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ABSTRACT

"Soil-Water-Atmosphere-Plant (SWAP)" model was used to investigate the effect of land use and climate change on groundwater recharge in the Gnangara Groundwater System, Perth, Western Australia. The hydrological and meteorological data (1992-2012) were collected from Bureau of Meteorology and Department of Water, Government of Western Australia. Six different land use scenarios were identified in the spatial map of the area and the results suggest a decline in groundwater recharge under all scenarios. The results revealed that the groundwater recharge is greatly affected by annual rainfall, vegetation and soil hydraulic properties. The rooting depth and leaf area index have significant impact on groundwater recharge. But plant transpiration was found as the major limiting factor for groundwater recharge. Results further showed a non-linear relationship between rainfall and recharge because of non-linearity among other factors such as, weather, soil and crop data.

KEY WORDS: Groundwater recharge; Soil-water; Land-use; Rainfall.

INTRODUCTION

Climate change, and its effect on temperature and rainfall, is an important factor contributing to the change in groundwater recharge. Changes in temperature and precipitation alter groundwater recharge and cause shifts in water tables as a first response to climate change (Changnon et al., 1988 and Zektser and Loaiciga, 1993; IPCC, 2007; Nicholls et al., 1997; Stanley et al., 1988). Groundwater recharge is a vital element in the water cycle, and thus the factors affecting groundwater are of high importance. About three quarters of all water used in the south-western Australia is from groundwater (Ali et al., 2012). The Gnangara Groundwater System (GGS), located in the southwest region of Western Australia covering an approximate area of 214896 ha, is the main source of drinking water supply for Perth, providing about 165 GL a year for residential and commercial use (Tapsuwan et al., 2009). Land usage in GGS consists of 69000 ha of native woodlands, 22000 ha of commercial pine plantation, 37174 ha of urban land (with another 3569 ha for future urban expansion) and 4395 ha of agricultural and horticultural land (Ranjan et al., 2009).

The continuing drier conditions, extraction of groundwater for public and private purposes, and reduced recharge has resulted in groundwater storages in the upper and mid parts of the GGS declining by about 45 GL per year since late 1990s (Dawes et al., 2012). Rapid economic development has resulted in total water use rising dramatically. Since 1963, Perth's population has grown from 590,200 to 1.7 million, with projections indicating that the city's population will increase to 2.45 million by 2031, 2.82 million by 2041, and 3.1 million by 2051 (WAPC 2013). With the increase of population in Perth, it is forecasted that GGS will have increase in water demand in future. In order to assess the groundwater recharge, several groundwater models have been used in the past such as, WAVES (Ali et al., 2012), HELP3 (Jyrkama and Sykes, 2007), SWAT (Eckhardt and Ulbrich, 2003), HUMUS (Rosenberg et al., 1999), MODFLOW (Xu et al., 2012) and SWAP (Anuraga et al., 2006). This study will use SWAP (a hydrologic model: Soil-Water-Atmosphere-Plant) to investigate the effect of land use and climatic factors on groundwater recharge in GGS for 1992-2012.

METHODOLOGY

In this study, the hydrologic model Soil-Water-Atmosphere-Plant (SWAP) model was used to estimate the groundwater recharge. SWAP simulates transport of water, solutes and heat in the vadose zone incorporating land-use and climatic data using Richard's equation (van Dam et al., 2008). The Mualem-Van Genuchten function was used for determining hydraulic conductivity in SWAP (Mualem, 1976; van Genuchten, 1980). The SWAP was chosen in this study because of the availability of data such as daily rainfall, soil properties, drainage and vegetation. Meteorological data was collected from the weather station of Bureau of Meteorology located at Perth Airport (station ID 009021) for 1992-2012. This weather station was chosen due to its close proximity to the study area and completeness for all parameters compared to other stations nearby. The SWAP is a one-dimensional, vertical directed model conceptualized as a single soil column. Upper boundary is represented by the atmosphere and vegetation, and the lower boundary is represented by different soil types. In order to show the impacts of climate change and land use on GGS, six scenarios were considered based on the land-use pattern, leaf area index (LAI) and rooting depth as shown in Table 1. Detail description and local distribution of Banksia and Pine plantation can be found in FloraBase (2016a, 2016b) and UBC (2016).

The SWAP model was developed using catchment hydrological and meteorological data and calibrated with the observed groundwater level data of GGS. The observed available groundwater level data was collected from the Department of Water, Western Australia for 8 years. The calibration of SWAP model is shown in Fig. 1.

RESULTS AND DISCUSSION

Interception

Interception is an important factor in the hydrologic cycle as it largely influences the amount of precipitation that reaches the ground surface. The interception results for each scenario are shown in Fig. 2. The simulation of the pine plantation land use resulted in the greatest interception, with an annual average of 179.5mm and 208.5mm (25.6% and 29.7% of the annual average rainfall) for the low density and high density plantations respectively. This is due to the large LAI for the pines resulting in a large canopy. The native vegetation land use resulted in a lower interception with an annual average of 69.4mm and 101.7mm (9.9% and 14.5% of the annual average rainfall) for the low density and medium density banksia woodlands respectively. The interception in the agriculture land use simulated an annual average of 40.5mm of precipitation (5.7% of the annual average rainfall) for the pasture.

Table 1. Land Use Scenarios

Scenario	Land Use Category	Description	LAI	Rooting Depth (m)	Soil type
1	Native Vegetation	Banksia – Low Density	1.00	8.00	Bassendean
2	Native Vegetation	Banksia – Med Density	1.50	8.00	Bassendean
3	Pine Plantation	Pine – Med Density	2.00	10.00	Spearwood
4	Pine Plantation	Pine – High Density	2.50	10.00	Spearwood
5	Agriculture	Pasture	1.00	0.50	Guildford
6	Urban	Soak well/ Basin	N/A	N/A	Spearwood

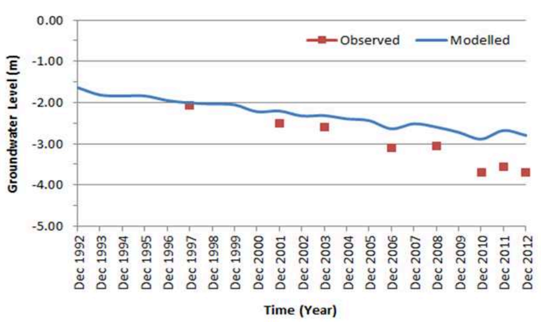

Fig. 1 Calibration of SWAP model

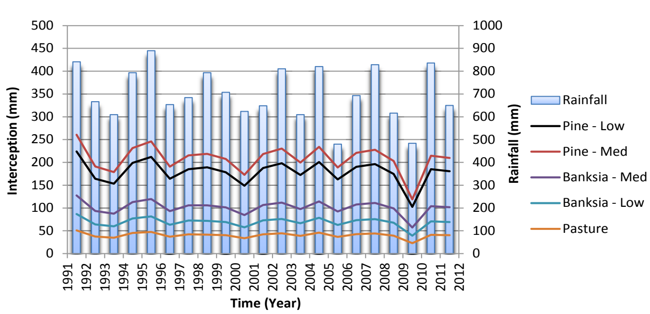

Fig. 2 Annual rainfall and interception for different scenarios

Transpiration

Often transpiration is expressed combined with evaporation as evapotranspiration. This process is a part of the water cycle as it is the process by which moisture is carried through plants from roots to small pores on the underside of leaves, stems, flowers and roots, where it changes to vapour and is released to the atmosphere. The measurement of transpiration is hard and it varies with local hydrological situations. SWAP takes basic weather data as input and simulates transpiration using Penman-Monteith equation shown in Fig. 3 for all scenarios. The highest transpiration was found in the agriculture land use with an annual average of 439.7mm (62.7% of the annual average rainfall) for the pasture. The native vegetation had an average of 404.2mm and 418.3mm (57.6% and 59.6% of the annual average rainfall) of transpiration for the low density and medium density banksia woodlands respectively. The pine plantation has the least amount of transpiration of 381.8mm and 393.9mm (54.4% and 56.2% of the annual average rainfall) for the low density and medium density plantations respectively.

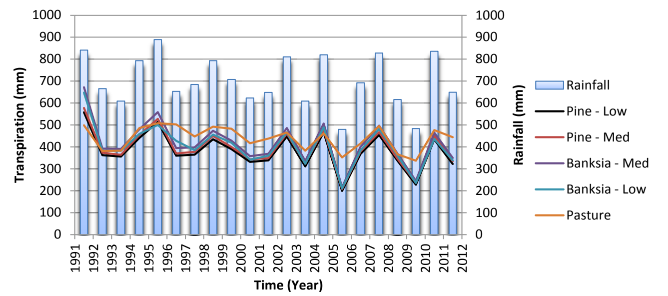

Fig. 3 Annual rainfall and transpiration for different scenarios

Evaporation

Soil evaporation is a term of major loss in water balance. Most cases, this water balance parameter is combined with plant transpiration as evapotranspiration (ET). But SWAP treats evaporation and transpiration separately in the simulation because of difference in the physical behavior of these parameters. Soil evaporation results found in SWAP are shown in Fig. 4.

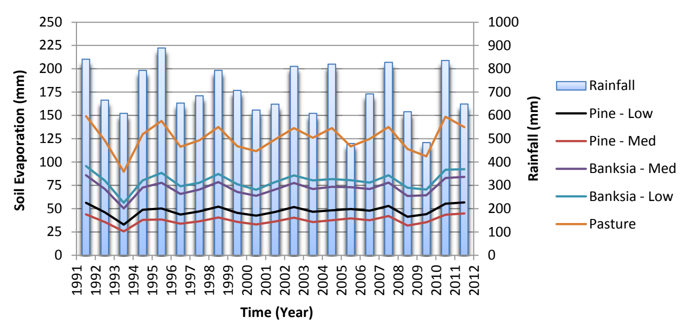

Fig. 4 Annual rainfall and soil evaporation for different land use pattern

The greatest soil evaporation was found from the agriculture land use with an average of 126.2mm (18.0% of the annual average rainfall) for the pasture. This is because of larger amount of soil reaching the ground surface due to low LAI. This region also contains more clayey soil (Guildford Clay) with a relatively lower hydraulic conductivity compared to the soil in the pine plantation and native vegetation land use, causing slower percolation thus more chance of the soil to be evaporated. The lower LAI also means more direct solar radiation will hit the ground surface thereby increasing soil evaporation. The native vegetation land use had an average evaporation of 80.2mm and 72.1mm (11.4% and 10.3% of the annual average rainfall) for low density and medium density banksia woodlands respectively. Whereas the pine plantation land use had an average of 47.9mm (6.8% of the annual average rainfall) of evaporation for the low density pine plantation, and an average of 37.5mm (5.3% of the annual average rainfall) for the medium density pine plantation respectively.

Groundwater Recharge

Groundwater recharge levels for each scenario are shown in Fig. 5. The average annual recharge was 65.9mm (9.4% of average annual rainfall) and 16.1mm (2.3% of the average annual rainfall) for the low and medium density pine plantations respectively. In both scenarios, the groundwater recharge levels show a gradual decline throughout the study period, although a much more pronounced decline is evident in the low density scenario. The results suggest that groundwater recharge under the pine plantation scenario is relatively low and also that the density of the plantation is a large factor in the total recharge and the decline of recharge. The reason for lower recharge rates under the pine plantation is due to the soil hydraulic characteristics, the rooting depth of pines, and the depth to water table. The large rooting depth of the pines (10m) means the pines can extract large amounts of groundwater for fulfilling its water requirements. The larger LAI of pine plantation also contributes to the low recharge. Less precipitation ultimately reached the ground due to the high interception and transpiration.

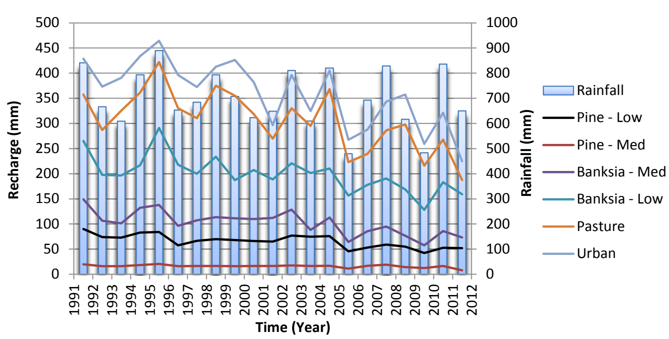

Fig. 5 Groundwater recharge for different land use scenarios

The recharge from native vegetation scenario produced an annual average recharge of 199.9mm (28.5% of annual rainfall) and 102.1mm (14.6% of annual rainfall) for the low and medium density banksia woodlands respectively. The results suggest a decline in the recharge from 1992 to 2005, with a further reduction evident from 2006 to 2012. The lower rainfall in 2006 (479.6mm) and 2010 (483.4mm) have significant effect on the decline of groundwater recharge. Results also suggest that the banksia woodlands are more sensitive to a lower rainfall than pine plantations with a greater decline. Recharge is higher in the banksia woodlands due to lower LAI and shallower rooting depth (8m). More precipitation reaches the ground surface thereby increasing the potential for a greater recharge. A shallower rooting depth of banksia means they are not able to extract as much water as pines; but they still extract groundwater.

Results for the agriculture land use scenario showed an average annual recharge of 305.9mm (43.6% of the annual average rainfall). Results show similar pattern of decline of groundwater recharge with respect to relatively drier year such as 2006 and 2010. As stated earlier, the vegetation under pastures and agricultural fields use lesser water compared to deep rooted trees (Ali et al., 2012). This is shown by the larger amount of recharge experienced under the agriculture land use scenario compared to that of pine plantation and native vegetation. The shallow rooting depth of pasture (0.5m) means the ability to extract groundwater is greatly reduced even though the depth to the water table is shorter than pine or banksia woodlands. The shallow rooting depth also negated the effect that the clayey soil profile had on the recharge.

The simulated results under the urban scenario showed an average annual recharge of 360.2mm (51.4% of the annual average rainfall). The reduction of recharge was not prominent as found in other land use scenarios. This was because of the collection method of urban rainfall. Rainfall input data for urban scenario was taken as the run-off from impervious surfaces such as roofs and roads that flow into soakwells, sumps or storm infiltration basins, acting as point sources. This means that the interception, transpiration and soil evaporation was zero as the water passed through pipes and deposited directly into the soil. Changes in the soil hydraulic characteristics therefore have relatively less impact on recharge in this scenario.

CONCLUSIONS

The effect of ago-climatic factors was investigated for GGS using SWAP model. The model was calibrated for groundwater level data. Six different scenarios were considered based on different land use pattern in the study area. The results revealed that groundwater recharge is decreasing under all land use scenarios with the greatest reduction in agriculture land and urban scenarios. Results also suggest that the rooting depth and LAI have significant impact on the overall groundwater recharge. The smallest recharge was found for the medium pine plantations. The pines cover a total area of 22000 ha of GGS (10.24% of the land) and situated in the central part of the mound where the main superficial aquifer is located. This has greater influence on the overall groundwater recharge in the area because pine plants have greater interception, transpiration and/or soil evaporation. However, the model results might have some degree of uncertainties because of SAWP one-dimensional nature and simplification of land use pattern in the study area.

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