Development of a simplified unsaturated module for inclusion in the US Geological Survey three-dimensional finite difference groundwater flow model MODFLOW

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Abstract This paper describes the development of an integrated saturated/unsaturated catchment model of salinity processes and its application to an irrigated and dryland district in northern Victoria. The model simulates a coupled surface water and groundwater system in which a lumped conceptual model is used to model one-dimensional movement through the unsaturated zone, and a distributed model is used to simulate two-dimensional groundwater flow. Movement of water through the unsaturated zone was found to be dominated by macropore flow, and accordingly the classical matrix flow approximations described by the Richards equation were not used. Instead, a conceptual model of the unsaturated zone was developed to simulate soil infiltration, recharge to the underlying groundwater system, capillary rise and evapotranspiration on a daily time step for each active cell within the model domain. Sub-surface lateral flow between each vertical soil column is not permitted, though once in the saturated zone lateral flows are handled by the groundwater model. Salt movement through the profile is simulated using a mass balance approach, and separate conceptual formulations are used to generate salt export along the drainage lines. The model is a component of a decision support framework for exploring the impact of policy and programs on irrigation futures over a 20 year time period.

Introduction

Highly saline shallow groundwater fluctuations effect agricultural productivity and stream water quality. Shallow water table fluctuations increase the potential of waterlogging and land salinisation. This is most evident within irrigated areas of eastern and southern Australia where records show that the groundwater table has risen markedly resulting in an increase in land salinisation. Salinity is a significant cause of land degradation in south-west Victoria. Currently 30,000 ha of land is affected and the annual cost arising from lost agricultural productivity and decline in water quality is estimated to exceed $5million (Dyson 1996). In order to formulate effective long term farm management practices and options it is necessary to quantify the dominant processes affecting water table movement.

Fluctuations in the water table are in response to unsaturated and saturated physical processes that occur both on a local and regional scale. Mathematical models have been developed to gain a better understanding of the physical processes and to predict the catchment response to changed land use practices. The mathematical models must be capable of representing the spatial and temporal variability in climate, soil, hydrogeology and vegetation at the appropriate scale.

Few mathematical models are currently available that purport to simulate physical processes affecting water table fluctuations. To investigate processes at a point scale the crop water use and solute transport model called SWAGMAN Destiny has been developed by CSIRO. This model is comparable to the one-dimensional eco-hydrological model WAVES. On a sub-catchment scale, SWAGSIM (also developed by CSIRO) has been widely used. This model approximates evaporative demand based on a modified Penman formulation and adopts an analytical solution to estimate net recharge to a single layer groundwater model (Prathapar *et al.* 1995). The fully distributed physically based catchment model Mike-SHE has been applied to irrigated catchments with some success (Mudgway *et al.* 1997) but requires considerable data, computational resources and simulation time.

The objectives of this study were to formulate and integrate a simplified unsaturated module into the US Geological Survey three dimensional finite difference groundwater flow model MODFLOW (McDonald 1988).

The model presented in this paper is called SMILE (an acronym for Simple Macropore Infiltration, Leakage and Evaporation) and it consists of a spatially explicit model of saturated groundwater flow and a lumped conceptual model of vertical unsaturated flow. The model concentrates on the dominant processes that control recharge and salt load discharge at the catchment scale. Model development of the unsaturated flow processes proceeded from the simple to the more complex, where additional complexity was only retained where it could be shown that it yielded a significant improvement. While there are (arguably) a number of physically-based models that have the potential to model the coupled processes of interest, it was considered that there was not the data available to validate model response at the required spatial and temporal scales. The amount of calibration data available for this model application is typical of many catchment investigations, and is representative of the fundamental limitations imposed on physically-based models that has been discussed by such authors as Klemes (1986) and Beven (1989). The process of model development adopted here follows the suggestions of Grayson and Nathan (1993), in which the model was developed for a specific problem at a complexity commensurate with the available data.

The developed conceptual model simulates a well connected surface water/groundwater system dominated by either matrix or macropore flow. As such, the classical matrix flow approximations described by the Richards Equation were not used. The simplified conceptual model approximates one-dimensional vertical soil moisture movement which recharges a three-dimensional finite difference groundwater model. The vertical soil moisture model simulates soil infiltration, recharge to a underlying groundwater system and evapotranspiration on a daily timestep for each active cell within the model domain. Sub-surface lateral flow within each soil column is not permitted. A detailed description of the conceptual model is provided below.

Evapotranspiration

Evapotranspiration is a function of soil moisture and an assigned crop factor as defined by:

$$q_{et} = \begin{cases} q_{etpot}\, c_{fact}\, \theta^* & \theta^* \leq 0.7 \\ q_{etpot}\, c_{fact} & \theta^* > 0.7 \end{cases} \qquad (1)$$

where q_{et} is the daily evapotranspiration flux, q_{etpot} is the daily potential evapotranspiration flux, c_{fact} is the land use crop factor and θ^* is the normalised soil moisture content defined by:

$$\theta^* = \frac{\theta' - \theta_{dry}}{\theta_{sat} - \theta_{dry}} \qquad (2)$$

θ' is the current soil moisture content, θ_{sat} is the saturated soil moisture content and θ_{dry} is the residual soil moisture content.

The calculated daily evapotranspiration flux is partitioned into a soil component and a groundwater component based on the soil moisture content and depth to water table. The depth to water table is normalised as defined by:

$$dwt^* = 1 - \left(\frac{dwt - dwt_{shallow}}{dwt_{deep} - dwt_{shallow}} \right) \qquad (3)$$

The amount of evapotranspiration flux sourced from the unsaturated soil column is defined by

$$q_{et\_soil} = q_{et}\left(1 - dwt^{*k}\right) \qquad (4)$$

such that when the depth to water table falls below dwt_{deep} metres the daily evapotranspiration flux is sourced entirely from the unsaturated soil column. By contrast the amount of evapotranspiration flux sourced from the saturated groundwater is defined by

$$q_{et\_gw} = q_{et} - q_{et\_soil} \qquad (5)$$

Figure 1 shows the form of the weighting function that partitions evapotranspiration demand between the soil column and the groundwater system as described above.

Infiltration

Potential daily infiltration (q_{avin}) is the sum of daily rainfall plus irrigation plus residual free standing water (infiltration excess from the previous time step) less evaporation. Evapotranspiration is a function of the available soil moisture based on the previous day's soil moisture content and a crop factor as previously described. It is assumed that when dry the soil is cracked resulting in an infiltration volume in excess of the saturated soil conductivity, *Ksat*.

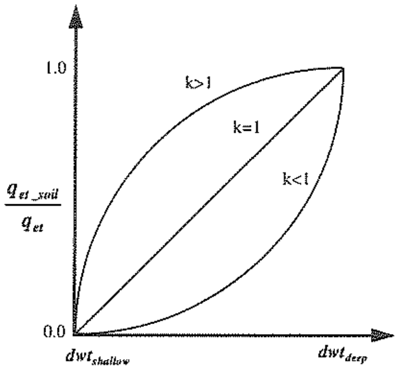

Figure 1 : Form of the weighting function that partitions evapotranspiration demand between the soil column and the groundwater system.

Two infiltration functions are incorporated in the model. Each of these functions are detailed below:

a) Available infiltration ≥ saturated soil conductivity

$$q_{in} = \hat{q}\; q_{avin} \qquad (6)$$

where q_{in} is the actual daily infiltration, q_{avin}, is the available daily infiltration (m/day) and $\hat{q}$ is the infiltration coefficient defined by

$$\hat{q}= 1+(q^* -1)\theta^{*n}$$

(7)

and is based on the normalised minimum daily infiltration:

$$q^* = \frac{K_{sat}}{q_{avin}} \tag{8}$$

where K_{sat} is the saturated soil conductivity, n is the degree of infiltration asymmetry and θ^* is defined by equation (2). The form of the infiltration coefficient as a function of the θ^* and n is shown in Figure 2

b) Available infiltration < saturated soil conductivity

$$q_{in} = q_{avin} \tag{9}$$

where q_{in} is the infiltration flux and q_{avin} is the available infiltration.

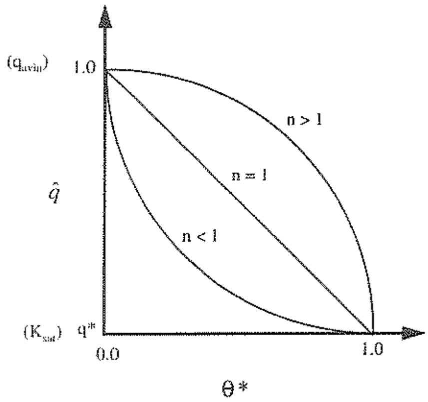

Figure 2 : Infiltration function adopted by the model when available infiltration is greater than saturated soil conductivity.

Recharge

Recharge from the soil column to the underlying groundwater system is a function of soil moisture content and depth to water table. A minimal parameterisation must account for the changes in the unsaturated zone storage (and therefore soil moisture) and depth to the water table allowing for the fact that any functional relationships may be highly nonlinear. Two fundamental approaches have been adopted in the current model namely;

1. matrix/crack flow formulation
2. Darcian flux formulation

Each of these formulations are described below.

a) Matrix/crack recharge formulation

The model caters for both matrix dominated and crack flow dominated accession to groundwater. The depth to groundwater is normalised as defined by equation (3) such that as the depth to groundwater increases the normalised depth decays to zero. Infiltration is partitioned to groundwater according to:

$$\overline{q} = \begin{cases} dwt^* \; \theta^{*\,m} & matrix \\ dwt^* \left(1-\theta^*\right)^m & crack \end{cases} \tag{10}$$

$$q_{rech} = \overline{q}\; q_{in} \qquad q_{in} \geq 0 \tag{11}$$

where q_{rech} is the recharge flux, dwt is the depth to water table, $dwt_{shallow}$ is the assigned depth to shallow water table, dwt_{deep} is the assumed maximum depth to water table beyond which recharge from the soil column does not occur and m is the degree of recharge asymmetry, all other variables being defined above. Recharge to the groundwater system is assumed to be zero when the depth to water table falls below dwt_{deep} metres and equal to the soil saturated conductivity when the soil moisture approaches saturation.

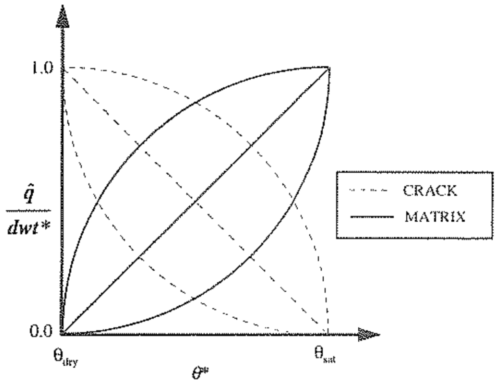

Figure 3 : Recharge functions adopted by the model for both crack dominated and matrix flow approximations.

b) Darcian flow recharge approximation

Based on Darcian flux at the base of any unsaturated soil column, Beven (1986) suggested that a suitable functional form for approximating vertical recharge flux can be expressed by:

$$q_{rech} = \alpha K_0 \, e^{-fz} \tag{12}$$

where α is the effective vertical hydraulic gradient, K_0 the saturated soil conductivity at the surface, f is a scaling parameter and z the local water table depth. The current model includes a modified TOPMODEL functional form of the recharge flux defined by

$$q_{rech} = \theta^* \, \alpha \, K_0 \, e^{-m\,dwt} \qquad 0 \leq q_{rech} \leq \theta^* \, \alpha \, K_0 \tag{13}$$

Infiltration excess

Infiltration excess is accumulated from one day to the next. Potential evaporation is modified in the presence of ponded surface water according to the following:

- ☐ if the ponded surface water depth is less than potential evaporation, the potential evaporation is reduced by an amount equal to the depth of surface water and the depth of surface water is reduced to zero;
- ☐ if the ponded surface water depth is greater than potential evaporation, the ponded surface water depth is reduced by an amount equal to the potential evaporation and the potential evaporation is set to zero.

Surface drain flow

Surface drains, as distinct from those drains in contact with the groundwater and specified in standard MODFLOW files, can be specified to intercept surface runoff. The amount of intercepted overland flow is a function of soil moisture content adjacent to the drain, a user specified drain width and available daily infiltration as defined by:

$$Q_{drain} = \hat{d}(\theta)\, l\, w_{drain}\, q_{avin} \qquad (14)$$

where Q_{drain} is the intercepted overland flow drain volume, $\hat{d}(\theta)$ is the drainage fraction, l is the drain length based on cell dimensions, w_{drain} is the user specified drain width and q_{avin} is the available infiltration assumed to be the sum of rainfall, irrigation and ponded water. The drainage fraction is a function of normalised soil moisture content and a user specified drainage exponent as defined by:

$$\hat{d}(\theta) = \theta^{*n} \qquad 0 \le \hat{d}(\theta) \le 1 \qquad (15)$$

and bounded by zero and unity.

Salt transport

The salt transport processes adopted in the model are a derivation of those reported by Nathan (1993). Salt transport is represented by simple mass balance accounting based on complete mixing. Rainfall and irrigation inputs are assigned fixed salinities, and complete mixing within the soil and groundwater stores are assumed to occur.

The salinity of all internal accessions - including the groundwater movement to and from drainage channels - is determined by the salinity of their source (e.g. the salinity of water moving from the groundwater store to the soil store by capillary rise is at the current salinity of the groundwater store).

The salinity of partial area runoff and groundwater exfiltration is evaluated to be a fixed leaching fraction of the current groundwater salinity, in which the value of the leaching fraction is determined by calibration. This approach reflects the fact that the salinity of groundwater has been observed to increase with depth such that salt concentrations are not the product of complete mixing.

Model application

The appropriateness of the conceptual numerical framework was assessed by application of the model to both an irrigated and dryland catchment. A description of each of the selected study areas and simulation results are described below.

Irrigated catchment

The chosen irrigated catchment was that used to calibrate the SWAGSIM model, namely the Drain 14 catchment located in the Kerang Irrigation District of northern Victoria. The Drain 14 catchment has an area of 2728 ha and is characterised by the existence of a shallow water table over a large proportion of the catchment that generally lies within one to two metres of the soil surface. Refer to the SWAGSIM model application study for a full description of the study area and input data (Prathapar *et al.* 1995).

The data set used in the validation of SWAGSIM was adopted in the current study. River stage data, spatially variable irrigation scheduling data and climatic data was reviewed and altered where necessary; the groundwater parameterisation was accepted without modification. All available hydrograph data was collated to define an objective function that was used by the model to optimise the infiltration and recharge exponents assigned to each of the three spatially assigned soil classes. The model optimiser seeks to minimise the error between the simulated groundwater heads and the observed hydrograph data based on the algorithm developed by Nelder and Mead (1965).

The calibrated model simulated the groundwater trends within acceptable limits of accuracy. Figures 4 and 5 show the simulated depth to water table for selected cells relative to the corresponding observation data.

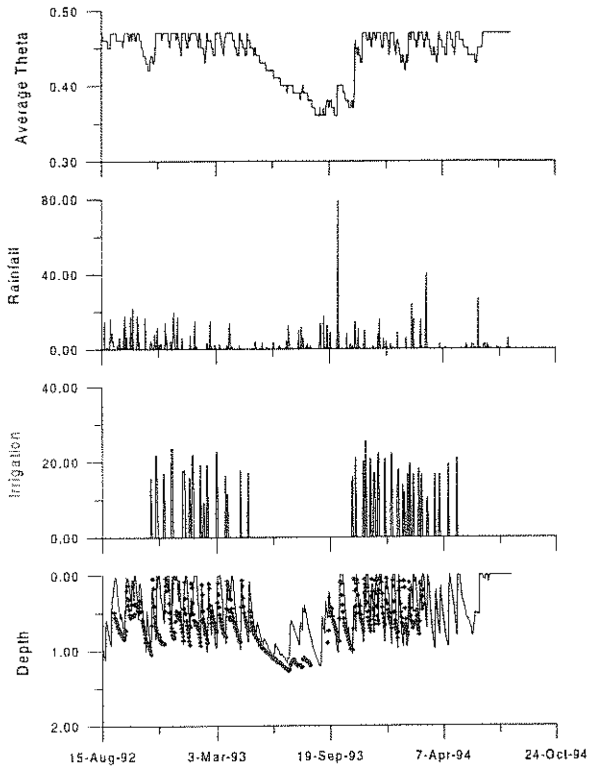

Figure 4 : Simulated and observed hydrograph for bore 221; also shown is the corresponding soil moisture content, the daily rainfall (mm) and applied irrigation (mm).

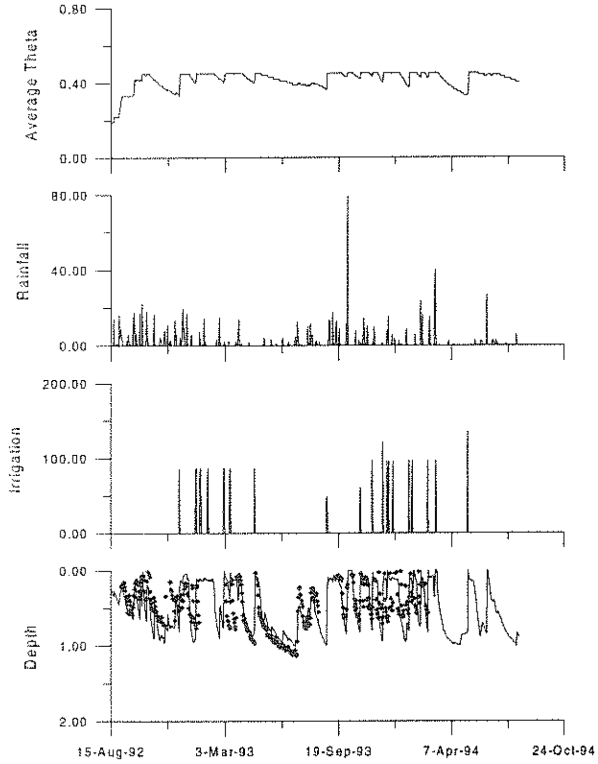

Figure 5 : Simulated and observed hydrograph for bore 241; also shown is the corresponding soil moisture content, the daily rainfall (mm) and applied irrigation (mm).

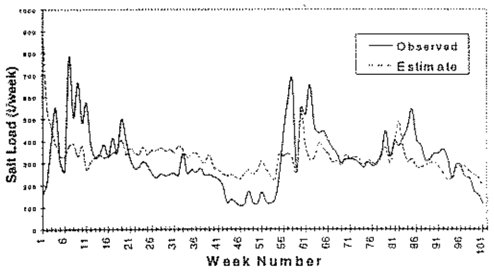

Figure 6 : Simulated and observed catchment weekly salt hydrograph.

Also shown is the applied irrigation, rainfall and simulated soil moisture contents. The maximum hydrograph rms calculated for the 17 observation bores was 0.36 m; the simulated soil moisture contents were supported by field observations.

Simulated salt export from the catchment is shown in Figure 6 and broadly reflects measured data.

Dryland catchment

The site chosen for the preliminary dryland study was Gerangamete located south-western Victoria. This dryland catchment covers 200 ha with an average annual rainfall of approximately 770mm. The catchment is characterised by low permeability duplex soils. Sheep and cattle grazing are the dominant land uses and saline discharge commonly occurs at the break of slope.

The model domain incorporates The Centre for Land Protection Research sub-catchment of the Agro-forestry site and was extended to encompass the larger catchment, bounded by the West and East branch of the Barwon River and the Bambra Fault to the south. This was done to enable a better representation of the regional groundwater system and to also incorporate possible (wider) causes to the salinity problem within the sub-catchment. Three soil types were spatially assigned across the domain; a single crop type was uniformly applied across the catchment. The groundwater system was conceptualised as a two layer aquifer system.

Figures 7 and 8 show the simulated and observed hydrographs for two bores, one in soil group #3 (high permeability) the other in soil group #1 (low permeability).

A surface drainage network, constructed to intercept overland flow, is a feature of the study catchment. The width and depth of each drain is approximately 3m and 1.5m respectively. Figure 9 shows the simulated drain flow (m^3/day) relative to monthly observed spot data. Given the conceptual nature of the model, the simulated drain flow is in good agreement with the recorded field data.

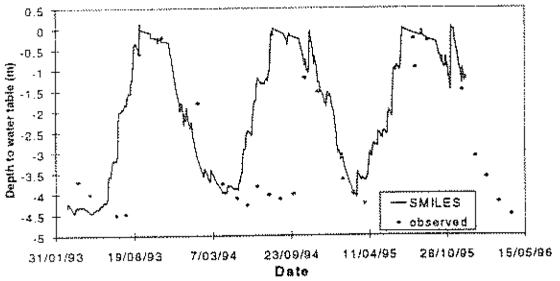

Figure 7 : Simulated hydrograph for bore 4504 (soil group #3) derived using SMILES relative to observed data.

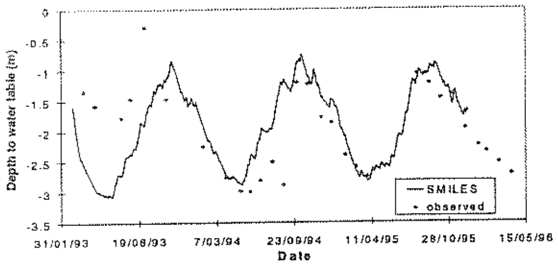

Figure 8 : Simulated hydrograph for bore 4524 (soil group #1) derived using SMILES relative to observed data.

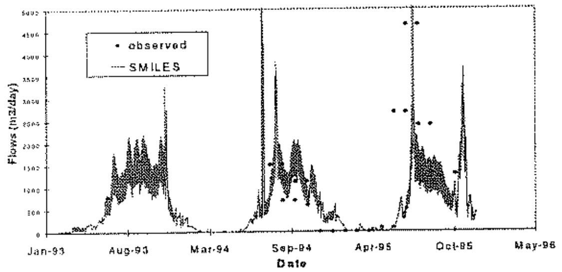

Figure 9 : Simulated drainage flows derived using SMILES relative to observed data.

Conclusions

The simplified unsaturated model presented in this paper offers a fast and robust coupled saturated/unsaturated fully distributed solution scheme The degree of process description is commensurate with data availability. The model is shown to adequately describe groundwater response, soil moisture dynamics and salt export from both irrigated and dryland catchments. The conceptualisation of the unsaturated processes is a component of a decision support framework for exploring the impact of policy and programs on irrigation futures over a 20 year time period (Fordham and Malafant 1997).

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