Catchment Salt and Water Balance Effects of Irrigation with Groundwater in Rainfed Areas

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EXTENDED 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 Management of Catchment Salinisation (MCS) modelling approach has been described in earlier work (Daamen & Hoxley, 2003). It links a one-dimensional soil water model with a groundwater model to investigate the effects of management options in study areas of approximately 50 km2. The one dimensional model is used to characterise the annual soil water balance as a function of underlying aquifer potential for all required combinations of soil, vegetation and groundwater salinity. It includes the effect of salt accumulation on plant water use. A 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.

The MCS model is used to investigate the potential effects of future land use scenarios on catchment salt and water balance. Land use scenarios that have been considered include: forest plantations, revegetation with native trees and shrubs, and development of small areas of crops (10 to 20 ha) irrigated with groundwater. This paper focuses on the development of small crop areas irrigated with groundwater and investigates the sustainability of these schemes. It also compares the reduction of catchment salt load export under irrigation development with the reduction under afforestation.

The MCS model is used to compare these land management options in the Gardiner Creek catchment within the area managed by the Goulburn-Broken Catchment Management Authority in Victoria.

The reduction in catchment salt load export due to the introduction of irrigated vines is calculated from model outputs to be 1.01 t/y per hectare of irrigated vines. The salt load reduction of planting trees is calculated to be 0.50 t/y per hectare of trees. Therefore the salt load reductions caused by an increase in the area of irrigated grapes is up to twice as effective as planting trees on a land area basis.

A rough cost estimate for the installation of groundwater pumps is $20,000 per pump. In contrast, planting or seeding areas to native shrubs/trees is estimated at $1000/ha. Thus in the modelled example the development of 200 ha of native trees would cost $200,000 and the installation of 8 groundwater pumps to irrigate 100 ha would cost $160,000. These are costs that may be subsidised by the Goulburn Broken Catchment Management Authority to achieve a similar salt load benefit.

Thus groundwater based irrigation enterprises are likely to provide a more cost effective return on public investment for salt load reduction than revegetation where suitable groundwater reserves are available.

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 to reduce groundwater recharge. Engineering options may include pumping of groundwater for small-scale irrigation schemes in these environments. Land 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.

In MODSIM 2003 we described a numerical modelling approach capable of representing: (a) catchment salt and water balance; and (b) associated salt accumulation in plant root zones (Daamen & Hoxley, 2003). The Management of Catchment Salinisation (MCS) model 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 MCS model is also described by Daamen et al. (2002). The approach is briefly summarized again below.

Earlier work has investigated the effects of different areas of tree cover and different approaches to location of tree cover within two subcatchments of approximately 50 km2 (Daamen & Hoxley, 2003; Sinclair Knight Merz, 2004a). Here we investigate the sustainability of small-scale irrigation schemes using groundwater in an otherwise rainfed or 'dry' catchment. The aims of this work are:

- To provide a first-cut estimate of the equivalence in terms of effect on catchment salt load export of [a groundwater pump] and [an area in hectares revegetated with trees].
- To undertake preliminary assessment of some potential risks in these developments. For example: salt accumulation in the soil profile under irrigation with saline water (1000 mg/L) and the effects on irrigated crop productivity; and reliability of groundwater supply in the unconfined aquifer systems.

This is a 'conceptual model' assessment of the feasibility of small-scale groundwater pumping schemes using the MCS model. The investigation presented here is only intended to be a pre-feasibility study and more detailed investigations would be required to make reliable recommendations about irrigated land use development at specific sites.

2. MCS MODEL APPROACH

2.1. Model 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 MCS model is 'conceptual' in that it represents the catchment-wide water movement processes to our best understanding. Furthermore detailed testing of the accuracy of all model components is often not possible.

Daamen & Hoxley (2003) provide a comprehensive description of the MCS model, the points most relevant to this paper are presented again below.

2.2. Overview of Approach

Firstly, the vertical movement of water and solutes is modelled from the soil surface through unsaturated and saturated soil to a depth of 10 metres using daily climate inputs at the 'plot' scale. Secondly, the lateral movement of groundwater is modelled at the catchment scale (of order 5 000 ha) using average annual groundwater recharge rates. There are three stages in the combined approach:

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

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

Stage 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 potential.

Stage 1 and 2 are further described below

2.3. Stage 1 – Vertical soil water and solute movement

The first step is to establish how the water input (rainfall or irrigation) 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). The SoilFlux model estimates soil water flow using the Richards equation, and solute flow using the advection-dispersion equation. 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. SoilFlux requires daily inputs of rainfall and potential evaporation at the land surface, and underlying water pressure at the base of the simulated profile (as described in earlier papers).

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 to be an approximate 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 that combines the 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.

Four different vegetation types are described in Figure 1. 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. Root depths for annual pasture, perennial pasture and trees are 0.6 m, 1.5 m and 8.0 m respectively.

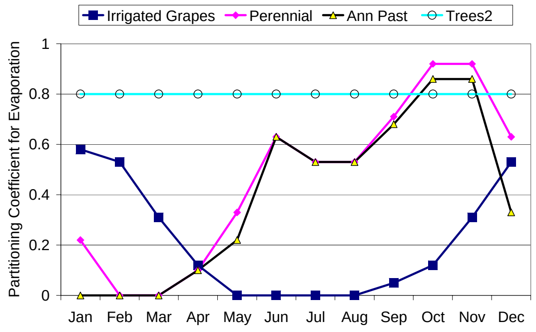

Figure 1. Monthly partitioning coefficients for potential evaporation for 4 vegetation types. This coefficient is approximately equal to the fractional ground cover of the plant canopy.

Three different soil profiles were identified within the study catchment (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.

2.4. Irrigated Grapevines

Daamen & Hoxley (2003) used the following land uses: annual pasture, perennial pasture, native pasture and native shrubs/trees in the MCS model. To these dryland options, we add irrigated grapes as a land use. The annual development of a canopy for grapevines is taken from another study (Sinclair Knight Merz, 2004b) and is shown in Figure 1. The root distribution for grapevines used in the model lies mainly between the land surface and 1 metre with some roots extending to 2 m. It is similar but a little deeper than the root distribution used for perennial pasture.

It is assumed in the model that grapevines will be irrigated with an average of 2 ML of groundwater per hectare per year and that the volume of groundwater pumped is applied to the land surface as irrigation. [Later studies could also consider evaporative loss from farm dams used to hold the groundwater.]

Grapevines are often drip irrigated on a daily basis with irrigation applied at a rate that does not meet the potential water demand (i.e. the maximum possible water use) of the crop. (This is called reduced deficit irrigation). The irrigation regime is modelled by applying irrigation at a rate of 1.3

mm/day during periods when the crop canopy is present and when the cumulative sum of potential evaporation minus rainfall exceeds a selected value. An average irrigation volume of 200 mm/year is applied over the 51 year climate record used in the simulation allowing the irrigation volume to differ between years.

2.5. 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.

The recharge and evapotranspiration inputs to a groundwater model are characterised for vegetation and soil types using the outputs from the SoilFlux model. (An example is given in Section 4.1).

The groundwater model used three layers. Faults and folds were represented as zones of increased hydraulic conductivity. Limited 'slug tests' of groundwater bores within the catchments were undertaken to provide estimates of hydraulic conductivity (CLPR, 2003).

The ephemeral streams within the catchment were represented as drains at a depth of 2 m below the land surface. Groundwater bores are added to the model in the irrigation scenario.

Additional details are given in Section 3 and by Daamen & Hoxley (2003).

3. STUDY CATCHMENT

The MCS model was developed to evaluate options for management of catchment salt and water balance in the upland areas of the Murray Darling Basin bordering the extensive alluvial plains. Daamen & Hoxley (2003) presented results from two study areas within the Goulburn-Broken catchment in Victoria. In this study we use the model of the upper Gardiner Creek catchment in the South West Goulburn.

In Gardiner Creek the average annual rainfall is 650 mm/year. The potential evaporation in the study area is estimated using the areal potential evaporation (Wang et al., 2001), approximately 1100 mm/year.

Vineyards and olive groves are two land uses that are beginning to be established in the South West Goulburn. Irrigated grapevines were chosen as the land use to be considered in this investigation because less information was immediately available for the characterisation and management of olive orchards.

One of the primary constraints of irrigation development in these areas is the groundwater yield that is sustainable in the long term. It is thought that acceptable conditions for small-scale groundwater developments may occur in the Gardiner Creek case study area because of higher aquifer hydraulic conductivities expected around the Moormbool fault.

There is only one small area of irrigation (<10 ha) in the study area currently. We speculate that development of irrigated vineyards might occur as a number of small areas of 10 to 20 ha. This type of development is consistent with the need to have a groundwater source that is sustainable in the long term. The total area of irrigated development in Gardiner Creek is taken to be 100 ha.

Eight groundwater pumps were added into the groundwater model of the Gardiner Creek case study area. The pumps were located within or alongside the areas marked as irrigated grapes in Figure 2. The land use 'irrigated grapes' was modelled so that it did not replace any areas currently modelled as native trees/shrubs.

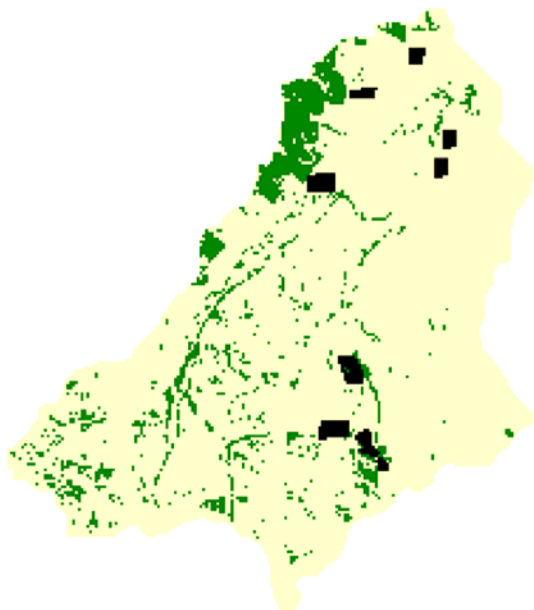

Figure 2. Gardiner Creek land uses under scenario of irrigated grapes. Irrigated grapes are shown in black, current trees in dark green, other land uses in light yellow. Groundwater pumps are located in or immediately beside the irrigated areas.

4. RESULTS AND DISCUSSION

4.1. Summary of Stage 1 Outputs

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. This is the output from Stage 1 in the MCS model. 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. In Figure 3 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.

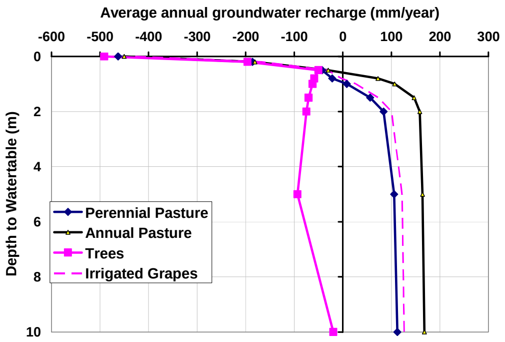

Figure 3. Average annual groundwater recharge vs depth to watertable for 4 vegetation types. Note that recharge < 0 indicates groundwater discharge.

4.2. Current catchment conditions

Daamen & Hoxley (2003) described testing of the MCS model at the catchment scale for the Gardiner Creek study area and one other, the Hamilton/Dry study area. Some changes have been implemented to the MCS model since that study but the catchment scale results are similar. A good correspondence between model and measurements was obtained with average annual stream flow but stream salt load was overestimated in the model.

4.3. Sustainability of Irrigation

One aim of this study was to investigate the sustainability of irrigation with groundwater. Irrigation with saline water did not result in any significant salt accumulation in soil profiles (Figure 4). Note that root zone salinity does not rise above 1.3 dS/m and is below 1 dS/m for most of the simulation period. Variation in soil salinity is mostly due to changes in annual rainfall over the modeled period. Effects of soil salinity on plant productivity are usually first noticeable when soil salinity is 2 dS/m or above.

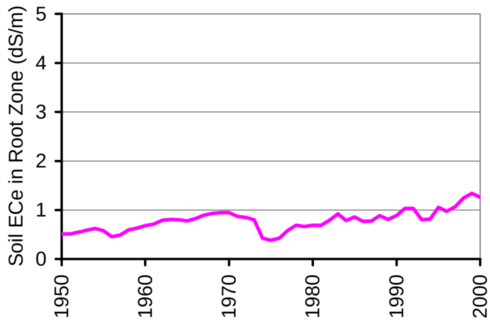

Figure 4. Average annual soil ECe in the root zone of irrigated grapes over the modelled 51 year period.

Low soil salinities are maintained because the salt load is low and the opportunity for flushing salts out of the root zone is high. The average annual water inputs are:

- 650 mm/year rainfall at 10 mg/L
- 200 mm/year irrigation at 1000 mg/L

The average loss of water to evaporation is less than or equal to the areal potential evaporation at the site (Wang et al., 2001), approximately 1100 mm/year.

In these upland catchments soil profiles are reasonably permeable, typically the saturated hydraulic conductivity of subsoils is estimated at 25 mm/day (CLPR, 2003). Irrigated areas are located where the depth to watertable is greater than or equal to 2 m. Under these conditions, climatic variability (especially the wet winters) are more than enough to flush salt from the vineyard root zone.

The groundwater model indicated that pumps along the Moormbool fault could pump 33 ML/year without causing excessive drawdown in the local watertable. The Moormbool fault runs roughly North-South through the middle of the catchment and is modelled with higher aquifer hydraulic conductivity. Outside the fault zone pumping rates of 16.7 ML/y were sustainable although this depended on the pump location. Please note that these pumping rates are ***NOT*** reliable as indicators of the bore yield possible in the Gardiner Creek catchment. Sustainable groundwater bore yield is highly dependent on the heterogeneous aquifer conditions in the immediate area of a bore and further field investigations (including drilling and pump tests) are required to provide a reliable estimate of sustainable yield.

In this investigation, 4 groundwater bores pumping at 33 ML/y and another 4 bores at 17 ML/y were located at different points in the model to provide the total 200 ML/y required to supply irrigation to 100 ha of irrigated grapes. This was achieved without significant watertable drawdown simulated in the groundwater model at the pump site.

4.4. Catchment Salt and Water Balance

Table 1 lists selected outputs from three land use scenarios in the Gardiner Creek case study area including the scenario with 100 ha of irrigated vines.

The reduction in catchment salt load due to introduction of irrigated vines is calculated to be 1.01 t/y per hectare of irrigated vines (using the data in Table 1). The salt load benefit of planting trees is calculated to be 0.50 t/y per hectare of trees. Therefore the salt load reduction of irrigated grapes is up to twice as effective as planting trees on a land area basis.

4.5. Cost Effective Salt Load Reduction

A rough cost estimate for the installation of groundwater pumps is $20,000 per pump. In contrast, planting or seeding areas to native shrubs/trees is estimated at $1000/ha. Thus in the modelled example the development of 200 ha of native trees would cost $200,000 and the installation of 8 groundwater pumps to irrigate 100 ha would cost $160,000. These are costs that may be subsidised by the Goulburn Broken Catchment Management Authority to achieve a similar salt load benefit.

4.6. Conclusion

In conclusion, this application of the MCS model indicates that the development of small-scale groundwater pumping schemes should be further evaluated as an effective approach to reducing salt load. The salt load benefit of establishing an area of irrigated grapes is found to be up to twice as effective in reducing salt load as planting an equally-sized area to trees. The intensification of production that results from such developments has other additional benefits that are not considered here.

A preliminary economic analysis was undertaken using typical incentives available through the Goulburn Broken CMAs program. It indicates that groundwater based irrigation enterprises are likely to provide a more cost effective return on public investment for salt load reduction than revegetation where suitable groundwater reserves are available. Note that this analysis only considers incentives that could be offered by the CMA and does not evaluate operational costs of the different enterprises.

Table 1 Gardiner Creek: summary of modeled stream flow and salt load for three scenarios of land use.

	Total Catchment Area (hectares)	Area of Trees (hectares)	Area of Irrigated Vines (hectares)	Total Flow from Gardiner Creek (mm/year)	Total Salt Load from Gardiner Creek (t/year)	Salt Load Reduction (t/ha/year)
Current Land Use	5119	496	0	79.20	2714	-
30 % Tree Cover (from SWG Part 1)	5119	1552	0	70.25	2183	0.50
Current Land Use plus 100 ha irrigated vines	5119	496	100	77.62	2613	1.01

5. ACKNOWLEDGEMENTS

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