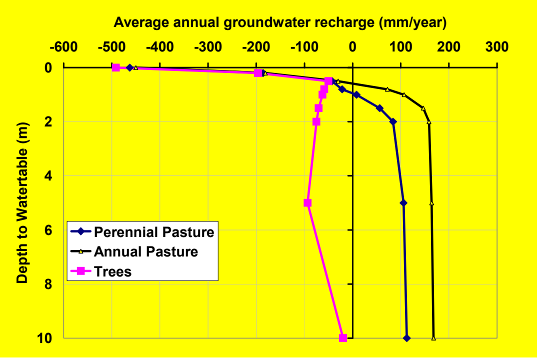

Figure 3. Average annual groundwater recharge vs depth to watertable for 3 vegetation types.

2.4. Stage 2 – Groundwater model of lateral movement

In Stage 1, the vertical flow of water to and from the water table was described; in Stage 2, lateral movement (and redistribution) of groundwater is estimated. Topographic and geological information was used to construct a groundwater model of the study area in MODFLOW using a 50 metre by 50 metre grid. Spot heights and contours from the state-wide 1:25 000 data set were combined with surveyed bore elevations to produce a digital terrain model (DTM). This DTM was also calibrated against the local stream network to ensure that the surface was "drainage enforced".

The recharge and evapotranspiration inputs to a groundwater model are characterised for vegetation and soil types using the outputs from the SoilFlux model. Figure 3 is an example.

The groundwater model used three layers. The deepest layer represents very low permeability fresh rock and the upper two layers rock with characteristics of increased weathering (CLPR, 2003). Faults and folds were represented as zones of increased hydraulic conductivity. Limited 'slug tests' of bores within the catchments were undertaken to provide estimates of hydraulic conductivity.

The ephemeral streams within the catchment were represented as drains at a depth of 2 m below the land surface. Other boundary conditions are described briefly below in Section 3.

2.5. Stage 3 – Data analysis

In Stage 1, soils and vegetation types were characterised in terms of the average annual fluxes (recharge, runoff, or salt load in runoff) that occur as a function of groundwater pressure at the base of the profile (10 metres). The relationship between recharge and groundwater pressure was used to calculate the evapotranspiration and recharge inputs to MODFLOW in Stage 2. A Stage 2 output is the resulting groundwater pressure across a study area. In Stage 3, the groundwater pressure of each grid cell in the groundwater model is used to estimate average annual runoff and salt load in runoff using the relationships from Stage 1. In Stage 3, a catchment or study area water balance is calculated by integrating the fluxes across the study area and adding the stream flow output from Stage 2.

2.6. Assumptions

The approach assumes that the groundwater system is at (or close to) hydraulic equilibrium and therefore can be modelled in steady state. Put simply, this implies that the watertable is not rising, and over several years, flows "in" are approximately equal to flows "out" of the groundwater system. A balance between inputs and outputs is expected in areas with established high watertables. Seasonal and inter-annual variation in flow to and from groundwater is characterised in the one-dimensional simulation using the SoilFlux model.

The hydraulic equilibrium can be disturbed by land salinisation (i.e., the accumulation of salt at the land surface and in the root zone of vegetation). In an area where vegetation is able to use water from a high watertable, increasing salinity in the root zone over time will usually decrease the uptake of water from the watertable thus changing the hydraulic equilibrium of the groundwater system. In this study, it is assumed that the process of salt accumulation is slow relative to the short time required for hydraulic adjustment of the groundwater system to a change in soil water balance.

The modelling approach is used to evaluate the salt and water balance of a study area after a given length of time since establishment of a shallow watertable. In the study areas the salt and water balance are assessed for the year 2050 under a range of management options established in the year 2000.

3. STUDY CATCHMENTS

This study investigates the salt and water balance of two areas in the South West of the upper Goulburn catchment. The identification of vegetation types and a description of the two study catchments is given briefly below.

3.1. Identification of vegetation types

The four primary vegetation types in the catchments are annual pasture, native pasture, exotic perennial pasture and native trees/shrubs. Pasture surveys of parts of the two study catchments were used to estimate percentage areas of native pasture. Tree cover across the catchments was estimated using satellite images with a resolution of 2.4 m^2 that allow identification of single tree canopies. Details of the methods used to locate trees and pasture in the study catchments are given by CLPR (2003).

Five future land management scenarios were modelled:

- 1) Current land use distribution
- 2) 30 % tree cover
- 3) 45 % tree cover
- 4) 60 % tree cover
- 5) 45 % tree cover with new trees aligned along stream lines

In scenarios 2, 3 and 4 the extra tree cover was located to enhance biodiversity within the catchments without encroaching on areas surveyed as native pasture. In scenario 5, extra tree cover was located along stream lines in the major valleys. The distribution of vegetation types within the catchments is shown in CLPR (2003) for all scenarios.

3.2. Catchment 1

Catchment 1 is the upper catchment of Gardiner Creek near Seymour, Victoria. The surface water catchment boundary is used as the model boundary for all but a short length at the catchment outlet.

The analysis of satellite images indicated a tree cover of 10 %. Perennial pasture was estimated to cover 65 % of the catchment and annual pasture 25 %. The high perennial pasture cover was used because half of all pasture cover was estimated to be native pasture species within this catchment. Both native pasture and exotic perennial pasture were modelled as 'perennial pasture' because of their very similar soil water balance.

The catchment boundary was represented in the groundwater model as a MODFLOW general head boundary although no-flow conditions were expected. General head boundaries increase model stability and input parameters for these boundary conditions were set to minimise flow across the boundaries. Some groundwater outflow was allowed down-valley at the catchment outlet but the flow volume was insignificant.

3.3. Catchment 2

Catchment 2 lies between Kilmore and Broadford and includes the upper catchment of Hamilton Creek and the adjacent section of Dry Creek. Again the model boundaries follow the surface water catchment boundary where possible and cut across valley outlets perpendicular to elevation contour lines. The Dry Creek valley segment has an inlet and an outlet cross section.

The distribution of vegetation across the catchment was: 9 % trees, 32 % perennial pasture and 59 % annual pasture. The representation of catchment boundaries was similar to that described for Catchment 1.

4. RESULTS AND DISCUSSION

4.1. Verification of modelling approach

The modelling approach was tested on the two study catchments using the current land use distribution. The average annual stream flow and salt load from the study catchments was estimated from stream gauge data in the surrounding area using an approach similar to the one described by Daamen et al. (2002). Stream salinity measurements are not recorded at as many points as stream flow and continuous records of salinity (required to estimate salt load) have only been kept since 1990. 'Measured' and modelled annual stream flow and salt load are compared in Figures 4 and 5.

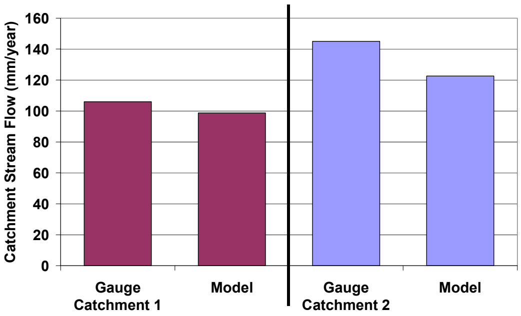

Figure 4. Measured and modelled stream flow under current land use for both study catchments.

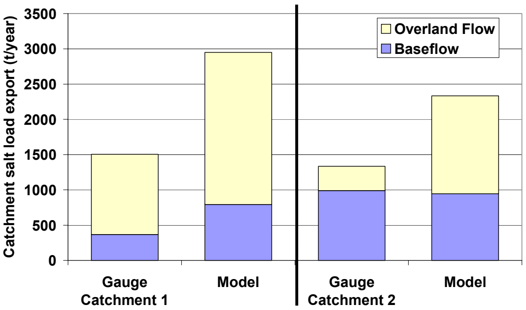

Figure 5. Measured and modelled salt load under current land use for both study catchments. Salt load components carried in baseflow and overland flow are shown.

The modelling approach provides a good estimate of annual stream flow volume (Figure 4). In contrast, salt load is not as well estimated (Figure 5). In particular the fraction of salt load carried in overland flow appears to be over-estimated by the modelling approach.

In an earlier application of this modelling approach the modelled runoff volume was too large (by a factor of 2) and the total salt load matched closely to gauge estimates (Daamen et al., 2002). However land elevation ranges over hundreds of metres in the catchments of this study and only changed by tens of metres at the earlier study site. It is likely that an improved representation of land surface runoff processes that takes account of these differences would benefit the modelling approach.

A detailed measurement program has been proposed for Catchments 1 and 2 of this study. This program would improve understanding of the processes of salt movement to streams and to provide an enlarged data set to compare with model results.

4.2. Evaluation of land management options

The modelling approach was applied to evaluate the possible effects of increasing the tree cover within the catchment. The effects on stream flow and salt load in Catchment 1 are presented in Figures 6 and 7. The two study catchments showed similar responses to increased areas of tree cover although the effects were less marked in Catchment 2 (results not shown).

Figure 6 shows that increasing tree cover decreases flow volume (catchment yield) as expected. This is a distinct disadvantage of increased tree cover that needs to be considered in conjunction with the changes to salt load export.

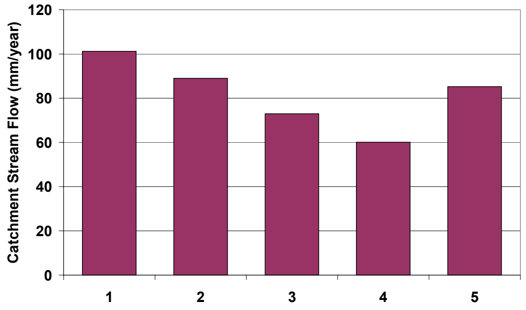

Figure 6. Catchment 1: Annual stream flow in 2050 for 5 future land management scenarios (described in Section 3.1).

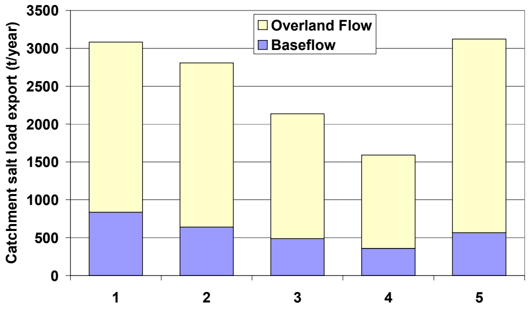

Figure 7. Catchment 1: Annual salt load in 2050 for 5 future land management scenarios (described in Section 3.1).

Another interesting finding is that the alignment of trees along drainage lines in Scenario 5 does not result in a decreased salt load at all. The modelling approach indicates that trees are not effective in this scenario because the watertables are shallow near to drainage lines and accumulation of salt in the root zone of trees occurs (and was modelled) in these locations. After a period of 20 to 30 years trees cause the soil profile to become salinised and this effectively 'delivers' salt to the streams.

5. CONCLUSIONS

The modelling approach described in this study provides a good representation of fluxes at the catchment scale. The application to two study catchments indicates that catchment water balance is modelled well and that the representation of salt balance could be improved. The representation of overland flow and the salt carried in this water volume will be improved when a detailed data set is collected.

Catchment hydrology and salt balance are sensitive to the placement of trees within the landscape. In these environments corridors of trees along the drainage lines will not be effective in the long term.

6. ACKNOWLEDGEMENTS

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