Construction of a Vertical Flux Model Manager for the Swan Coastal Plain

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Abstract: Perth relies on groundwater for 60% of its water supply. The demand for groundwater raises serious concerns for the competing users of the resource – the groundwater dependent natural ecosystems, pine plantations, irrigated horticulture, domestic bores, industry and public water supply. As an aid to management of the complex system the Water Corporation and the Water and Rivers Commission (now DEWCP – Department of Environment, Water and Catchment Protection) commissioned CSIRO Land and Water to develop a computer model to calculate recharge to the coastal aquifers. This recharge model is known as the Vertical Flux Model (VFM) Manager and forms a new package for MODFLOW. Because of the size of the domain (over 6000 km^2) and computational constraints, we have divided the domain into a number of Representative Recharge Units (RRUs). The RRUs are determined by soil, climate, land-use and watertable depth. There are a large number of possible RRU combinations, but only a few hundred are actually extant at any one time. Recharge is calculated on a daily basis for each existing RRU and accumulated for each MODFLOW stress period. The daily recharge is calculated by a number of models depending on land use. For pine plantations, native bushland and pasture, recharge is calculated by a detailed 1-dimensional biophysical model (WAVES). For urban areas, irrigated horticulture and watered parkland a simple model based on rainfall and potential evaporation is used. For each time step in the MODFLOW model a new watertable surface is determined. The depth to watertable is used by the VFM Manager to interpolate the recharge between the closest RRUs. Land use information, incorporating vegetation leaf area index (LAI), can be updated at each stress period if required. This enabled an investigation of the effects of natural events such as bushfires, and changes in land use on the distribution of recharge.

Keywords: *Recharge; MODFLOW; Modelling*

1. INTRODUCTION

The south-west of Western Australia is in a drought that has lasted now for 30 years. Average annual rainfall which for most of the 20th Century was around 850 mm, has fallen to around 800 mm over the last 30 years. More significantly, at the same time stream flow to dams has reduced by 40%. Since the mid 1970s the City of Perth has had an increasing reliance on groundwater to meet its supply, to the extent that it now depends on this resource for 60% of water use.

The primary groundwater source is a shallow unconfined aquifer in the surficial sands north of the City, known as the Gnangara Groundwater Mound. This water is used for domestic supply, irrigated horticulture, industry, by pine plantations and large areas of native bushland. With these competing demands and with the fall in rainfall, the watertable is falling under large areas of the Mound.

It is in this context that a new model has been developed to aid management of the Mound. This paper presents the design and creation of a new Vertical Flux Model (VFM) Manager for MODFLOW (McDonald & Harbaugh, 1988; Harbaugh & McDonald, 1996; Harbaugh *et al.*, 2000) developed for the Water Corporation of Western Australia for use with the Perth Regional Aquifer Model System (PRAMS). PRAMS is a MODFLOW model incorporating the unconfined and confined aquifers under the Perth region (Yu *et al*. 2002). The VFM Manager uses a number of models to calculate the recharge to the aquifer, including the unsaturated zone model WAVES (Zhang & Dawes, 1998; Dawes *et al.*, 1998).

2. BACKGROUND

A large part of the Perth Regional Aquifer Model System (PRAMS) is to estimate the recharge and discharge from the aquifer system. The Perth Urban Water Balance Study, known as PUWBS (Cargeeg *et al.*, 1987) used a number of algorithms to calculate the recharge and evapotranspiration through three layers in the unsaturated zone. These three layers were labelled:

1. Grass, for the top 1 m of the profile,
2. Trees, for the remainder of the root zone, and
3. Free for the layer below the root zone and above the watertable.

The recharge and evapotranspiration calculations depended on partitioning the surface into paved, roofed and tree canopy areas, with the remainder being grassed or bare ground. It was felt that although the PUWBS represented the recharge well in urban areas, as it was intended, in the surrounding vegetated areas there was insufficient detail. As this vegetated area surrounding the city is the subject of uncertainty in the competing demands for water between the city water supply and the water requirements of the flora and wetlands, a more detailed model was required. The most suitable model for this was chosen to be WAVES. WAVES is a 1-Dimensional biophysical model that simulates vertical water flow through soil and water uptake by vegetation. Developed by CSIRO WAVES is now in the public domain (Zhang & Dawes, 1998; Dawes *et al*., 1998).

3. MODEL DESCRIPTION

The new model is a combination of three components: the two existing models MODFLOW and WAVES, and the Vertical Flux Model (VFM) Manager, which is the interface between the MODFLOW model and a number of recharge models, of which WAVES is one. Each component is described in the following sections.

The VFM Manager provides a link between MODFLOW and a selection of recharge models. The VFM Manager replaces the functions of the two MODFLOW packages RCH and EVT. The VFM Manager manages the spatial selection of which recharge model to run in each cell of the model domain, data input to the recharge models, and passes the calculated recharge back to MODFLOW for each cell. The recharge models are run on daily time steps, with net recharge accumulated through a run covering each MODFLOW stress period (nominally 1 month, but could be any length). The total recharge is passed as a recharge rate to MODFLOW for each time step. The recharge model conditions at the end of each stress period are stored by the VFM Manager to be used as the initial conditions for the recharge calculations for the next stress period. Recharge passed to MODFLOW may be positive (downwards) or negative (indicating water uptake from the watertable).

The MODFLOW saturated zone model is run as usual, with the exception that some subprogram calls have been modified to use the VFM Manager, and to facilitate the passing of information to the VFM Manager.

4. REPRESENTATIVE RECHARGE UNITS (RRUS) FOR WAVES

Initially it was proposed to use a recharge model for each cell of the PRAMS. However it was clear that the time requirements using WAVES simulations for each cell in a single simulation would currently be prohibitive. Instead it was decided that a number of Representative Recharge Units (RRUs) be found that could reasonably simulate all the possible WAVES recharge regimes to the aquifer. The other recharge models are able to simulate each cell because they are only a few lines of code and hence take negligible time to run.

To create these RRUs for WAVES four important factors controlling the recharge and evapotranspiration were identified. These factors were:

1. Depth to the watertable,
2. Land use, which includes the type and density of vegetation,
3. Climate, and
4. Soil profile.

Also, in order to simplify the resulting WAVES simulations, it was decided that a number of WAVES options would not be used. The excluded options are solute (salt) transport, vegetation growth, grazing, and surface flooding. It was also decided that no understorey layer of vegetation would be used. These options may be available in later versions of the VFM Manager.

The RRUs are all referenced in the program and described by 8 digit codes, constructed from four 2-digit codes for each of the four attributes used in defining the RRUs. Each attribute has a two-digit code designation between 01 and 99 which is combined to give the RRU code of the form *WTLUCLSP*, where

1. *WT* is the two-digit code of the watertable,
2. *LU* is the two-digit code of the land use,
3. *CL* is the two-digit code of the climate zone, and
4. *SP* is the two-digit code for the soil profile.

As the last three of these attributes are fixed for each period according to the users input, it is convenient to describe a preliminary RRU or preRRU, which is a combination of the last three factors. This is represented by a six-digit code

LUCLSP. WAVES simulations are run for each preRRU at a predefined set of groundwater depths. The recharge for each cell is calculated from the set of WAVES simulations using the cell's preRRU based on the depth to the watertable in the cell.

The VFM Manager assembles the combinations of RRUs, determines and discards the combinations that do not occur within the model domain, and manages the choice of recharge model and input data for each stress period. For each period the conditions are re-assessed and if the land use, climate or soil profile has changed, then a new distribution of preRRUs and thus RRUs is developed prior to the next set of recharge calculations.

5. NON-WAVES RECHARGE MODELS

In some cells the use of the WAVES model is inappropriate. This may be because the watertable is above or close to the ground surface (e.g. lakes and wetlands) or because anthropogenic factors govern the recharge (e.g. market gardens, urban areas). For these areas two simple models are currently available. These models are selected by the user or automatically used when the watertable is close to the surface. Because WAVES uses a discretised soil profile, when the watertable is close to the surface, the number of nodes in the unsaturated zone can be small. This may cause large errors in the recharge calculated using the WAVES model. Therefore, when the watertable is at or above a user-specified depth below the ground surface, it is assumed that the lake or wetland recharge algorithm is applicable, and the WAVES model is replaced with one of the simple models described below. The distance below the ground surface at which this transition between models takes place is known as the WAVES watertable-to-lake depth. The default depth for this transition is 1.0 m.

The first model uses a constant multiplier for each of the rainfall and potential evaporation to calculate the recharge as shown:

$$R_{i,j} = RNMLT_{i,j} * RN_{i,j} - EVMLT_{i,j} * EV_{i,j} \quad (1)$$

where $R_{i,j}$ is the rate of recharge per unit surface area of watertable in cell i,j, $RNMLT_{i,j}$ is a non-dimensional multiplier for the rainfall in that cell, $RN_{i,j}$ is the rainfall per unit surface area per unit time; $EVMLT_{i,j}$ is the non-dimensional multiplier for the evaporation; and $EV_{i,j}$ is the potential evaporation per unit surface area per unit time.

The second model is slightly more complex. The model is based on a piece-wise linear relationship about two critical watertable depths. The uppermost critical watertable depth is the ground surface, and the lowest is a cut-off depth, below which the multipliers for the climate data are constant. This lower point corresponds to the extinction depth used in the evapotranspiration (EVT) module in MODFLOW. Between the two critical depths, the multiplier varies linearly. This is shown in (2) for the rain, (3) for the evapotranspiration, with the resultant recharge calculated using (4):

$h_{i,j,k} \geq hs_{i,j}$

$$RRN_{i,j} = RNMLTS_{i,j} * RN_{i,j} \quad (2a)$$

$h_{i,j,k} \leq hs_{i,j} - drnx_{i,j}$

$$RRN_{i,j} = RNMLTX_{i,j} * RN_{i,j} \quad (2b)$$

$hs_{i,j} - drnx_{i,j} < h_{i,j,k} < hs_{i,j}$

$$RRN_{i,j} = \left(\frac{\left(RNMLTX_{i,j} - RNMLTS_{i,j} \right)}{drnx_{i,j}} * \left(hs_{i,j} - h_{i,j,k} \right) \right) * RN_{i,j} \quad (2c)$$

$h_{i,j,k} \geq hs_{i,j}$

$$REV_{i,j} = EVMLTS_{i,j} * EV_{i,j} \quad (3a)$$

$h_{i,j,k} \leq hs_{i,j} - devx_{i,j}$

$$REV_{i,j} = EVMLTX_{i,j} * EV_{i,j} \quad (3b)$$

$hs_{i,j} - devx_{i,j} < h_{i,j,k} < hs_{i,j}$

$$REV_{i,j} = \left(\frac{\left(EVMLTX_{i,j} - EVMLTS_{i,j} \right)}{devx_{i,j}} * \left(hs_{i,j} - h_{i,j,k} \right) \right) * EV_{i,j} \quad (3c)$$

$$R_{i,j} = RRN_{i,j} - REV_{i,j} \quad (4)$$

where $RRN_{i,j}$ is the recharge per unit area per unit time associated with the rainfall in the cell i,j; $RNMLTS_{i,j}$ is the multiplier for rainfall when the watertable is at or above the ground surface; $drnx_{i,j}$ is the depth below the surface beneath which the rainfall is unaffected by the depth of the watertable (cut-off depth); $RNMLTX_{i,j}$ is the multiplier for the rainfall when the watertable is at or below the rainfall cut-off depth; $h_{i,j,k}$ is the watertable level; $hs_{i,j}$ is the ground surface level; $REV_{i,j}$ is the evapotranspiration per unit are per unit time associated with the evaporation; $EVMLTS_{i,j}$ is the multiplier for the evaporation when the watertable is at or above the ground surface; $devx_{i,j}$ is the cut-off depth below the surface beneath which the evapotranspiration is unaffected by the depth of the watertable; and $EVMLTX_{i,j}$ is the multiplier for the evaporation when the depth to groundwater is greater than the cut-off depth. Figure 1 shows the multiplier as a function of depth to watertable.

It is suggested that for evapotranspiration the multiplier (*EVMLTX*) is zero, indicating no evapotranspiration, at the cut-off depth, or is given a small value for dry soils where vapour transport moves some moisture away from the aquifer. A combination of a constant multiplier for one climate component and a linear relationship for the other is permitted.

6. CALCULATION OF RECHARGE

At the start of each MODFLOW stress period, the VFM Manager runs WAVES for each current RRU to calculate the cumulative recharge for the stress period. It also accumulates the rainfall and evaporation for each climate zone over the period. At the start of each MODFLOW time step within the stress period, the VFM Manager calculates the recharge for each cell using the appropriate model. The procedure used for calculating the recharge is shown in Figure 2. For a WAVES cell, the recharge is interpolated from the adjacent RRU watertable depths. For non-WAVES models, the cumulative rainfall and evaporation are used to calculate the cell recharge. Multiplying the recharge calculated using the method in Figure 2 by the time step and dividing by the stress period gives the total recharge for each cell in the time step.

7. CONCLUSIONS

The use of a dynamic unsaturated vertical flow model for recharge in conjunction with a MODFLOW model provides a better method for the evaluation of recharge. However the use of such a model was found to be computationally expensive. The reduction of the expense was found to occur if the recharge in cells could be amalgamated to a number of different distinct Representative Recharge Units based on depth to the watertable, the land use, the climate and the soil profile. The calculated recharge in an individual cell is found by interpolating between the individual RRUs based on the watertable. The use of such a dynamic recharge model allows antecedent conditions to be included within the unsaturated zone that provides a better estimate of recharge and evapotranspiration for a groundwater model.

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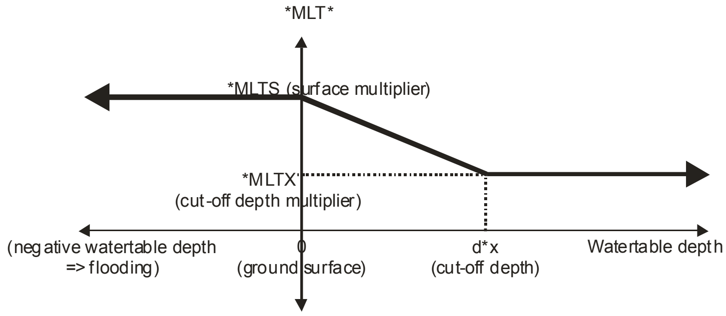

Figure 1 Illustration of relationship between multiplier and depth to watertable

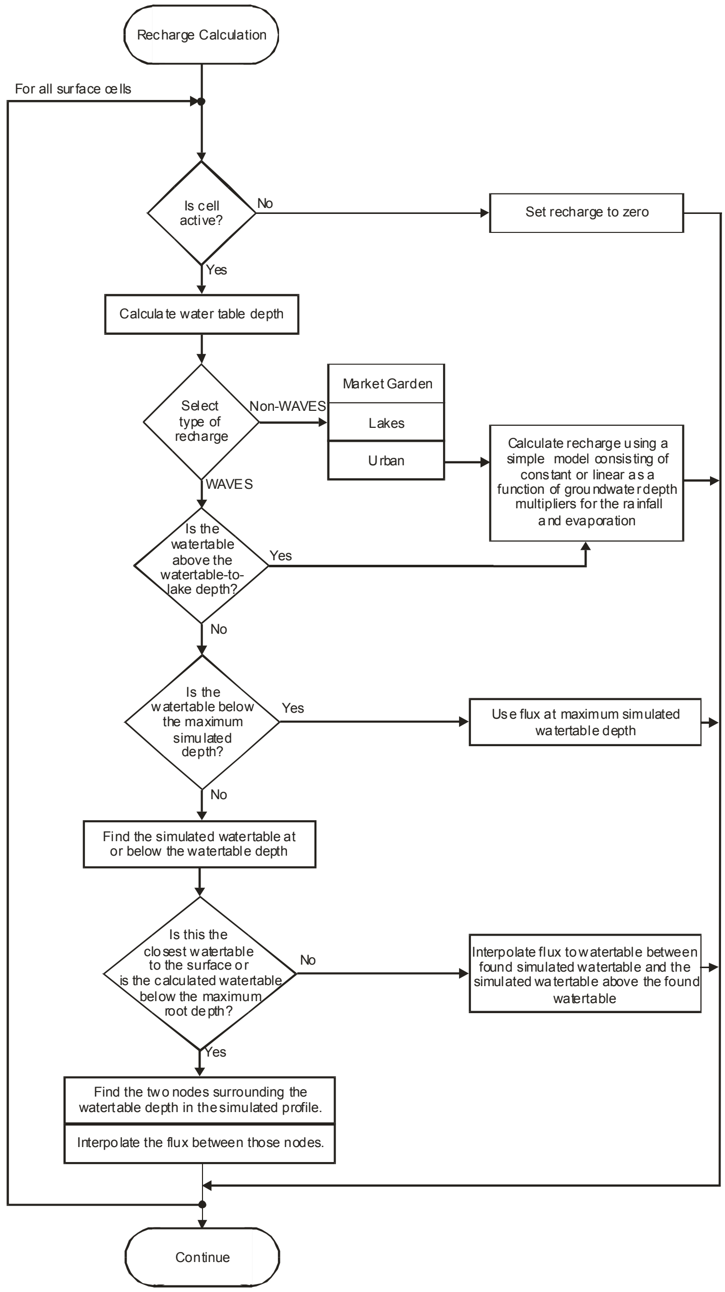

Figure 2 Recharge calculation flowchart in VFM Manager