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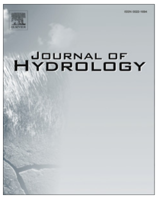

Research papers

Estimation of groundwater recharge via percolation outputs from a rainfall/runoff model for the Verlorenvlei estuarine system, west coast, South Africa

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ABSTRACT

Wetlands are conservation priorities worldwide, due to their high biodiversity and productivity, but are under threat from agricultural and climate change stresses. To improve the water management practices and resource allocation in these complex systems, a modelling approach has been developed to estimate potential recharge for data poor catchments using rainfall data and basic assumptions regarding soil and aquifer properties. The Verlorenvlei estuarine lake (RAMSAR #525) on the west coast of South Africa is a data poor catchment where rainfall records have been supplemented with farmer's rainfall records. The catchment has multiple competing users. To determine the ecological reserve for the wetlands, the spatial and temporal distribution of recharge had to be well constrained using the J2000 rainfall/runoff model. The majority of rainfall occurs in the mountains (±650 mm/yr) and considerably less in the valley (±280 mm/yr). Percolation was modelled as ~3.6% of rainfall in the driest parts of the catchment, ~10% of rainfall in the moderately wet parts of the catchment and ~8.4% but up to 28.9% of rainfall in the wettest parts of the catchment. The model results are representative of rainfall and water level measurements in the catchment, and compare well with water table fluctuation technique, although estimates are dissimilar to previous estimates within the catchment. This is most likely due to the daily timestep nature of the model, in comparison to other yearly average methods. These results go some way in understanding the fact that although most semi-arid catchments have very low yearly recharge estimates, they are still capable of sustaining high biodiversity levels. This demonstrates the importance of incorporating shorter term recharge event modeling for improving recharge estimates.

1. Introduction

Wetlands are systems that are saturated either by surface or groundwater with vegetation that has adapted to periods of saturated soil conditions. These systems are regarded as one of the most productive ecosystems on earth, providing valuable functions in filtering water, collecting sediments and retarding flow during flood events (Barbier et al., 1997; Baron et al., 2002). Due to the highly productive nature of these systems, they have also been the target of often intensive agricultural development (Schuyt, 2005), resulting in competition for water resources. The availability of water is further impacted by climate change (Fay et al., 2016) and high potential evapotranspiration (Přibáň and Ondok, 1985), which exacerbate this competition. Whilst the amount of water needed to sustain different agricultural crops is well constrained (Allen et al., 1998), less constrained is the water needed for the ecology and biodiversity profile of natural wetlands, often termed the ecological reserve. The ecological reserve is defined by the quantity and quality of water that is required to maintain aquatic ecosystems (Hughes, 2001). These maintenance conditions are identified using ecological, geomorphological, hydraulic and hydrological knowledge of each system. Usually maintenance flow requirements are set for both peak and low flow periods, during average and low rainfall years, although the survival of wetlands is critically dependent on the degree to which the ecological reserve is met during low flow, especially during drought years. During such times, baseflow from aquifers contributes the majority of the ecological reserve, and for this reason baseflow is one of the most important parameters to constrain in a wetland catchment.

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While there are many factors that influence baseflow from aquifers, the most important and variable is the rate of groundwater recharge. Various approaches can be used to estimate recharge, but essentially they can be grouped into three methods: 1) physical, for example water table fluctuation (WTF) (Crosbie et al., 2005) or channel water budget (Rantz, 1982); 2) chemical, for example chloride mass balance (Ting et al., 1998) or applied tracers (Forrer et al., 1999); and 3) numerical, for example rainfall/runoff modelling (SWAT, Arnold et al., 2000) or variably saturated flow modelling (HYDRUS: Šimůnek et al., 2006). For the physical and chemical methods, some component of climate is compared to a groundwater component, for example the comparison between precipitation volume and groundwater level. This approach can also be called actual recharge, as it determines the amount of water that reaches the groundwater table (Rushton, 1997), but in doing so it neglects any processes that occur in the unsaturated zone, thereby reducing its spatial and temporal extent. However, for numerical modelling of recharge, it is not possible to neglect what is happening in the unsaturated zone, as most models require information on the physical and chemical pathways of recharge. Therefore, this type of approach is rather defined as potential recharge, which is constrained by the amount of water that has percolated through the unsaturated zone, contributing to the saturated zone (Rushton, 1997), and hence requires knowledge of the percolation rate.

Within numerical modelling, the percolation rate (Scanlon et al., 2002) can be modelled either by looking at variably saturated flow or rainfall/runoff partitioning. Both these methods use a water-balance to determine the percolation volume using input data, such as climate (rainfall, temperature), vegetation (interception) and biosphere (soil texture) to partition water into runoff, infiltration, evaporation and recharge. These two methods differ in their ability to simulate soil moisture. Variably saturated flow models can simulate vertical distributions of soil moisture and estimate recharge by routing water through the soil column using soil hydraulic conductivities. Many rainfall/runoff models partition infiltrated water into storages based on soil type parameters (J2000: Krause, 2001; and ACRU: Schulze, 1995). This makes variably saturated flow more favourable for estimating recharge for detailed studies due to its ability to simulate soil moisture. However, for larger spatial scales, rainfall/runoff models are able to model representative recharge (Scanlon et al., 2002) and are therefore more commonly used in regional scale studies.

This study looks at evaluating how well the percolation output from a J2000 rainfall/runoff model represents actual recharge and whether this can be used as a valid recharge input to a groundwater model for a wetland catchment. The J2000 model is a distributive hydrological model that can be used to simulate various components of the hydrological cycle by calibration of parameters using streamflow, climate and rainfall data. The validation of the percolation output is done by comparison to physical rainfall and water level data in the Verlorenvlei estuarine lake, a RAMSAR Convention (#525) listed wetland on the west coast of South Africa, north of Cape Town, where the high biodiversity profile is linked to the intermittent connection between fresh and salt water. The catchment is also an important agricultural area, in particular supporting 15% of the South African potato industry (Potatoes South Africa, 2015). Despite the value of the region and lake system, the catchment is relatively data poor, partly because of a lack of operating gauging stations, and in spite of ongoing agricultural monitoring. At present, it is not sufficient to allow groundwater abstraction rates to be in equilibrium with recharge estimates, as this does not consider the requirements of the ecological reserve. Therefore, a groundwater model is needed to assess permissible abstraction rates, of which large spatial (catchment) and high temporal (daily) estimates of recharge are needed. Data poor catchments are a common feature across much of Africa, and this method may provide a mechanism for establishing sustainable groundwater management in other data scarce regions, particularly those that are also semi-arid to arid.

2. Environmental setting

The Verlorenvlei catchment makes up the southern part of the Sandveld, a sub-region along the south-western coastline of South Africa, where the soils are particularly sandy. The catchment consists of the Piketberg Mountains in the east, which form the highest topographic elevation (1446 m) and the eastern boundary of the catchment, down to Elandsbaai on the west coast. The dominant feature of the catchment is the Verlorenvlei estuarine lake, which is situated between Redelinghuis and Elandsbaai (Fig. 1), where the estuary transports semi-fresh water into the ocean (Fig. 1). The estuarine lake itself is around 15 km^2 in size, where the catchment has an area of 1832 km^2.

2.1. Hydrology

The estuarine lake is fed by four main rivers, the Kruismans, Bergvallei, Hol and Krom Antonies (Fig. 1). Previously, gauging stations existed along the Kruismans and Hol rivers, but have not been operational since 2009. There is still active water level monitoring within the estuarine lake close to Elandsbaai (Fig. 1). During dry periods, when the water level in the lake is low, stagnant and saline conditions exist, which favours the growth of large algal blooms. During the last seventeen years of monitoring, low water levels of below 0.5 m have been measured for 5 months in 2001, 9 months between 2004 and 2005, and more recently for 4 months between 2015 and 2016 (Fig. 2). The likely cause of these low water levels can be attributed to changes in rainfall patterns, although agricultural abstraction has potential in reducing flow in the lake's major feeding rivers. Although no gauging stations currently exist on the Krom Antonies River, it is considered the most significant contributor of both the quantity and quality of flow into the lake, as it receives water from the Piketberg Mountains. The Kruismans River originates from the east side of the Piketberg Mountains, which drains a large, relatively flat agricultural region (Fig. 1). The river passes through a wide neck in the eastern arm of the Piketberg Mountains, and then firstly joins up with the south draining Bergvallei River, and thereafter the north draining Krom Antonies and Hol Rivers (Fig. 1). The point on the Kruismans River after these three rivers have joined is termed the confluence. Below the confluence, the river is variably referred to as the Kruismans River and the Verloren River, but essentially drains westward until the beginning of the actual lake west of Redelinghuis.

2.2. Hydrogeology

The catchment geology is comprised of three major rock units (Fig. 3). The oldest rocks in the area are the Neoproterozoic Malmesbury Group, represented by the Piketberg Formation comprised of greywacke, sercitic schist, quartzite, conglomerate and limestone (Rozendaal and Gresse, 1994). These rocks make up the secondary fractured rock aquifer (Fig. 3). These rocks have been intruded by the Cambrian Cape Granite Suite. Although drilling has indicated their presence at depth, outcrops within the catchment are very poor to non-existent. The youngest rocks in the catchment are the sedimentary rocks of the Cambrian Table Mountain Group (TMG) which overlies both the Malmesbury Group and the Cape Granite Suite. The TMG makes up the Piketberg Mountains, and in this region is dominated by three formations, which are the