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Water resources modelling in the Vaal River Basin: an integrated approach

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ABSTRACT

The Vaal River Basin (VRB) is a key economic zone in the interior of South Africa; it is marked by intense mining, industrial, and agricultural activities. It experiences a predominantly semi-arid climate with an average annual rainfall of 570 mm. Population increase and the recurrence of drought places water supplies under pressure. Increasing groundwater use in the VRB as an alternative water source can reduce pressure on water supplies. The successful development and use of groundwater in the basin will largely depend on improved understanding of the groundwater system. This study aims to quantify the groundwater storage, trend and variability as well as to assess the effects of both human and natural stressors on groundwater resources. Groundwater storage was estimated by subtracting soil moisture and surface water storage from the Grace Recovery and Climate Experiment (GRACE) based terrestrial water storage. Graphical and statistical tools such as Mann-Kendall (M-K) Test, Sen's Slope Estimator, cumulative rainfall departure (CRD), hierarchical cluster analysis (HCA), and principal component analysis (PCA) were used to analyse groundwater levels and chemistry data. The Soil and Water Assessment Tool (SWAT) was used to simulate streamflow responses to changes in rainfall.

The chemical analysis shows that the main water types are Ca-Mg-HCO_3 and Ca-Mg-SO_4-Cl, which are indicative of the dissolution of the dolomitic aquifer and mine pollution of pristine dolomitic groundwater. Four principal components (PCs) were extracted using PCA; these four components account for up to 82% of the total variance in the groundwater chemistry data. PC1 indicates silicate weathering and dissociation of evaporites, whilst PC2 represents dissolution of carbonate minerals such as dolomite and gypsum in the mining footprint. PC3 and PC4 show high loading of nitrates and ammonia from agricultural activities, respectively. The M-K Test and Sen's Slope Estimator reveal that there is a statistically significant increasing and decreasing trend in groundwater levels at 0.1%, 1% and 5% level of significance. The change in groundwater levels ranges from -2.818 to 0.5327 m/year. A comparison of CRD series and groundwater levels reveals that groundwater levels are more sensitive to human activities than rainfall changes. Human actions such as aquifer

dewatering in active mining areas and over pumping for irrigation are possibly the main causes of drops in water levels, amongst other factors. It also suggests that extreme rainfall events, irrigation return flows, and regular recharge of shallow aquifers near riverbanks cause a recovery in groundwater levels in the basin. The GRACE-based groundwater storage was estimated to be 39.72 km^3 from 2003 to 2014 with an increase of 3.31 km^3/year. The GRACE groundwater storage captures annual variability in water storage distribution. It also mimics the rainfall amount with a time lag of less than six months. The SWAT model results indicate low percolation and high surface runoff in the urban area, and high percolation and low surface runoff in the rural areas. These results suggest a potential increase in groundwater storage in rural areas and a reduction in urban areas of the basin. The model performance statistics for weather data (2010 to 2015) and stationary land use/land cover data for 2014 exhibit a Nash-Sutcliffe Efficiency (NSE) of 0.21 and percent bias (PBIAS) of 10.6%. These results suggest that the observed data are a better predictor of the variance than the simulated results.

This study demonstrates that groundwater quality and availability are more sensitive to human modification of basins than natural influences such as geological and climatic variability. The application of integrated approaches that involve space-based observations and ground data to study groundwater systems in complex basins is of great value in data-scarce basins. More effort must be directed to collecting and monitoring groundwater data to help understand how the quality and quantity of groundwater is evolving in real time for more sustainable development and use of this resource.

Keywords: groundwater storage; GRACE; Vaal River Basin, Mann-Kendall Test, Principal Component Analysis; SWAT model