GROUNDWATER RECHARGE: ACCURATELY REPRESENTING EVAPOTRANSPIRATION

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Abstract

Groundwater recharge is the basis for accurate estimation of groundwater resources, for determining the modes of water allocation and groundwater resource susceptibility to climate change. Accurate estimations of groundwater recharge with models depend on the accuracy of the input data used. The accurate estimation of evapotranspiration (ET) is often negated in recharge quantification techniques. In this study a field trial was established at a site which exhibits groundwater recharge through vertical fluxes in the soil profile (Riverlands Nature Reserve in the Western Cape). The main aim of this investigation is to develop improved process-based estimates of groundwater recharge by accurately quantifying the ET component using scintillometry. The HYDRUS-2D model applies the Feddes method to calculate reduced actual ET due to water stress. Groundwater recharge quantified with HYDRUS-2D exhibited sensitivity to the vegetation factor used to quantify actual ET from the potential ET. Recharge during the simulation period was simulated to be 85 mm (vegetation factor of 1.5) and 220 mm (vegetation factor of 0.69). The results also indicate that recharge mainly occurred between the months of May to August corresponding to the main rainfall season in the Western Cape. In summer groundwater levels declined due to capillary processes, considerably contributing to actual ET. The calculation of actual ET using crop factors should however be used with caution in non-uniform systems of vegetation. The preliminary results from this investigation however highlights the need for the incorporation of accurate and representative actual ET estimation methods in groundwater recharge estimation methods. It is envisaged that the methodology applied and the results from this investigation may be applicable to similar physiographic environments.

1. INTRODUCTION

The quantification of groundwater resources is of utmost importance for possible future water allocations, taking into account the legal requirements of ensuring the reserve and associated water quality. To this effect a study was commissioned by the Department of Water Affairs and Forestry (DWAF), i.e. Groundwater Resource Assessment (GRA) II, which was published in 2005. This study aimed to quantify the groundwater resources of South Africa at a national scale. Results were based on the quantification of a static storage zone (volume of groundwater available in the permeable portion of the aquifer below the zone of natural groundwater level fluctuation) and dynamic storage zone (volume of groundwater available in the zone of natural groundwater level fluctuation). The key parameter of the dynamic storage zone that determines natural groundwater replenishment and level fluctuations is groundwater recharge. This physical parameter is the basis for the accurate quantification of groundwater resources, for determining the modes of water allocation and groundwater resource susceptibility to climate change.

Several methods for the estimation of groundwater recharge were applied in the past, which exhibit varying degrees of success. Xu and Beekman (2003) reviewed commonly used recharge estimation methods in southern Africa. The methods range from direct estimates with lysimetry and soil water fluxes to indirect estimates such as water balance equations and tracer investigations. Meyer (2005) used time series analysis of groundwater levels to derive estimates of groundwater recharge/discharge. Bredenkamp *et al*. (1995) used the chloride mass balance method to estimate recharge. Most of the groundwater recharge estimation methodologies are applicable at the large scale and in certain cases these ignore the influence of local scale processes.

There is a large degree of variability and consequently uncertainty, associated with reported groundwater recharge values. For example, various studies within the same physiographic area, e.g. quaternary catchment G21D in the Western Cape, have yielded strikingly different recharge estimates. Groundwater recharge in quaternary catchment G21D is estimated to be 81 mm a^{-1} (Vegter, 1995). Bredenkamp and Vandoolaeghe (1982) estimated groundwater recharge in the Atlantis area (approximately 20 km from Riverlands), using a mass balance approach to be 25% of mean annual precipitation (MAP, 390 mm), i.e. 97 mm. DWAF (2006) estimated recharge in quaternary catchment G21D to be 15.4% of MAP (450 mm), i.e. 69 mm, using a chloride mass balance approach. DWAF (2006) also applied a generic, GIS based, groundwater recharge algorithm and estimated recharge in G21D to be 23.56 mm a^{-1} or 5% of MAP. Woodford (2007) estimated groundwater recharge in the vicinity of Riverlands to be 13 % of MAP (603 mm), i.e. 78 mm.

The successful prediction of groundwater recharge with models depends on the accuracy of the input data used and the correct representation of the system. For example, uncertainties still exist in the estimation of the actual evapotranspiration (ET) component that would account for below/above-potential water use by vegetation and consequently affect recharge estimates. For this reason, a study funded by the Water Research Commission (WRC), was initiated in 2009 (completion in 2012). The general aim of this investigation is to illustrate the effect ET on groundwater recharge. ET was quantified using scintillometry, which measures the total evaporation (the sum of evaporation from the soil surface, transpiration by vegetation, and evaporation of water intercepted by vegetation) over distances of 400 to 5 000 m. This ET data served as input data to a process based model (HYDRUS-2D) which was used to evaluate the effects on groundwater recharge. It is envisaged that the methodology applied and results from this investigation may be applicable to similar physiographic environments.

2. METHODOLOGY

Experimental Site

The experimental site was chosen based on the expected mechanism of groundwater recharge and the potential to extrapolate the applied methodology and results to similar environments. The Riverlands Nature Reserve, which is managed by Cape Nature Conservation, is located approximately 10 km South of the town of Malmesbury (Western Cape) and within the boundaries of quaternary catchment G21D. At this site groundwater recharge is characterized by pre-dominantly vertical fluxes in the unsaturated zone. This mechanism occurs typically in coastal plain sandy aquifers, dominated by light-textured soils and shallow groundwater tables, which exhibit seasonal fluctuations. These characteristics are interpreted to be representative of the West Coast and Cape Flats sandy aquifers. The reserve is situated on Cenozoic deposits (deep, well-leached and coarse sandy soils) with Cape granite outcrops occurring in the surroundings. The mean annual rainfall is about 450 mm, occurring mainly from May to August. The annual mean potential ET is about 2150 mm (Jovanovic *et al*., 2009). The vegetation in the reserve is dominated by Atlantis Sand Plain Fynbos. The variations in reported recharge values in the vicinity of the study area are reported in Section 1. The location of the experimental sites is shown in Figure 1.

Monitoring

The monitoring programme is informed by the expected mechanism of groundwater recharge and the aims of the investigation, i.e. the accurate quantification of the ET component and its impact on groundwater recharge, and to provide input data to modelling.

At Riverlands, the monitoring network includes:

- Groundwater level monitoring: groundwater levels are measured manually or logged hourly at 14 boreholes which are located in the reserve. The location of the boreholes is shown in Figure 2.
- Soil water content and temperature are logged hourly at different depths in the soil profile.
- Daily weather data is gathered from the Malmesbury station (South African Weather Services).
- Daily rainfall (monitored in the reserve by Cape Nature).

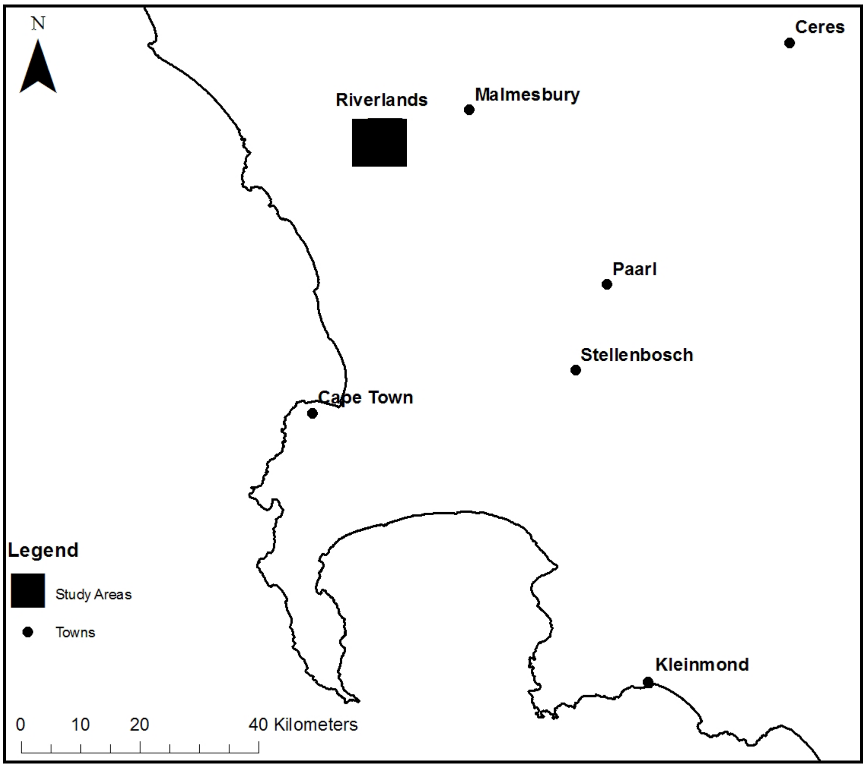

Figure 1. The location of the experimental site.

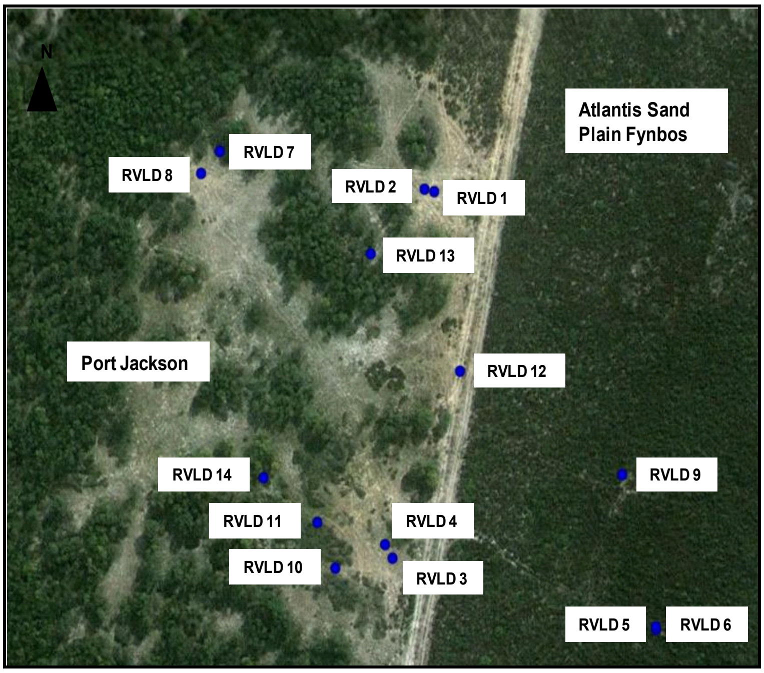

Figure 2. Monitoring boreholes and vegetation at Riverlands.

Evapotranspiration Measurements

The total evaporation of the endemic fynbos (Atlantis Sand Plain Fynbos) at Riverlands was measured in the period 14–27 October 2010 as described in Jarmain *et al* (2011). This window period for the campaign was chosen to be at season change in spring when both sunny days with high atmospheric evaporative demand and overcast days when low ET could be expected. This enabled the accurate quantification of actual ET for the site as measured by the scintillometer system and that derived from the potential evapotranspiration (ETo) according to Allen et al., (1998) to be compared.

The large aperture boundary layer scintillometer (BLS900, Scintec Ltd, Germany) was used to measure the sensible heat flux compenent of the surface energy balance over a 1 km transect at the Riverlands site. The remaining components of the surface energy balance equation were quantified using an energy balance system comprising a net radiometer and a network of three soil heat flux plates located at 3 and 8 cm depths, respectively. The surface energy balance theory and methods for measurement of ET are extensively discussed by Savage *et al*. (2004) and Jarmain *et al*. (2009). Additional climate data to correct the scintillometer data for the surface characteristics of the site was obtained from an automatic weather station which measured the solar radiation, wind speed and direction, air temperature, relative humidity, and the air temperature gradient. The scintillometer, energy balance and weather data was logged at 5 minute intervals throughout the campaign.

Modeling

The purpose of modelling at Riverlands is to quantify ET and groundwater recharge. HDRUS-2D (Simunek *et al.,* 1999) was considered suitable for application at Riverlands, as it is able to simulate the predominantly vertical water fluxes in the unsaturated zone (sandy soil).

In Jovanovic *et al*. (2009), HYDRUS-2D was set-up for Riverlands. HYDRUS-2D is able to simulate two-dimensional water flow, heat transport and movement of solutes in unsaturated, partially saturated and fully saturated porous media (Simunek *et al.,* 1999). It uses Richards' equation for variably-saturated water flow and the convection-dispersion equations for heat and solute transport, based on Fick’s Law. The water flow equation accounts for water uptake by plant roots through a sink term. A database of soil hydraulic properties is also included in the model. The HYDRUS-2D model allows the user to set up the geometry of the system. The water flow region can be of irregular shape and having non-uniform soil with a prescribed degree of anisotropy. Water flow can occur in the vertical plane, horizontal plane or radially on both sides of a vertical axis of symmetry. The boundaries of the system can be set at constant or variable heads or fluxes, driven by atmospheric conditions, free drainage, deep drainage (governed by a prescribed water table depth) and seepage.

In Jovanovic *et al.* (2009), HYDRUS-2D was used to calculate groundwater recharge at Riverlands. HYDRUS-2D estimates deep drainage below the root zone or recharge in response to meteorological forcing. As the ET of Atlantis Sand Plain Fynbos was not measured, a vegetation factor of 1.5 was used to convert ETo into actual ET (non-water limiting) of the vegetation (actual ET = vegetation factor x ETo). The 1.5 factor originated from earlier winter measurements of ET in a different vegetation type, i.e. renosterveld, with scintillometry as described in De Clercq *et al.* (2010). In that study, the renosterveld exhibited an almost complete canopy closure (~80%). The availability of ET estimates from this study allowed for this model to be refined and consequently the influence on groundwater recharge to be evaluated.

3. RESULTS AND DISCUSSION

The groundwater level from RVLD8, which is interpreted to be representative of Riverlands, is shown in Figure 3. Groundwater levels exhibited seasonal oscillations, which ranged between 0.5–1.5m. Groundwater levels also exhibited responses to individual rainfall events. This may be indicative of rapid infiltration and groundwater recharge.

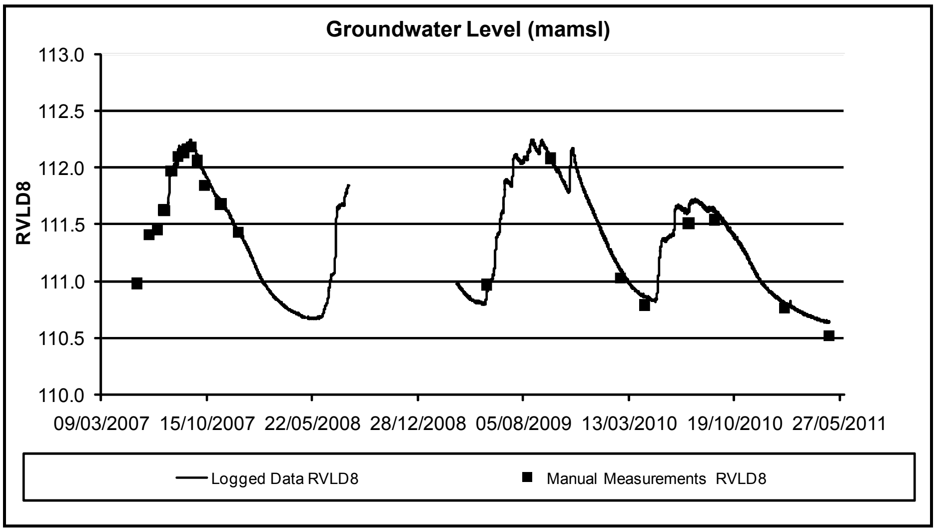

Figure 3. Groundwater levels (mamsl) measured at Riverlands

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Daily rainfall data were obtained from Cape Nature for Riverlands. Total rainfall at Riverlands was 718 mm in 2008, 804 mm in 2009 and 390 mm in 2010. The peak rainfall intensity recorded for Riverlands amounts to 70 mm d^{-1} on 12/07/2009. The rainfall data are shown in Figure 4.

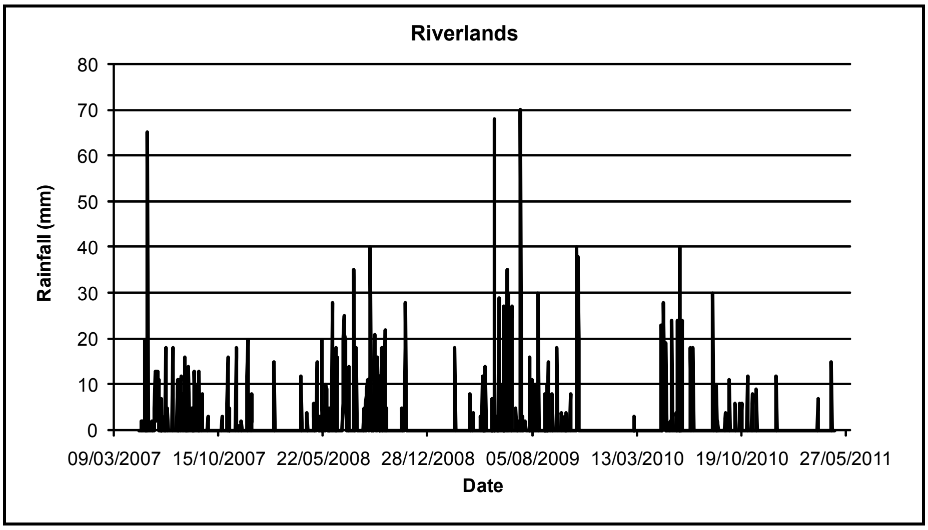

Figure 4. Rainfall (mm) measured at Riverlands

The scintillometer investigation at Riverlands used the BLS9000 scintillometer and the weather monitoring systems to determine the total evaporation. High ET values were measured between 14 and 27 October 2010 as a considerable amount of water is stored in the soil for ET at the end of the rainy season, a shallow water table occurs (~1 m below ground level) and well-established fynbos species have root systems deeper than 1 m (Jovanovic *et al*., 2009). The actual ET from the Atlantis Sand Plain Fynbos surface ranged between 0.8 mm d^{-1} on 21 October 2010 (rainy day) and 5.3 mm d^{-1} on 26 October 2010 (sunny day). For comparative purposes, reference/potential ET (ETo) was calculated with the Penman-Monteith equation (Allen *et al*., 1998) and ranged between 2.6 mm d^{-1} (21 October 2010) and 6.8 mm d^{-1} (27 October 2010). The average ratio of actual ET/ETo for the measurement period was 0.69, which represents the vegetation/crop factor, with a standard deviation of 0.18. It should be considered that this ratio integrates vegetation and large patches of land not covered by the vegetation and the limited direct evaporation from the soil.

The HYDRUS-2D model input data set produced in Jovanovic *et al.* (2009) was used to re-run the model using new values of actual ET derived for Atlantis fynbos. A comparison of actual ET and groundwater recharge simulated with HYDRUS-2D using vegetation factors of 1.5 and 0.69 was done.

The model was run for the period May-December 2007. Daily actual ET (non-water limiting) was calculated as:

actual ET = 1.5 ETo (representing the vegetation factor for renosterveld); and
actual ET = 0.69 ETo (representing the vegetation factor for Atlantis Sand Plain Fynbos)

The vegetation factor of 0.69 is much lower than the one measured for renosterveld (1.5), mainly because of the sparse canopy of Atlantis Sand Plain Fynbos. The model was calibrated using a comparison between simulated and observed volumetric soil water content (VWC). The simulated VWC matched measured data generally well in terms of trends, absolute values, depths and response to rainfall events (Jovanovic *et al.,* 2009).

The HYDRUS-2D model applies the Feddes method to calculate reduced actual ET due to water stress. Figure 5 shows the simulated cumulative fluxes at the atmospheric boundary, namely rainfall and actual ET (water stressed) with factors of 1.5 and 0.69. The graphs in Figure 4 are outputs of HYDRUS-2D and the units are equivalent to cm of water. The cumulative flux in the top graph represents rainfall and it is expressed as a negative number because water enters the system. Total rainfall for the season was 45.4 cm. The actual ET fluxes are expressed as positive numbers because they represent water leaving the system. Cumulative actual ET, using a vegetation factor of 1.5, was about 77 cm for the period between May and

December 2007. When a vegetation factor of 0.69 was used, cumulative actual ET was about 48 cm. A sparse canopy with a lower vegetation factor takes up less water from the soil and groundwater table compared to a dense and almost completely closed canopy. Actual ET was relatively high both in winter and summer, indicating that the root system taps from the water table during the dry summer months when the soil is dry.

The simulation results presented in Figure 6 represents the cumulative flux of water moving into or from groundwater and the units are cm of water. The increase in cumulative fluxes indicates downwards movement of water into the water table (groundwater recharge, water leaving the system), whilst the decrease in cumulative fluxes indicates capillary rise (water entering the system). It is evident from the output graphs that recharge occurred mainly during the rainy season in the period from May to August 2007 (first 120 days of simulation). During this period, recharge was between 8.5 cm (vegetation factor of 1.5) and 22 cm (vegetation factor of 0.69), which is represented by the maximum cumulative water flux in the output graphs (Figure 5). The simulated groundwater recharge is thus well in excess of reported values (Section 2.1). Cumulative water flux decreased from September to December 2007, indicating that groundwater feeds the unsaturated zone and the root system through capillary action. The total estimated capillary rise during this period was between 18 cm (vegetation factor of 0.69) and 30.5 cm (vegetation factor of 1.5), which represents in both cases a considerable contribution to actual ET. It should however be noted that the simulation results from HYDRUS-2D require further validation through increasing the modelling period.

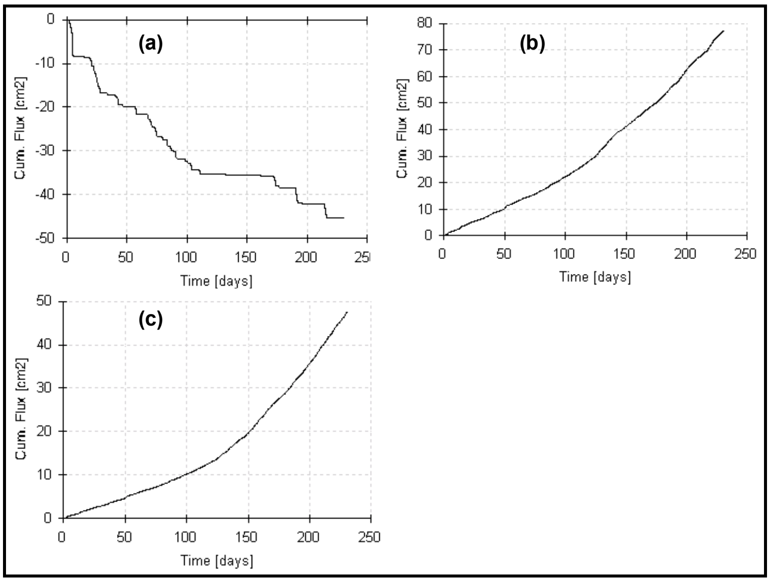

Figure 5. Simulated cumulative fluxes at the atmospheric boundary: rainfall (a); actual evapotranspiration of renosterveld using a vegetation factor of 1.5 (b); actual evapotranspiration of Atlantis Sand Plain Fynbos using a vegetation factor of 0.69 (c).

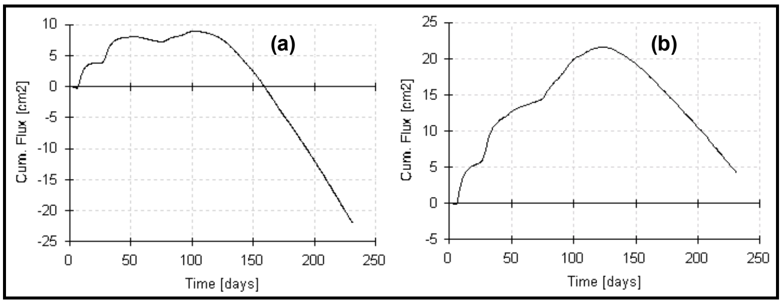

Figure 6. Simulated cumulative fluxes at the bottom profile boundary (groundwater table): recharge/capillary rise using vegetation factors of 1.5 (a) and 0.69 (b).

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4. CONCLUSIONS

The use of crop factors is common in systems with spatially uniform canopies, e.g. for crop water requirements (Allen *et al.,* 1998). In this study, a similar concept was used to convert ETo into PET of natural vegetation through a vegetation factor. However, it should be borne in mind that natural vegetation is generally much more variable in terms of spatial canopy cover, structure and speciation compared to cropped fields. Thus, the linear conversion of ETo into Potential ET through crop (vegetation) factors should be used with caution in non-uniform systems of natural vegetation.

The HYDRUS-2D modelling at Riverlands illustrated the sensitivity of groundwater recharge to ET. The results will however be further validated by applying HYDRUS-2D for the period December 2007 – current. The preliminary results however highlights the need for the incorporation of accurate and representative ET estimation techniques in groundwater recharge estimation methods. It is envisaged that the methodology applied and the results from this investigation may be applicable to similar physiographic environments.

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