Estimates of Groundwater Recharge beneath Banksia Woodland on the Swan Coastal Plain Using a Vertical Flux Model (WAVES): Sensitivity Analysis

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Abstract: To aid management of the regional groundwater system around the city of Perth, a new coupled unsaturated vertical flux and saturated 3-D groundwater flow model, based on MODFLOW has been developed. The Vertical Flux Model (VFM) used depends on land-use, but for pastured areas, pine plantations and native bushland is based on WAVES, a detailed biophysical model linking transpiration, and soil-water uptake to climate and soil conditions. Application of WAVES requires a number of parameters that characterise the vegetation and soil hydraulic properties, some of which can only be determined approximately. Uncertainty in the model input parameters would affect the accuracy of recharge estimates. This paper investigates the sensitivity of groundwater recharge estimates to a wide range of vegetation parameters, climate conditions and soil hydraulic properties. Sensitivity analysis indicates that estimated groundwater recharge is relatively sensitive to leaf area index (LAI), light extinction coefficient and the maximum rooting depth of the vegetation, soil water holding capacity and, of course, the rainfall.

Keywords: *WAVES, Groundwater recharge modelling, Sensitivity analysis*

1. INTRODUCTION

The Water Corporation, the Water and Rivers Commission and CSIRO, have developed a groundwater model for the Perth Region known as the Perth Region Aquifer Modelling System (PRAMS). The PRAMS model consists of two coupled components: a Vertical Flux Model (VFM) package which calculates the net recharge/discharge into/from the watertable (Barr et al., 2003) and a saturated groundwater model based on MODFLOW for flows in the multi-layer aquifer system below (Yu et al., 2002). The VFM package consists of a number of modules including a Recharge Manager and several recharge models for different land-uses with the key module being the WAVES model developed by CSIRO (Zhang and Dawes, 1998), which is used to estimate the recharge beneath pine plantation, banksia woodland and pastures and crops.

WAVES is a one-dimensional, daily time step model that simulates the fluxes of water and energy between the atmosphere, vegetation, and soil systems. It is a process-based model that couples these systems by modelling the interaction and feedback between them. WAVES uses an efficient numerical solution to solve Richards equation for unsaturated water flow. Daily transpiration is estimated by the Penman-Monteith equation and is extracted from the soil profile using weighting factors determined by the modelled root density and a normalised weighted sum of the matric and osmotic soil water potential of each layer. This model has been shown to simulate water dynamics and vegetation growth correctly for a wide variety and combinations of climate, soil and vegetation type (Zhang et al., 1996; Zhang et al., 1998).

The WAVES model requires inputs of daily climatic and watertable data, parameters that characterise the vegetation type and soil parameters describing the water holding capacity and hydraulic properties of soil layers. The performance of the model application will, to some extent, be dependent upon reliable estimates of these parameters. However, most of these data have to be measured from plot scale field measurements. Due to the spatial and temporal variability of the measured attributes, extrapolation of the point measurements to a regional scale may introduce large uncertainty. The uncertainty in the model parameters will result in inaccuracy in the modelling results. It is therefore important to understand how sensitive the estimate of groundwater recharge/discharge is to these model parameters so limited resources can be best directed to reduce the uncertainty of parameters that have a significant effect on the model results.

The varied land uses on the Swan Coastal Plan include native bush, pine plantation, urban, market garden horticulture and pasture grazing. The Gnangara groundwater mound, located north of Perth is a major groundwater resource for public and private water supply. The two major land-uses over much of the mound are banksia woodland and pine plantations. This paper describes the application of WAVES to estimate groundwater recharge under native banksia woodland in the Swan Coastal Plain in Perth, Western Australia, and explores the sensitivity of the groundwater recharge estimates to the model input parameters.

2. SENSITIVITY EXPERIMENTS

The effect of the variation of a particular model parameter on the groundwater recharge is examined by repeatedly running the model over the 20 year period with the value of a single parameter altered while holding all other parameters constant. For comparison purposes, percentage of rainfall that becomes recharge over the simulation period is used to assess the sensitivity.

2.1. Climate

Daily meteorological data [Point Patched Data (PPD) from SILO] for the period 1978 to 1997 at the Perth Region Office (Station 9023) were used to drive the model simulations. The climate in Perth can be characterised as Mediterranean with mild wet winters and hot dry summers. About 90% of the rain falls between April and October. The long-term average rainfall for Perth is 870 mm/yr but rainfall over last thirty years has reduced significantly due to climate variability. The mean annual rainfall during 1978-1997 is about 805 mm/yr and class ‘A’ Pan evaporation for the same period is about 1760 mm/yr.

2.2. Soil Characteristics

A typical soil profile for Bassendean sand is used for this study, which is defined by three soil layers: two top soils and one subsoil (Table 1). The soil hydraulic properties were derived from data in Salama et al. (1999) for the topsoil and recent data in Vermooten (2002) and Smettem (2002) for the subsoil. These data show that the Bassendean sand has very little water holding capacity and has very high saturated hydraulic conductivity. In this study, a value of 15 m/d is used to be consistent with the average hydraulic conductivity of the regional aquifer. Campbell’s soil hydraulic model has been fit to the field data to generate soil retention functions for the model (Table 1).

2.3. Vegetation

The plant growth component of WAVES is inactive for the current implementation of the VFM, and so the rooting density with depth and the leaf area index (LAI) of the vegetation were predetermined as defined model inputs. For banksia woodlands, the rooting density used decays logarithmically to a maximum rooting depth. Traditionally models of root function have often used an exponential decaying function with depth (e.g. Gardner, 1991), however we found this to limit the native banksia’s access to deeper groundwater, particularly in times of drought. The logarithmic function instead attempts to mimic the drought-tolerant nature of the native vegetation, which is considered to have the ability to extract water more evenly from soil profile. Confirmation, or otherwise, of this behaviour will be tested as part of a field measurement campaign. Work presented in this paper assumes leaf area index as a constant throughout the simulation period. The most critical vegetation parameters are discussed in Section 3.5.

3. SENSITIVITY ANALYSIS

3.1. Rainfall

To evaluate the groundwater recharge response to a wide range of rainfall scenarios, a 20 year dry climate sequence with a mean annual rainfall of 650 mm/yr and a 20 year wet climate sequence with a mean annual rainfall of 900 mm/yr were synthesised by scaling the historical rainfall. These climatic datasets were then used to drive the model simulations. Depths to watertable on the Swan Coastal Plain vary from zero to over 50 m but results from only two depths to watertable are presented here, 6 and 15 m being within and just below the natural rooting depth of the banksia. Simulation results indicate that there is a strong relationship between the rainfall and recharge (Figure 1). For a shallow depth (6 m) to watertable, the annual groundwater recharge (GR) correlates strongly with the annual rainfall (R) (GR= 0.801R-440 with r^2=0.90).

Table 1. Soil profile, soil hydraulic properties and fitted Campbell model parameters

Soil layer	Depth (m)	K_s (m/d)	θ_s*	b	ψ_e (m)
Topsoil A	0-0.15	1.63	0.38	0.9	-0.12
Topsoil B	0.15-0.5	3.59	0.35	0.8	-0.15
Subsoil C	0.5-30	15	0.33	0.9	-0.12

θ_s is effective saturated moisture content, b is Campbell’s shape parameter, and Ψ_e the pressure potential at air entry.

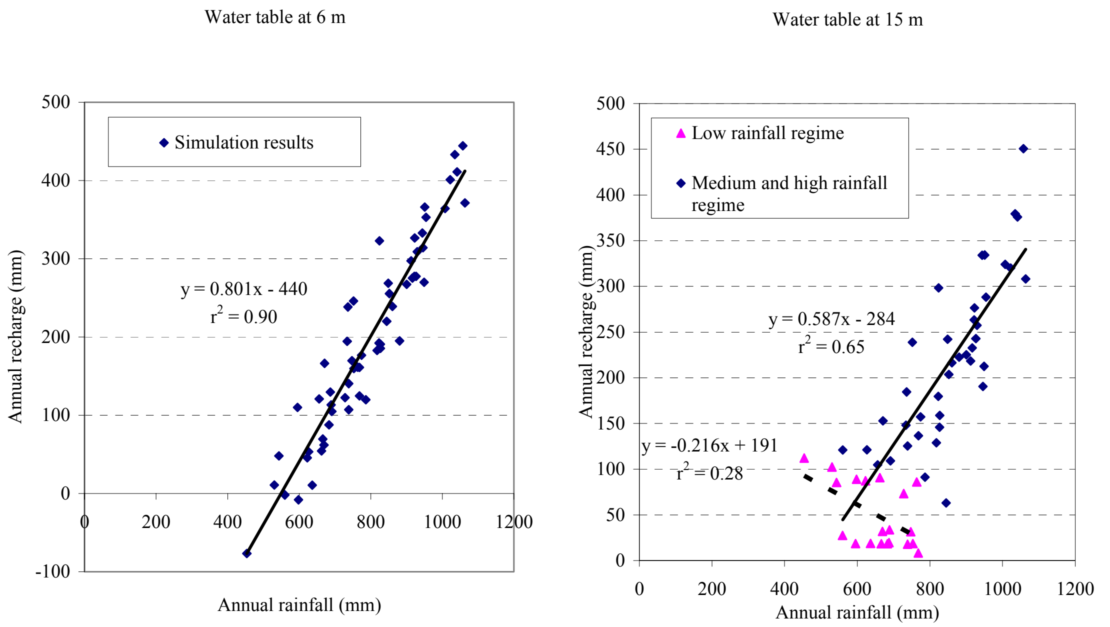


Figure 1. Relationship between annual recharge and rainfall for shallow (6 m) and deep (15 m) watertables.

The linear function indicates that there will be no net annual groundwater recharge, but rather net discharge by vegetation uptake, when annual rainfall falls below the x-axis intercept at 550 mm. When the watertable is deeper (15 m), the annual recharge has a good correlation with the annual rainfall only in the high rainfall regime (GR=0.587R-284 with r^2=0.65). For the low rainfall regime, it seems that there is no direct relationship between the annual rainfall and recharge (GR=-0.216R+190 with R^2=0.28). Close examination of the modelling results, however, revealed that this poor correlation for the low rainfall regime may be due to the fact that wet fronts move very slowly through a very dry soil profile causing significant delay for recharge reaching the watertable. The annual recharge in any particular year may be related to the rainfall in the previous years and hence long term average recharge is a more appropriate measure of the recharge response to rainfall. Although not shown, when collated into long-term totals the mean annual recharge is strongly correlated to the mean annual rainfall (GR=0.858R-510 with r^2=0.999). It should be noted that the above results were obtained with a fixed LAI. Under natural conditions, it is expected that vegetation will respond to the availability of water by changing the LAI, hence the recharge and rainfall relationship may also change.

3.2. LAI and Depth to Watertable

Recharge is clearly very sensitive to the variation in the leaf area index LAI regardless of the depth to watertable (Figure 2), although the magnitude of the effect clearly depends on depth to water. An increase in LAI will reduce the groundwater recharge, because it will result in a higher transpiration rate and increase in interception by the canopy, thereby reducing the amount of the rainfall available for infiltration into the soil. Recharge could become negative as LAI increases, which means that the vegetation is extracting more groundwater from the roots tapping into the capillary fringe than rainfall reaching the watertable.

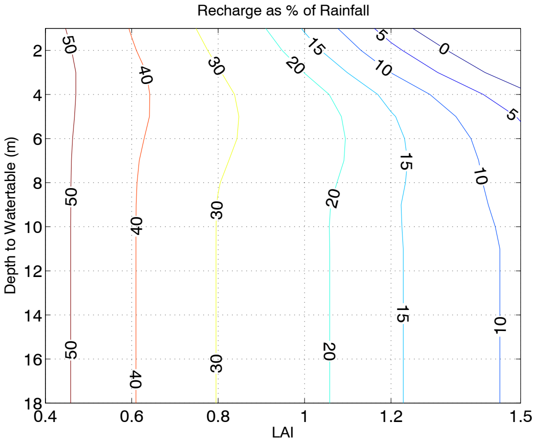


Figure 2. Recharge vs LAI and depth to watertable for a mean annual rainfall of 805 mm.

The sensitivity of recharge to the depth to the watertable varies depending on the level of LAI. For low LAI, the recharge is insensitive to the depth to watertable because the rainfall and soil water are sufficient to meet the transpiration demand and hence vegetation will not use much of the groundwater even when it is very shallow. As LAI increases, the groundwater recharge become increasingly sensitive to the depth to watertable particularly when depth to watertable is shallow (<6 m).

Note that several curves show recharge increases initially as the depth to watertable increases, peaks at a depth that varies with level of vegetation density and then reduces slightly thereafter. While this behaviour appears counter-intuitive since one may expect the vegetation will transpire more water when it is able to tap into the capillary fringe, it is a result of the combination of water extraction distribution by roots, rate of wetting front infiltration, timing of infiltration events and depth to the watertable. Field work is currently being undertaken to explore this issue.

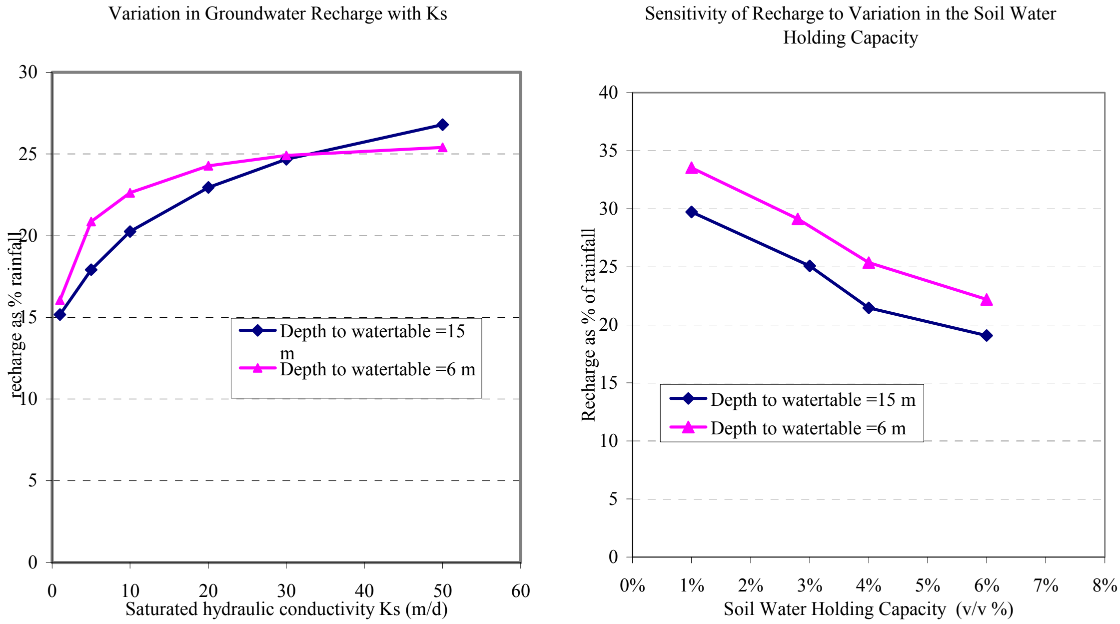
3.3. Soil Hydraulic Properties

The sensitivity of groundwater recharge to two key soil parameters, the saturated hydraulic conductivity K_s and soil water holding capacity, were examined. Modelling results indicate that groundwater recharge is relatively insensitive to change in the two topsoil layers, largely because together they make up only 0.5 m of a 6 or 15 m unsaturated profile. Also, we have better measurements of these layers than the rest of the profile. Results are therefore presented for the sensitivity of recharge to the variation of K_s and soil water holding capacity in the subsoil only.

Increase in saturated hydraulic conductivity (Ks) of the subsoil results in increased groundwater recharge (Figure 3). This is because the more permeable soil profile will enable the wetting front to move downward more rapidly and pass below the root zone. The relationship between the recharge and Ks is non-linear particularly at the low end of Ks, although it tends to linearity and becomes less sensitive to Ks at the higher values. Groundwater recharge reduces gradually as the soil water holding capacity increases. This is expected since increase in soil water holding capacity will increase the amount of rainfall stored in the water profile during the rain season in winter, which is later available for vegetation to use for transpiration in summer. It should be noted that the relationship between recharge and K_s cannot be divorced from the hydraulic model chosen to represent the soil (see Table 1.). The critical conductivity is that at field capacity because very little of the soil profile remains above field capacity for any length of time. Since we lack data on unsaturated conductivity, we can effectively represent the rate of wetting front infiltration with a number of different soil models.

3.4. Maximum Rooting Depth and Rooting Distribution

While increasing the rooting depth decreases the amount of groundwater recharge (Figure 4), the relationship between recharge and maximum rooting depth is non-linear with the effects being much more pronounced when maximum rooting depth is less then 12 m. Recharge becomes insensitive to the maximum root depth when the rooting depth is over 15 m.


Variation in Groundwater Recharge with Ks

Sensitivity of Recharge to Variation in the Soil Water Holding Capacity

Figure 3. Sensitivity of recharge to variation of saturated hydraulic conductivity (Ks) and to soil water holding capacity in the subsoil.

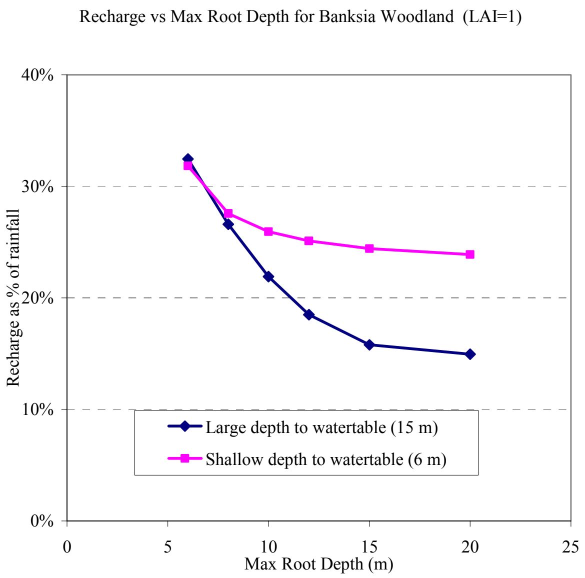


Figure 4. Sensitivity of recharge to maximum root depth and depth to watertable.

Recharge is also moderately sensitive to the rooting distribution within the soil profile. Table 2 illustrates effects on recharge of three rooting patterns that decay linearly, exponentially and logarithmically to a maximum rooting depth of 10 m. Recharge is greatest for an exponential and least for the logarithmic root distribution, with the linear distribution between these two. This is expected because the rooting pattern with logarithmical distribution has roots more evenly distributed throughout the soil profile, which enables the vegetation to extract more soil water in the lower part of the soil profile. The difference in recharge between the two watertable depths occurs because the maximum root depth given in the model adjusts the distribution of root water uptake, and therefore modifies how much water is taken from the capillary fringe above the watertable.

3.5. Other Vegetation Parameters

The sensitivity of recharge to the relevant vegetation parameters listed in Table 3 was examined by increasing each parameter by 10% while keeping other parameters constant. Percentage change in recharge compared with the "reference" recharge value is used to measure the sensitivity. Results are similar under large and shallow depths to watertable so only results for large depth to watertable is presented in Table 3. In order to compare relative sensitivity of model parameters, some of the parameters already discussed are also included here.

The groundwater recharge estimate is relatively insensitive to most of the vegetation parameters, and only those with significant impacts are listed. Interestingly, the impact of litter was very small. The most sensitive parameter is LAI, followed by the light extinction coefficient. Decreasing the light extinction coefficient by 10% will increase the vegetation transpiration and hence reduce the recharge by similar percentage. Light extinction coefficient depends on the leaf characteristics and on the geometry of radiation scattering with respect to the architecture of canopy and can be determined by measuring the attenuation of radiation in a plant canopy. Recharge is also sensitive to the maximum rooting depth, maximum carbon assimilation rate, slope of the conductance. For the soil properties, the groundwater recharge is not very sensitive to the change in the saturated hydraulic conductivity but is moderately sensitive to the soil water holding capacity. The information presented in Table 3 can be used to direct efforts on future data collection for further model improvement.

Table 2. Effect on recharge of rooting patterns.

Depth to watertable (m)	Recharge as % Rainfall for Different Rooting Distributions		
	Exponential	Linear	Logarithmic
6 m	30.8%	27.0%	25.9%
15 m	27.6%	23.6%	21.9%

Table 3. Sensitivity of recharge to a list of model parameters.

Model parameters	Units	Value	Change by 10%	% change in recharge
Rainfall interception	m day^{-1} LAI^{-1}	0.0007	0.00077	-2.9%
Light extinction coefficient	-	-0.45	-0.495	-12.2%
Max carbon assimilation rate	kg(C) m^{-2}day^{-1}	0.022	0.0242	-6.5%
Slope of the conductance	-	0.9	0.99	-6.5%
Max rooting depth	m	10	11	-7.7%
LAI	-	1	1.1	-14.2%
Litter	kg m^{-2}	0.05	0.055	-0.5%
Ks	m day^{-1}	15	16.5	1.6%
Soil holding capacity	(v/v %)	0.03	0.033	-4.1%

4. CONCLUSIONS

We have presented a sensitivity analysis of the biophysical vertical flux model WAVES, examining the resulting recharge with different depths to watertable, leaf area indices, soil hydraulic characteristics, and climates. The sensitivity analysis found that in the long term mean annual groundwater recharge is strongly correlated with the mean annual rainfall, despite individual years showing significant discrepancies. Where the depth to watertable is shallow, annual recharge is correlated well with annual rainfall. However, where the depth to watertable is large, the correlation between the annual rainfall and annual recharge is very poor due to the delay in the recharge response. Sensitivity analysis indicates that estimates of groundwater recharge are very sensitive to LAI, light extinction coefficient and the maximum rooting depth of the vegetation and moderately sensitive to vegetation parameters of maximum carbon assimilation rate, slope of the conductance, rainfall interception and the soil holding water capacity.

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