

# **WATER RESOURCES MODELLING IN THE VAAL RIVER BASIN: AN INTEGRATED APPROACH**

by

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**WITS**  
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## **CANDIDATE'S DECLARATION**

I declare that this thesis is my own, unaided work. It is being submitted for the Degree of Doctor of Philosophy at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other university.

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(Signature of candidates)

\_\_\_\_\_ Day of \_\_\_\_\_ 2021

## 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<sub>3</sub> and Ca-Mg-SO<sub>4</sub>-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 overpumping 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<sup>3</sup> from 2003 to 2014 with an increase of 3.31 km<sup>3</sup>/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



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## PUBLICATIONS

**Contributions to publication that form part of and/or include research presented in this thesis are:**

### **Publication 1: Published in Journal of Environmental Earth Sciences**

**Masindi, K.** and Abiye, T., 2018. Assessment of natural and anthropogenic influences on regional groundwater chemistry in a highly industrialized and urbanized region: a case study of the Vaal River Basin, South Africa. *Environmental Earth Sciences*, 77(20): 1-14.7

The published paper form part and include research presented in this thesis in the sections Analysis of groundwater chemistry and Hydrochemical characteristics of groundwater (6.1).

## CONFERENCES AND WORKSHOPS ATTENDED

**Masindi, K.** and Abiye, T.A. 2017. Application of satellite-based techniques in monitoring water storage in the Vaal River Basin, South Africa. Oral presentation at the 15<sup>th</sup> Biennial Groundwater Division Conference held in Stellenbosch, South Africa, 14<sup>th</sup> -18<sup>th</sup> October 2017.

**Masindi, K.**, Kramers, G. and Abiye, T.A. 2016. GRACE gravity approach in estimating changes in Total Water Storage in the Vaal River Basin, South Africa. Oral presentation at the 35<sup>th</sup> International Geological Congress held in Cape Town, South Africa, 27<sup>th</sup> August – 2<sup>nd</sup> September 2016

**Masindi, K.** 2016. Remote Sensing Applications in water resource management: Gravity Recovery and Climate Experiment (GRACE). Groundwater recharge training held in Johannesburg, South Africa, 11<sup>th</sup>-12<sup>th</sup> October 2016.

**Masindi, K.** and Abiye, T.A. 2015. Using gravity anomalies from GRACE to estimate changes in groundwater storage in the Vaal River Basin. Oral presentation at the 15<sup>th</sup> Biennial Groundwater Division Conference Groundwater Division of the Geological Society of South Africa held in Muldersdrift, 21<sup>st</sup> -23<sup>rd</sup> September 2015.

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## NOTATIONS

$\alpha$       alpha (level of statistical significance)



## ABBREVIATIONS AND ACRONYMS

|                                     |                                                                                   |
|-------------------------------------|-----------------------------------------------------------------------------------|
| AAR                                 | Areal Average Rainfall                                                            |
| AER                                 | Actual Evapotranspiration                                                         |
| ARC-SCW                             | Agricultural Research Council-Soil Climate and Water                              |
| BH                                  | Borehole                                                                          |
| CBE                                 | Charge Balance Error                                                              |
| Ca                                  | Calcium                                                                           |
| CaCO <sub>3</sub>                   | Limestone                                                                         |
| CaMg(CO <sub>3</sub> ) <sub>2</sub> | Dolomite                                                                          |
| Cd                                  | Cadmium                                                                           |
| CHRS                                | Center for Hydrometeorology and Remote Sensing                                    |
| CL <sup>-</sup>                     | Chloride                                                                          |
| CN2                                 | Curve Number                                                                      |
| CRD                                 | Cumulative Rainfall Departure                                                     |
| CRWR                                | Centre for Research in Water Resources                                            |
| CSR                                 | Center for Space and Research                                                     |
| DEA                                 | Department of Environmental Affairs                                               |
| DEM                                 | Digital Elevation Model                                                           |
| DHET                                | Department of Higher Education and Training                                       |
| DSSAT                               | Decision Support System for Agrotechnology Transfer                               |
| DWAF                                | Department of Water Affairs and Forestry                                          |
| DWS                                 | Department of Water and Sanitation                                                |
| EC                                  | Electrical Conductivity                                                           |
| ENSO                                | El Niño Southern Oscillation                                                      |
| ET                                  | Evapotranspiration                                                                |
| EOS                                 | Earth Observing System                                                            |
| FAO                                 | Food and Agriculture Organisation                                                 |
| FLDAS                               | The Famine Early Warning Systems Network (FEWS NET) Land Data Assimilation System |

|                  |                                               |
|------------------|-----------------------------------------------|
| FSC              | Full Storage Capacity                         |
| GFZ              | GeoforschungsZentrum Potsdam                  |
| GIS              | Geographical Positioning Systems              |
| GPS              | Geographical Position System                  |
| GRACE            | Gravity Recovery and Climate Experiment       |
| GRACE-FO         | GRACE Follow-On mission                       |
| GRACETWSa        | GRACE-based terrestrial water storage anomaly |
| GW_DELAY         | Groundwater Recession Coefficient             |
| GW               | Groundwater                                   |
| GWSa             | Groundwater Storage Anomaly                   |
| HCA              | Hierarchical Cluster Analysis                 |
| HCO <sub>3</sub> | Bicarbonate                                   |
| HRU              | Hydrological Response Units                   |
| IPCC             | Intergovernmental Panel on Climate Change     |
| IPSS             | Ingula Pumped Storage Scheme                  |
| IPU              | Instrument-Processing Unit                    |
| IWRM             | Integrated Water Resource Management          |
| JPL              | Jet Propulsion Lab                            |
| K                | Potassium                                     |
| KBR              | K-Band Ranging System                         |
| KMO Test         | Kaiser-Meyer-Olkin Test                       |
| K-S Test         | Kolmogorov-Smirnov Test                       |
| LHWP             | Lesotho Highlands Water Project               |
| LULC             | Land use/land cover                           |
| Ma               | Million years Ago                             |
| mamsl            | Metres above mean sea level                   |
| Mbgl             | Metres below ground level                     |
| Meq/L            | Milliequivalents per Litre                    |
| Mg/L             | Milligrams Per Litre                          |

|                               |                                                                                                                |
|-------------------------------|----------------------------------------------------------------------------------------------------------------|
| Mg                            | Magnesium                                                                                                      |
| M-K Test                      | Mann-Kendall Test                                                                                              |
| MODFLOW                       | Modular Three-Dimensional Finite Difference Groundwater Flow Model                                             |
| MODIS                         | Moderate Resolution Imaging Spectroradiometer                                                                  |
| Na                            | Sodium                                                                                                         |
| NASA                          | National Aeronautics and Space Administration                                                                  |
| NGA                           | National Groundwater Archive                                                                                   |
| NIWIS                         | National Integrated Water Information System                                                                   |
| NO <sub>3</sub>               | Nitrate                                                                                                        |
| NSE                           | Nash-Sutcliffe Efficiency                                                                                      |
| PBIAS                         | Percent Bias                                                                                                   |
| PCA                           | Principal Component Analysis                                                                                   |
| PERSIANN-CDR                  | Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks-Climate Data Record |
| pH                            | Potential of Hydrogen                                                                                          |
| r                             | Correlation Coefficient                                                                                        |
| r <sup>2</sup>                | Square of the Correlation                                                                                      |
| ROF                           | Runoff                                                                                                         |
| PRMS                          | Precipitation-Runoff Modelling System                                                                          |
| SA                            | South Africa                                                                                                   |
| SANS                          | South African National Standard                                                                                |
| SAWS                          | South African Weather Service                                                                                  |
| S-K Test                      | Shapiro-Wilk (S-W) Test                                                                                        |
| SM                            | Soil Moisture                                                                                                  |
| SMa                           | Soil Moisture Anomaly                                                                                          |
| SO <sub>4</sub>               | Sulphate                                                                                                       |
| SO <sub>4</sub> <sup>2-</sup> | Sulphate                                                                                                       |
| SOL_AWC                       | Soil available water capacity                                                                                  |

|          |                                                                       |
|----------|-----------------------------------------------------------------------|
| SOTER    | Soil and Terrain Database                                             |
| SP       | Snow Water                                                            |
| SPAW     | Soil Plant Atmosphere Water                                           |
| SST      | Satellite-to-Satellite Tracking                                       |
| SUFI     | Sequential Uncertainty Fitting                                        |
| SWa      | Surface Water Anomaly                                                 |
| SW       | Surface Water                                                         |
| SWS      | Surface Water Storage                                                 |
| SWAT     | Soil and Water Assessment Tool                                        |
| SWAT-CUP | Soil Water Assessment Tool – Calibration and Uncertainty Procedures   |
| TAL      | Total Alkalinity                                                      |
| TDS      | Total Dissolved Solids                                                |
| TSSDGM   | Twin Shaft South Deep Gold Mine                                       |
| TWS      | Terrestrial water storage                                             |
| TWSwb    | Terrestrial water storage as estimated from the water budget          |
| PBIAS    | Percent Bias                                                          |
| PET      | Potential Evapotranspiration                                          |
| USDA-ARS | United States Department of Agriculture–Agricultural Research Service |
| VRB      | Vaal River Basin                                                      |
| VW       | Vegetation Water                                                      |
| WHO      | World Health Organisation                                             |

# 1 INTRODUCTION

## 1.1 General introduction

The availability of freshwater is important for all forms of life on Earth. Its distribution across the planet is, however, uneven. In arid to semi-arid regions, the potential evaporation exceeds rainfall (Allison & Hughes, 1983), which consequently results in water scarcity. In this climatic setting, groundwater is often the main source of dependable water supply. Clarke et al. (1996) estimate that more than 1.5 billion of the world's population depends on groundwater for drinking water. An estimated 40% of the world's population uses groundwater for agricultural food production (Morris et al., 2003). High water demands driven by a fast-growing population and the recurrence of intensified drought in arid and semi-arid regions puts already stressed water resources under pressure (Arnell, 1999; Vörösmarty et al., 2000; Ragab & Prudhomme, 2002). This pressure necessitates the careful management of water resources to sustain livelihoods and economic prosperity in regions experiencing climate aridity.

Global warming is likely to worsen water shortages in arid to semi-arid regions, although its impacts are still somewhat uncertain. Arnell (1999) showed that extreme dry conditions linked to global warming are likely to exacerbate water scarcity in semi-arid regions such as southern Africa, southern Asia, and the Middle East and around the Mediterranean. The consequences of water scarcity are far-reaching, given that the lack of water is correlated with poverty, health and food security in most developing countries (Oki & Kanae, 2006; Bates et al., 2008). Water scarcity is more worrying for African countries because to a large extent it is a continent of poverty with low adaptive capacity to natural disasters such as floods and droughts (Callaway, 2004; Oki & Kanae, 2006; Bates et al., 2008; Kusangaya et al., 2014).

MacDonald et al. (2012) estimated the total groundwater storage volume in Africa to be about 0.66 million km<sup>3</sup>, which is 100 times greater than annual renewable freshwater resources in Africa. Thus, groundwater can play an important role as an adaptive tool to meet future water demands because it is more resilient to climate variability than surface waters. Yet the regional groundwater storage, geometry of the

aquifers and the response of aquifers to human and natural stressors remains unknown and understudied for a large part of Africa. The lack of groundwater studies is also recognised by the scientific findings in the Intergovernmental Panel on Climate Change (IPCC) report (2014), which has little information on the impacts of climate change on groundwater in Africa. The lack or non-existence of monitoring networks to collect groundwater data hampers hydrogeological investigations in most parts of Africa. South Africa, however, has made huge progress in the monitoring and collection of groundwater data, although gaps do remain (Hughes, 2006; Pitman, 2011). The availability of groundwater data allows for the appraisal of groundwater storage and quality in a given basin, which is so important for the management of groundwater resources (Sharma, 1986).

In South Africa (SA), groundwater is important in meeting water demands for various sectors. In remote parts of the country, boreholes and springs are the main sources of water supply for communal activities (van Tonder, 1999). Groundwater supplies water to more than 280 towns in South Africa; most of the schools, clinics and hospitals in rural areas depend on it. Woodford et al. (2006) suggest that groundwater in SA is not utilised to its full potential due to the lack of hydrogeological data. There is a great potential for upscaling groundwater use in the water supply system. Thus, quantification of groundwater storage, analysis of groundwater quality, groundwater levels trend analysis, and streamflow sensitivity modelling are pre-requisites in the optimal development and sustainable use of groundwater.

The development and use of groundwater without data can cause misinterpretations of the groundwater system. These misinterpretations can lead to the overestimation of the borehole yield and an increasing number of boreholes drying up (van Tonder, 1999). Recent advances in Earth observation technology such as the Gravity Recovery and Climate Experiment (GRACE) satellite present a unique opportunity to effectively monitor and collect regional measurements of terrestrial water storage (TWS) (Dickey et al., 1998; Dunn et al., 2003). The GRACE satellite - in combination with ancillary data - can be used to estimate groundwater storage. The GRACE satellite thus enables the study of basin-scale hydrological processes in data-scarce regions by providing data that were previously unobtainable. The use of remotely

sensed data in combination with ground-based data is useful in studying groundwater systems and can help in evaluating the effects of human and natural stressors on the groundwater.

There are several studies in data-scarce regions that have combined satellite observations data with in-situ point measurements to study the linkages between hydrological systems and environmental change (e.g. Syed et al., 2008; Moiwo et al., 2009; Ahmed et al., 2014; Ndehedehe et al., 2017). In this study, GRACE data was used in the estimation of groundwater storage in the arid to semi-arid VRB. In addition to this, non-parametric statistical tools were used to analyse the groundwater quality and groundwater level trends. The Soil and Water Assessment Tool (SWAT) was also used to model streamflow response to climatic and land use/cover changes. This quantitative analysis of groundwater data helps improve our understanding of the groundwater resource availability and the factors influencing the groundwater trends and quality.

## **1.2 Background for this research**

This research is carried out in the Vaal River Basin (VRB) - the most industrialised and urbanised part of SA. The VRB contributes more than 24% to the country's gross domestic product (GDP) (van Vuuren, 2008). The Vaal River is the most over-allocated in the central South Africa plateau (Department of Water Affairs and Forestry [DWAF], 2003a; DWAF, 2003b; Mare, 2007). The Vaal River is also the main source of water supply to the economic hub of South Africa that encompasses the metropolis of Johannesburg, Pretoria and Ekurhuleni (DWAF, 2003a; DWAF, 2003b; NWRS2, 2013). Water is imported from the adjacent basins to the VRB to meet water demands in the metropolis because of a supply deficit. More than 70 m<sup>3</sup>/s of water that flows into the VRB is sourced from the Lesotho Highlands as part of an inter-basin water transfer scheme (Lepono et al., 2003).

The total water requirements projection for the VRB shows that water demand in the basin will increase from 3 019.54 million m<sup>3</sup>/annum (Mm<sup>3</sup>/annum) in 2015 to 3 212.47 Mm<sup>3</sup>/annum in 2025 (Mare, 2007). The water demands in the basin are largely driven

by urban population growth and increasing economic activities that will no doubt place water supplies – particularly surface waters - under pressure (DWAF, 2006; van Vuuren, 2008).

Surface water supplies are more vulnerable to the recurrence of drought, which directly threatens water availability. For example, the VRB and other parts of the country experienced the most intense drought in 2015-2016 compared to droughts in 1997/1998 and 1982/1983 (Blamey et al., 2018; Siderius et al., 2018). Blamey et al. (2018) reported a standard precipitation index (SPI) of -2 during October to December in the 2015/2016 period; this SPI implies that it was severely dry. The impacts of this most recent drought were direct and immediate resulting in a significant drop in dam levels, water shedding, and a decline in maize production - all of which, combined, affected livelihoods on a day-to-day basis. Hence, there is a need to consider sustainable groundwater use as an alternative water source to augment surface water supplies.

With increasing water demands in the highly industrialised and urbanised VRB, SA groundwater can play an increasingly significant role in the water supply system. Consideration of groundwater as an alternative source of water will reduce the burden on the surface water supply in the VRB. The National Act 38 of 1998 already makes provision for the consideration of groundwater as an important water resource. This provision is, however, largely limited to theory rather than used in practice. The successful use of groundwater resources requires an understanding of the aquifer systems, properties and behaviour in relation to other components of the hydrological system.

### **1.3 Rationale and relevance of the study**

The impacts of human action and changes in rainfall patterns on the groundwater storage in the VRB remains relatively understudied. Being an economic hub of SA means that the availability of water resources in the VRB is critical in meeting competing water demands for poverty eradication and economic prosperity. The sustainable use and management of groundwater can help meet future water



demands. Groundwater as a resource in the VRB is underdeveloped; there is a need to tap into this resource as a supplemental source to use with surface waters or as an alternative water supply. The current study attempts to provide insights into the groundwater trends, quality and storage dynamics in a constantly changing environment by using in-situ and satellite data. Understanding the functioning of the groundwater system in the VRB is key in the development and sustainable use of groundwater resources. An integrated approach, consisting of multiple techniques such as multivariate statistics, Soil Water Assessment Tool (SWAT) and graphical methods, is used because of the interrelationships of water resources with other elements in the hydrological system. This integrated approach makes use of ground-based data and remotely sensed data (i.e. Gravity Recovery and Climate Experiment (GRACE)) to help in improving understanding of the groundwater system in the complex VRB.

## **1.4 Research aims and objectives**

The current research aims to assess the groundwater storage, groundwater level trends and variability, and to characterise the groundwater chemistry using an integrated approach. Moreover, this research uses the Soil and Water Assessment Tool (SWAT) to simulate the hydrological response to land use and/or change, and variability in rainfall. The findings of this study will improve our understanding of the effects of human and natural factors on groundwater availability and quality, which will aid in the management and safe use of groundwater resources. The specific objectives of this study are to:

1. Characterise the groundwater chemistry to develop insights about the extent of groundwater quality.
2. Detect the presence of statistically significant trends in long-term groundwater levels.
3. Identify key factors influencing groundwater level fluctuations.
4. Estimate the volume of groundwater storage changes and identify the drivers of the changes to this storage.

5. Estimate the percolation and surface runoff rates in response to land cover/use.

## **1.5 Limitations of the study**

The limitations identified in this research are associated with the limited availability of data, which is important in carrying out the research over the entire VRB. In general, groundwater data in the VRB are sparse and there are gaps in the long-term records. The sparseness of, and gaps in, data limit the extent of assessing and evaluating long-term (>30 years) trends in the groundwater levels. Groundwater monitoring networks are largely clustered in the upper VRB; this means that a large part of the basin is poorly monitored. Detailed point measurements of the physical characteristics of the soil over the modelling domain are not available, which means that the actual field conditions are not well represented in the SWAT. To address the lack of data, a combination of remotely sensed and in-situ data were used to estimate the volumetric groundwater storage changes. For groundwater trends and hydrochemical characterisation, analyses were limited to the part of the basin where groundwater data was available.

## **1.6 Previous hydrogeological investigations in the VRB**

A search of the literature reveals two trends. First: most hydrogeological investigations focus on the upper VRB (Kafri, 1989; Haji, 2011; Dennis et al., 2020), where more groundwater data is available compared to other parts of the basin. Second: no single study has attempted to quantify the changes in groundwater storage and groundwater trends, and to employ multivariate statistics in the characterisation of the groundwater chemistry in the VRB. These two trends signify an important gap in groundwater knowledge in the basin. Using integrated approaches, this study attempts to improve current understanding of the quality and quantity of groundwater resources in the basin. The sub-sections below provide details about the gaps in knowledge about the VRB.

### 1.6.1 Estimation of groundwater storage changes using GRACE satellite data

According to the author's knowledge, this is the first study to use the gravity data from the GRACE satellite to estimate groundwater storage changes in southern Africa. Although the GRACE satellite has gained popularity in Europe, America and Asia (Reager & Famiglietti, 2009; Rodell et al., 2009; Famiglietti et al., 2011; Feng et al., 2013; Breña-Naranjo et al., 2014; Huang et al., 2019; Boergens et al., 2020; Liu et al., 2020a; Ojha, 2020), it is under-utilised in southern Africa. This study attempts to advance the understanding of the groundwater storage dynamics using remotely sensed observation and in-situ data using the VRB as a study site. The findings will improve local knowledge of the factors influencing groundwater storage variations and reveal the groundwater storage trends. It will also advance current knowledge on the applicability of GRACE satellite data and ancillary datasets in groundwater investigations and management.

Although GRACE data has not been applied in groundwater investigations in South Africa, a few studies have recognised the potential of GRACE satellites in groundwater investigations. The reviews by Makapela et al. (2015) and Mahed (2016) only briefly mentioned GRACE satellites, with no study undertaken. For example, Makapela et al. (2015) highlight the need for applications of remote sensing tools such as GRACE satellites for integrated water resource management (IWRM) in South Africa.

Vegter (1995), in the form of maps and an explanation booklet, demonstrated the groundwater availability on a national scale, with maps showing the borehole yields, groundwater quality, recharge, and groundwater level based on the data collected by The Department of Water and Sanitation (DWS). Although the study was at a national scale, it provides a basis for understanding the groundwater availability in the VRB.

Woodford and Rosewarne (2006) developed algorithms and estimated the aquifer recharge ( $30\,520\text{ Mm}^3/\text{a}$ ), aquifer storage ( $235\,500\text{ Mm}^3/\text{a}$ ) and extractable groundwater ( $19\,000\text{ Mm}^3/\text{a}$ ). The work by Woodford and Rosewarne (2006) is linked to the work reported in the DWAf report on *Groundwater Resource Assessment Phase II* for the entire country. The DWAf (2005) report estimates that the potential amount of groundwater in storage in SA ranges from  $47.7\text{ Mm}^3/\text{km}^2/\text{a}$  to  $7.5$

Mm<sup>3</sup>/km<sup>2</sup>/a. These two studies provide insights about the status of groundwater storage at a national scale, which is important in guiding water managers on how aquifers can be best utilised. The current study estimates the groundwater storage variations, detects the trends in groundwater storage, and also attempts to identify possible factors influencing those variations within the VRB.

### **1.6.2 Quantitative analysis of groundwater level trends**

Meyer (2005), using the standard precipitation index (SPI) and groundwater level time series, demonstrated that rapid fluctuation in water level correlated with wet years (high SPI values) and declining water levels correlated with dry years (low SPI values). The study was carried out in the interior of South Africa of which part of it is the VRB, and relied solely on the SPI to assess the effect of rainfall variability on groundwater levels.

Using harmonic means and cumulative rainfall departure (CRD), Abiye et al. (2018), reported that the combined effect of natural and human activities are the causes of the groundwater level fluctuations in the upper VRB. The study by Abiye et al. (2018) did not reveal the statistical significance of the groundwater level trends.

The aforementioned studies do not necessarily show subtle changes of groundwater levels over time and the factors influencing such observed changes. The current research applies non-parametric statistical tools in the systematic analysis of groundwater level trends and variability, and the identification of the possible factors that are influencing the observed trends. The current study will improve current understanding of the groundwater level dynamics in the highly industrialised and urbanised VRB.

### **1.6.3 Hydrochemical characterisation of groundwater quality**

Using data from the national groundwater database of the DWS, Vegter (1995) produced maps showing the quality of groundwater. These maps are useful in understanding the salinity and basic quality information for different regions in the

country including the areas covering the VRB. These maps do not, however, provide a detailed quantitative analysis of the groundwater chemistry because the study was qualitative in nature.

Studies by Naicker et al. (2003), Nengovhela (2006), Tutu et al. (2008), Durand (2012) and Abiye (2014) have focused, largely, on the impacts of acid mine drainage on groundwater quality. All these studies suggest mine pollution as a source of groundwater contamination. All these studies are, however, limited to local surveys.

Hobbs et al. (2013) used piper diagrams and descriptive statistics to characterise the groundwater chemistry in the upper and middle parts of the VRB. The study provided an overview of the evolutionary trends in groundwater chemistry and the influence of the local geological formations on groundwater quality.

In the current study, the novel aspect is to improve understanding of hydrochemical processes. This study also seeks to understand how human and geological factors influence groundwater chemistry in the VRB using graphical and multivariate statistics. This research will generate fresh insights into the hydrochemical characteristics of groundwater chemistry in the VRB.

#### **1.6.4 Simulating streamflow sensitivity to climate variability and land use/cover changes using SWAT model**

Ngubane (2017) conducted hydrological modelling using ArcSWAT in the catchment area (21.15 km<sup>2</sup>) of the Ingula Pumped Storage Scheme (IPSS), in the uppermost part of the VRB. Whilst the study yielded positive results, the focus of the current study is to simulate the hydrological response to land cover/use and rainfall changes.

### **1.7 Contribution to science and society**

The findings on the application of GRACE satellite data will illuminate the applicability of GRACE satellite data for estimating groundwater storage variations in the VRB and southern Africa. The quantification of groundwater storage using GRACE satellite

data will also provide insights into the variability of groundwater storage as well as a rough approximation of the amount of groundwater that is available in storage in the VRB.

The outcomes of the analysis of groundwater levels form the basis for guiding policy decisions in the VRB. This approach could, in turn, be expanded to the national level. The outcomes also help water managers and researchers in identifying regions that require urgent attention to monitor and manage groundwater resources.

The outcome of the hydrochemical analysis will help in identifying pollution hot spots where measures must be taken to protect the aquifers and to develop policy that will help in safeguarding the groundwater resources from pollution. The outcomes will also give those who reside in the VRB an idea of the general water quality.

The SWAT model will provide insights into how land cover/use influences percolation and surface runoff rates. The percolation and surface runoff rates exert a significant impact on groundwater and surface water storages.

Overall, the findings of this research will contribute to the groundwater resources management across South Africa to ensure equitable allocation and use of water for socio-economic development of the people of South Africa. The findings of the current research may serve as a reference for future studies in SA and elsewhere on the use of integrated approaches to hydrogeology in the management of groundwater resources.

## **2 DESCRIPTION OF THE VAAL RIVER BASIN**

### **2.1 Introduction**

The interplay among topography, geology, and climate plays a significant role in the occurrence and flow of groundwater in a basin (Winter, 2001; Adelana & MacDonald, 2008). The topography and the underlying geology also control the rate of recharge and discharge processes, and determine the physical extent of an aquifer in a hydrological basin. Thus, understanding the physical setting and geological conditions of a site are necessary in carrying out any hydrogeological investigation. Human development such as urbanisation and industrialisation in a basin alters the natural functioning of a hydrological system. In this study, a description of the Vaal River Basin's (VRB) physical and climatic characteristics aided in identifying the factors affecting groundwater's level long-term trends, changes in groundwater storage and changes in groundwater quality.

Note that the maps were created using shapefile and raster spatial files from various sources with the aid of ArcGIS10.6 and QGIS 2.18.24 software. In cases where point data is used the inverse distance weighted (IDW) technique was used for the interpolation. The source of rivers, dams and quaternary catchment shapefiles is the Department of Water and Sanitation (DWA). The other sources of specific maps is provided in the figure caption throughout the thesis.

### **2.2 Location**

The VRB is situated in the interior plateau of South Africa and covers an area of approximately 196 274 km<sup>2</sup> (Figure 2.1). It straddles six provinces in South Africa: the Gauteng and Mpumalanga provinces (north and northeast part), the Free State and KwaZulu-Natal provinces (southern and southeastern part), and lastly, the North West and Northern Cape provinces (northwest and southwest part) (Figure 2.1).

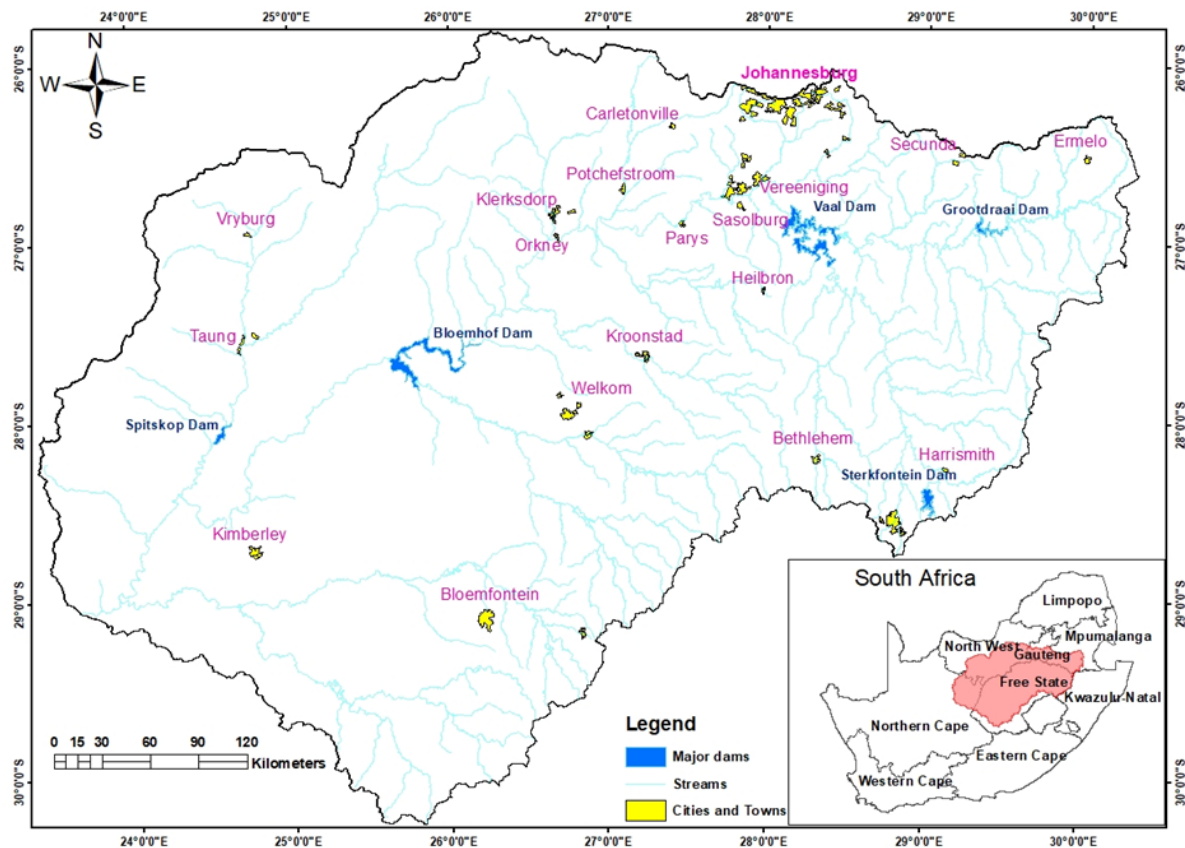


Figure 2.1: Simplified physical map of the Vaal River Basin (VRB); insert map shows the VRB in the interior of South Africa.

The Vaal River originates in the eastern escarpment of the basin and flows towards the southwest direction. It discharges into the Orange River about 115 km southwest of Kimberley (Figure 2.1). There are more than 36 reservoirs in the basin, but the dams with the highest capacity are: Vaal, Grootdraai, Sterkfontein and Bloemhof. The VRB is made up of one hundred and ninety-four (194) quaternary catchments (Figure 2.2)

The Vaal Dam is a major source of water supply for major cities and towns in the VRB, and in the Limpopo Basin.



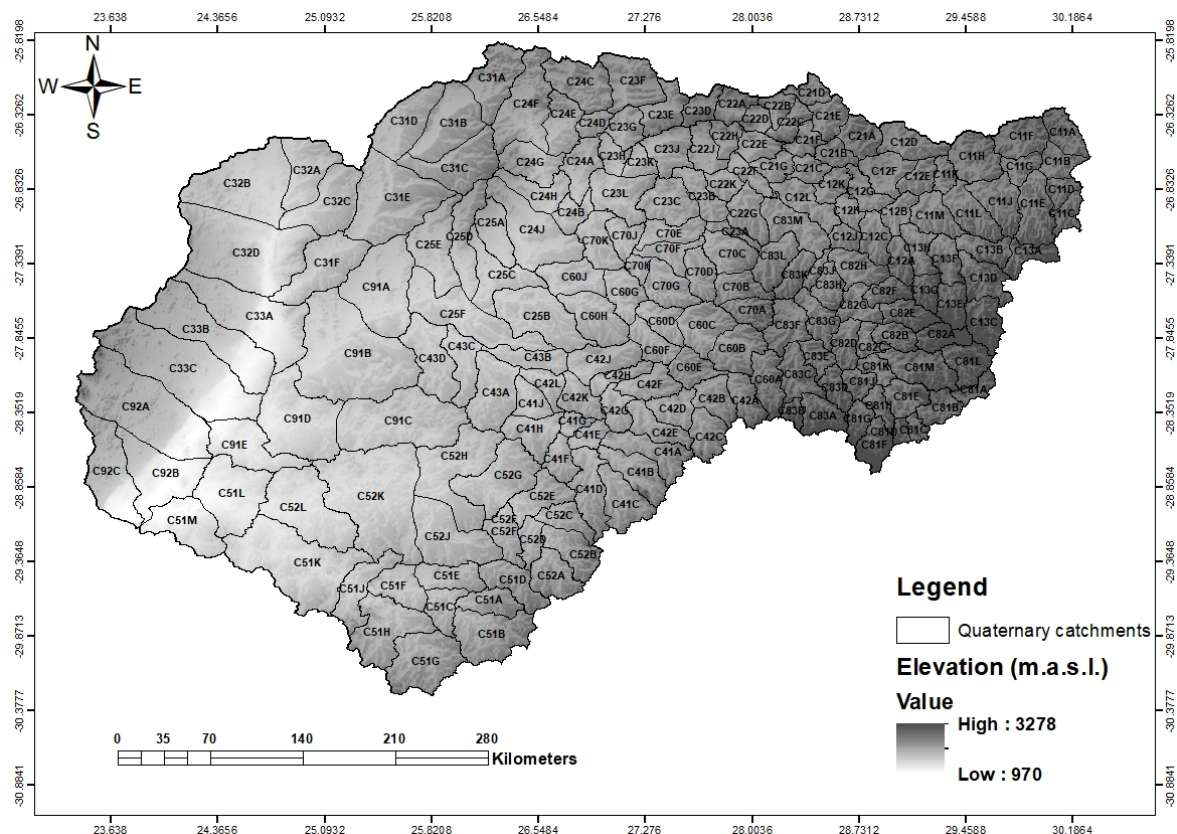


Figure 2.2: The Quaternary catchments of the Vaal River Basin (note the increasing catchment size at low elevation) (Source of Digital Elevation Model: United States Geological Survey Earth Explorer, <https://earthexplorer.usgs.gov/>).

## 2.3 Groundwater availability and use

Groundwater is the source of water supply for various sectors such as mining, agriculture and industry in the VRB. The rural parts of the basin largely depend on groundwater for domestic use, particularly in the drier parts of the basin towards the northwest and southwest. Based on the reported volumes of abstraction relative to the available groundwater resource, it can be seen in Figure 2.3 that groundwater is relatively underused in the basin. The surplus groundwater volume represents a significant resource that could be integrated into the water supply of the basin.

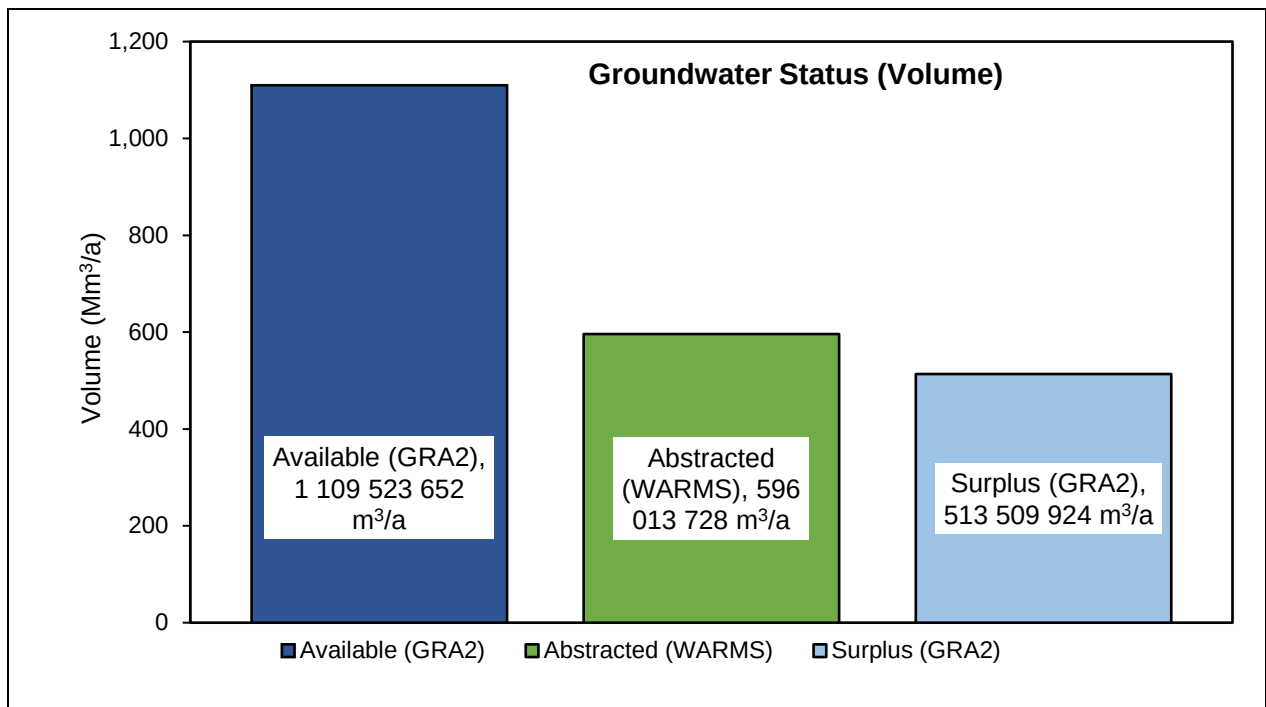


Figure 2.3: Groundwater volume and volume status in the Vaal River Basin (source of groundwater volume data: <http://www.dwa.gov.za/niwis2/GroundWaterStatus>).

## 2.4 Climate

There are many climatic parameters that interact at various degrees and influence the amount of water available in the basin at any given time. These include, but are not limited to: precipitation, evapotranspiration, wind speed, relative humidity, temperature, and solar radiation. The weather data were obtained from three sources: South African Weather Service (SAWS), Agricultural Research Council-Soil Climate and Water (ARC-SCW), and Department of Water and Sanitation (DWS). These three institutions have made commendable progress in collecting weather data, despite the data gaps in some meteorological stations and a poor monitoring network in the southern part of the VRB. Only 45 meteorological stations were used in the descriptive analysis of the weather data: 26 (DWS), 13 (SAWS) and 6 (ARC-SCW). The weather stations are mainly found in major towns and cities. The climatic data were analysed for errors and gaps were filled using the “Fill with monthly means and stochastic rain” option of the weatherman tool in the Decision Support System for Agronotechnology

and Transfer (DSSAT) software. The weatherman tool requires daily weather data for any analysis.

### 2.4.1 Rainfall

Among many other elements, climatic factors such as temperature and pressure, and the geographic location of an area with respect to moisture source and circulation, influence the type and distribution of precipitation. Precipitation in the study area is mainly in the form of rainfall and to a lesser extent occasional light snow at high altitudes. The accurate measurement of rainfall is important in understanding water availability - an important input in water balance calculations - and has a direct impact on livelihoods. Figure 2.4 shows that the distribution of the rainfall gauges in the VRB is irregular and they are clustered in the northeast quadrant of the map – the area where most economic activity is taking place.

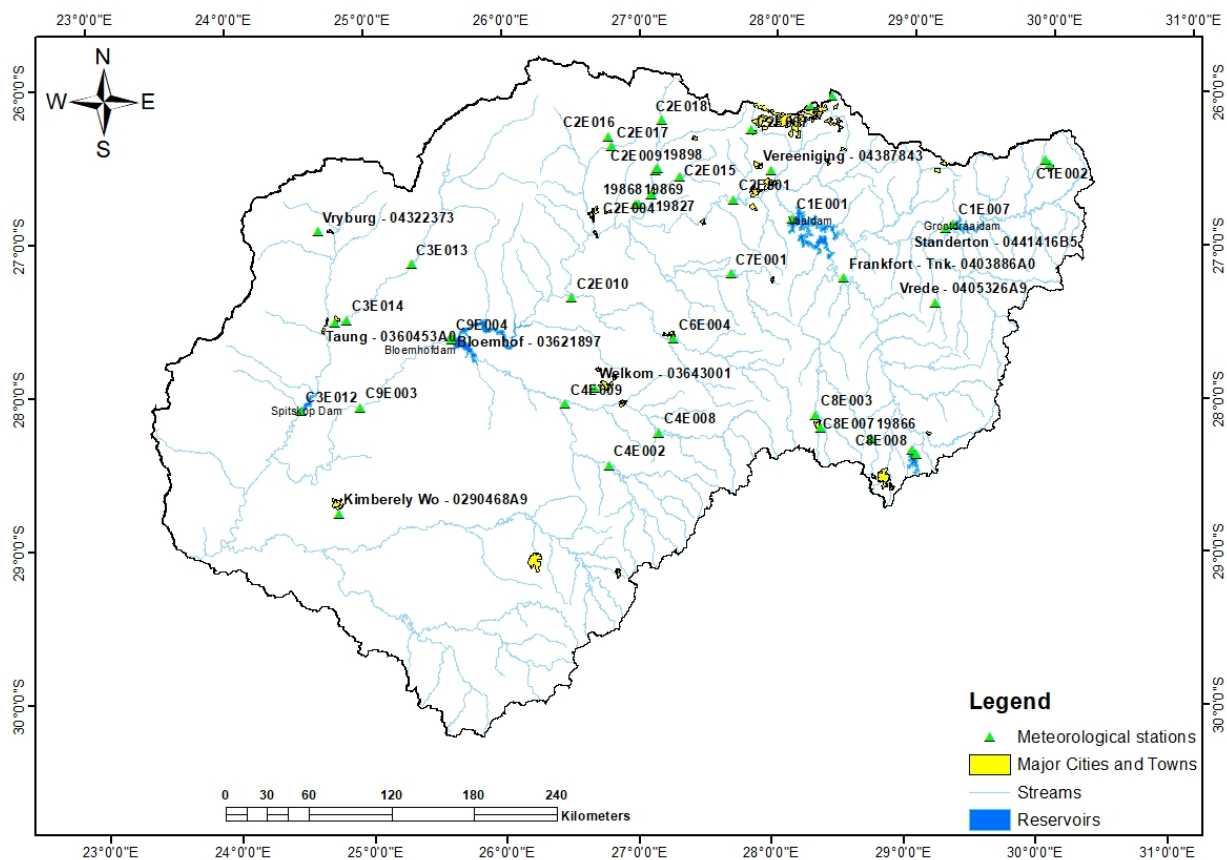


Figure 2.4: The distribution of meteorological stations in the Vaal River Basin.

The monthly rainfall for selected stations shows that the upper part of the basin (Figure 2.5) receives higher monthly rainfall than the lower part (Figure 2.6). It is important to note that the hydrological year in South Africa starts in October and ends in September. The monthly hyetographs in Figure 2.5 and Figure 2.6, however, start in January and end in December.

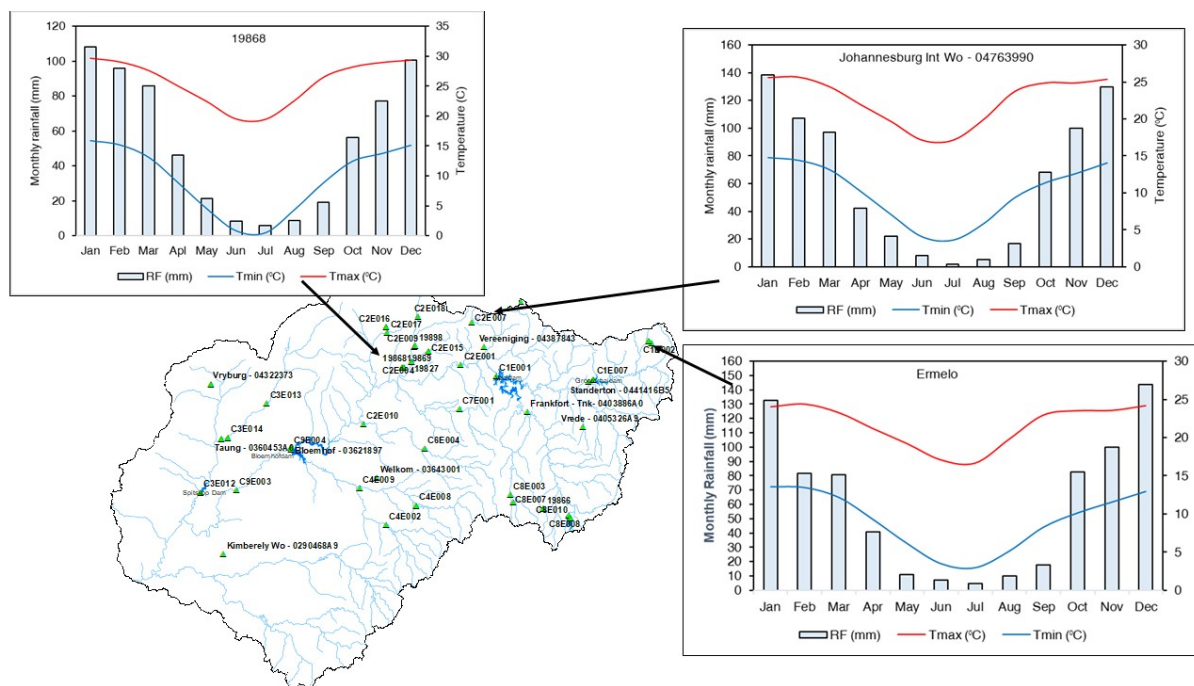


Figure 2.5: Monthly rainfall and temperatures for the upper part of the Vaal River Basin.

The rainfall in the basin is strongly seasonal and often occurs as a convective thunderstorm in the late evening and early morning during the summer months (October to March). During winter, there is hardly any precipitation, apart from the light snow in the eastern escarpment, Drakensberg, and Lesotho Highlands.

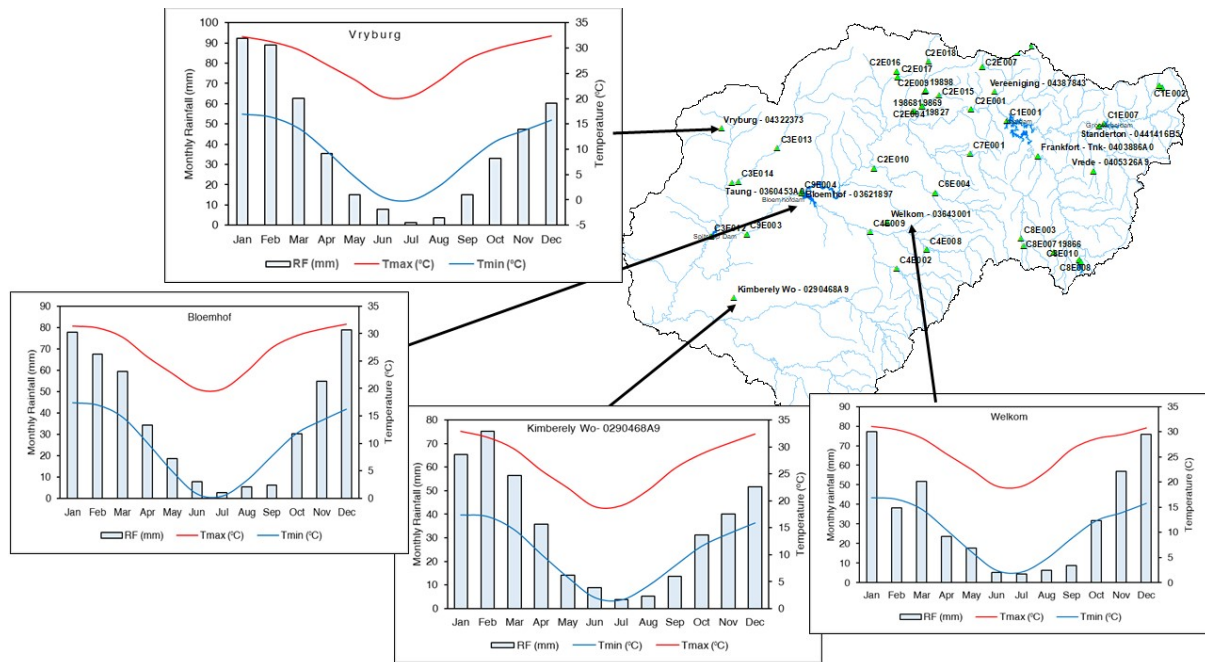


Figure 2.6: Monthly rainfall and temperatures for the lower part of the Vaal River Basin.

Rainfall in the VRB shows a strong spatial variation from the escarpment in the northeast to the southwest, downstream of the Vaal River. The amount of rainfall decreases from 778 mm/year in the northeast to 397 mm/year in the southwest (Figure 2.7). The area at high altitude receives a higher amount of rainfall compared to the low elevation area downstream. The VRB experiences an arid to semi-arid climate from southwest to northeast of the VRB. In all climatic settings, potential evapotranspiration (PET) exceeds precipitation; this trend means that there is a limited amount of water available in the basin to meet the ecosystem and human needs.

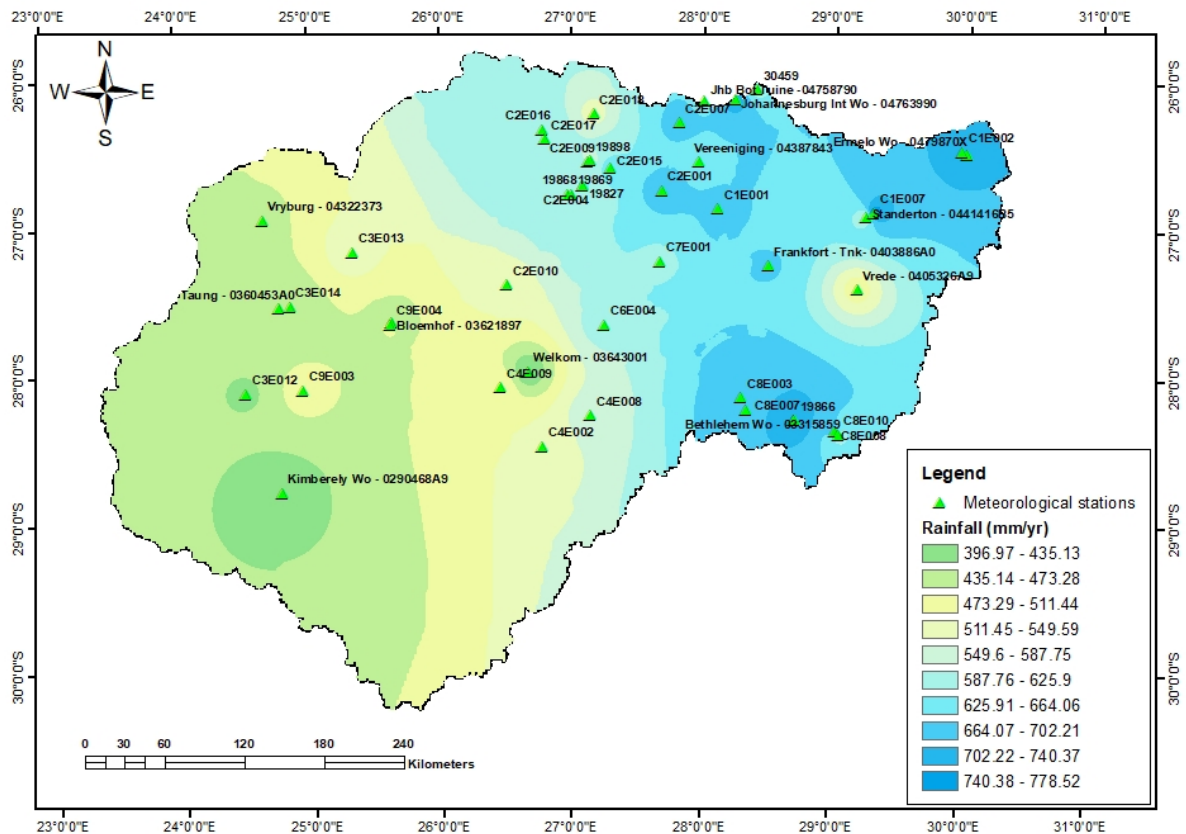


Figure 2.7: Map showing the location of meteorological stations and the spatial variability of annual rainfall in mm/year across the Vaal River Basin.

#### 2.4.1.1 Spatial interpolation of aerial average rainfall

Rainfall gauge networks provide point measurements of rainfall depth rather than areal-based rainfall. Interpolation of point measurements of rainfall provides information about the general areal average rainfall (AAR), which is important for rainfall-runoff analysis and water budget studies. Three common methods used in the estimation of AAR in the basin are: Arithmetic Mean, Thiessen Polygons and Isohyets. The long-term mean annual rainfall depth from 45 rainfall gauges was used as input for the three methods (Appendix A). These methods have their own strengths and drawbacks. Singh and Chowdhury (1986), however, used 13 methods to estimate AAR and demonstrated that all methods yielded comparable results over yearly periods. They found that the selection of each method should be based on site-specific conditions.



The arithmetic mean estimates annual precipitation without any weighting. It is more effective for sites with a random spatial distribution of rainfall. These sites are, typically, characterised by uniform topography and evenly distributed rain gauges. The arithmetic mean (Figure 2.8a) estimated the AAR to be 593.36 mm/year using the formula below:

$$P_A = \frac{\sum_{n=1}^n P}{n} \quad (2.1)$$

Where  $P$  denotes the precipitation (mm) measurement at each station and  $n$  is the total number of rainfall gauges.

The Thiessen Polygon Method is much more reliable than the Arithmetic Mean because it considers the area of influence of each rainfall gauge when estimating rainfall (Hendriks, 2010). It is effective when applied in landscapes with uniform topography. Thiessen Polygons are calculated as follows:

$$P_A = \frac{\sum_{i=1}^n A_i P_i}{A_t} \quad (2.2)$$

Where  $P_i$  denotes aerial precipitation (mm),  $A_i$  denotes the  $i^{th}$  polygon area (km<sup>2</sup>),  $P_i$  denotes the precipitation (mm) recorded at the  $i^{th}$  rain gauge and  $A_t$  denotes the total area (km<sup>2</sup>) of the study site.

The Thiessen Polygon Method's output is spatial as shown in Figure 2.8a. The major drawbacks of the Thiessen Polygon Method is that it requires construction of a new network where there are missing data. It is ineffective in regions that receive orographic rainfall. Nonetheless, the Thiessen Polygon Method estimate of the AAR is 541 mm/yr.

Isohyets are an effective approach for calculating the AAR. Using this method requires knowledge about site topography. Figure 2.8b shows the Isohyets for the basin, with contour spacing of 50 meters. Isohyets take into account the influence of mountainous

landscapes on precipitation. The estimation of AAR using Isohyets gives a result of 556.91 mm/yr. The AAR estimate is for 92.10% of the study site area, but it is assumed that this estimate is representative of the entire VRB. The less than 7.9% that is unaccounted for is because of the error associated with the delineation of the area between the Isohyets.

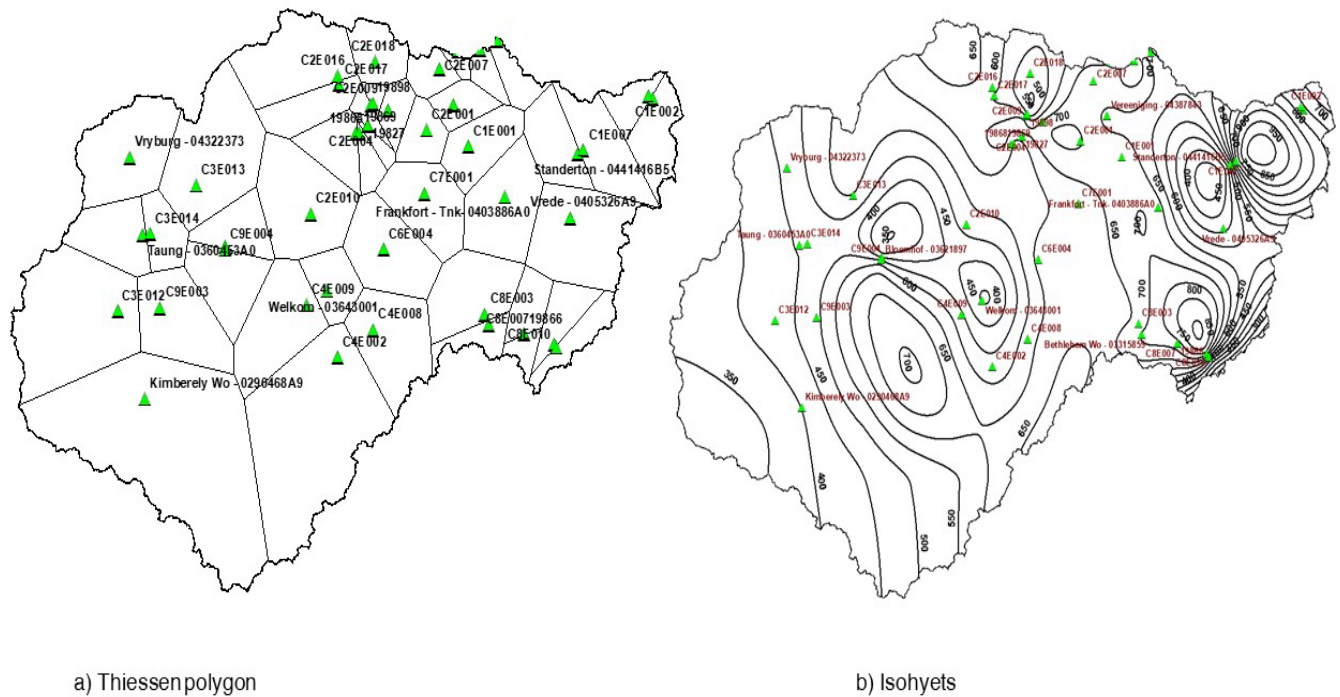


Figure 2.8: The Thiessen Polygons and Isohyets used in estimating aerial annual rainfall.

The AAR estimates by the three methods are comparable; they are shown in Table 2.1. The AAR estimate based on these three methods in the VRB is 563.76 mm/year. It is apparent from the AAR results that the spatial distribution of rain gauge networks and the spatial distribution of rainfall and density of the rainfall gauges influences the AAR estimates (Lee et al., 2018). Lee et al. (2018) demonstrated that the estimation error of the AAR is largest in basins with clustered and poorly distributed rain gauge networks, but low for basins with well distributed rainfall gauge networks.

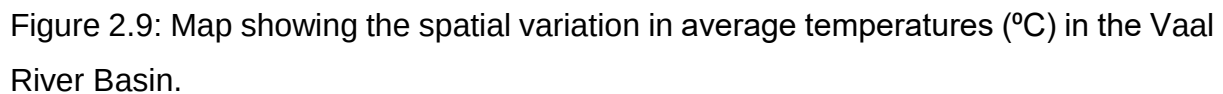


Table 2.1: Aerial average rainfall estimated by three methods: Arithmetic Mean, Thiessen Polygons and Isohyets.

| Arithmetic Mean Method |               | Thiessen Polygon Method |            | Isohyet Method |         |                         |              |               |
|------------------------|---------------|-------------------------|------------|----------------|---------|-------------------------|--------------|---------------|
| Station                | RF (mm/yr)    | Area                    | RF (mm)    | Isohyets (mm)  | Average | Area (Km <sup>2</sup> ) | % Area       | RF (mm)       |
| C3E012                 | 428.22        | 12336                   | 27         | <400           | 350     | 20526.81                | 10.46        | 39.74         |
| C9E003                 | 490.46        | 5976                    | 15         | 400-500        | 450     | 43789.88                | 22.31        | 109.00        |
| C4E009                 | 507.81        | 6290                    | 16         | 500-600        | 550     | 40084.97                | 20.42        | 121.96        |
| C3E014                 | 451.65        | 2296                    | 5          | 600-700        | 650     | 61881.39                | 31.53        | 222.50        |
| C9E004                 | 491.77        | 4166                    | 10         | 700-800        | 750     | 9713.95                 | 4.95         | 40.30         |
| 0290468A9              | 401.47        | 26228                   | 54         | 800-900        | 850     | 3097.31                 | 1.58         | 14.56         |
| C4E002                 | 519.85        | 17712                   | 47         | >900           | 950     | 1681.79                 | 0.86         | 8.84          |
| 3621897                | 443.07        | 2879                    | 6          | <b>Total</b>   |         | <b>180776.09</b>        | <b>92.10</b> | <b>556.91</b> |
| C3E013                 | 546.30        | 9256                    | 26         |                |         |                         |              |               |
| C2E018                 | 523.52        | 2642                    | 7          |                |         |                         |              |               |
| 0360453A0              | 452.69        | 3955                    | 9          |                |         |                         |              |               |
| C2E017                 | 597.03        | 2834                    | 9          |                |         |                         |              |               |
| 4322373                | 462.42        | 7093                    | 17         |                |         |                         |              |               |
| 3643001                | 396.97        | 2585                    | 5          |                |         |                         |              |               |
| 19827                  | 622.01        | 321                     | 1          |                |         |                         |              |               |
| 19869                  | 587.58        | 993                     | 3          |                |         |                         |              |               |
| C2E004                 | 640.18        | 501                     | 2          |                |         |                         |              |               |
| C6E004                 | 611.69        | 5591                    | 17         |                |         |                         |              |               |
| C2E009                 | 602.56        | 399                     | 1          |                |         |                         |              |               |
| C2E010                 | 520.22        | 7473                    | 20         |                |         |                         |              |               |
| C7E001                 | 616.91        | 4936                    | 16         |                |         |                         |              |               |
| C2E016                 | 621.65        | 6742                    | 21         |                |         |                         |              |               |
| 19868                  | 618.97        | 2652                    | 8          |                |         |                         |              |               |
| C8E008                 | 705.78        | 2162                    | 8          |                |         |                         |              |               |
| C8E007                 | 729.33        | 1901                    | 7          |                |         |                         |              |               |
| C8E010                 | 579.37        | 2177                    | 6          |                |         |                         |              |               |
| 19866                  | 732.70        | 872                     | 3          |                |         |                         |              |               |
| 0441416B5              | 566.25        | 3521                    | 10         |                |         |                         |              |               |
| 3315859                | 703.04        | 1623                    | 6          |                |         |                         |              |               |
| C4E008                 | 577.09        | 6152                    | 18         |                |         |                         |              |               |
| C8E003                 | 669.99        | 5143                    | 18         |                |         |                         |              |               |
| 0405326A9              | 489.24        | 7647                    | 19         |                |         |                         |              |               |
| 19898                  | 554.34        | 385                     | 1          |                |         |                         |              |               |
| C2E007                 | 684.61        | 1557                    | 5          |                |         |                         |              |               |
| C2E015                 | 657.38        | 1400                    | 5          |                |         |                         |              |               |
| 4387843                | 640.12        | 1853                    | 6          |                |         |                         |              |               |
| C2E001                 | 702.40        | 2048                    | 7          |                |         |                         |              |               |
| 4763990                | 737.04        | 1063                    | 4          |                |         |                         |              |               |
| 30459                  | 609.34        | 1566                    | 5          |                |         |                         |              |               |
| 0403886A0              | 667.81        | 5865                    | 20         |                |         |                         |              |               |
| C1E001                 | 675.06        | 3579                    | 12         |                |         |                         |              |               |
| C1E002                 | 718.35        | 1611                    | 6          |                |         |                         |              |               |
| 4758790                | 652.81        | 386                     | 1          |                |         |                         |              |               |
| C1E007                 | 782.39        | 4578                    | 18         |                |         |                         |              |               |
| 0479870X               | 711.88        | 3329                    | 12         |                |         |                         |              |               |
| <b>Mean (mm/yr)</b>    | <b>593.36</b> | <b>196273</b>           | <b>541</b> |                |         |                         |              |               |

## 2.4.2 Temperature and potential evapotranspiration

Temperature and evaporation (S-pan) exhibit a similar but opposite spatial variability compared to rainfall. Temperature changes are a function of climate parameters and



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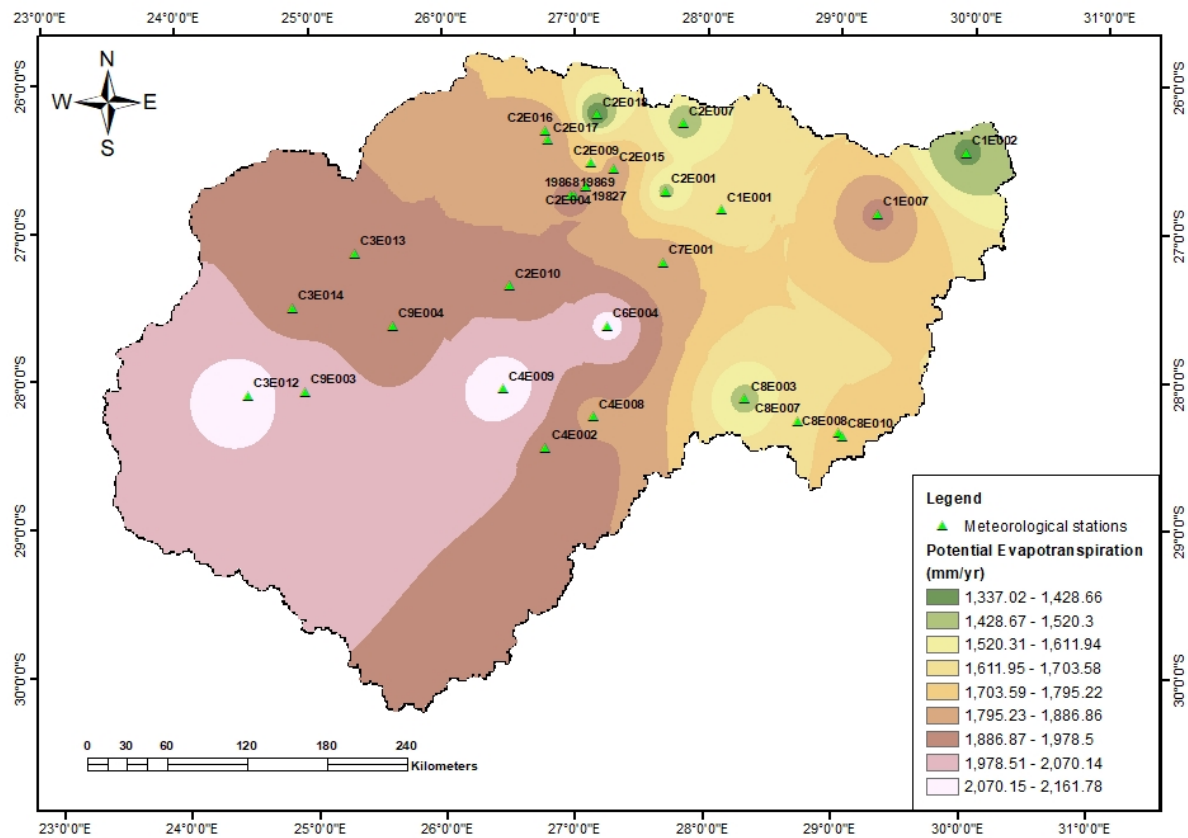


Figure 2.10: Potential evapotranspiration spatial variation map of the Vaal River Basin.

The spatial variability in rainfall, temperature, and evapotranspiration (ET) in the VRB shows the extent of the variability in climate parameters as well as physiographic variation in the basin. The climate variability and physiographic features of the basin have an effect on the amount of overland flow and infiltration, which has a direct effect on terrestrial water storage (TWS).

## 2.5 Land use/cover

The VRB is the economic hub of South Africa (Department of Water Affairs and Forestry [DWAF], 2003a; DWAF, 2003b; van Vuuren, 2008). It has a high concentration of urbanised, industrial, and mining land (see Figure 2.11).

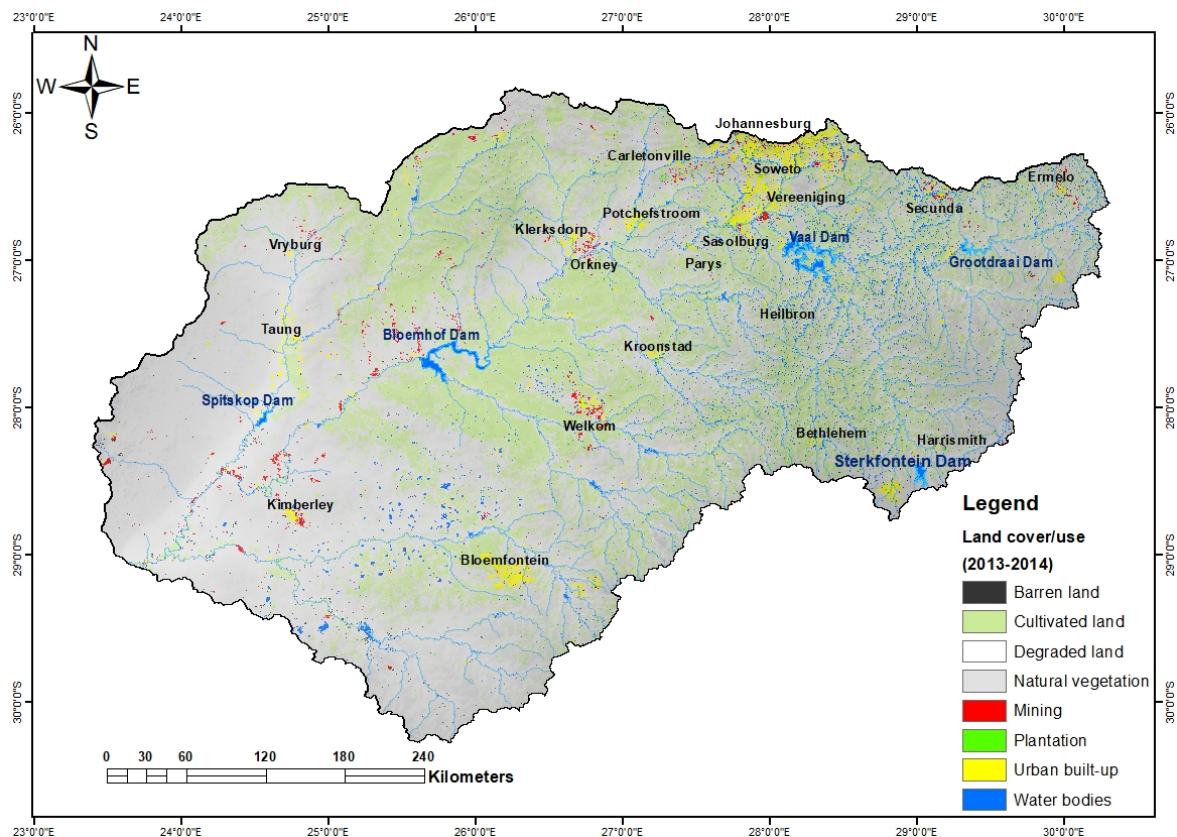


Figure 2.11: Map showing broader land use/cover for the Vaal River Basin (Source of land use/cover shapefiles: Department of Environmental Affairs).

The 2011 Census of SA estimates show that there were more than 12 million people living in the VRB out of a population of 51 million people in SA (Lehohla, 2011). The VRB is characterised by metropolitan towns in close association with mine dumps. More than 79 % of the population in the VRB resides in the upper part of the basin, where economic activities are intense (Lehohla, 2011). Major industries include the petrochemical industries at Sasolburg and steel industries at Vereeniging.

Table 2.2 shows a wide variety of land use/cover (LULC) in the VRB which has no doubt modified the hydrological basin. Agricultural farming is one of the chief land uses in the study area with the largest spatial coverage (23.67%); in most cases, the agricultural lands are generally in the proximity of coal mines and industrial plants.

Table 2.2: The percentage weight of land use/cover in the Vaal River Basin. The land cover/use percentage are calculated from the 2013-2014 National Land Cover-72 classes over the VRB (Source of land use/cover shapefiles: Department of Environmental affairs).

| Land cover/use     | %     |
|--------------------|-------|
| Natural vegetation | 69.25 |
| Cultivated land    | 23.67 |
| Urban built-up     | 2.3   |
| Water bodies       | 2.07  |
| Plantation         | 1.29  |
| Barren land        | 0.65  |
| Mining             | 0.56  |
| Degraded land      | 0.21  |
| Total              | 100   |

The impact of land use practice on the groundwater system varies depending on the intensity of the specific land use practice in the VRB than the percentage of LULC. For example, mining activities and the urban built-up area, which covers less than 3% of the land surface area in the VRB, can have a high impact on groundwater quality than cultivated lands that cover 23.67% of the study area. The impact of mining and the urban-up area could be high because of dewatering associated with mining drainage and waste generation in tailing dams or industrial effluent discharged to rivers.

The VRB continues to experience sprawling urbanisation and industrialisation, which, in turn, puts pressure on the water resources in the area. It is likely that such growth could also severely affect the entire ecosystem.

## 2.6 Drainage and slope

The drainage of a basin is influenced by several factors that includes but is not limited to the slope, soil type, and underlying geology (Yetemen et al., 2010). Figure 2.12 shows that the elevation in the eastern part of the study site is high (>2 000 mamsl) and in the western section it is as low as 1 000 mamsl. The slope and altitude influence

the amount of percolation and surface runoff which governs the redistribution of water in the basin to various water storages such as surface water and soil moisture.

The eastern part of the basin, which is upstream of the Vaal River, has a high drainage density of about  $0.098 \text{ km}^{-1}$ . The western part of the basin, which is downstream of the Vaal River, has a low drainage density of approximately  $0.04 \text{ km}^{-1}$ . Thus, the high drainage density in the basin is most likely because of underlying meta-sedimentary rocks that are relatively impermeable and favour surface runoff rather than infiltration (see Figure 2.15). The low drainage density area is underlain by carbonates and sand that are highly permeable and favours infiltration rather than surface runoff.

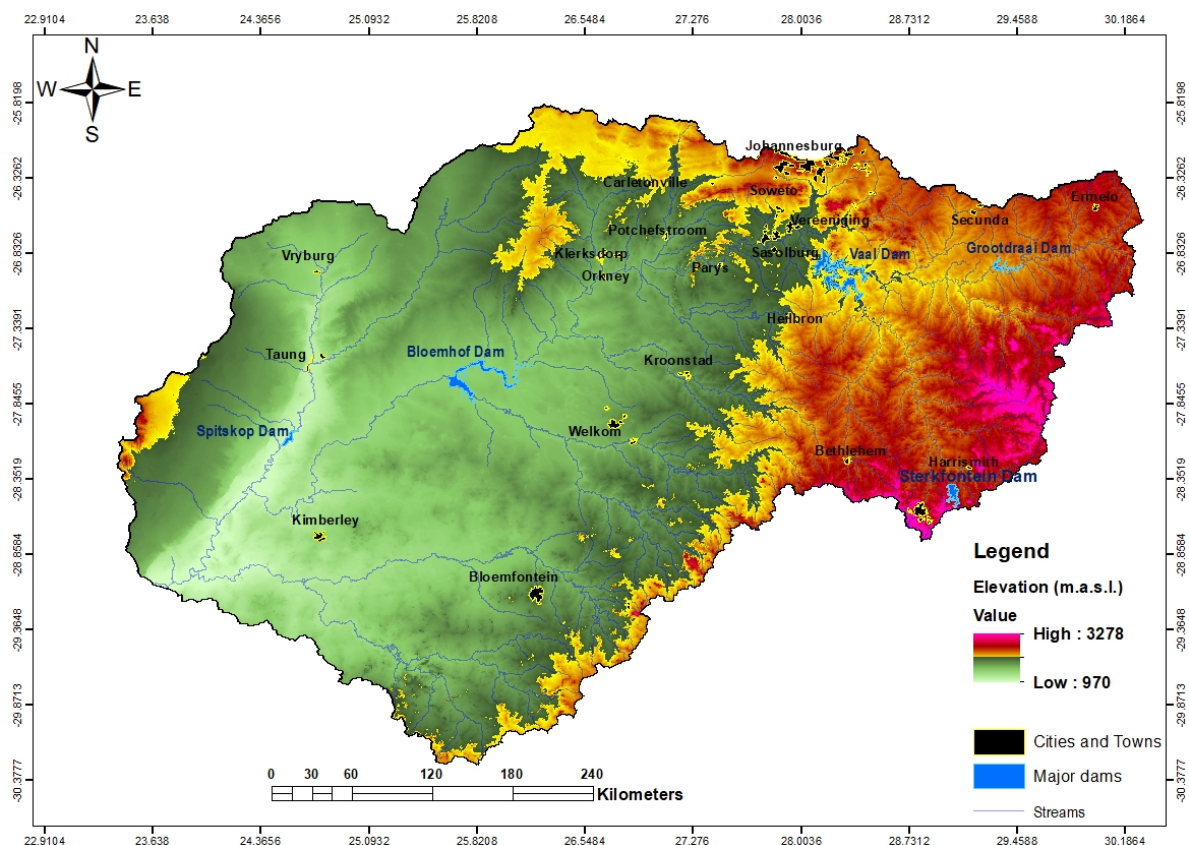


Figure 2.12: Digital elevation map of the Vaal River Basin showing the drainage network and elevation decreasing from the northeast to the southwest (Source of Digital Elevation Model: United States Geological Survey Earth Explorer, <https://earthexplorer.usgs.gov/>).



The topography of the basin is complex with multiple slopes ranging from gently undulating in the western part of the basin to hilly in the east (Figure 2.13). The slope of the topography is very high in the Drakensberg, which is the basin boundary in the southeast near Bethlehem and Harrismith (Figure 2.13).

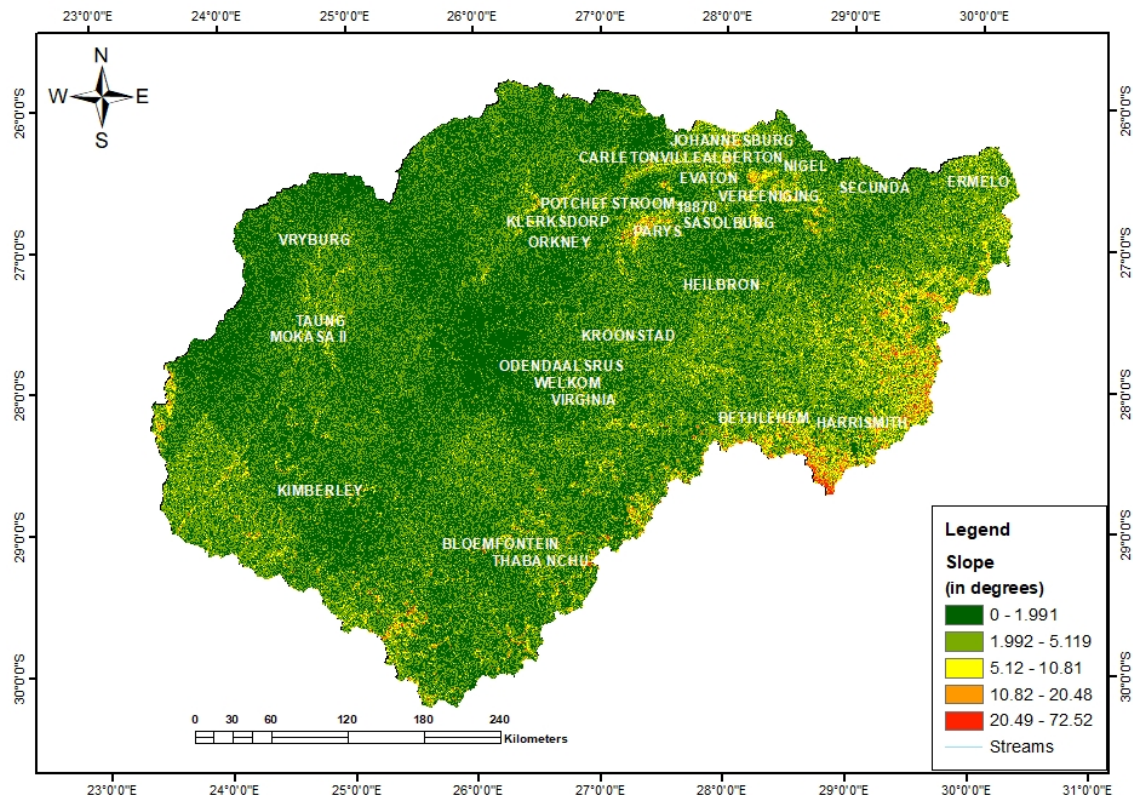


Figure 2.13: Map showing the slope (in degrees) of the Vaal River Basin.

The western part of the basin towards Vryburg and Kimberley and in the Welkom area has a near level slope ( $<5^\circ$ ); this is not surprising given that these locations are situated downstream of the Vaal River (Figure 2.13). The predominant slope class of the VRB is gently undulating – meaning that the slope is less than  $10^\circ$ . A notable feature of the VRB is the pronounced hills with very steep slopes ( $>60^\circ$ ) in the Vredefort Dome area situated about 120 km southwest of Johannesburg in Parys (Figure 2.14). In addition to the underlying geology, the steep slopes induce high surface runoff and low percolation whereas shallow slopes induce low surface runoff and high percolation.



Figure 2.14: Field observation of the undulating and hilly topography in the Vredefort Dome in Parys (Courtesy of Mr Khuliso Masindi).

## **2.7 Geological framework**

### **2.7.1 General overview of the geology**

SA contains some of the oldest rocks in the world; these rocks are diverse in nature and cover the entire geological record (Johnson et al., 2006). The rocks host significant economic minerals such as gold and coal that are found in the Witwatersrand Basin and the Karoo Basin (Johnson et al., 2006; McCarthy, 2006). The rocks of the Karoo Basin are rich in vertebrate fauna and fossil plant deposits



(Bamford, 1999). The geology of SA has been well studied and documented in various reports and publications. For detailed information on the tectonic setting, geological evolution and depositional environment of the rocks discussed below, the reader must refer to "*The Geology of South Africa*" first edition published in 2006 and edited by M.R Johnson, C.R Anhaeusser and R.J Thomas.

The geology of the VRB is heterogeneous, and complex. It is marked by lineaments in the southeastern and the southwestern parts of the basin (Figure 2.15). The VRB consists of a wide variety of rock types such as volcano-sedimentary, igneous, and metamorphic rocks that cover the entire geological record from the Palaeoarchaeon Archaeon to late Cenozoic. These rocks are within the Kaapvaal Craton, which is one of the most stable lithospheric fragments in the world (Anhaeusser, 2006). The rocks found in the VRB crops out at several localities with varying spatial coverage, thus the focus is on rocks with wide spatial coverage.

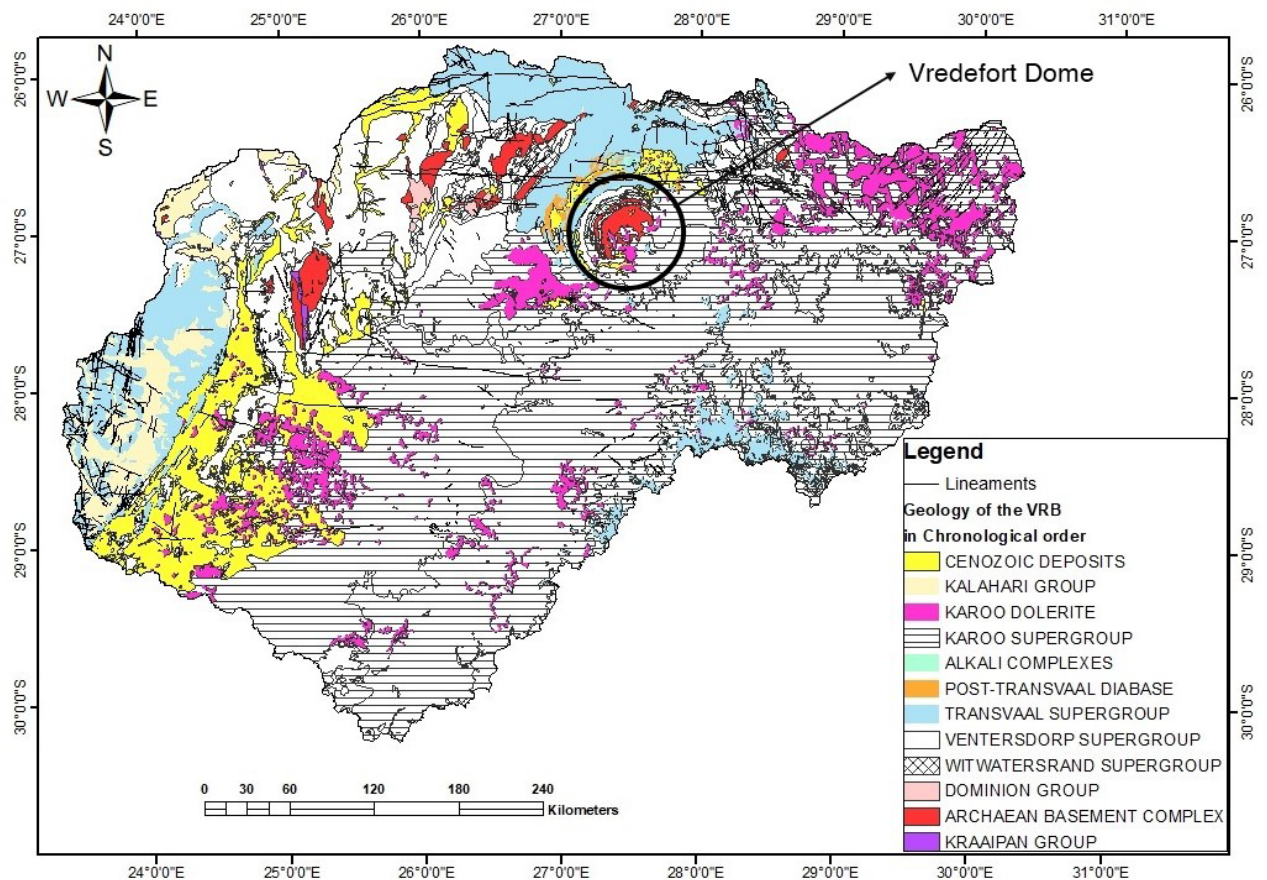


Figure 2.15: A simplified geological map of the Vaal River Basin (Source of geological data: Council for Geosciences From the 1:1000000 geological map of South Africa prepared by the Council for Geosciences). The predominant rocks associated with a particular stratigraphic unit are included in the legend. Note: Spg and Gp refer to Supergroup and Group, respectively.

### 2.7.2 The Archaean Granite and Gneiss, Kraaipan Group, and Dominion Group

Some of the oldest rocks in the VRB are the Kraaipan and Amalia greenstone belts. The granitic gneisses range in age from approximately 3 500 to 2 700 Million years Ago (Ma) (Barton et al., 1989; Brandl et al., 2006). The greenstone in the VRB is poorly exposed, and there are outcrops in the western part of the basin. The granitic gneisses and granitoids are exposed in the western part of the basin and in the core of the Vredefort Dome (Figure 2.15). The volcanic and subordinate clastic sedimentary rocks of the Dominion Group (3074±6 Ga, Single Zircon U-Pb SHRIMP; Armstrong et al.,

1991) overlay the granitic gneiss basement (Marsh, 2006). The Dominion Group rocks are metamorphosed at greenschist-amphibolite grade. Surface exposure of the Dominion Group is limited to the northeastern part of the VRB (Figure 2.15). The Dominion Group and the Archaean basement granites are unconformably overlain by the Witwatersrand Supergroup (ca. 2 985-2 849 Ma, Kositsin & Krapež, 2004) (Marsh, 2006).

### 2.7.3 The Witwatersrand Supergroup

The Witwatersrand Supergroup is poorly exposed across the VRB (Figure 2.16). It outcrops as a thin veneer at the collar of the Vredefort Dome and northwest of Johannesburg at Heidelberg and Johannesburg (Figure 2.16). Younger sediments of the Transvaal and Karoo Supergroup cover a large part of the Witwatersrand.

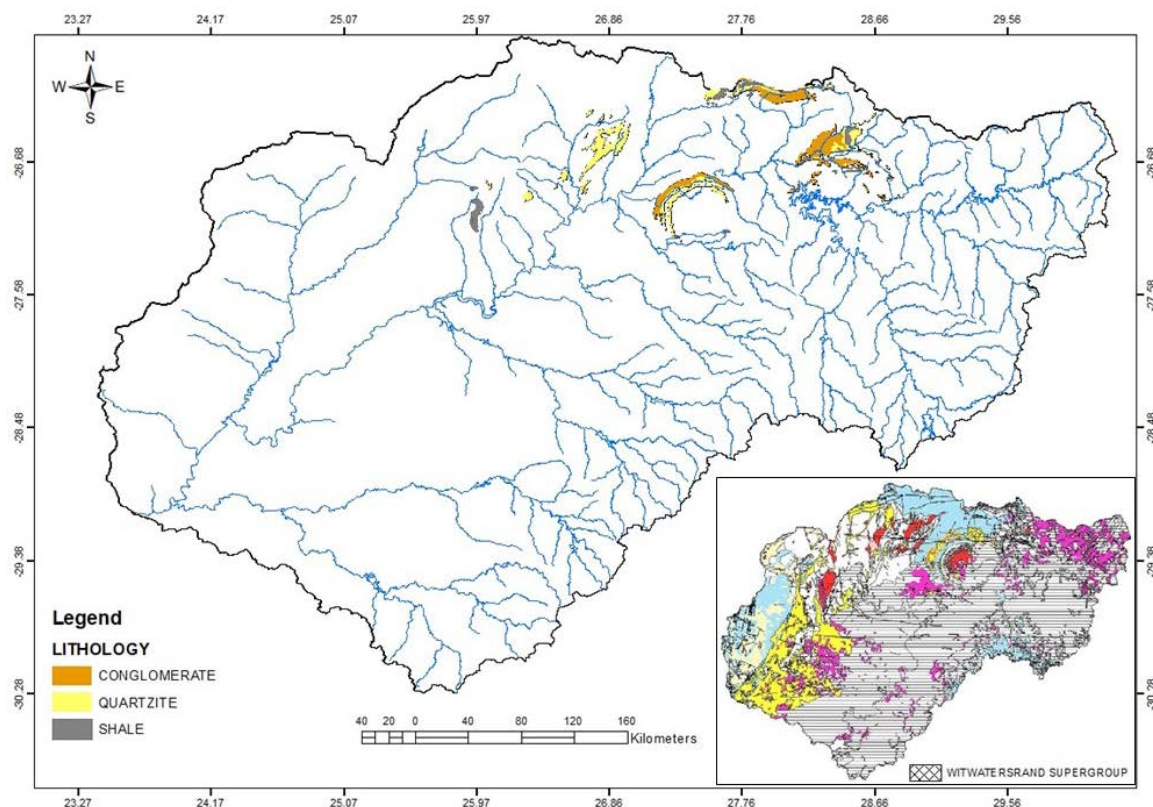


Figure 2.16: Exposure of the Witwatersrand Supergroup rocks in the Vaal River Basin (Source of geological data: Council for Geosciences, South Africa).

The Witwatersrand Supergroup consists of 7 km of thick sedimentary rocks, mainly: quartzite, shale, and conglomerate. These rocks represent sediments deposited in a fluvio-deltaic environment (Barton et al., 1989; Robb & Meyer, 1995; McCarthy, 2006). The Witwatersrand Supergroup is subdivided into the lower West Rand Group and the upper Central Rand Group. The Central Rand Group is further subdivided into the Turffontein Subgroup and the Johannesburg Subgroup. The West Rand Group is subdivided into three subgroups: Hospital Hill Subgroup, Government Subgroup and Jeppestown Subgroup. The West Rand Group comprises predominantly quartzite and iron-rich shale about 4.5 km thick (Barton et al., 1989; McCarthy, 2006) at a ratio of 1:1 (Pretorius, 1976). The West Rand Group also consist of eight magnetite-bearing shales and iron formations interlayered with the shales (McCarthy, 2006). There are also diamictite units that contain granitic clasts (ibid.). The Central Rand Group consists primarily of quartzite and shale at a ratio of 12.6:1 (Pretorius, 1976), conglomerate and gold-rich subgraywacke and diamictite (Barton et al., 1989; McCarthy, 2006). The Ventersdorp Supergroup unconformably or conformably overlies the Witwatersrand Supergroup (van der Westhuizen et al., 1991; van der Westhuizen & Bruijn, 2000).

#### **2.7.4 Ventersdorp Supergroup**

The poor exposure of the Ventersdorp Supergroup in the VRB is a result of sedimentary and volcanic rocks of the Transvaal and Karoo Supergroups that cover it. Outcrops occur mainly in the western parts of the basin and have little exposure in the northeast (Figure 2.17). The Ventersdorp Supergroup (Neoarchaeon) represents the most extensive volcano-sedimentary sequence within the Kaapvaal Craton (van der Westhuizen et al., 1991).

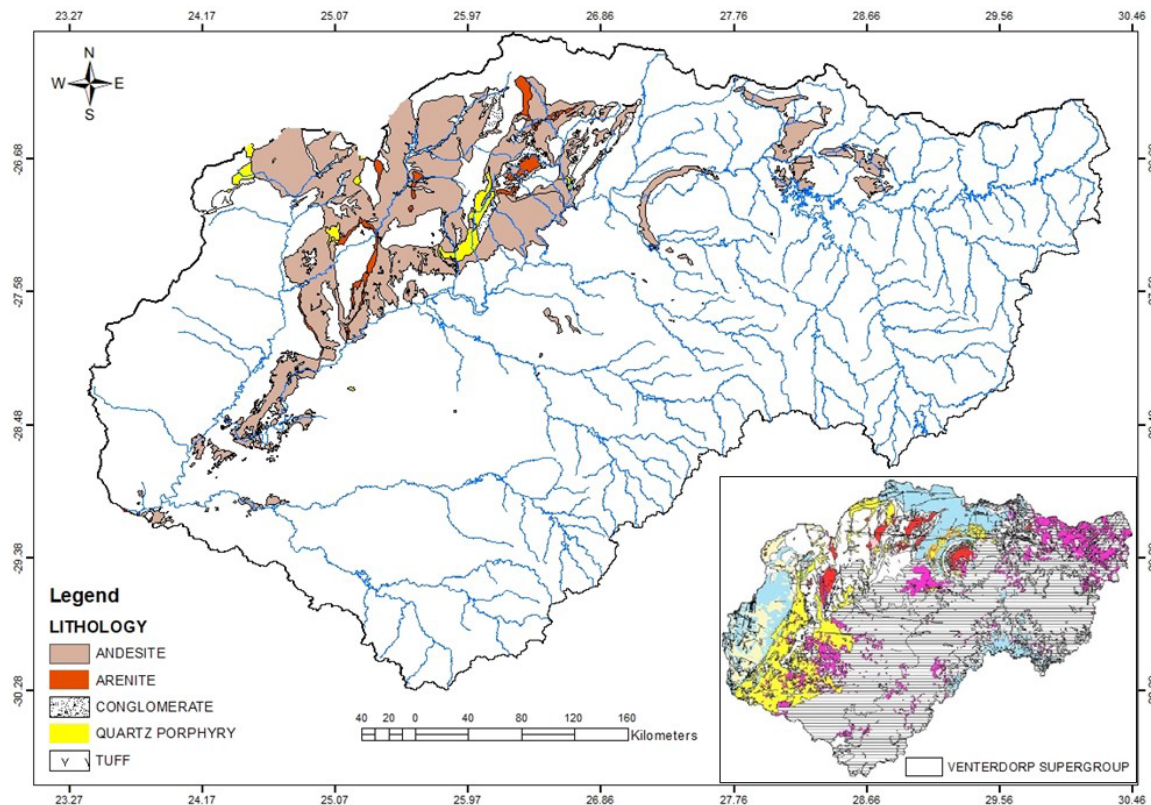


Figure 2.17: Exposure of the lithology of the Ventersdorp Supergroup in the Vaal River Basin (Source of geological data: Council for Geosciences, South Africa).

The Ventersdorp Supergroup comprises mainly volcanic, pyroclastic and mature sediments (Winter, 1976; Crow & Condie, 1988; van der Westhuizen et al., 1991; van der Westhuizen & Bruijn, 2000) within three stratigraphic subdivisions: the basal Klipriviersberg, Platberg and Pniel groups (Winter, 1976). The Klipriviersberg Group covers a widespread area of the Gauteng and North West Province, in the Witwatersrand Basin (Figure 2.17). The Klipriviersberg Group is marked by the prevalence of sub-aerially extruded mafic lavas (tholeiitic basalt) and lesser pyroclastic rocks (e.g. tuff) (Crow et al., 1988; van der Westhuizen et al., 1991; van der Westhuizen & Bruijn, 2000). The Platberg Group unconformably overlies the Klipriviersberg and comprises volcano-sedimentary rocks. Volcanic and pyroclastic rocks and mature sediments of the Pniel Group (van der Westhuizen et al., 1991), in turn, overlie the Platberg Group. Crow et al. (1988) suggest that the lack of sedimentary rocks in the Klipriviersberg Group is probably due to the rapid ascent of



lava. The Transvaal Supergroup (Neoarchaeon to Palaeoproterozoic) unconformably overlies the Ventersdorp Supergroup.

### 2.7.5 The Transvaal Supergroup

The Transvaal sequence (Neoarchaeon to Paleoproterozoic) is preserved in three structural basins: Transvaal, Kanye, and Griqualand West (Altermann & Wotherspoon, 1995; Eriksson et al., 1995; Eriksson & Altermann, 1998). In the VRB, the Transvaal Supergroup is preserved in the Transvaal and Griqualand West basins (Figure 2.18). The predominant lithology includes carbonates, quartzite, volcanic and fine to coarse sedimentary rocks. These rocks are exposed in the central part of the VRB where the Transvaal Basin is found and in the southwestern part within the Griqualand West Basin (Figure 2.18).

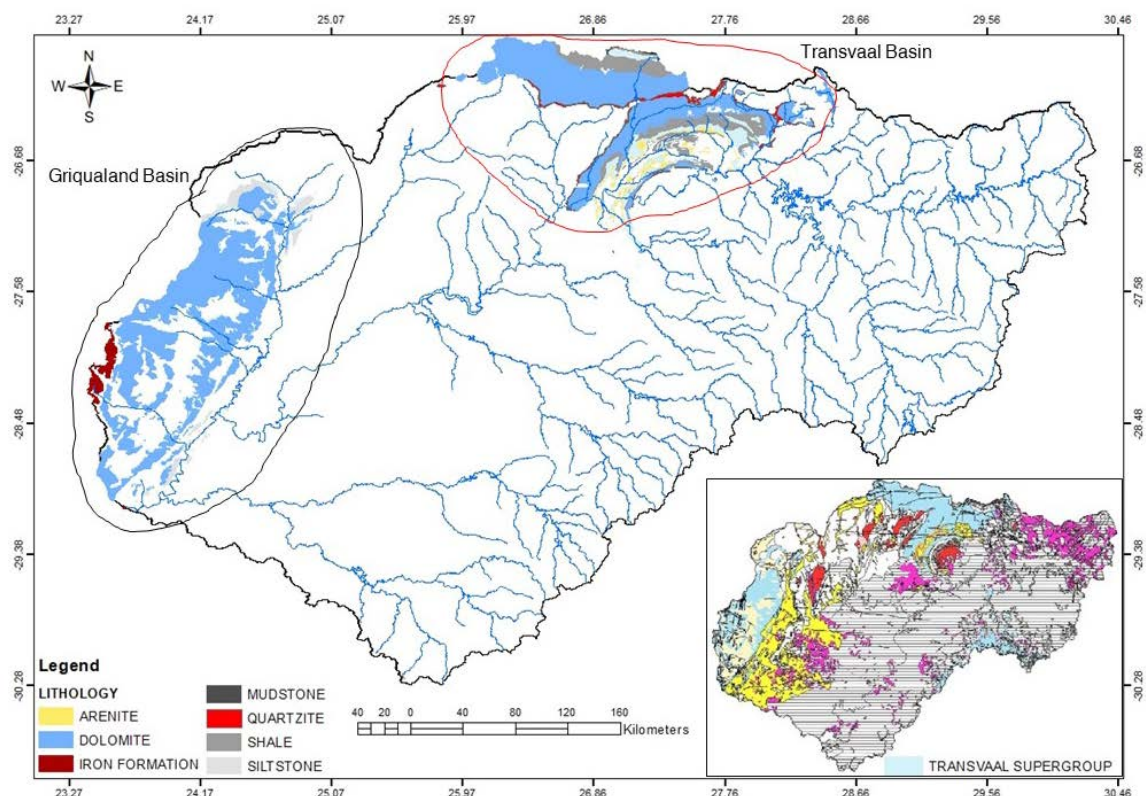


Figure 2.18: Locality map of the Transvaal Supergroup in the Vaal River Basin (Source of geological data: Council for Geosciences, South Africa).

In the Transvaal-Griqualand West Basin, the geology is sub-divided into three lithostratigraphic units: Chuniespoort-Ghaap Group, Pretoria-Postmansburg Group, and Rooiberg Group (SACS, 1980; Eriksson et al., 2006). The Chuniespoort-Ghaap Group overlies the Black Reef Quartzite-Vryburg Formation which, in turn, is overlain by the Pretoria Group (Eriksson et al., 2006; Hobbs & Cobbing 2007). The Malmani-Campbellrand Subgroup that belongs to the Chuniespoort-Ghaap Group consists primarily of carbonates (dolomite and limestone) (Eriksson et al., 2006). The Malmani Subgroup is subdivided into the Frisco, Eccles, Lyttelton, Monte Christo, and Oak Tree Formations (ibid.). The subdivision is based on chert content, form and shape, algae in dolomite and provenance (SACS, 1980). The Pretoria Group consists predominantly of alternating fine to coarse-grained sedimentary and volcanic rocks (Eriksson et al., 2006). Syenite dykes associated with the Pilanesberg Complex intrude the Pretoria Group and the underlying Chuniespoort Group (Swart et al., 2003). Eriksson and Altermann (1998) suggest that the likely environment of deposition of the Transvaal sequence is a shallow marine environment.

#### **2.7.6 The Karoo Supergroup**

More than two-thirds of the study area is covered by younger alternating argillaceous and arenaceous rocks that belong to the Late Carboniferous to Early Jurassic Karoo Supergroup (Figure 2.19) (Mason & Christie, 1986; Johnson et al., 2006). The Karoo Supergroup is well-known for sub-continental economic coal that is actively mined in the upstream portion of the VRB, in the Mpumalanga Province (Johnson et al., 1996; Johnson et al., 2006) (Figure 2.19). The Karoo sediments can reach up to 12 km in thickness (Johnson et al., 2006).

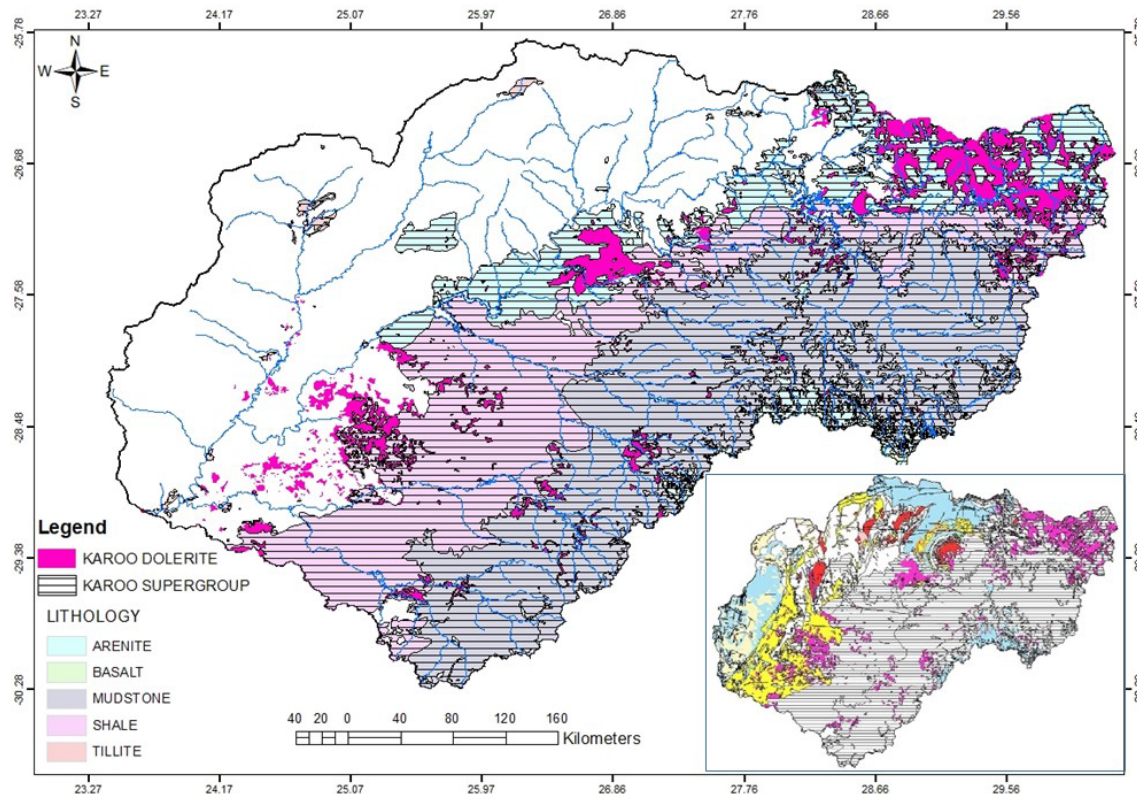


Figure 2.19: Locality map of the Karoo Supergroup in the Vaal River Basin (Source of Geological data: Council for Geosciences, South Africa).

The Karoo Supergroup is famously known for rich vertebrate and plant fossils (ibid.). It is sub-divided into the Dwyka, Eccca, and Beaufort and Stormberg Groups plus Drakensberg volcanics (Johnson et al., 1996; Duncan & Marsh, 2006). The Vryheid Formation of the Eccca Group comprises sandstone, shale and coal (Johnson et al., 1996) which is currently mined in the Vereeniging and Mpumalanga areas (Johnson et al., 1996; Johnson et al., 2006). Dolerite dykes and sills intrude the Karoo Supergroup.

The dolerite intrusions are widely exposed in the VRB, particularly in the southeast part of the basin (Figure 2.19). These dolerite intrusions occur as an interconnected network of dykes and sills in saucer-shaped sheets (Coetzee, 2016). The dolerite intrusions represent a shallow feeder system of the Drakensburg volcanics.



### 2.7.7 The Cenozoic Deposits and the Kalahari Group

The Kalahari Group of Cenozoic Era covers a large part of the basin in the southwest part (Figure 2.20). It is comprised of sediments up to 130 m in thickness, including clayey gravels, calcareous clays, calcified root casts, unconsolidated sands and sandstone, and siltstone with a thin pebble layer at the base (Patridge et al., 2006).

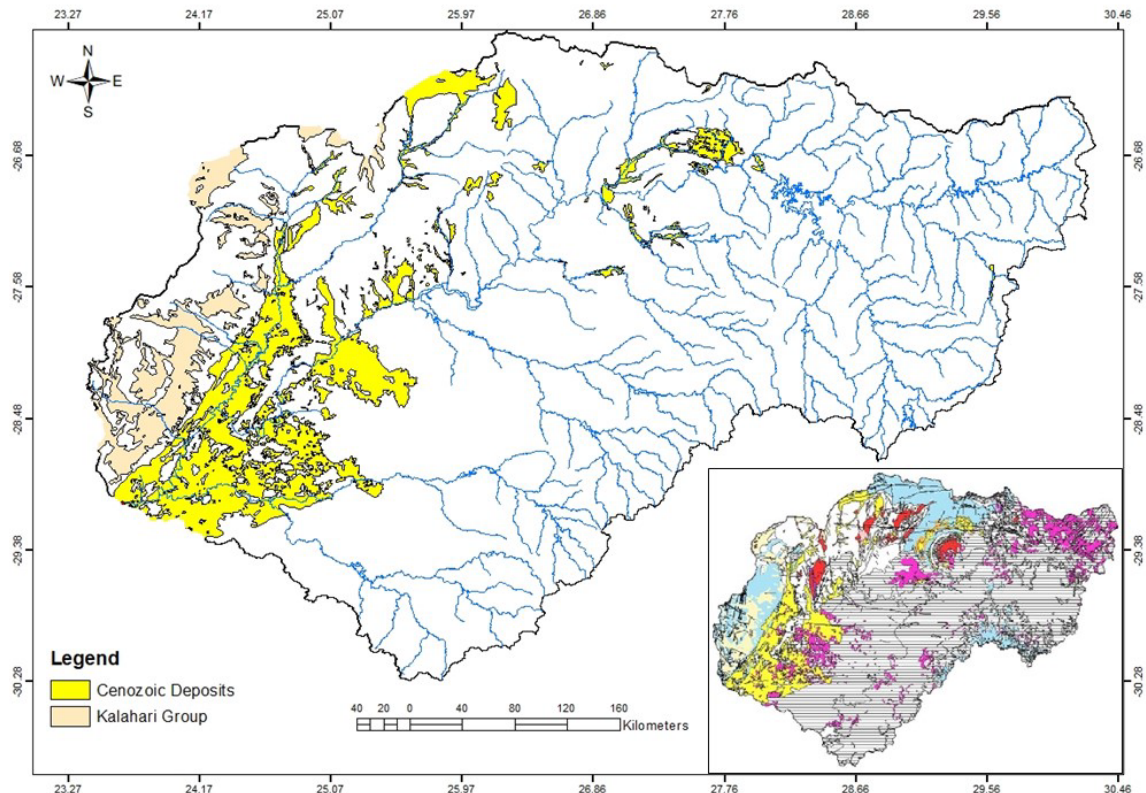


Figure 2.20: Locality map of the Cenozoic Deposits (Source of Geological data: Council for Geosciences, South Africa)

### 2.7.8 The Vredefort Dome

The Vredefort Dome is exposed in the north-central part of the VRB (Figure 2.15). At its core are weathered Archaean basement rocks such as granitoid gneisses and migmatites (Figure 2.21). It also consists of pelite, iron formation, and mafic gneiss xenoliths that have been metamorphosed to upper amphibolite to granulite grade (Brandl et al., 2006). The collar rocks comprise a thin veneer of the Witwatersrand Supergroup, which is partially covered by the Karoo sediments in the northeast.



Figure 2.21: Archean basement granite at the core of the Vredefort Dome in Parys (Courtesy of Mr Khuliso Masindi).

Field surveys show that the sedimentary and volcanic strata dip at an angle ranging from  $42^{\circ}$  to  $68^{\circ}$  in the southerly direction. The collar meta-sedimentary rocks are intensely fractured and jointed. The intense fracturing of the quartzite in the Vredefort Dome can be seen in (Figure 2.22). There is no doubt that the fractures and joints facilitate recharge and groundwater flow in the fractured crystalline rocks within the Vredefort Dome.





Figure 2.22: Highly fractured quartzite in the Vredefort Dome (\*pen shown for scale)  
Courtesy of Mr Khuliso Masindi).

The study site of this research also hosts of several ultramafic and mafic intrusions that exhibit a wide range of geochemical composition and occur in variable sized intrusive bodies. These igneous intrusions in the Kaapvaal Craton of South Africa have an age range from the Archaean (>3 600 Ma) to the late Cretaceous Period (c. 65 Ma) (Anhaeusser et al., 2006).

#### **2.7.9 Major deformation events in the Vaal River Basin**

The VRB is characterised by numerous discontinuities of various size and extent in the form of faults, dykes, and sills. These structural discontinuities in the VRB facilitate percolation and groundwater circulation in the crystalline rocks. Very few deformation events have occurred in the basin but are instead linked to the sedimentation of the

Witwatersrand Basin, and volcanism of the Ventersdorp Supergroup and intrusions of complexes (McCarthy, 2006).

McCarthy (2006) reported three deformation events in the Witwatersrand Basin. The first is a result of regional compressional stress linked to the sedimentation of the Central Rand Group. This regional compression is believed to have caused fragmentation of the basins into sub-domains bounded by discontinuities and accompanied by uplift and thrusting. The resultant geological structures are overfolds, horst blocks, and faults. The second deformation event is related to the eruption and volcanism in the Klipriviersberg Group. McCarthy (2006) indicated that this volcanism was an extensional event resulting in the reactivation of earlier thrust faults to normal faults, and that the movement is strike-slip. Uplift of the surrounding basement consequently deforms the adjacent sedimentary sequence, which is post-Transvaal deformation (McCarthy et al., 1986). The folding and faulting of rocks linked to the Vredefort Dome influences groundwater recharge and circulation at a local and regional scale.

## **2.8 Hydrogeological framework**

The underlying lithology and latter geological activities (brittle and ductile deformation) and processes (weathering) have a tremendous influence on the groundwater occurrence in an area. The Malmani Subgroup is regarded as an excellent aquifer of high groundwater productivity in the basin (Barnard, 2000). The volcano-sedimentary and meta-sedimentary successions are characterised by low groundwater productivity because of low primary effective porosity and permeability (Vegter, 2001).

From a hydrogeological point of view, four types of aquifers are identified in the study site based on how groundwater flows and is stored in the void spaces of the rocks. These four aquifer types are based on those presented in the explanatory note compiled by Barnard (2000) of the 2526 Johannesburg map, namely:

1. Karst aquifers in the Transvaal Supergroup carbonates

2. Intergranular aquifers in alluvial-covered areas
3. Fractured aquifers in the Witwatersrand Supergroup
4. Intergranular and fractured rock aquifers in the Dominion Group, Klipriviersberg Group, and Karoo Supergroup.

### **2.8.1 Karst aquifers**

The dissolution of carbonate in the VRB along bedding planes and structural discontinuities result in the development of dissolution cavities, sinkholes, caves, and fissures which act as media for groundwater flow and storage. In general, the dissolution cavities, fissures, and fracture network act as conduits for groundwater movement and recharge (Holland & Witthüser, 2009; Abiye et al., 2011). The Malmani-Postmansburg Subgroup is recognised as the most productive aquifer in South Africa and in the VRB (Barnard, 2000; Vegter, 2001). The dolomite aquifer occurs as an extensive northwest to southwest belt around the Johannesburg area (Figure 2.18). It covers an area of 2 850 km<sup>2</sup> (DWAF, 2006). The chert layers intercalated with the dolomite influences the dolostone water-bearing capacity (Barnard, 2000). The chert layers are resistant to erosion, whereas the dolomite dissolves easily, resulting in the formation of cavities. The approximate thickness of the dolomite alternating with chert layers is about 380 m to 700 m, respectively (DWAF, 2006).

Buttrick et al. (1993) and DWAF (2006) reported high storativity values (9.7%) and transmissivity values (30 000 m<sup>3</sup>/day) for the dolomitic aquifer. The Karoo rocks (sandstone, shale, tillite, and clay) fill the valley topography in the dolomitic terrain and in some parts; quartzite ridges flank the dolomite (Kafri & Foster, 1989; Barnard, 2000; Swart et al., 2003).

The dolomitic aquifer is cross-cut by steeply dipping lineaments in the form of impervious and silicified faults and dykes into distinct groundwater compartments from east to west (Humphrey, 1909; Bredenkamp 1986; Buttrick et al., 1993). These dykes are also responsible for the occurrence of springs in the dolomitic terrain (Humphrey, 1909). There are WNW-ESE trending faults (e.g. Rietfontein Fault) and major fractures, resulting from post Transvaal tensional tectonics, that penetrated the whole

sequence of the Malmani Subgroup and Ventersdorp lavas into the underlying Witwatersrand Supergroup (Swart et al., 2003; Hobbs & Cobbing, 2007). Bredenkamp (1986) suggests that deep-seated faults and fractures provide a medium for groundwater circulation at considerable depth in non-karstified dolomite. The karst aquifer is therefore threatened by pollution from return flows from mining and industries, and effluent discharge from sewage works (Hobbs & Cobbing, 2007) which may penetrate along these deep-seated structures.

### **2.8.2 Intergranular aquifer**

This is associated with highly weathered rocks that have become loose and unconsolidated sediments such as sands and gravels that are found along topographical depressions such as valleys and riverbanks (Barnard, 2000). Data from the nearby Vaalkop Dam suggests that alluvial sediments have high yield potential that is above 5.0 l/s (ibid.).

The Kalahari Sands to the southwest of the VRB make up a large portion of the intergranular aquifers (Figure 2.20). The alluvial along stream banks, valleys, and dongas are also considered intergranular aquifers. They contain pore spaces which facilitate groundwater flux. The intergranular aquifer temporarily stores water and can recharge the underlying hard rocks.

### **2.8.3 Fractured aquifers**

The water-bearing lithology under the fractured aquifer includes, but is not limited to, the quartzite, conglomerate, and minor shale of the Pretoria Group and Witwatersrand Supergroup. Intense fracturing and jointing make these meta-sedimentary rocks good aquifers. Field observation shows intense fracturing of these rocks which, in turn, allows for preferential recharge (Figure 2.23).



Figure 2.23: Intense fracturing of a rock mass - quartzite; these fractures facilitate vertical recharge.

Groundwater occurrence is between 20 meters below ground level (mbgl) to 25 mbgl for the Witwatersrand Supergroup. The sub-vertical to vertical fractures act as pathways for groundwater flow and are important in regulating groundwater recharge (Abiye, 2011). Aquifer development is a result of the competent nature of the quartzite and conglomerate. The quartzite and conglomerate deform in a brittle manner resulting in secondary permeability (fractures and joints).

It was reported that sub vertical-to-vertical faults, fractures and joint sets die out at depth, consequently resulting in a decrease in permeability (Bredenkamp, 1986). The fractured aquifers have a low to moderate groundwater productivity with borehole yields of less than 2 l/s (Barnard, 2000). Hobbs and Cobbing (2007) reported relatively low to modest transmissivity values ( $<10 \text{ m}^2/\text{d}$ ) and low storativity ( $<1\%$ ) for both the Black Reef Quartzite Formation (Transvaal Supergroup) and the West Rand Group (Witwatersrand Supergroup). Groundwater flow is associated with zones characterised by high fracture density that intersect at right angles.



#### **2.8.4 Intergranular and fractured aquifers**

Groundwater penetration is through the weathered rocks and unconsolidated sediments. The weathered rocks and unconsolidated sediments serve as a reservoir, which then recharges the underlying fractured aquifers. The intergranular and fractured aquifers have average borehole yields of more than 2l/s (Barnard, 2000). The average groundwater levels range between 5 to 30 mbgl (ibid.).

### **2.9 Groundwater levels in the Vaal River Basin**

It can be seen in Figure 2.24 that the groundwater levels, as represented by red triangles mimic the topography. The dolomite –Figure 2.24 - has the greatest thickness compared to other lithology, which is not surprising given that in the preceding paragraphs it was noted that it is an excellent aquifer. Nonetheless, the thickness of the dolomite is highly variable, which influences its water bearing capacity. The dolomite has varying groundwater productivity depending on the local geological stress that they have underwent that impact their transmissivity and conductivity. The water table is often at the boundary between siltstone and dolomite.



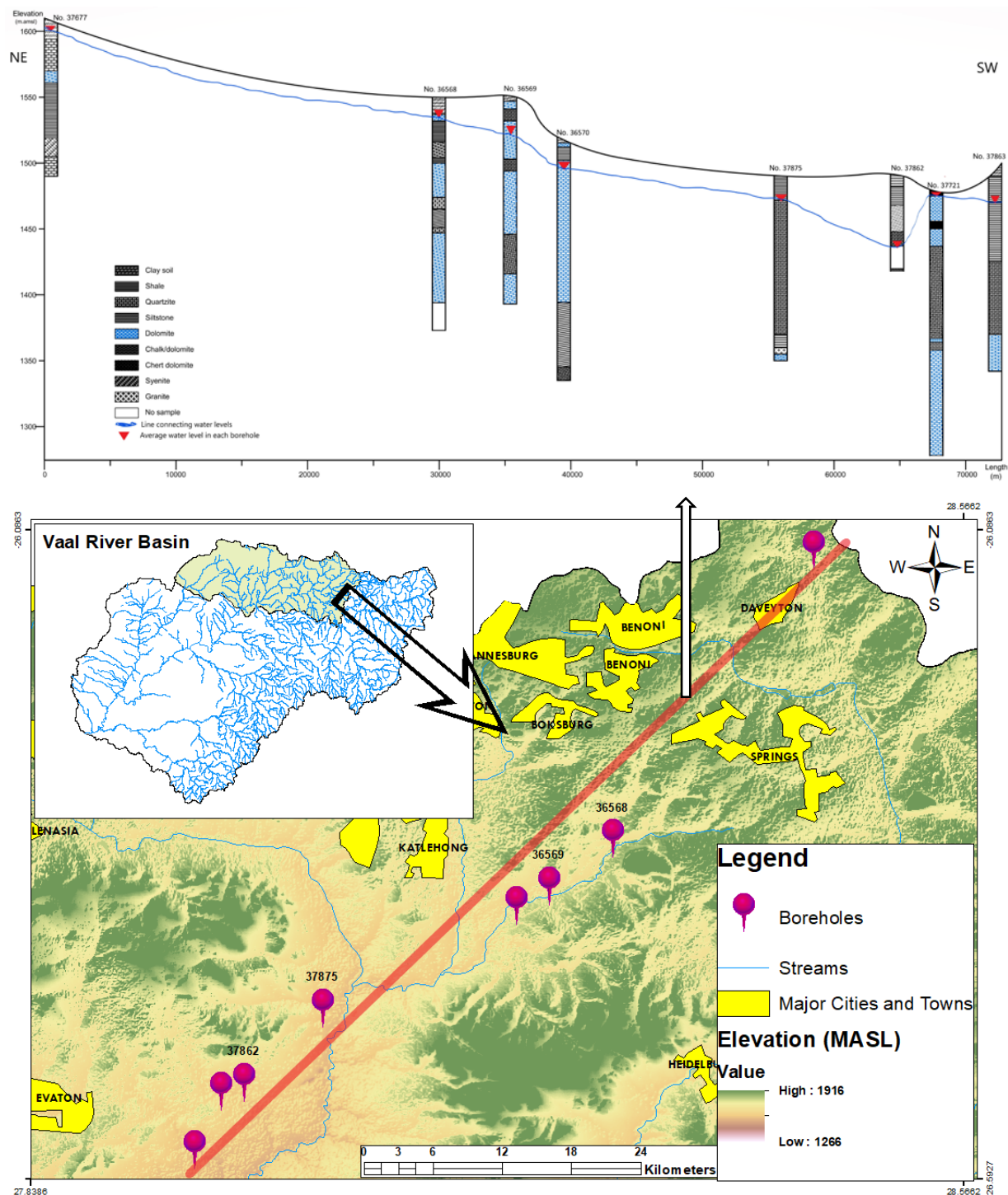


Figure 2.24 Fence diagram showing the logs of eight boreholes along the dolomite in the Vaal River Basin (Source of borehole log data: National Groundwater Archive). The black line represents the topography; red triangle denotes a water level. The red line is the cross-section line in the upper part of the VRB.

### **3 THEORETICAL FRAMEWORK AND CONCEPT**

In the previous chapter, a detailed description of the Vaal River Basin (VRB) was presented which illustrated the extent of variation in climatic variables, geology and hydrogeology. These influence the storage and quality of groundwater as well as streamflow. In the current chapter, an overview of essential concepts is presented. Each of the concepts discussed is crucial in the estimation of the changes in groundwater storage. Similarly, such concepts are also important in understanding how groundwater storage fits in the overall water balance and the hydrological cycle. Initially, a definition of the hydrological cycle is presented, followed by an explanation of terrestrial water storages. Finally, the linkage between simple water balance with terrestrial water storage estimation is highlighted.

#### **3.1 The Hydrological Cycle**

Most hydrological studies attempt to quantify the hydrological components in order to understand how the storage in a basin is changing. Therefore, explaining the main processes of the hydrological cycle is key to understanding and quantifying the influential factors in a basin.

The hydrological cycle is the process of circulation of water in various forms (gas, liquid and ice) among the ocean, land and atmosphere. It involves the transformation of liquid saline oceanic water to vapour during the evaporation process. The water vapour ascends under the influence of solar energy to join the atmospheric circulation, where it later condenses and returns to the land surface and the ocean as precipitation (Hendriks, 2010). Precipitation is then stored in various terrestrial water storage reservoirs (see Section 3.2). The gravitational force facilitates movement of overland water down-gradient to the ocean (ibid.). Through this endless circulation, the hydrological cycle plays a crucial role in replenishing the Earth's freshwater resources, which are necessary for sustaining life on Earth. The water cycle transcends water with linkages to the chemical, biological, and physical processes of the basin (Todd & Mays, 2005) - making it a very complex cycle. This complex cycle is also linked to the climate system, which provides energy through solar radiation, moisture inputs such as daily precipitation, which affect air temperature, relative humidity, and wind speed

that in turn, drives the balance in the hydrological system (Arnold et al., 2012). The availability of freshwater resources is important in sustaining ecosystems and life on Earth.

The rate at which the hydrological processes interact and occur largely depend on the spatial scale (Hendriks, 2010). To explore some of the most important aspects of the hydrological system, this research focuses on processes occurring on a watershed or basin scale. A drainage basin is an area of land that collects water for the river (ibid.). The water flows within the basin and exits at the outlet of the basin. A drainage basin provides a context for better understanding the interdependency of the hydrological processes, water storages, and inputs and outputs in the hydrological system. This interdependency enables impact assessment of how the environment naturally changes or how humans influences the hydrological system and water availability in the various reservoirs. Both human impact and water availability are key aspects in the management of water resources.

### **3.1.1 Hydrological system under natural conditions**

The hydrological system consists of: (1) input and output process, (2) hydrological processes, and (3) water storage (Figure 3.1) that interact at different spatial and temporal scales (ibid.). Liquid or solid precipitation from the atmosphere represents a major input of water in a basin. Interception by the vegetation cover occurs during a precipitation event and reduces the amount that reaches the groundwater surface. The precipitation that reaches the ground surface is “referred” to as the net precipitation (ibid.). On reaching the ground surface, the water will infiltrate into the soil and some will be surface runoff. The water that infiltrates the soil will be stored in the soil moisture zone - also referred to as the unsaturated zone; some of this water will flow through the unsaturated zone to the surface in the form of interflow. A certain amount of water from the soil moisture zone will reach the water table adding to the groundwater reservoir in a process termed effective recharge (Sharma, 1986). Groundwater flow will discharge into surface water as baseflow through springs and seepages into surface depressions that intersect the water table. The interflow, baseflow and direct

surface runoff constitute surface water that discharges at the outlet of the basin. This continuous movement of water in the basin influences the changes in the volume of water in hydrological stores.

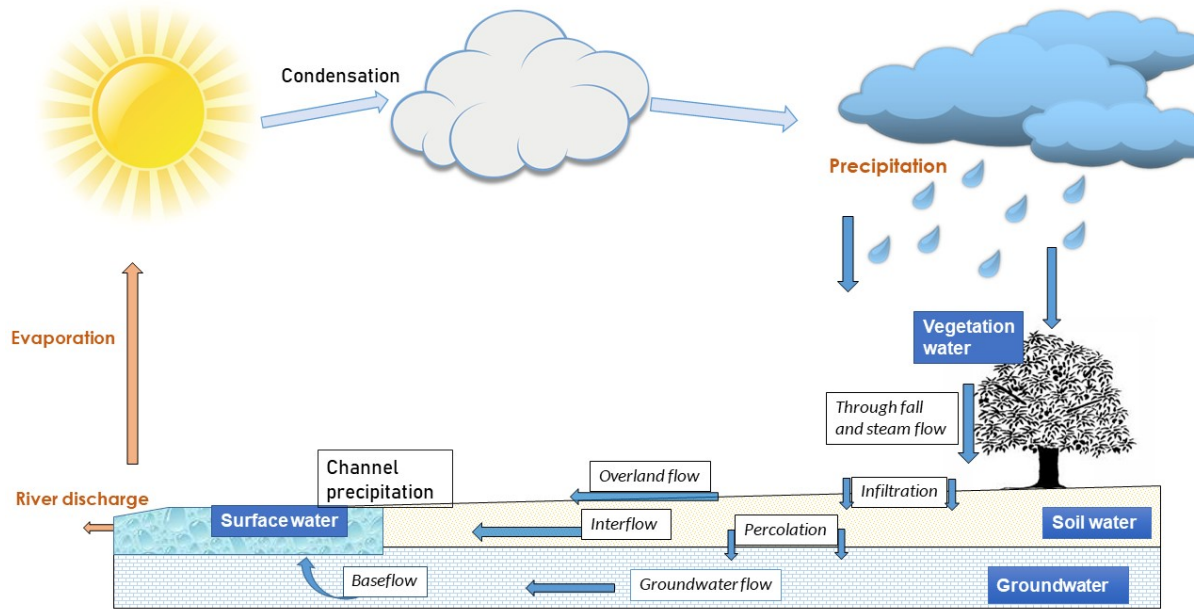


Figure 3.1: Simplified hydrological system in a basin. The boxes with a white background mark the hydrological processes, and terrestrial water storages are in blue boxes. The orange arrows represents the input and output process in the basin) (source: modified from Hendricks, 2010).

## 3.2 Terrestrial Water Storage

The term terrestrial water storage (TWS) refers to water in all its forms on the land surface and subsurface (Rodell & Famiglietti, 2001; Giroto & Rodell, 2019). Equation 3.1 shows that the *TWS* comprises of water in the soil moisture (*SM*), snow water (*SP*), groundwater (*GW*), vegetation water (*VW*) and surface water (*SW*).

$$TWS = SM + SP + W + GW + SW \quad (3.1)$$

The predominant TWS component will vary depending on the climatic setting of a region. For example, in arid regions, groundwater storage is more significant than snow water storage, whereas in the Polar regions snow water storage is more important (Güntner et al., 2007; Syed et al., 2008). TWS plays a key role in global climate and the water cycle (Rodell & Famiglietti, 1999). Human-made water stores such as dams contribute to surface water storage and therefore have a significant impact on the TWS changes of a basin. Ahmed et al. (2014) found that there was a significant increase in TWS in African countries because of the construction of reservoirs. Assessment of these influences on TWS can be achieved - with difficulty - considering the lack of access to data, which when available, have numerous gaps that lead to various uncertainties in the estimates. The monitoring and assessment of TWS is never-the-less an important part of water resource management.

### **3.2.1 Groundwater storage in the hydrological system**

Groundwater storage in this study refers to the volume of water that is stored in the aquifer as recharge and discharge occurs. Groundwater storage is a significant contributor to TWS in arid and semi-arid regions of the world (Wheater, 2010). On a global scale, groundwater remains the largest hydrological store of accessible freshwater on Earth, accounting for more than 96% of Earth's freshwater resources (excluding icecaps and glaciers) (Robinson & Ward, 1990; Shiklomanov, 1993).

The water enters (recharge) and exits (discharge) the groundwater storage via different pathways indirectly or directly depending on the physiographic make-up of the basin. After infiltration, some water is stored as soil moisture (SM). When the SM is saturated, the excess water drains under the influence of gravity and joins the groundwater system. The groundwater is discharged naturally to surface water bodies and to adjacent groundwater basins. Groundwater also exits the aquifer through human action such as groundwater withdrawal, which can also lead to depletion in groundwater storage.

Over a given time, the difference between recharge and discharge in the aquifer system results in a net gain or deficit in groundwater storage. If recharge exceeds

discharge, the groundwater storage increases, whereas if recharge is less than discharge, then there is a depletion in the groundwater storage.

The changes in groundwater storage are influenced by both natural factors and anthropogenic activities. The natural factors include the aquifer's physical properties such as aquifer geometry, transmissivity, and storativity. Furthermore, groundwater storage will be impacted by climatic variability (Jalota et al., 2018). Human factors include over-pumping and urbanisation, which result in lowering of water levels causing a decline in storage. Estimating the changes in groundwater storage on a continuous basis can help our understanding of the extent of human and natural factors on groundwater availability. The main challenges to estimating the changes in groundwater storage is the difficulty in directly measuring recharge and discharge. Recent advances in the Earth Observing System (EOS) such as the GRACE satellites provides an opportunity to estimate changes in groundwater storage in real time.

### **3.2.2 Soil moisture storage**

The soil moisture storage is water in the unsaturated zone or zone of aeration. The zone connects the land surface to the subsurface. The texture and hydraulic properties of the soil, amongst other things, have a direct influence on the amount of groundwater recharge. For infiltrating water to further percolate and replenish groundwater storage, the soil must first reach its field capacity. The field capacity is the amount of water that the soil can hold against gravitational forces (Hendriks, 2010).

## **3.3 Water balance**

The water balance, or hydrological budget, is an accounting for water entering and leaving a basin (Hendrick, 2010). The water balance is based on the principle of conservation of mass (Fitts 2002). The water balance is important in understanding the magnitude and rates of fluxes in the hydrological system. Several water balance formulas have been developed to quantify the amount of water available in a basin over a specified time. A simplified water balance is shown in Equation 3.2.

$$P = Q + ET \pm \Delta S \quad (3.2)$$

$P$  is Precipitation,  $Q$  is Runoff, and  $ET$  is the Evapotranspiration. The  $\Delta S$  denotes the change in storage. The  $\Delta S$  is an absolute value irrespective of the processes involved (Hendriks, 2010). The water balance equation 3.2 quantitatively shows the water entering and leaving the area of interest, as well as the water that is stored. On a global scale, there is no change in storage because the amount of water remains the same, thus  $\Delta S$  is 0. However, in a given area or basin,  $\Delta S$  can be positive or negative as the balance between input and output does not always exist. The positive  $\Delta S$  signifies a wetter basin or gain in TWS because of inflows that exceed outflows. In contrast, a negative  $\Delta S$  signifies a drier basin or depletion in TWS because the outflows exceed the inflows in the basin or area of interest.

The TWS for the basin is estimated using equation 3.3 which was compared to the GRACE satellite TWS. The equation is as follows:

$$TWS = P - (ET + Q) \quad (3.3)$$

where  $TWS$  is the Terrestrial Water Storage;  $P$  is Precipitation;  $ET$  is Evapotranspiration, and  $Q$  is Runoff.

The changes in the input and output in the water balance influences the amount of water that is available in a basin. In tropical areas,  $P$  is often greater than  $ET$ , which results in higher  $TWS$  and  $Q$ , whereas arid to semi-arid regions have less water available because potential  $ET$  is greater than  $P$ . The local physiographic conditions have an influence on the variability in the input parameter that, in turn, will result in variability in the  $TWS$ . The local hydrological processes in a basin or watershed are also linked to the global hydrological cycle and climate system.

The Hydrological Cycle is the backbone to understanding all process in a basin. The current study estimates groundwater storage changes, and the groundwater trends. Whilst the quantity of water in a basin is of importance, the quality is also relevant, and for that reason, characterisation of groundwater quality was necessary. This study also assesses the impact of human disturbances and climatic parameters on groundwater resources. For this reason, the next section provides a brief theoretical overview of the methods and techniques employed in the current study. Methods discussed include the SWAT model and GRACE satellite, and estimates of one or more components using water balance empirical relationships. The multivariate statistical tools are robust in determining trends in the groundwater level, rainfall, and hydrochemical time series.



## **4 REVIEW OF THE METHODS USED**

In the previous chapter, an overview of essential concepts used in the thesis were explained. The connections between the hydrological systems, terrestrial water storage as well as water balance were discussed. In the current chapter, the research methods and tools employed to realise the aims, objectives of the study are reviewed, and justification of their use is provided. Firstly, a brief general discussion on hydrological modelling and justification of the use of soil water assessment tool (SWAT) is presented. Secondly, the background of the gravity recovery and climate experiment (GRACE) mission background and data is presented as well as the applicability of GRACE in hydrological studies and the Vaal River Basin. Lastly, the statistical methods employed in detecting the magnitude and direction of trends in rainfall, groundwater levels and groundwater storage changes are discussed.

### **4.1 Hydrological modelling**

A hydrological model is a simplistic representation of hydrological processes over a given area (Lundin et al., 1999). It provides a means to describe and quantify important hydrological processes to improve knowledge of a complex system and make predictions (ibid.) of water availability for a given area. The usefulness of a model depends on many aspects, but one of the most important factors is the quality of the input data. Before any modelling exercise is carried out, it is important to identify the purpose/problem of the model or the problem that needs to be investigated. Knowing the purpose/problem and compiling a list of available data assists with model choice.

Most, if not all, hydrological models are based on the water balance using precipitation as the driving component and estimating the amount of water that is converted to runoff. A review of the literature reveals that there is a plethora of hydrological models, which shows that there are advances and innovation in water resource modelling. However, the many available hydrological models present a challenge when selecting a modelling tool that is fit for purpose. The commonly used and well-documented models include, but are not limited to, the Soil and Water Assessment Tool (SWAT),

MIKE SHE and the Precipitation-Runoff Modelling System (PRMS). The SWAT and MIKE SHE models are continuously updated and improved. Both can simulate the water balance variables in a catchment (Dhami & Pandey, 2013).

In this study, the criteria used for assessing the fitness for purpose for the hydrological model were mainly technical. The criteria for selection were that the hydrological model must (1) require easily available data, (2) computational efficiency (3) Integrate with GIS and other interfaces, (4) applicable and thoroughly tested across varying environments, (5) available to the public domain, and (6) easy to handle with a strong support community.

Based on the criteria for model selection and assessment of the hydrological models mentioned in the preceding paragraph. The SWAT model was selected for this study for estimation of percolation and surface runoff to understand how they are impacted by land cover/use.

SWAT was found to be more favourable because it is computationally efficient. The MIKE SHE and PRMS are computationally intensive and can suffer from computation instability because of the equations needing numerical approximations to their solutions (Dhami & Pandey, 2013).

The SWAT and PRMS are open source software, whereas MIKE SHE is commercially available. The strong support community and a large database of publications and freely available documentation (Gassman et al., 2007; Neitsch et al., 2011), make SWAT the model of choice. The SWAT model is easy to handle because of integration with any GIS interface, for example, QGIS. The SWAT model can also be coupled or linked with other software such as the modular three-dimensional finite-difference groundwater flow (MODFLOW) model (MacDonald and Harbaugh, 1988).

These models (SWAT, PRMS and MIKE SHE) require extensive data to define the physical characteristics of the watershed (Devia et al., 2015). The input data required for modelling is generally scarce in many watersheds, which limits the application of hydrological models. The SWAT model can be easily calibrated using readily available data and can use publicly available data sources. The SWAT model also has a weather generator model for estimating weather parameters (Dhami & Pandey, 2013).

Despite its wide application, the weakness of the SWAT is that there is no spatial reference of the hydrologic response unit (HRU). There is no transfer between sub-basins, which means that there is a potential for flows that are not accounted for in the HRU (Arnold & Fohrer, 2005; Gassman et al., 2007; Douglas-Mankin et al., 2010). The HRUs are areas with similar land use, soil type, and slope within a basin. Despite the non-spatial referencing of HRUs, SWAT is useful to help understand hydrological processes in a catchment and can continuously be refined.

Another weakness of the SWAT model is that the groundwater concept of the model is simplified, and the model performance will be poor in regions where groundwater is predominant or occurs in deep aquifers (Nguyen and Dietrich 2018). To address the shortcoming of the SWAT groundwater module, the model can be coupled with models that account for groundwater flow such as MODFLOW and Multicell Aquifer (MCA) model. Nguyen and Dietrich (2018) demonstrated that SWAT-MCA is better at simulating baseflow and groundwater flow in a porous aquifer in Germany. In a groundwater-dominated catchment in Denmark, SWAT-MODFLOW was successfully used to model streamflow response to groundwater abstractions (Liu et al., 2020b). In the current study, the SWAT model was to estimate percolation and surface runoff rates to help understand hydrological processes operating at a local scale.

#### **4.1.1 The Soil and Water Assessment Tool applied to the Vaal River Basin**

The SWAT model is a useful tool in the management of water resources and in the understanding hydrological processes (Arnold et al., 2012). The SWAT model can be interlinked with various additional models such as the Modular Three-Dimensional Finite-Difference Groundwater Flow Model (MODFLOW) that can provide holistic information about the hydrologic processes active in a given area.

The modelling for this research was carried out using SWAT version 2012 interface in the Quantum geographic information system (QGIS) software. The SWAT version compatible with the QGIS also known as QSWAT. QSWAT in QGIS allows for the creation of hydrological response units through spatial and temporal analyses of various spatial datasets for a given basin. It also has more functionality than other

models such as statistic and dynamic visualization of outputs, as well as allowing users to merge data from sub-basins (Dile et al., 2016).

The SWAT model is a semi-distributed, continuous time step and operational model developed to evaluate management plans and actions on water, sediment and agricultural chemical yield in large ungauged basins (Arnold et al., 1998; Arnold & Fohrer, 2005; Arnold et al., 2012; Gassman et al., 2014). The United States Department of Agriculture–Agricultural Research Service (USDA-ARS) developed this model in the 1990s. Since then, the SWAT model has undergone numerous developments and refinements to include nearly all the biophysical, chemical and physical processes linked to the hydrological system of a watershed or basin (Arnold & Fohrer, 2005). The model requires a large number of input parameters, which complicate the model parameterisation and calibration (Neitsch et al., 2011; Arnold et al., 2012).

The SWAT model is based on the water balance; the main components are hydrology and weather. The water balance is at the heart of all the hydrological processes occurring in any catchment. The water balance equation has precipitation as the main input in the basin influencing all the hydrological processes (Arnold et al., 1998). All the routing components of the model are in some way directly or indirectly linked to the water balance.

The following Equation 4.1 can define the hydrologic budget of the SWAT model (ibid.):

$$SW_t = SW_0 + \sum_{i=1}^t (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \quad (4.1)$$

where  $SW_t$  is the final water content (mm),  $SW_0$  is the initial water content on day i (mm),  $t$  is the time (days). Representing the amount of precipitation and surface runoff on day i (mm) are  $R_{day}$  and  $Q_{surf}$ , respectively.  $E_a$  is the amount of evapotranspiration on

day  $i$  (mm) and  $W_{seep}$  is the amount of water entering the vadose zone from the soil profile on day  $i$  (mm). Lastly,  $Q_{gw}$  is the amount of return flow on day  $i$  (mm).

#### **4.1.2 Model structure**

The SWAT model is a comprehensive hydrological model with 220 subroutines and over 4000 lines of code, and a FORTRAN 90 command language (Arnold & Fohrer, 2005). The components of the model include the weather, hydrology, erosion/sedimentation, plant growth, nutrients, agricultural management, soil properties, pesticides, stream routine, pond/reservoir routine, and urban routing (Arnold & Fohrer, 2005; Neitsch et al., 2011). The SWAT theoretical documentation Version 2009 by Neitsch et al. (2011) and the SWAT input/output document version 2012 by Arnold et al. (2012) provide a detailed explanation of the different components and input data required, including equations and algorithms.

The watershed delineation uses a Digital Elevation Model (DEM) which enables the SWAT model to create a watershed using topographic boundaries. If streams, reservoirs, ponds, and other water bodies are present they can be added to the model domain with ease. Thus, the hydrological attributes can be written into the user tables.

#### **4.1.3 Model calibration**

Model calibration is key in the evaluation of the input parameters and also for identifying errors in the model (Arnold et al., 2012). The model inputs must be within a realistic range that captures the site measurements as closely as possible (ibid.). The current study uses the SWAT Calibration and Uncertainty Procedures (SWAT-CUP) for model calibration. The calibration procedure also helps in identifying parameter sensitivity (ibid.). A set of parameters or datasets over two periods are used in the calibration.

#### 4.1.4 Model performance and evaluation

Moriasi et al. (2007) recommend the Nash-Sutcliffe Efficiency (NSE), percent bias (PBIAS), and root-mean-square-deviation (RMSD) of measured data for evaluating the model outputs. Here the focus will be on NSE and PBIAS that were used in the current study.

The NSE is useful in evaluating the model performance (ibid.). It calculates the amount of the residual variance in simulated data in comparison to the measured variance (Nash & Sutcliffe, 1970). See Equation 4.2 for calculating NSE below:

$$NSE = 1 - \left[ \frac{\sum_i^n (Q_i^0 - Q_i^{sim})^2}{\sum_i^n (Q_i^0 - \bar{Q})^2} \right] \quad (4.2)$$

where  $Q_i^0$  is the observed value of the parameter,  $Q_i^{sim}$  is the simulated value of the parameter and  $\bar{Q}$  is the average observed value for the parameter.

Percent bias (PBIAS) measures the average tendency at which the simulated data deviates from the corresponding counterparts (Gupta et al., 1999). Values closer to 0 show accurate simulation. The PBIAS is calculated using equation 4.3 as follows:

$$PBIAS = \left[ \frac{\sum_i^n (Q_i^0 - Q_i^{sim}) \times 100}{\sum_i^n Q_i^0} \right] \quad (4.3)$$

where  $Q_i^0$  is the observed value of the parameter,  $Q_i^{sim}$  is the simulated value of the parameter. The model can yield varying results depending on different factors. Table 4.1 shows a range of values that can help assess the suitability of the model in producing reliable results.

Table 4.1 A summary of the range of values used to measure the SWAT model performance (source: after Moriasi et al., 2007)

| <b>Model Performance</b> | <b>NSE</b> | <b>PBIAS (%)</b> |
|--------------------------|------------|------------------|
| Very Good                | 0.75-1     | $\leq 10$        |
| Good                     | 0.65-0.75  | 15-30            |
| Satisfactory             | 0.65-0.5   | 30-55            |
| Unsatisfactory           | $\leq 0.5$ | $\geq 55$        |

#### **4.1.5 Soil Water Assessment Tool model application**

The Soil Water Assessment Tool (SWAT) model can be applied to almost any hydro-climatic environment (Govender & Everson 2005; Cheng et al., 2009; Wang et al., 2009; Rahman et al., 2013; Narsimlu et al., 2013). The most important consideration for using this model is the quality of hydro-meteorological data input. Another important requirement is a thorough understanding of the physical properties of the soil and detailed characterisation of land use/cover (LULC) in the site under investigation. A few previous studies by Govender & Everson (2005) and Thavhana et al. (2018) published in peer reviewed journals show promising results using the SWAT model in South Africa (SA). These studies confirm the applicability of SWAT in SA catchments.

## **4.2 Gravity Recovery and Climate Experiment in the Vaal River Basin**

The focus of the review below is based on the initial Gravity Recovery and Climate Experiment (GRACE) mission. Data from this mission was used in the estimation of changes in groundwater storage in the VRB. The initial GRACE satellites were decommissioned in 2017; their successor, the GRACE Follow-On mission (GRACE-FO), was launched in 2018. GRACE-FO continues to take measurements of the Earth's gravitational field. The GRACE satellite data were chosen for this study because of the large spatial coverage as opposed to localised in-situ measurements.

#### 4.2.1 GRACE mission and objective

The GRACE mission is a joint collaboration between the National Aeronautics and Space Administration (NASA) and Geoforschungs Zentrum Potsdam (GFZ) launched in March 2002 with the objective of taking measurements of the Earth's gravitational field at an unmatched accuracy (Swenson & Wahr, 2002; Swenson et al., 2003; Wahr et al., 2004). The GRACE mission is made up of twin satellites (Figure 4.1) that track the globe at a low orbit at a near vertical inclination of  $89.5^\circ$ . The separation distance between the satellites was approximately 228 km at launch and the altitude was 450 km.

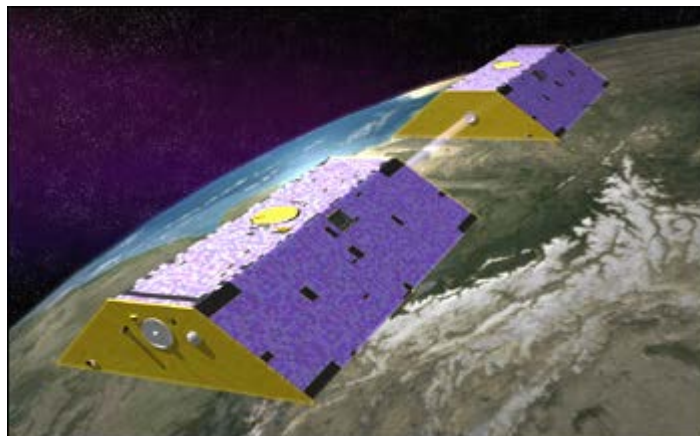


Figure 4.1: The twin GRACE satellites measuring the Earth's gravitational field as they orbit the Earth by measuring the separation distance between the two satellites (Source: <https://earthobservatory.nasa.gov/features/GRACE>).

Of great benefit to hydrologists is the ability of GRACE satellites to sense miniscule changes in the time-variable gravity field, thus providing information that was previously unobtainable. The time-varying gravity field is a result of mass movement on Earth over short periods; the static gravity field is related to movement of mass at a geological scales (Dickey et al., 1997). The current interest in the time-varying gravity field is associated with the movement and redistribution of continental waters



(ibid.). The GRACE satellites thus provide an opportunity to monitor water movement and assess water storages over large continental scales (ibid.; Rodell & Famiglietti, 1999).

#### **4.2.2 Measurement principle**

The GRACE mission consists of twin satellites that take gravimetric measurements of the Earth in unison using a satellite-to-satellite tracking (SST) system. Unlike traditional satellites that measure the travel time of the microwaves between the target feature and the satellite to obtain information about the target, the GRACE satellites measure the spacing or separation distance between themselves satellites in order to make gravity measurements. These gravity measurements are then resolved to estimate the water storages. The concept is that when the twin satellites encounter a strong gravity pull, the leading satellite (GRACE A) will move faster, and the distance between itself and the trailing satellite (GRACE B) increases. After passing the stronger gravity pull GRACE A will slow down and GRACE B will now encounter a stronger gravity pull and experiences the same effect. The changes in the separation distance between the satellites position, and acceleration are used to construct geoid maps and provide detailed information about mass movements associated with continental waters.

#### **4.2.3 GRACE instrumentation and data levels**

The GRACE satellites communicate using the K-band Ranging System (KBR) transmitted between the GRACE satellites in order to make gravity measurements of the Earth.

The GRACE satellites are mounted with highly precise Global Positioning Systems (GPSs) that measures the exact position of each satellite as they orbit the Earth. Another important component is the accelerometer at the centre of each satellite measuring the effect of acceleration due to atmospheric drag and on the ionosphere. The raw data collected by the GRACE twin satellites is sent directly to the ground

instrument-processing unit (IPU). The raw data is then distributed to three data processing centres namely, Jet Propulsion Lab (JPL), Centre for Space and Research (CSR) and GFZ.

The data processing centres apply different filters to the data to retrieve the spectral signature of continental water storage. The raw data includes precise satellite positions, as well as acceleration and separation distance between the satellites. These data are not available to the public and are referred to as GRACE level-1A. The data processing centres apply different filtering techniques to the data. The processed data is called GRACE level-1B which is available to the public and is often used by experts who apply further processing techniques to fit their purpose. Derivative products from the GRACE level-2 are made available to the public as gridded data; this data can be used without necessarily having to perform any filtering techniques.

#### **4.2.4 Application of GRACE satellite in hydrological studies.**

Rodell and Famiglietti (1999, 2001) and Wahr et al. (1998) were the first to demonstrate the ability of GRACE satellites to recover hydrological signal using GRACE synthetic data. Since its launch, numerous studies (e.g. Andersen et al., 2005; Long et al., 2015, Reager & Famiglietti, 2009) have used GRACE satellite data to recover terrestrial water storage (TWS) changes.

The applicability of the GRACE satellite largely depends on the size of an area and the magnitude of the variability in TWS, which both affect the GRACE satellite resolution (Rodell & Famiglietti, 1999; Swenson et al., 2003). An earlier study by Rodell and Famiglietti (1999) predicted that terrestrial water redistribution is detectable in a basin size of 201 000 km<sup>2</sup> over monthly and annual time scales, and detectable in a basin size of 184 000km<sup>2</sup> for seasonal scales. The larger the study area (>200 000 km<sup>2</sup>) the better the spatial resolution of the TWS estimate (Rodell & Famiglietti, 1999; Wahr et al., 2004). Recent improvements in data processing have made it possible to use GRACE satellite data at much smaller scales. For instance, Famiglietti et al. (2011) assessed the groundwater depletion in California's Central Valley over an area of about 154 000 km<sup>2</sup>.

#### **4.2.4.1 Terrestrial water storage changes**

To assess TWS studies have used the GRACE-derived data in combination with satellite observations (Reager & Famiglietti, 2009; Forootan, 2014), in-situ observations (Wang et al., 2011), and land surface models (Schmidt et al., 2006; Syed et al., 2008; Grippa et al., 2011). The GRACE mission data has been successfully employed in combination with other satellite data in the assessment of TWS changes in data-scarce basins across Africa (Syed et al., 2008; Ahmed et al., 2014). This suggests that the use of remote sensing tools, particularly GRACE satellites, are useful in water management in a basin with scarce in-situ data. Previous studies on the application of GRACE data in parts of Africa also include the Upper Zambezi (Winsemius et al., 2006), the Congo Basin (Crowley et al., 2006), and West Africa (Grippa et al., 2011); each of these studies demonstrate the usefulness of GRACE satellite data in hydrological studies.

#### **4.2.4.2 Groundwater storage changes**

Several studies across the world have used GRACE data and other ancillary data to monitor and assess groundwater storage variations. In the northwest of India, Rodell et al. (2009), using data from GRACE and other hydrological models, observed a volumetric loss of 109 km<sup>3</sup> in groundwater storage between August 2002 and October 2008. The magnitude of groundwater depletion is relative to the areal extent of the aquifer. Breña-Naranjo et al. (2014) reported a net loss of 125±4.3 km<sup>3</sup> from 2003 to 2013 in the High Plains aquifer, United States. Groundwater depletion has also been reported in East Africa (Nanteza et al., 2016), North China (Feng et al., 2013) and the Middle East (Voss et al., 2013). In each location, the groundwater depletion was mainly attributed to high groundwater use and to a lesser extent, climate variability (Rodell et al., 2009; Nanteza et al., 2016).

The GRACE satellites data has also been compared with in-situ water level data to assess the accuracy of GRACE data in estimating groundwater storage changes. For example, Rodell et al. (2007) and Bhanja et al. (2018) reported a good agreement between the in-situ based groundwater storage estimates and GRACE-derived

groundwater storage changes. In California's Central Valley, Kuss et al. (2012) reported that the GRACE-derived groundwater storage changes were comparable to a Groundwater-Surface Simulation Model (C2VSim).

The studies presented thus far provide evidence that when the GRACE data are combined with ancillary datasets, it is a robust tool for groundwater investigations.

#### **4.2.5 Applicability of GRACE data in the Vaal River Basin**

The GRACE satellites can be used to estimate groundwater storage changes in the VRB because it covers an area of 197,513 km<sup>2</sup>. The basin area is between the 10<sup>3</sup> to 10<sup>5</sup> km<sup>3</sup> range, and the period of review for this study is more than a decade - ranging from 2003 to 2014. Thus, the study area meets all the criteria for GRACE satellite data application in the estimation of groundwater storage changes as described in a technical commentary by Lakshmi (2016).

### **4.3 Statistical methods**

The non-parametric Mann-Kendall Test (M-K Test) and the Sen's Slope Estimator are well-established statistical tools that have been widely employed in the statistical analysis of hydro-meteorological time series. A review of the literature shows a number of studies that have applied the M-K Test in order to statistically assess the significance of trends in hydro-meteorological time-series data (Drápela & Drápelová, 2011; Gocic & Trajkovic, 2013; Da Silva et al., 2015) and water quality data (Hirsch et al., 1982). The M-K Test and Sen's Slope Estimator have also been widely applied to groundwater level time-series to determine the groundwater level trends and variability (e.g. Sishodia et al., 2016; Ndlovu & Molla, 2018; Anand et al., 2019).

#### **4.3.1 Mann-Kendall Test**

The M-K Test is non-parametric and is performed on time-series data to statistically detect the presence of monotonic decreasing or increasing trends. It is free of data

distribution, and it is applicable in cases of incomplete or missing data in the time-series, which is a common feature in hydrological data. Missing data, however, lowers the reliability and accuracy of the M-K Test output.

The M-K Test tests the null hypothesis ( $H_0$ ) of no monotonic trend in the observations against the alternative hypothesis ( $H_1$ ), where there is a presence of a monotonic increasing or decreasing trend in the time-series data. The data values are evaluated as an ordered time-series whereby each data value is compared with all successive data values.

The M-K Test statistic,  $S$ , is calculated using Equation 4.4 (Mann, 1945; Kendall, 1975):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i) \quad (4.4)$$

where  $n$  is the number of data points,  $x_i$  and  $x_j$  are the data values in the time series  $i$  and  $j$  ( $j > i$ ), respectively, and  $\text{sgn}(x_j - x_i)$  is the signum function. Trend analysis was applied to time-series data  $x_i$ , which is ranked from  $i = 1, 2 \dots n - 1$  and  $x_j$  from  $j = i + 1, \dots n$ . Each data point  $x_j$  in the time-series is a reference point and it is compared with the data points  $x_i$  such that:

$$\text{sgn}(x_j - x_i) = \begin{cases} 1 & \text{if } (x_j - x_i) > 0 \\ 0 & \text{if } (x_j - x_i) = 0 \\ -1 & \text{if } (x_j - x_i) < 0 \end{cases} \quad (4.5)$$

The variance statistics is computed using Equation 4.6:

$$\text{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^m t_i(t_i-1)(2t_i+5)}{18} \quad (4.6)$$

Where  $n$  is the number of observations,  $m$  is the number of tied groups, and  $t_i$  denotes the number of ties present with  $i$  as extent.

If  $n < 10$ , the calculated value of  $S$  is compared directly to the theoretical values of  $S$  derived by Mann (1945) and Kendall (1975). The two-tailed test is applied to groundwater level data and rainfall amount data for the VRB. At a specific probability level,  $H_0$  is rejected in favour of  $H_1$ , if  $|S| > S_{\alpha/2}$ ; where  $S_{\alpha/2}$  is the smaller  $S$  which has the probability of less than  $\alpha/2$  in the absence of a trend. The sign of  $S$  indicates the direction of a trend, which can either be positive or negative (Salmi et al., 2002). The former is indicative of an upward (increasing) trend and the latter of a downward (decreasing) trend.

In instances where the observation values are equals or greater than ten ( $n \geq 10$ ) as it is the case in this study, the detection of a statistically significant trend is calculated using the standard normal test statistic  $Z_C$ :

$$Z_C = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(s)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(s)}} & \text{if } S < 0 \end{cases} \quad (4.7)$$

A positive value of  $Z_C$  shows an upward trend, whereas a negative value is indicative of a downward trend.

#### 4.3.2 Sen's Slope Estimator

The Sen's Slope Estimator (Sen, 1968) predicts the magnitude of the linear trend, if it exists. The estimate of the slope  $Q_i$  is defined as follows (slope of all data pairs are calculated):

$$(Q_i) = \frac{X_j - X_k}{j - k} \text{ for } i = 1, 2, \dots, n, \quad (4.8)$$

where  $X_j$  and  $X_k$  are the data values at times  $j$  and  $k$ , ( $j > k$ ), respectively. The Sen's Slope Estimator is represented by the median of  $N$  values of  $Q_i$ . If there is one observation in each period, then  $N = n(n - 1)/2$ , where  $n$  is the number of periods. If there are several data in one or more period subsequently  $N < n(n - 1)/2$ . The  $n$  values of  $Q_i$  are ranked in increasing order and the Sen's Slope Estimator ( $Q_{med}$ ) is computed as follows:

$$Q_{med} = \begin{cases} Q_{[\frac{n+1}{2}]}, & \text{if } n \text{ is odd} \\ \frac{Q_{[\frac{n}{2}]} + Q_{[\frac{n+2}{2}]}}{2}, & \text{if } n \text{ is even} \end{cases} \quad (4.9)$$

The  $Q_{med}$  sign shows the direction of the trend if it exists; the  $Q_{med}$  value indicates the degree of the trend.

A 100 (1- $\alpha$ )% two-sided confidence interval of the median slope is computed at a specific probability in order to find out if the  $Q_{med}$  is statistically different from zero. The confidence interval about the median slope is calculated following Gilbert (1987):

$$C_\alpha = Z_{1-\alpha/2} \sqrt{\text{Var}(S)} \quad (4.10)$$

where  $\text{Var}(S)$  is defined in Equation 4.6 and  $Z_{1-\alpha}$  is obtained from the standard normal distribution table.

Thereafter,  $M_1 = (n - C_\alpha)/2$  and  $M_2 = (n + C_\alpha)/2$  are calculated. The lower ( $Q_{min}$ ) and upper ( $Q_{max}$ ) limits of the  $C_\alpha$  are the  $M_1^{\text{th}}$  largest and the  $(M_2 + 1)^{\text{th}}$  largest of the

N ordered slope estimates,  $Q_i$ . If the  $M_1$  and  $M_2$  are not whole numbers, then the lower and upper limit are interpolated (Salmi et al., 2002). If the limits have a similar sign it means that the median slope is statistically different from zero.

#### 4.3.3 Cumulative Rainfall Departure

The cumulative rainfall departure (CRD) method is based on the premise that groundwater fluctuations are caused by rainfall events (Xu & Beekman, 2003). Wentzel (1936) was the first to demonstrate the cause-effect relationship between rainfall and water levels. Bredenkamp et al. (1995) developed algorithms that combine the soil water balance and CRD for estimating aquifer recharge and storativity. The CRD series for rainfall is calculated as follows (Bredenkamp et al., 1995):

$${}_{av}^I CRD_i = R_{fi} - f_{av} + {}_{av}^I CRD_{i=1} \quad (4.10)$$

where  $CRD_i$  is the cumulative rainfall departure for months  $i$ ,  $R_{fi}$  is rainfall in month  $i$ ,  $f_{av}$  is the mean monthly rainfall for all the years.  ${}_{av}^I CRD$  is the CRD relative to the mean rainfall for all the months.

A positive  ${}_{av}^I CRD_i$  denotes a wet period where the rainfall amount is above the mean. In contrast, a negative  ${}_{av}^I CRD_i$  denotes a dry period where the rainfall amount is below the mean.

The CRD method is favoured in this study because of the minimal data requirement and ease of application. The method requires rainfall data which are available for the study area. Xu and Beekman (2003) indicated that the CRD method can be applied to data ranging between 1-20 years.

Recent studies successfully applied the CRD method to analyse the relationship between rainfall and groundwater levels' fluctuation in different parts of South Africa – see Abiye et al. (2018) and Demlie and Ndlovu (2018) – where the CRD method was applied in Johannesburg and Kwazulu-Natal, respectively. In both studies, rainfall, among other factors, was found to cause groundwater level fluctuations, although its effect on groundwater level differed in magnitude.



Despite the wide application of CRD, it is not free of criticism. Weber and Swart (2003) argue that the CRD method can be misapplied, particularly when dealing with longer (>20 years) rainfall records. They demonstrate that over long periods of above average rainfall events can cause resetting of the hydrologic system such that the cumulative rainfall has no influence on the groundwater level fluctuations. They advocate for using more robust statistical tools such as the M-K Test in the analysis of long-term rainfall data because of the non-distributed nature of the data. Xu and van Tonder (2001) and Xu and Beekman (2003) suggest that the CRD method must be applied with caution in fractured systems that have low storativity and that are sensitive to rainfall events.

## **5 RESEARCH METHODOLOGY**

In the previous chapter, a review of the methods and tools applied is provided. In this chapter, a description and an explanation of how the research methods were employed in addressing research objectives are presented. In this chapter, each subsection presents reproducible steps that were followed in applying each method and tool to achieve the objectives of the study. Firstly, the analysis of water chemistry data using multivariate statistics and graphs to characterise the groundwater chemistry and to develop insights about the extent of groundwater quality is presented. Secondly, application of the Mann-Kendall Test and Sen's Slope to rainfall and groundwater level data is provided as well as the cumulative rainfall departure method used to help identify factors influencing groundwater level trends and variability. Thirdly, the source of input data for the water balance and application of GRACE-derived data in the estimation of the volumetric of groundwater storage changes is presented. Lastly, the steps followed when using the soil water assessment tool (SWAT) to estimate the percolation and surface runoff rates were provided.

### **5.1 Analysis of groundwater chemistry**

#### **5.1.1 Hydrochemical data acquisition**

Groundwater chemistry data used in this study were acquired from the Department of Water and Sanitation's (DWS) database of South Africa. Given the purpose of the hydrogeological investigation, it was deemed necessary to use the water chemistry data from the DWS database because the DWS has been monitoring both surface and water chemistry in the Vaal River Basin (VRB), and as a result has long-term records of data since 1995. Despite the monitoring efforts by the DWS, a large part of the basin, particularly in the southern part, remains unmonitored. Monitoring points are largely populated in the industrial and mining zones in the basin as shown in Figure 5.1.

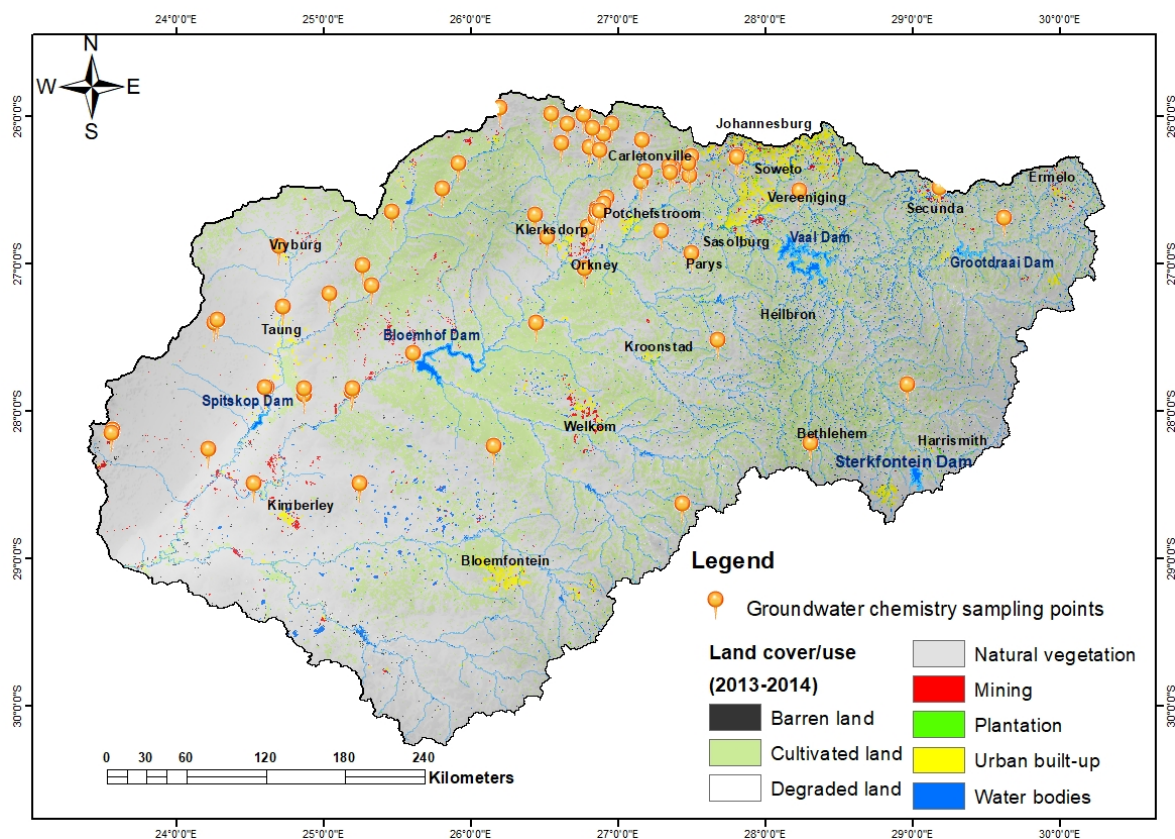


Figure 5.1: Map showing the groundwater chemistry sampling points in the Vaal River Basin.

### 5.1.2 Quality control of the hydrochemical data the Vaal River Basin

All monitoring points within the VRB were captured but only monitoring points with more than five years of monitoring records were used in the analysis for the current research. Monitoring points/stations with more than five years of records but missing a large number of chemical and physical parameters were omitted from the analysis thus leaving water chemistry data from 70 monitoring stations with excellent records. The quality of the major ions analysis was assessed by computing the charge balance error (CBE). The CBE values for the majority (84%) of the sample were less than  $\pm 5\%$  and just a few (16%) had values above  $\pm 5\%$  but below  $\pm 10\%$ . Thus, the major ions measurements were considered reliable, and of the quality acceptable for further analysis. The CBE values of  $\pm 5\%$  are considered the best analytical estimation, whereas the  $\pm 10\%$  is considered the maximum acceptable error (Güler et al., 2002;

Appelo & Postma, 2004). The CBE values above the maximum acceptable error are caused by, among other factors, technical flaws in sampling procedure and mishandling of water samples.

The sum of ions was compared with total dissolved solids (TDS) measurements as part of the quality control. Both the calculated ions and TDS measurements showed good agreement which implies that they are reliable. The time-series of water chemistry measurements was averaged over the entire period over which data was recorded for each monitoring station in order to obtain mean values. The consequence of averaging data over longer periods is that it removes anomalous values that could be a result of one-time point pollution. In addition, the mean values were calculated in order to discern the underlying hydrochemical processes and both natural and human-induced factors that influence the groundwater chemistry in the VRB. The mean values for the 70 monitoring stations comprises 59 boreholes, 9 springs, and 2 mine-water discharges.

### **5.1.3 Graphical analysis of groundwater chemistry data**

Graphical techniques such as the piper diagram are useful in depicting the evolutionary and mixing trends, and the predominant ions. The piper diagram was also helpful in identifying and understanding the role of geology in influencing the water chemistry. Aquachem 3.7 software was used to create the Piper Plot, Bivariate Plot, and Schoeller Diagram for the VRB.

#### **5.1.3.1 Piper Plot**

The major ions for the different groups/clusters were graphically represented in a Piper Plot (Piper, 1944) – a plot which helps in the classification of water types according to the predominant ions. The Piper Plot requires the normalisation of major ions in water such as Ca, Mg, Na,  $\text{SO}_4$ ,  $\text{HCO}_3$  and Cl and plotting them on a ternary diagram and projecting them to the diamond diagram of the Piper Plot. The Piper Plot also gives

insights into possible mixing of water types and evolutionary paths of the groundwater chemistry in the basin.

#### **5.1.3.2 Bivariate Plot**

Using Bivariate Plots, various ionic ratios were plotted to identify predominant hydrochemical processes in the basin such as salinisation, silicate weathering, carbonate weathering, and ion-exchange processes. The ionic ratios are represented in units of Meq/L and logarithmic scale, which allows for a clear distinction of the possible hydrochemical processes in the basin.

#### **5.1.3.3 Schoeller Diagram**

The Schoeller Diagram (Schoeller, 1965) was used to depict the relative abundance of major ions for the various groups of water samples.

### **5.1.4 Application of multivariate statistics to groundwater chemistry data**

Multivariate statistical methods were useful in the analysis of the large dataset making it easier to identify both possible controls on the groundwater chemistry and similarity among the samples as a function of their hydrochemical characteristics.

#### **5.1.4.1 Assessing the suitability of hydrochemical data for multivariate statistical analysis**

The statistical analysis of the groundwater chemistry was achieved with the aid of SPSS software (version 25). Prior to performing any statistical analysis, it was necessary to evaluate the normality of the water chemistry data using the Shapiro-Wilk (S-W) and Kolmogorov-Smirnov (K-S) Tests. The S-K and K-S Tests revealed that the hydrochemical variables were non-distributed - which is normally the case in Earth science measurements. Normality tests are necessary and recommended when using non-parametric statistical methods to avoid misinterpretation.

The hydrochemical measurements were log-transformed in order to improve the normality of the data, which is an important requirement for applying the Principal

Component Analysis (PCA) (Jolliffe, 2011). PCA assumes that the dataset analysed is normally distributed, which is often not the case for measurement in Earth science data. In addition to log-transforming the dataset, the Kaiser-Meyer-Olkin Test (KMO Test) measure of sampling adequacy and Bartlett's Test of Sphericity were performed to assess the applicability of PCA to the hydrochemical datasets in the basin. The K-M-O value for the hydrochemical dataset is 0.756, which according to Kaiser (1959), is within the middling range and thus it is moderately adequate for PCA. The Bartlett's Test of Sphericity tests the null hypothesis that the correlation matrix is an identity matrix. In this study, the null hypothesis that the correlation matrix is an identity matrix is rejected because the significance value is less than 0.05 ( $p < 0.05$ ). Both the KMO test and Bartlett's Test of Sphericity outputs show that the dataset is fit or well-suited for PCA analysis.

#### **5.1.4.2 Hierarchical Cluster Analysis**

Hydrochemical data for 70 groundwater samples were clustered based on their similarity using Hierarchical Cluster Analysis (HCA). The Ward's Method was used for linking the clusters, and the squared Euclidean distance interval measured the interval of the clusters. The clusters were based on similarity/dissimilarity of the hydrochemical variables rather than on the location, sub-basin or hydrological response units. The HCA reveals information about possible common sources and hydrochemical processes that influence the groundwater chemistry along its flow path. Using the z-scores, the hydrochemical variables of varying magnitude, for example, calcium and fluoride, were standardised to allow for a fair comparison. The HCA was helpful in clustering the monitoring stations into groups, which was useful when plotting the Piper Plot, Schoeller Diagram and Bivariate Plots for data from the 70 groundwater monitoring sites across the VRB.

#### **5.1.4.3 Principal Component Analysis**

The log-transformed groundwater chemistry data were used for Principal Component Analysis (PCA). Using the SPSS software (version 25), principal components with

eigenvalues above one were extracted with extraction communalities exceeding 0.6 points. The extraction communality exceeding 0.5 points to a higher level of extraction. Using a Varimax rotation with Kaiser Normalisation (1959), the principal components were rotated to maximise the loading of each variable on each component at the same time, while also reducing the loading on other components (Güler et al., 2002; Güler et al., 2012).

## **5.2 Detecting long-term trends in groundwater levels**

### **5.2.1 Groundwater level data acquisition**

The analyses of groundwater levels were limited to the upper part of the VRB (Figure 5.2). The upper VRB was selected since it has a large dataset of reliable groundwater levels. The groundwater level data were retrieved from the National Groundwater Archive (NGA) of the DWS.

Prior to the acquisition of the water level data, the National Integrated Water Information System (NIWIS) of the DWS was used to first identify boreholes that contained reliable records. Only 184 boreholes contained acceptable records but had less than 3 years of groundwater level data. Of the 184 monitoring boreholes that had acceptable records, 72 monitoring boreholes had sufficient long-term records (>10 years) useful for detecting trends in groundwater levels. The groundwater monitoring boreholes are clustered in the northeast of the VRB, which is underlain by the dolomite, and which occur in the proximity of industrial, urban and mining zones.

The monitoring boreholes were divided into three Groups based on the length of the water records. These groups were named: Group 1, Group 2 and Group 3. In Group 1, the groundwater levels are from 12 monitoring boreholes with records starting from the 1970s. The water level data for Group 2 are from 45 groundwater monitoring stations with records starting from the 1980s. Group 3 consists of water level data from 15 monitoring boreholes with records starting in the 1990s. What is common in all three groups is that the end date of the records is 2004. The M-K Test and Sen's Slope Estimator results for groundwater levels are presented in a systematic manner

– see: Sections 6.3.1 (Group 1), 6.3.2 (Group 2) and 6.3.3 (Group 3) in the following chapter.

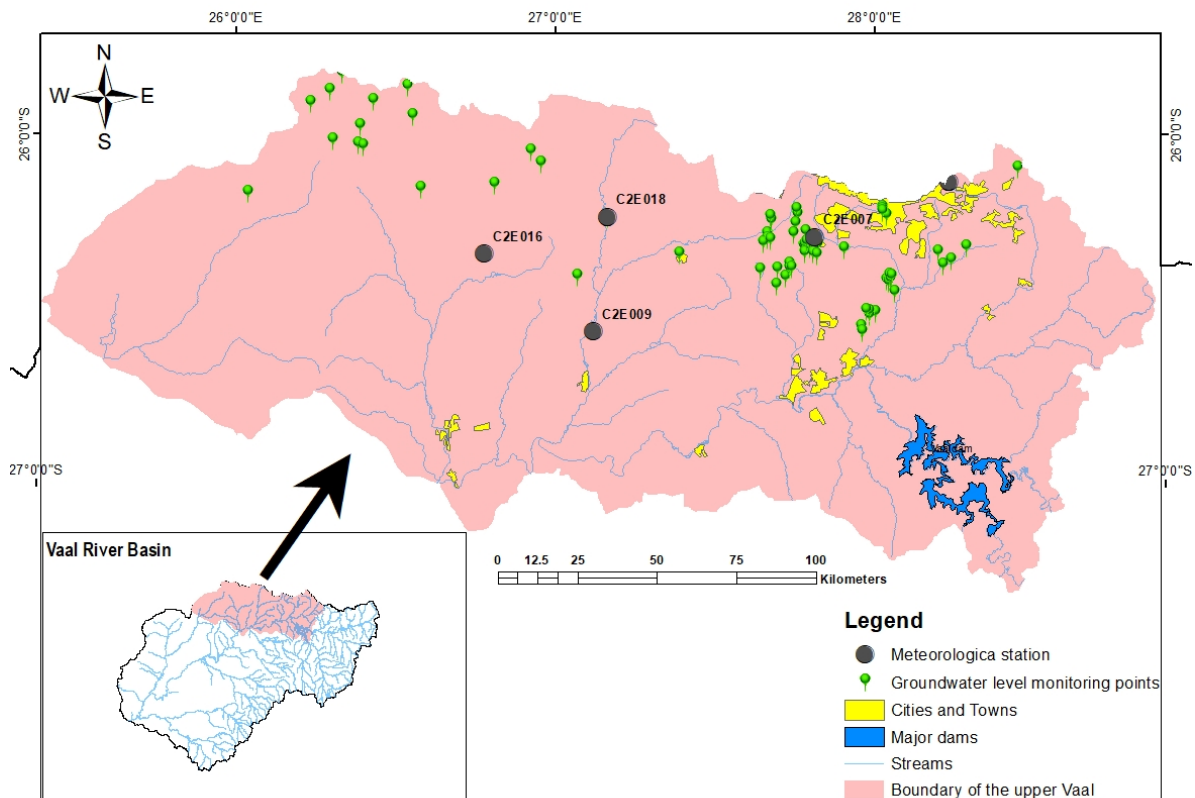


Figure 5.2: Locality map of the upper Vaal River Basin; the insert map shows the location of the upper Vaal in the Vaal River Basin

### 5.2.2 Application of the Mann-Kendall Test and the Sen's Slope Estimator to groundwater level-time series data in the upper Vaal River Basin

Groundwater levels and rainfall data were statistically analysed for trends using the M-K Test and Sen's Slope Estimator with the aid of an Excel macro, MAKESENS, created by the Finnish Meteorological Institute. Thereafter, the Sen's Slope Estimator was applied to quantify the magnitude of the trends. In the current study, a two-tailed M-K Trend Test is performed on groundwater level and rainfall time-series data at significance levels  $\alpha = 0.001$ ,  $\alpha = 0.01$ , and  $\alpha = 0.05$ , respectively. At the 0.1%, 1% and



5% significance level,  $H_0$  of no trend is rejected in favour of  $H_1$  of the presence of a trend if  $|Z_{cal}| > 1.960, 2.576$  and  $3.291$ , respectively. The  $Z_{\alpha/2}$  values are obtained from the standard distribution table.

The Sen's Slope Estimator procedure (Sen 1968) was applied in the estimation of the slope (change per unit time) in the groundwater levels and rainfall time-series dataset to be able to detect the trend direction.

### 5.2.3 Estimating the percentage change of rainfall

The groundwater level trends were compared with the percentage change of rainfall over the monitoring period without including the time lag by approximating it to a linear trend following Yue and Hashino (2003):

$$\text{Percentage change (\%)} = \frac{TQ_i}{\text{average rainfall}} \times 100 \quad (5.1)$$

where  $T$  is the duration of observation and  $Q_i$  is the Sen's Slope Estimator defined in the equation. The distribution of the rainfall gauges that were used to estimate the percentage change in rainfall and to construct cumulative rainfall departure (CRD) plots can be seen in Figure 5.2.

### 5.2.4 Rainfall data used in the calculation of cumulative rainfall departure in the upper Vaal River Basin

The CRD series was computed for rainfall stations situated near the groundwater monitoring sites downstream of the Vaal Dam from the northeast to the northwest (Figure 5.2). Only rainfall gauges less than a 25 km radius from the groundwater monitoring stations were chosen, particularly in cases where there was no nearby rainfall gauge. The rainfall gauges within 25 km radius are assumed to have an impact on the groundwater level fluctuations downstream of the Vaal Dam. The CRD series

was plotted against the monitoring boreholes in which statistically significant trends were detected using the M-K Test. The CRD series was computed for rainfall records of up to 34 years, which is more than the 20 years recommended by Xu and Beekman (2003). To address concerns by Webber and Swart (2003) on the application of CRD over longer terms (mentioned in Section 4.3.3) the current study uses robust statistical tools such as the M-K Test for the analysis of rainfall data. The outputs of the M-K Test, CRD series, and groundwater level plots helped in identifying climatic factors (i.e. rainfall) and human actions causing groundwater level fluctuation in the in the upper Vaal River Basin.

#### **5.2.5 Detecting long-term trends in rainfall data using the Mann-Kendall test and Sen's slope in the Vaal River Basin**

The rainfall data from rain gauges across the VRB were analysed for trends to detect if there is a general increase or decrease in the rainfall amount over longer periods (>40 years). The M-K Test and Sen's Slope Estimator were used to detect the trend direction and the magnitude of rainfall change. The analyses were limited to rainfall data from 1970 to 2018 (Table 5.1).

The annual variability between different years provides information about the dry and wet years over a given time. The wet years are likely to cause an increase in soil and surface water, and fill reservoirs that will eventually cause a net increase in groundwater storage. Conversely, dry years are more likely to result in reduction of water available for groundwater recharge, resulting in a net depletion of groundwater storage.

Table 5.1: Rainfall stations used in the analysis of long-term trends (source: Department of Water and Sanitation).

| Rain gauge ID | Latitude (°) | Longitude (°) | Elevation (m) |
|---------------|--------------|---------------|---------------|
| C2E001        | -26.7627     | 27.68292      | 1431          |
| C2E009        | -26.5713     | 27.118        | 1398          |
| C2E010        | -27.4069     | 26.50416      | 1266          |
| C4E002        | -28.5014     | 26.77551      | 1331          |
| C4E008        | -28.2911     | 27.14361      | 1379          |
| C7E001        | -27.2469     | 27.66861      | 1414          |
| C9E003        | -28.1088     | 24.94126      | 1199          |

### 5.3 Estimation of groundwater storage changes using GRACE data

It should be stressed that in the current study and the interest is on estimating volumetric groundwater storages changes rather than the absolute values of groundwater storage. The estimation of groundwater storage is relatively impractical and difficult to estimate over large areas because it requires aquifer information such as the 3-dimensional aquifer volume, hydraulic parameters, and storativity (Lakshmi 2016), all of which are not widely available in this research area. The term groundwater storage change is used interchangeably with groundwater storage anomaly. This is the anomaly or change relative to 2004 to 2009 time-mean baseline.

#### 5.3.1 Data acquisition and analysis of in-situ and remotely sensed data

##### 5.3.1.1 GRACE-derived data

The de-stripped GRACE data Release-05 produced by Sean Swenson of the University of Texas, Centre for Space and Research (CSR) ([ftp://podaac-ftp.jpl.nasa.gov/allData/tellus/L3/land mass/RL05/](ftp://podaac-ftp.jpl.nasa.gov/allData/tellus/L3/land%20mass/RL05/)) is used in this study. The gridded-scaled data differs from the standard GRACE spherical harmonic geopotential coefficients in that it enables users without processing expertise to make use of GRACE data in the estimation of terrestrial water storage over a target region of interest (Landerer & Swenson, 2012). Readers interested in the details of methods of extracting regional mass anomalies from the GRACE gravity coefficient should refer

to Swenson et al. (2003). The gridded fields of leakage and GRACE measurement errors are also available, which also allow users to estimate regional TWS uncertainties (Landerer & Swenson, 2012). GRACE TWS anomalies are in equivalent water height (cm) and, were used to estimate groundwater storage in the VRB.

The 132 months gridded and scaled GRACE TWS anomalies from January 2003 to March 2014 were analysed for long-term trends and compared with the water budget of the basin. Sen's Slope Estimator was fitted to the dataset in order to quantify the long-term TWS changes in km<sup>3</sup> (considering the study area). GRACE TWS anomalies were estimated by subtracting monthly values from a pre-defined average time baseline (from 2004.0 to 2009.999) (<https://grace.jpl.nasa.gov/data/get-data/monthly-mass-grids-land/>). The average baseline was similarly applied to other datasets such as surface water, including reservoir and soil moisture data, to allow for comparison.

The GRACE Tellus land data is in 1 degree (Latitude) x 1 degree (Longitude) grid cells format at a monthly resolution. The GRACE Tellus data was multiplied by the provided scaling grid in order to restore signals removed during post-processing of GRACE data (<https://grace.jpl.nasa.gov/data/get-data/monthly-mass-grids-land/>). The reliability of the TWS estimates largely depend on the leakage error and measurement error (Rodell & Famiglietti, 1999), which are mainly caused by the nature of the orbit of the earth and gravity field (Wahr et al., 2006). A Gaussian filter at a width of 300 km at 60° is applied by the CSR in order to attenuate the geophysical signal of interest.

#### **5.3.1.2 Precipitation**

Precipitation data in the form of rainfall was obtained from various sources such as the SAWS, DWS and the ARC-SCW of South Africa. Daily rainfall data for 39 rainfall gauges from 2003 to 2014 were aggregated to obtain yearly values. The rainfall stations are unevenly distributed and mainly clustered in the upper part of the basin. The southwestern and southern parts of the VRB have limited rainfall gauges because minimal economic activities and residential areas occur in these two regions. The rainfall data across the Vaal River Basin was validated with the satellite based rainfall product from the Precipitation Estimation from Remotely Sensed Information using

Artificial Neural Networks-Climate Data Record (PERSIANN-CDR), accessed through Centre for Hydrometeorology and Remote Sensing (CHRS) Rain Sphere (<http://rainsphere.eng.uci.edu/>). The ground-based rainfall and PERSIANN-CDR were comparable with a coefficient of determination of 93.7%, which justifies the use of data from 39 stations as representative of rainfall for the entire basin. The precipitation data were used as input in the calculation of the water budget for the basin.

#### **5.3.1.3 Evapotranspiration**

Monthly average evapotranspiration (ET) estimates from 2003 to 2014 for the study area were captured using the Moderate Resolution Imaging Spectroradiometer (MODIS) Toolbox - a processing tool for ArcGIS users. Thereafter, monthly average values for the entire basin were extracted from the ET images to use as input for the water budget. Similar to other parameters, evapotranspiration anomalies were calculated by subtracting the average (2004 to 2009) and a linear regression line was fitted to the data.

The MODIS sensor aboard the National Aeronautics and Space Administration (NASA) satellite Terra collects global images that are processed to estimate evapotranspiration (Mu et al., 2011). The Centre for Research in Water Resources (CRWR) at the University of Texas created the MODIS Toolbox that allows ArcGIS users to import MODIS images into ArcMap. The regular 1 km<sup>2</sup> MOD16 global ET data over the land surface were developed by Mu et al. (2011) using the improved ET algorithm based on the vegetated surface of the earth excluding ET from barren and urban areas (ibid.). Jovanovic et al. (2015) demonstrated a 15% deficit for water balance closure in South Africa when using the MOD16 ET algorithm. Land cover, vegetation cover, and landscape are variables in the study area that have implications on the estimated ET using the MOD16 ET algorithm (ibid.). Given that the focus of this study is on a regional scale, localised heterogeneities are not of concern.

#### 5.3.1.4 Surface water

Surface water storage (SW) here refers to water in major dams or reservoirs in the VRB. Surface water storage data were obtained by request from the DWS. The DWS provided reservoir storage data from 1936 to 2016 in percentage of full storage capacity (% FSC) for the Integrated Vaal River System (IVRS) and the Vaal Dam. The IVRS encompasses Vaal Dam storage and all the storage capacity involved in the inter-basin water transfer scheme. To estimate monthly surface water storage, we assumed that fluctuations in the % FSC in the Vaal Dam reflect changes in surface water storage capacity across the VRB. The storage capacity of the VRB was then multiplied with the % FSC of the Vaal Dam for the period 2003 to 2014. The resultant calculated total storage capacity of the VRB is 8037.2 Mm<sup>3</sup> (<http://niwis.dws.gov.za/niwis2/SurfaceWaterStorage>).

#### 5.3.1.5 Soil moisture

The monthly soil moisture data from 2003 to 2014 for four soil layer depths: 0-10 cm, 10-40 cm, 40-100 cm and 100-200 cm were acquired from Earth data, Giovanni (<https://giovanni.gsfc.nasa.gov/giovanni/>) expressed in m<sup>3</sup><sub>water</sub>/m<sup>3</sup><sub>soil</sub>. Giovanni is an interface that allows users to visualise and spatially analyse geophysical parameters such as soil moisture data prior to downloading the data. The soil moisture content data are in 0.10° spatial resolution and the temporal resolution is monthly. The specific soil moisture content products for this study are from The Famine Early Warning Systems Network (FEWS NET) Land Data Assimilation System (FLDAS) Noah Land Surface Model L4. The soil moisture content expressed in m<sup>3</sup><sub>water</sub>/m<sup>3</sup><sub>soil</sub> were converted to mm. Soil moisture anomalies were calculated by subtracting the time mean (2004 to 2009) from the monthly soil moisture values using Equation 5.2 below:

$$SM_{\alpha} = SM - \overline{SM} \quad (5.2)$$

where  $SM_{\alpha}$  is the anomaly difference of soil moisture is for a certain month,  $SM$  is the soil moisture for a specific month, and  $\overline{SM}$  is the soil moisture time mean (2004 to 2009).

The FLDAS data products are freely available to the public. These products are applicable and useful for: i) hydro-climatic studies; ii) in regions with limited data - particularly in Africa, and iii) where there is a need for early disaster and famine early warning (McNally et al., 2017).

#### 5.3.1.6 Runoff

Real time daily mean discharge data for both the Vaal River at Schmidtsdrif (C9H024) and its tributary and the Riet River at Klipdrift (C5H014) were obtained from the DWS hydrological services. Gauges were selected based on their proximity to the mouth of the Vaal River, which is located 115 km southwest of Kimberley to record maximum runoff for the VRB. The monthly totals were used as input for the water balance.

#### 5.3.2 Estimating the water budget-derived Terrestrial Water Storage

The GRACE TWS anomaly (GRACETWSa) was compared with the water budget for the basin in order to evaluate the accuracy of the GRACETWSa. The water budget provides a measure of change in water storage by accounting for inflows and outflows in a basin over a given time. The change in storage estimated by the water budget gives an idea of water availability in a basin. Thus, the change in water storage from the water budget can also be defined as the terrestrial water storage (TWS<sub>wb</sub>). The  $TWS_{wb}$  is estimated using Equation 5.3:

$$TWS_{wb} = P - (ET + Q) \quad (5.3)$$

where  $P$  is precipitation,  $ET$  is evapotranspiration and  $Q$  is runoff. Similar to the  $GRACETWS_a$ , it is also necessary to remove the baseline period (2004 to 2009) to estimate the  $TWS_{wb}$  anomaly, shortened to  $TWS_{awb}$ .

The  $TWS_{awb}$  uses input from in-situ and satellite data. The variability in the inputs influences the amount of water that will be stored in various TWS. The sources of the input data are described in Sections: 5.3.1.2, 5.3.1.3 and 5.3.1.6.

### 5.3.3 Groundwater storage change estimation using GRACE data

The GRACE-based groundwater storage anomalies (GWSa) are estimated using a water balance approach as a residual by removing all the water storages in the basin. In the current study, the assumption is that the major components contributing to the  $GRACETWS_a$  are groundwater ( $GW_a$ ), surface water ( $SW_a$ ) and soil moisture ( $SM_a$ ) anomalies. The time-mean was subtracted from the TWS values in order to estimate the anomalies. Therefore, the GRACE-based GWSa can be estimated using Equation 5.4:

$$GWSa = GRACETWSa - (SWa + SMa) \quad (5.4)$$

The  $SW_a$  and  $SM_a$  were estimated using ground-based and satellite data, described in Sections 5.3.1.4 and 5.3.1.5.

### 5.3.4 Assumptions and limitations for using the Gravity Recovery and Climate Experiment mission data in the Vaal River Basin

The snow water and vegetation water anomalies were excluded from the equation above for two reasons. Firstly, the basin experiences a generally warmer climate and it is at a relatively low altitude. As a result, there is no snow, except for a small portion of the study area along the western escarpment, where snow occasionally fall in winter. The snow water was assumed to be a negligible component of the TWS in the



Vaal River Basin (VRB). Secondly, the VRB experiences an arid to semi-arid climate with few trees, scattered bushes, and shrubs observed. Thus, evaporation is high and it is highly unlikely that vegetation water contributes significantly to the water storage.

The GRACE-based assessment of groundwater storage changes was not validated with observed groundwater levels because of the paucity of groundwater data in the basin over the same period for which GRACE data is available. The GRACE data does not directly estimate the groundwater storage, but in combination with other tools it can aid in the estimation of volumetric changes in groundwater storage relative to the time-mean baseline.

## **5.4 Soil and Water Assessment Tool**

### **5.4.1 Materials and data availability**

As mentioned earlier, the QSWAT interface for the SWAT2012 was used in modelling hydrological processes of the C52F Quaternary Catchment within the VRB (Figure 5.3). The Soil and Water Assessment Tool (SWAT) model requires various levels of data input depending on the purpose of the model.

#### **5.4.1.1 Weather data**

Weather data provides the moisture and energy sources that drive the water balance in a basin. The daily weather data from 01/01/1991 to 31/12/2017 were retrieved from the South African Weather Service (SAWS). The daily weather data from the Bloemfontein Wo – 0261516B0 station, which is situated in Bloemfontein City at - 29.1030° S and 26.2980° E at an elevation of 1354masl were used. The daily weather data includes rainfall amount, temperature, humidity, and wind speed. The Weatherman tool of the Decision Support System for Agrotechnology Transfer (DASST) was used to fill missing data and suspicious values in the daily weather records, and to estimate missing parameters such as solar radiation.

#### **5.4.1.2 Soil and land cover/use**

The physical property of soil data in the C52F Quaternary Catchment was obtained from the Food and Agriculture Organisation (FAO) soil and terrain database (SOTER) (<https://files.isric.org/public/soter/>). The FAO has a regional soil and terrain database for southern Africa that is based on the soil map for each country. The data obtained from the soil and terrain database were soil content and soil depth. The missing soil parameters such as hydraulic conductivity (SOL\_K) and available soil water content (SOL\_AWC) were calculated using the Soil Plant Atmosphere Water (SPAW) hydrology model. The clay, sand, and organic carbon content were used as inputs for the SPAW hydrological model. The soil erodibility factor (USLE\_K) and soil albedo (SOL\_ALB) were calculated using empirical formulas contained in the freely- available SWAT documentation on pages 308 to 309 by Arnold et al. (2012b).

The land use/land cover (LULC) spatial datasets were sourced from the Department of Environmental Affairs (DEA). The LULC that was used is the 2013-2014 National Land Cover that consist of 72 classes. The 72 classes of LULC included natural and man-made features in the VRB.

#### **5.4.1.3 Stream discharge**

The streamflow data for the C5H054 stream gauge were downloaded from the DWS hydrological website tool (<http://www.dwa.gov.za/Hydrology/Verified/hymain.aspx>). The stream gauge selected is located in Bishop's Glen along the Renosterspruit River, which is in the proximity of the C52F catchment outlet. The C5H054 stream gauge provides stream discharge measurements from 1995 to 2015 which are within the modelling period.

#### **5.4.1.4 Spatial datasets**

The Digital Elevation Map (DEM) that is important in the delineation of the catchment sourced from the United States Geological Survey Earth Explorer (USG), <https://earthexplorer.usgs.gov/>. The vector data such as rivers and quaternary drainage regions were sourced from the DWS.

#### 5.4.2 Modelling domain

The initial plan was to model the upper part of the VRB, which has an area of 55 000 km<sup>2</sup>. Because of the complex nature of the basin and the paucity of data it was, however, necessary to consider a smaller area. The C52F Quaternary Catchment was chosen for its relatively small size of 690 km<sup>2</sup> (Figure 5.3) and availability of weather data.

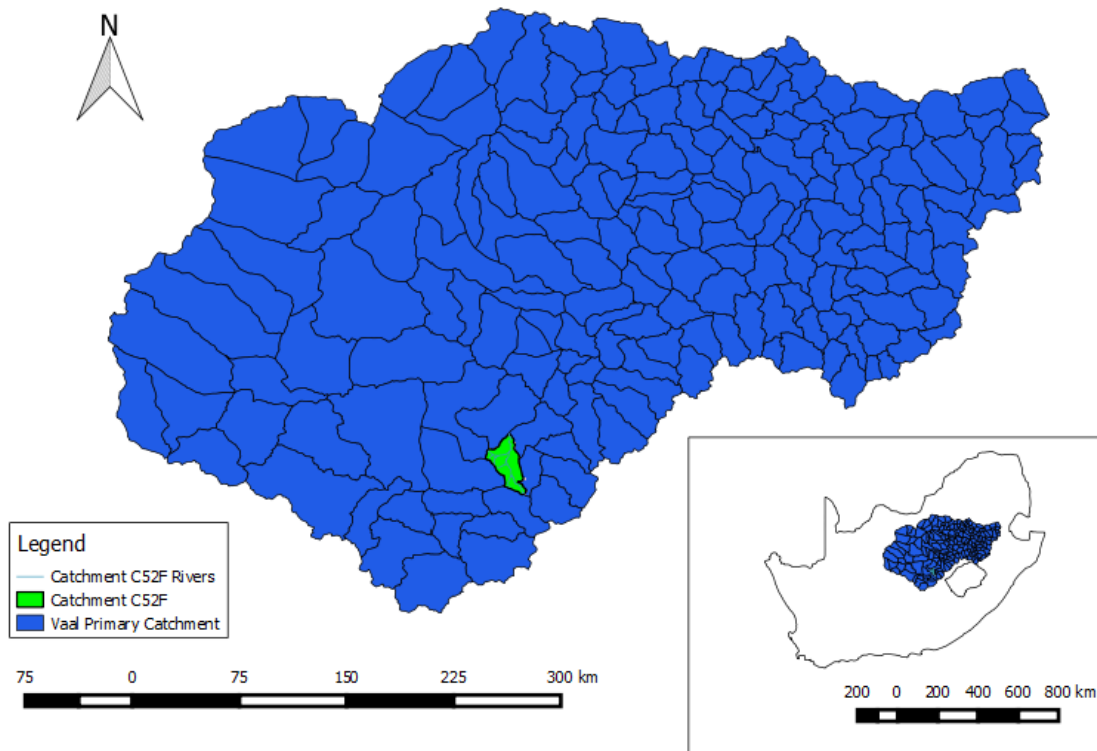


Figure 5.3: Locality map of the C52F Quaternary Catchment in the Vaal River Basin; the insert map shows the geographical extent of the Vaal River Basin in South Africa.

#### 5.4.3 Hydrological modelling design and setup

The QSWAT interface consists of three main steps: i) delineate the watershed; ii) create hydrological response units (HRUs), and iii) editing inputs and running SWAT.

The procedure followed and the input data used for each step are shown in Figure 5.4. See Sections 5.4.3.1, 5.4.3.2, and 5.4.3.3 for a detailed explanation of the main QSWAT steps followed in this study.

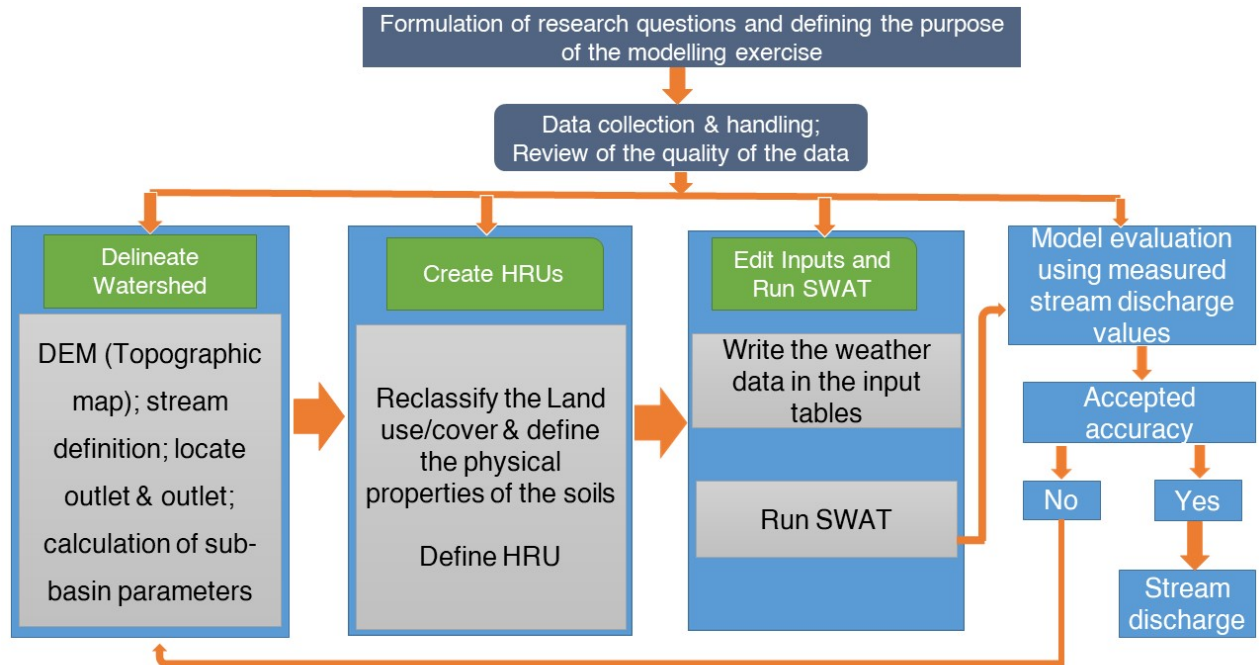


Figure 5.4: Schematic representation of the steps followed in the modelling of C52F Quaternary Catchment using QSWAT.

#### 5.4.3.1 Watershed delineation

The first step of the modelling process in QSWAT is delineating the watershed, which is the modelling domain. A threshold value of 50 km<sup>2</sup> was chosen in the watershed delineation process. The pre-defined stream network was useful in locating the inlets and outlets of the basin. Five sub-basins were produced that corresponded to the quaternary drainage region of catchment C52F.

#### 5.4.3.2 Creating hydrological response units

After basin delineation, the spatial data for land use/cover was used to generate hydrological response units (HRUs). The soil and LULC information were reclassified

in order to match what is required by the SWAT database because the default SWAT database is based on the United States' classification system. This reclassification led to the reduction of the 72 classes of LULC to 21 as shown in Table 5.2.

Table 5.2: Land use/cover classes for the C52F Quaternary Catchment.

|    | SWAT Land use/cover Code | Land use/cover                    |
|----|--------------------------|-----------------------------------|
| 1  | AGRL                     | Agricultural land                 |
| 2  | BSVG                     | Barren or sparsely vegetated land |
| 3  | CRWO                     | Cropland/woodland                 |
| 4  | FRST                     | Forest                            |
| 5  | GRAP                     | Vineyard                          |
| 6  | GRAS                     | Grassland                         |
| 7  | ORCD                     | Orchard                           |
| 8  | PINP                     | Pineapple                         |
| 9  | RNGB                     | Brush                             |
| 10 | RNGE                     | Grasses                           |
| 11 | SHRB                     | Shrubland                         |
| 12 | SUGC                     | Sugar cane                        |
| 13 | UCOM                     | Commercial                        |
| 14 | UIDU                     | Industrial                        |
| 15 | UINS                     | Institutional                     |
| 16 | URBN                     | Residential                       |
| 17 | URHD                     | Urban- high density               |
| 18 | URLD                     | Urban- low density                |
| 19 | URMD                     | Urban- medium density             |
| 20 | WATR                     | Water                             |
| 21 | WETL                     | Wetland                           |

#### 5.4.3.3 Edit input and run SWAT

In this step, the QSWAT project database was connected with the reference database. The writing of input tables in the SWAT editor using the weather data followed this connection. The starting and ending data of the simulation was from 01/01/2010 to 31/12/2015. The model output was chosen to be in monthly steps. A warm up period (NYSKIP) for 10 years was specified in order for the water storages in the basin to fill up and reach reasonable values. Thereafter, the QSWAT “run SWAT” option was

activated allowing for the simulation of water budget components of interest (these are explained in the next chapter).

#### **5.4.4 Calibration**

The calibration and uncertainty analysis of the SWAT model was accomplished using the Sequential Uncertainty Fitting version 2 (SUFI-2), which is part of the SWAT Calibration and Uncertainty Programs (SWAT-CUP) (Arnold et al., 2012). The SUFI-2 program allows for manual and automated calibration at the same time taking into account the sensitivity and uncertainty of the hydrological parameters in the analysis (ibid.). The SUFI-2 program was useful in identifying the hydrological parameters that are more sensitive in the C52F Quaternary Catchment. Stream discharge data for the C5H054 stream gauge for the period January 2010 to December 2015 was used for the calibration. More than 20 hydrological parameters that influence the hydrological processes in the C52F Quaternary Catchment were identified; however, the SUFI-2 program reveals that streamflow was most sensitive to only 9 hydrological parameters. The most sensitive hydrological parameters were added as input for the simulation, and results are presented in the following chapter - specifically Section 6.5.1.

The research methods and tools applied to reveal information about the nature of groundwater quantity and quality based on the availability of the data. The analysis of groundwater level trends and variability and the estimation of percolation and surface runoff rates were on a much smaller scale. The analysis of hydrochemical data and estimation of GRACE-derived groundwater storage changes were for the entire basin. These differences in scale imply that the results obtained will only be limited to that particular scale. Therefore, the results are presented and discussed in the next section taking into account the scale at which data was obtained.

## **6 RESULTS AND DISCUSSION**

In this preceding chapter, a detailed description of the methods and tools applied in the analysis of hydrological and meteorological data to achieve the aims and objectives of the study was provided. In the current chapter, the outputs from the analysis of data at varying scales are discussed. Lastly, an attempt is made to link the different components of the sub-topics discussed.

### **6.1 Hydrochemical characteristics of groundwater**

The hierarchical cluster analysis (HCA) output is represented in the form of a dendrogram (Figure 6.1). The HCA was performed in order to cluster the monitoring stations based on the similarity of their hydrochemical variables. This cluster analysis resulted in seven distinct groups and three outliers. This particular outcome means that the monitoring stations within a group have relatively similar values and are distinct from those in the other groups.

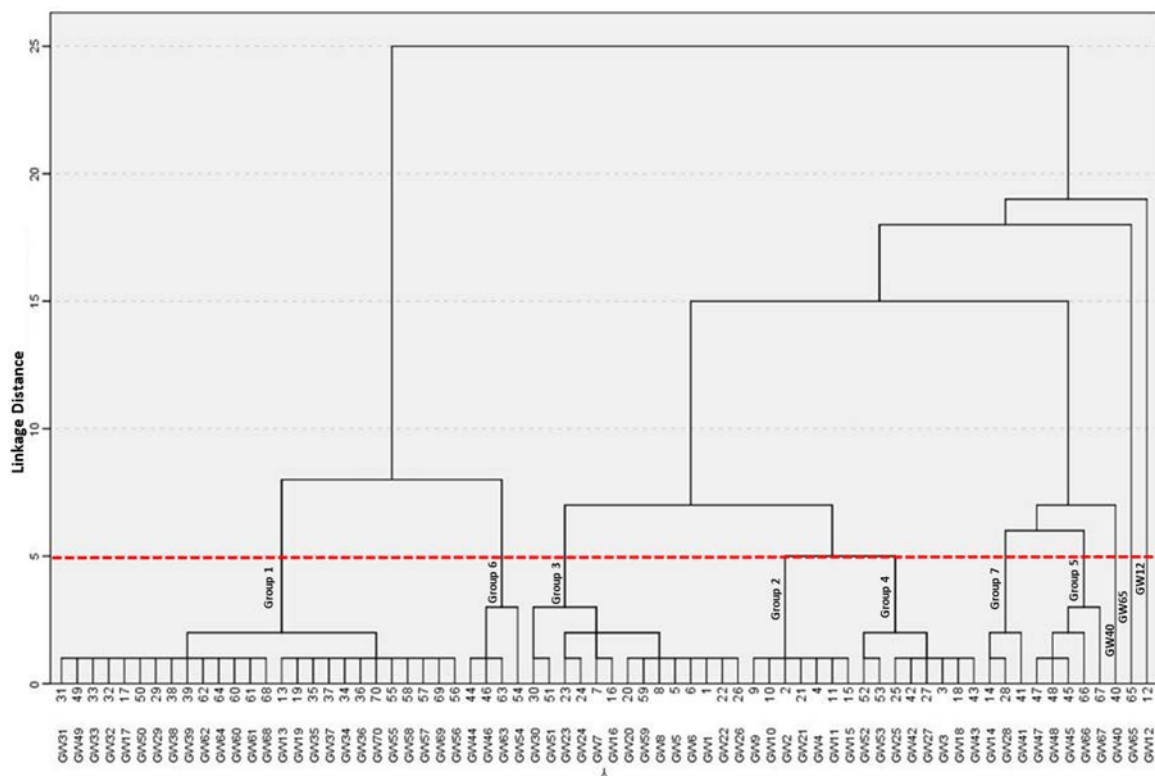


Figure 6.1: Hierarchical cluster analysis results in the form of a dendrogram for the water samples from 70 monitoring points in the Vaal River Basin (The linkage distance selected is 5, and it is marked by a dashed line) (Source: Masindi & Abiye 2018).

Few water samples did not fall into any group but were represented as standalone groups since they are not a mathematical artefact but a true representation of groundwater chemistry in a particular monitoring station. These outliers are: GW12, GW40 and GW65. Thus, they are chemically distinct from any other group and from each other. It is possible that the outliers could be indicative of a segment that has been under-sampled in the Vaal River Basin.

The seven identified groups and outliers were plotted in the land use/cover (LULC) map (Figure 6.2) in order to visualise the spatial linkages between the groundwater samples and the land uses in the Vaal River Basin. The geological map presented in section 2.7.1 will be referred to in the discussion ahead as it provides context for making connections between minerals responsible for the observed groundwater chemical characteristics.



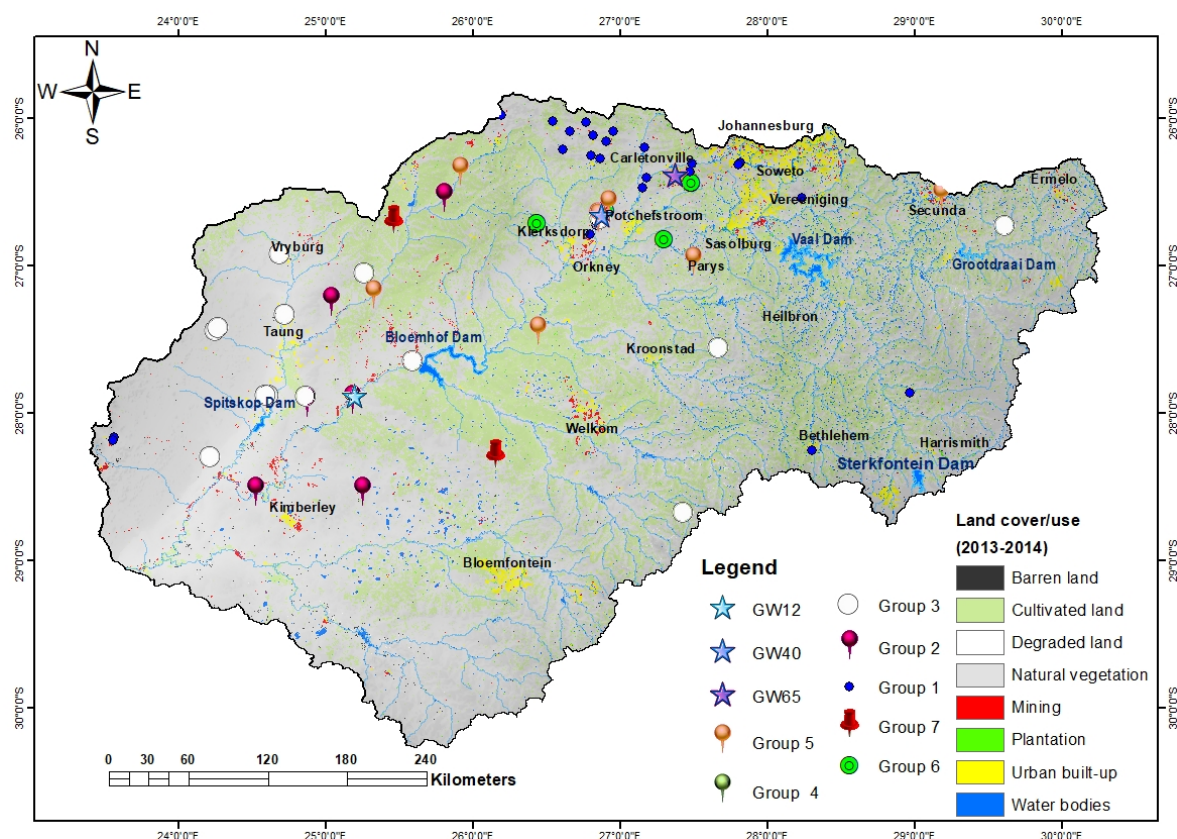


Figure 6.2: Land use/cover map for the Vaal River Basin showing the sites were seven identified groups and three outliers are situated.

The mean values of the chemical variables for the seven identified groups and outliers are shown in Table 6.1. This table also shows that the potential of hydrogen (pH) values of the groups is alkaline ( $>7$ ) in nature, except for slightly acidic (6.99) waters for Group 6. Group 6 water samples are also least mineralised compared to all the other groups. The alkaline nature of the water is not surprising given that most of the monitoring stations are located in a terrain underlain by carbonates of the Malmani Subgroup in the northeast of the VRB. Carbonate dissolution in the basin removes hydrogen from the weakly acidic water which results in an alkaline type of water. The weakly alkaline and mineralised nature of water for Group 6 can be explained by recently weak acidic water recharging the aquifer system.

Table 6.1: Comparison of accepted drinking water standards by World Health Organization (2004) and South African National Standard (SANS 241: 2015) to hydrochemical variables in the VRB (Source: Masindi & Abiye 2018).

| Parameter       | MEAN   | SD     | WHO (2004)      | Group 1 | Group 2 | Group 3 | Group 4 | Group 5 | Group 6 | Group 7 | GW12    | GW40    | GW65   |
|-----------------|--------|--------|-----------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|--------|
| n               |        |        |                 | 26      | 7       | 14      | 8       | 5       | 4       | 3       | 1       | 1       | 1      |
| pH              | 8.02   | 0.38   | 6.5-8.5 (5-9.7) | 8.20    | 8.01    | 8.13    | 8.03    | 7.91    | 6.99    | 7.90    | 7.87    | 7.53    | 7.58   |
| TDS             | 648.39 | 385.53 | 500 (1200)      | 427.51  | 892.52  | 739.72  | 453.93  | 1075.46 | 90.77   | 1148.95 | 1949.39 | 2168.20 | 732.35 |
| EC (µS/Cm)      | 92.85  | 57.98  | (170 mS/cm)     | 58.44   | 136.40  | 103.79  | 78.55   | 142.89  | 14.07   | 164.92  | 327.49  | 248.68  | 102.16 |
| Ca              | 72.16  | 44.41  | (150)           | 52.14   | 109.83  | 73.41   | 45.81   | 136.62  | 8.41    | 145.18  | 50.66   | 257.43  | 72.20  |
| Mg              | 44.46  | 30.30  | (70)            | 30.70   | 61.48   | 53.50   | 31.89   | 64.90   | 6.49    | 82.76   | 34.58   | 205.84  | 40.57  |
| Na              | 41.99  | 74.59  | 200 (200)       | 13.66   | 52.08   | 47.59   | 25.42   | 88.51   | 4.17    | 62.03   | 574.06  | 48.00   | 82.37  |
| K               | 3.36   | 3.00   | (50)            | 1.68    | 3.21    | 3.24    | 4.06    | 4.24    | 1.17    | 13.42   | 7.82    | 7.88    | 9.32   |
| Cl              | 58.49  | 112.59 | 250 (300)       | 13.86   | 114.39  | 50.67   | 27.16   | 91.78   | 6.26    | 216.07  | 796.80  | 19.44   | 58.37  |
| SO <sub>4</sub> | 112.76 | 183.26 | 250 (250)       | 50.47   | 106.11  | 68.82   | 29.50   | 515.31  | 8.07    | 157.78  | 146.48  | 1083.80 | 326.29 |
| TAL             | 235.58 | 108.90 |                 | 208.11  | 297.59  | 340.21  | 197.53  | 131.41  | 33.47   | 350.54  | 273.89  | 447.11  | 90.07  |
| Si              | 12.62  | 6.46   |                 | 8.36    | 20.74   | 12.60   | 22.94   | 10.90   | 6.16    | 18.32   | 9.85    | 10.46   | 6.79   |
| F               | 0.30   | 0.30   | (1.5)           | 0.17    | 0.37    | 0.49    | 0.21    | 0.23    | 0.10    | 0.42    | 2.02    | 0.17    | 0.23   |
| NH <sub>4</sub> | 0.12   | 0.43   | (1.5)           | 0.05    | 0.04    | 0.06    | 0.04    | 0.29    | 0.04    | 0.07    | 0.08    | 0.05    | 3.58   |
| NO <sub>3</sub> | 5.81   | 6.16   | 50 (11)         | 2.47    | 18.59   | 4.42    | 11.04   | 3.08    | 3.29    | 9.37    | 0.64    | 0.08    | 4.73   |
| PO <sub>4</sub> | 0.08   | 0.31   |                 | 0.02    | 0.02    | 0.11    | 0.02    | 0.07    | 0.02    | 0.02    | 0.01    | 0.02    | 2.50   |

\* All chemical parameters are in mg/L unless specified

High total dissolved solids (TDS) (>1000 mg/L) and sulphate concentrations (>140 mg/L) is characteristic of Group 5, Group 7, GW12, GW40 and GW65, and is indicative of highly mineralised water. This observation can be attributed to mine-pollution in the basin with the exception of GW12 (Figure 6.2). The water sample GW12 has the

highest concentrations of sodium (Na) (547.06 mg/L) and chloride (Cl<sup>-</sup>) (796.80 mg/L) in the basin. However, there are several explanations for the high Na and Cl in the basin. Such high concentrations of Na and Cl can be explained by elevated evaporation rates in the arid southwest part of the basin, which increases the soil salinity. It can also be seen in Figure 6.3 that the arid region in the southwest has a higher salinity compared to the upper part of the Vaal River Basin (VRB) that experiences semi-arid climatic conditions. There are minor variations in the mean values for the hydrochemical parameters for Group 1, Group 2, Group 3, and Group 4 water samples. Their mean values are consistent with groundwater in circulation undergoing moderate dissolution. Interestingly, Group 2 has the highest nitrate (NO<sub>3</sub>) concentration of 18.59 mg/L, indicating that agriculture and urbanisation affects groundwater in the basin.

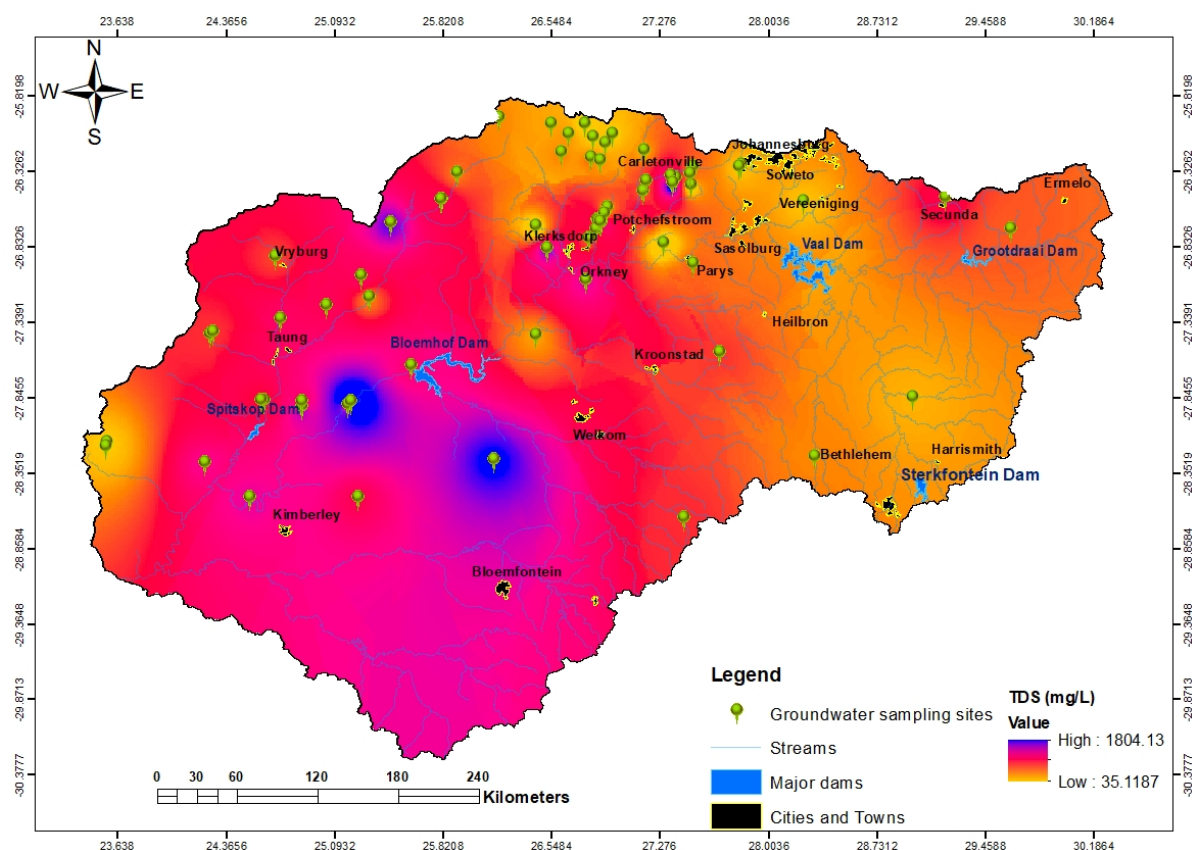


Figure 6.3: Spatial distribution map of groundwater total dissolved solids in the Vaal River Basin showing increasing salinity from southeast to southwest of the basin.

The major ions among the groups show a greater variation as is shown on the Schoeller Diagram in Figure 6.4; this variation could be a result of unique geological conditions, residence time, and prevailing human activities in the basin.

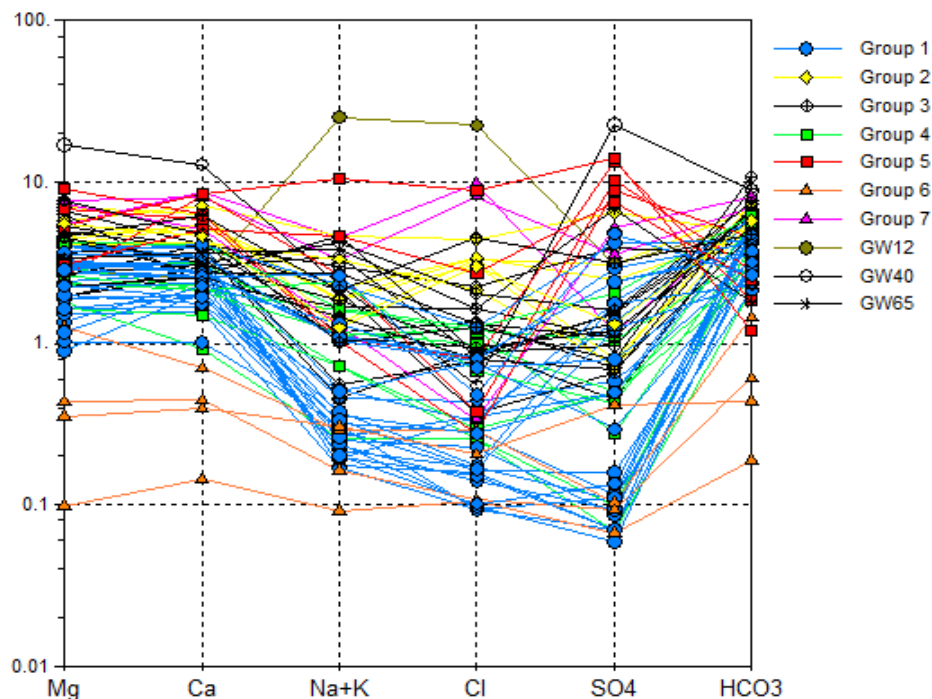


Figure 6.4: Schoeller Diagram showing the relative abundance of major ions for the groundwater samples from the Vaal River Basin (Source: Masindi & Abiye 2018).

From a drinking water quality point of view, the relative concentrations of the hydrochemical variables are within WHO (2004) and SANS (241:2015) drinking water guidelines, with the exception of GW12. Caution must be taken because the results did not include bacteriological characteristics of the water or heavy metals such as palladium (Pd) and cadmium (Cd), both of which can pose serious risk to human health.

The plot of major ions in the Piper Plot (Figure 6.5) shows the groundwater types in the Vaal River Basin (VRB). The Piper Plot helped with the hydrochemical facies classification and the identification of probable mixing and evolutionary trends in the groundwater chemistry.

The Piper Plot (Figure 6.5) shows that the most abundant cations are alkaline earths (calcium and magnesium; Ca and Mg) compared to alkalis (sodium and potassium; Na and K), whereas the most dominant anions are weak acids (bicarbonate;  $\text{HCO}_3$ ) compared to strong acids (sulphate and chloride;  $\text{SO}_4$  and  $\text{Cl}$ ). The water samples can therefore be broadly classified into Ca-Mg- $\text{SO}_4$ -Cl and Ca-Mg- $\text{HCO}_3$  types. The Ca-Mg- $\text{HCO}_3$  is the dominant water type, which is characteristic of Groups 1,2,3,4, and 6. This is a result of groundwater interacting with heterogeneous geological materials along its flow path such as carbonates and volcanics situated in the western part of the basin (Figure 2.15). Hobbs et al. (2013) showed that the Ca-Mg- $\text{HCO}_3$  type water is characteristic of the pristine groundwater in the dolomitic aquifer.

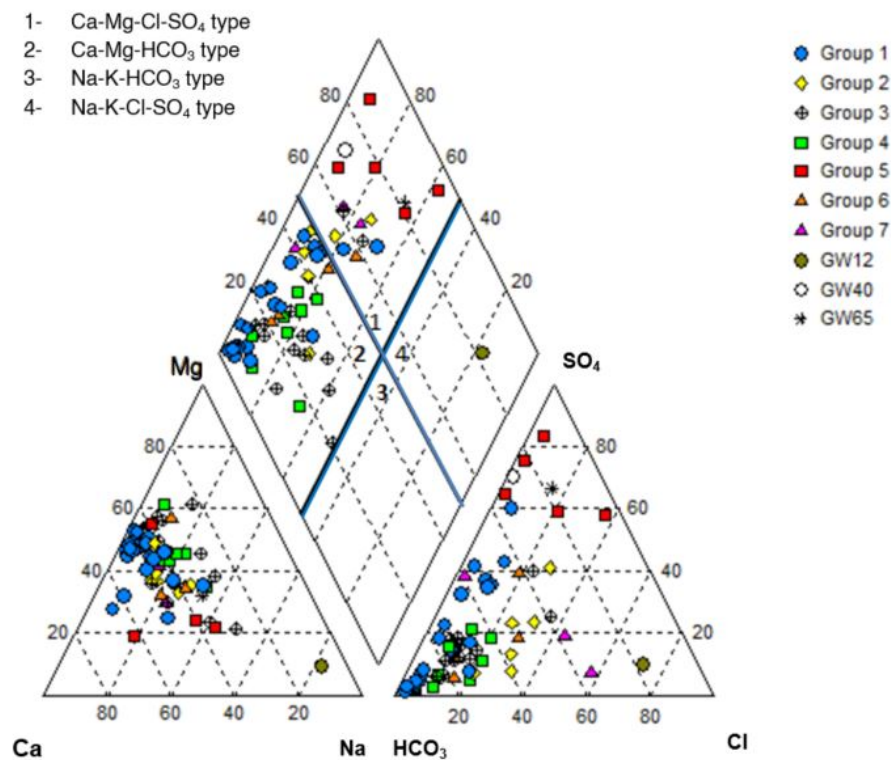


Figure 6.5: Piper Plot showing the water types for the groundwater samples in the Vaal River Basin (Source: Masindi & Abiye 2018). The predominant cations and anions in increasing order are:  $\text{Na} < \text{Mg} < \text{Ca}$  and  $\text{Cl} < \text{SO}_4 < \text{HCO}_3$ .

Group 5, Group 7, GW40 and GW65 that are heavily mineralised plot in the Ca-Mg-SO<sub>4</sub>-Cl field which is characteristic of polluted water. Based on local knowledge of the basin, the Ca-Mg-SO<sub>4</sub>-Cl water type can be attributed to possible pollution of pristine dolomitic water through mixing with acidic water from mines in the area, and also effluent from urban and industrial sources that are rich in highly soluble chloride compounds. This agrees well with studies by McCarthy (2011), Durand (2012) and Abiye (2014) who all demonstrated sulphate (SO<sub>4</sub><sup>2-</sup>) enrichment in groundwater as a result of mine pollution in the mining regions, which covers a greater part of the VRB. The Ca-SO<sub>4</sub> can be explained by the mixing of groundwater from the pristine dolomite aquifers with mine-polluted water. Hobbs et al. (2013) reported similar findings in the Cradle of Humankind Heritage Site, South Africa. Only one sample (GW12) has a Na-Cl water type, which could be related to deep saline water given that is situated in the arid part of the VRB (Figure 6.2). The groundwater sample, GW12, could also be indicative of another aquifer totally unrelated to the dolomitic aquifer, as it appears to not be impacted by mining activities (Figure 6.2). Nonetheless, most of the groundwater samples have no dominant ions as can be seen in Figure 6.5 with groundwater samples plotting at the centre of the ternary plot. This trend in the groundwater samples could possibly be a result of mixing of water from different aquifers, impacted by various human activities, cation exchange between Mg-Ca-Na, and the substitution of bicarbonate (HCO<sub>3</sub><sup>-</sup>) and sulphate (SO<sub>4</sub><sup>2-</sup>).

Using the Pearson Correlation, the statistical correlation between two or more variables in hydrochemical data were analysed. These results are presented in Table 6.2.

Table 6.2: Correlation matrix of the groundwater chemical variables (Source: Masindi & Abiye 2018).

|                       | TDS         | EC          | pH          | Ca          | Mg          | Na          | K           | Cl          | SO <sub>4</sub> | TAL  | F    | Si          | PO <sub>4</sub> | NO <sub>3</sub> | NH <sub>4</sub> |
|-----------------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-----------------|------|------|-------------|-----------------|-----------------|-----------------|
| <b>TDS</b>            | 1.00        |             |             |             |             |             |             |             |                 |      |      |             |                 |                 |                 |
| <b>EC</b>             | <b>0.94</b> | 1.00        |             |             |             |             |             |             |                 |      |      |             |                 |                 |                 |
| <b>pH</b>             | 0.42        | 0.29        | 1.00        |             |             |             |             |             |                 |      |      |             |                 |                 |                 |
| <b>Ca</b>             | <b>0.94</b> | <b>0.86</b> | 0.44        | 1.00        |             |             |             |             |                 |      |      |             |                 |                 |                 |
| <b>Mg</b>             | <b>0.92</b> | <b>0.84</b> | 0.45        | <b>0.90</b> | 1.00        |             |             |             |                 |      |      |             |                 |                 |                 |
| <b>Na</b>             | <b>0.74</b> | <b>0.78</b> | 0.13        | <b>0.59</b> | 0.50        | 1.00        |             |             |                 |      |      |             |                 |                 |                 |
| <b>K</b>              | 0.58        | 0.61        | 0.04        | 0.48        | 0.42        | <b>0.72</b> | 1.00        |             |                 |      |      |             |                 |                 |                 |
| <b>Cl</b>             | <b>0.70</b> | <b>0.77</b> | 0.08        | <b>0.59</b> | 0.54        | <b>0.85</b> | 0.62        | 1.00        |                 |      |      |             |                 |                 |                 |
| <b>SO<sub>4</sub></b> | <b>0.70</b> | <b>0.72</b> | 0.03        | <b>0.67</b> | 0.60        | <b>0.73</b> | <b>0.53</b> | <b>0.61</b> | 1.00            |      |      |             |                 |                 |                 |
| <b>TAL</b>            | <b>0.74</b> | 0.64        | <b>0.65</b> | <b>0.72</b> | <b>0.77</b> | 0.34        | 0.27        | 0.34        | 0.21            | 1.00 |      |             |                 |                 |                 |
| <b>F</b>              | 0.59        | 0.59        | 0.22        | 0.40        | 0.36        | <b>0.75</b> | <b>0.51</b> | <b>0.66</b> | 0.39            | 0.46 | 1.00 |             |                 |                 |                 |
| <b>Si</b>             | 0.41        | 0.47        | 0.15        | 0.39        | 0.43        | 0.39        | 0.38        | 0.45        | 0.10            | 0.41 | 0.30 | 1.00        |                 |                 |                 |
| <b>PO<sub>4</sub></b> | 0.21        | 0.18        | 0.06        | 0.21        | 0.18        | 0.23        | 0.20        | 0.23        | 0.30            | 0.01 | 0.16 | 0.17        | 1.00            |                 |                 |
| <b>NO<sub>3</sub></b> | 0.15        | 0.23        | 0.11        | 0.17        | 0.23        | 0.12        | 0.02        | 0.39        | 0.09            | 0.14 | 0.02 | <b>0.58</b> | 0.02            | 1.00            |                 |
| <b>NH<sub>4</sub></b> | 0.30        | 0.24        | 0.00        | 0.25        | 0.22        | 0.34        | 0.33        | 0.24        | 0.47            | 0.10 | 0.14 | 0.28        | <b>0.60</b>     | 0.09            | 1.00            |

Note: N=70. Correlation is significant at the 0.05 level (2-tailed). r (68)=0.5, p<0.05

Statistical correlation was observed among the hydrochemical variables; the significance values were below 0.05 (p-value<0.05). The correlation coefficient for most of the variables is greater than the critical value (R) of 0.24. The R-value is found on the critical value table, at the intersection between the 0.05 level of significance and 68 degree of freedom. In this study, the assumption is that the statistical correlation between the variables greater than 0.5 is meaningful. A simple criteria are developed to describe the strength of the statistical correlation as follows: very strong (r: 0.80-1), strong (r: 0.70-0.79), moderate (r: 0.50-0.69) and weak (r: 0.00- 0.49).

It can be seen in Table 6.2 that total dissolved solids (TDS) and EC are strongly correlated, and very strongly correlated to the major constituents but moderately correlated with the minor ion, flouride (F<sup>-</sup>). This is not surprising given that major ions are the chief contributors to groundwater salinity and mineralisation. Mg and Ca are strongly correlated with total alkalinity (TAL), which is more likely due to carbonate dissolution processes that release CO<sub>3</sub><sup>2-</sup> and HCO<sub>3</sub><sup>-</sup> in the aquifer system. Groundwater in the basin appears to have a high buffering capacity based on the

moderate correlation between pH and TAL. The TAL and pH are moderately correlated, which is indicative of a high buffering capacity of the groundwater system. This is supported by neutral to basic pH values in the groundwater as shown in Table 6.1.

Ca and Mg show a strong positive correlation,  $r=0.90$ , which can be attributed to chemical weathering of dolomite ( $\text{CaMg}(\text{CO}_3)_2$ ) and limestone ( $\text{CaCO}_3$ ) that covers a large part of the northwestern and southwestern part of the basin (Figure 2.18). It can be seen from Table 6.2 that the correlation between Na and K is 0.72, which could be explained by silicate weathering. The moderate correlation between Na and Ca, and between Mg and Na is 0.59 and 0.50, respectively. These could be a result of ion exchange processes and chemical weathering of silicates (i.e. granite, sandstone and quartzite).

Interestingly, sulphate shows a moderate to strong correlation with major constituents in water. The statistical correlation between  $\text{SO}_4$  and other ions is as follows; Na- $\text{SO}_4$  (0.73), Ca- $\text{SO}_4$  (0.67), Cl- $\text{SO}_4$  (0.61), Mg- $\text{SO}_4$  (0.60) and K- $\text{SO}_4$  (0.53). The  $\text{SO}_4^{2-}$  enrichment in the basin, as mentioned in the preceding paragraph, is linked to mine pollution (Figure 6.7). Minerals such as gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ), anhydrite ( $\text{CaSO}_4$ ) and magnesium sulphate ( $\text{MgSO}_4$ ) generated by gold mining activities are the sources of  $\text{SO}_4$  in the groundwater. On breaking down gypsum and magnesium sulphate, Mg, Ca, and  $\text{SO}_4$  are released. Thus, mine pollution is a severe problem in the upper part of the basin because of intense mining activities as shown in Figure 6.2.

The correlation coefficient between Na and Cl is 0.85, whereas the correlation coefficient between Cl and K is 0.62. These relationships between the ionic pairs could be a result of dissolution of minerals such as halite ( $\text{NaCl}$ ) and sylvite ( $\text{KCl}$ ) in the southwestern part of the basin that characteristically experiences climate aridity and where surficial features are aeolian sands and salt pans. It is suggested that leaching of minerals from the saline soils and salt pans during percolation of rainwater is the source of Na, Cl, and K. The deposition of marine salts through rainfall that recharges the aquifer could be another possibility. Furthermore, Cl moderately correlates with F (0.66), Ca (0.59) and Mg (0.54); this could be attributed to soluble salts discharged from industrial and urbanised activities in the upper part of the VRB (Figure 6.2).



Several highly soluble salts such as CaF, MgCl<sub>2</sub>, CaCl<sub>2</sub> and NaF are as a result of the breakdown of minerals such as albite, anorthite and apatite that are weathered from sandstone, granites, quartzites, and mudstone underlying some parts of the basin to cause Ca-, Na-, and F- enrichment in groundwater.

The ionic pairs Na and F have a strong correlation ( $r=0.75$ ), which suggests that they could be derived from a similar source in the basin. Ncube and Schutte (2004) have reported high fluoride concentration in the Northwest Province. They attribute the fluoride enrichment in groundwater to chemical weathering of basement rocks in the eastern and central parts of the VRB. The concentration of fluoride will be restricted by the solubility of fluorite and the common-ion effect caused by a high concentration of calcium ions in water.

The agricultural activities and sewage sludge that discharges to the Vaal River and its tributaries is the most probable source of NH<sub>4</sub><sup>+</sup> and PO<sub>4</sub><sup>3-</sup>, which are moderately correlated (0.58) - as can be seen in Table 6.2. The impact is more likely to be on shallow aquifers that have direct interaction with streams. Besides the anthropogenic sources, the chemical weathering of granitic rocks that contain minerals such as apatite (Ca<sub>5</sub>(PO<sub>4</sub>)<sub>3</sub>(F, Cl, OH)), could be sources of PO<sub>4</sub><sup>2-</sup> in groundwater. A moderate correlation between NO<sub>3</sub> and Si of 0.58 was observed. This relationship can be explained by groundwater interaction with meta-sediments and chert that are source rocks for silica. Sources for NO<sub>3</sub> are agricultural return flows and sewage wastewater discharge into streams with close linkages to aquifers. The oxidation of ammonium ions contributes, in part, to the nitrate sources in the basin.

It can be seen in Figure 6.6 that the ionic ratio plots reveal the predominant hydrochemical processes that control the water chemistry in the basin. The plot of Na+K versus Cl+SO<sub>4</sub> in Figure 6.6(a), shows that Cl and SO<sub>4</sub> are more dominant than the Na+K in the basin as indicated by approximately 85% of the water samples that are above the 1:1 line. The dominance of Cl and SO<sub>4</sub> suggests that mining activities and urbanisation exert the most influence on the groundwater chemistry, since they are the main sources for the predominant ions. Group 5 waters are all above the 1:1 line, which indicates mine pollution. The observations in Figure 6.6(a) also shows that

Na and K sources have less influence on the groundwater chemistry, but influence less than 25% of the water in the basin.

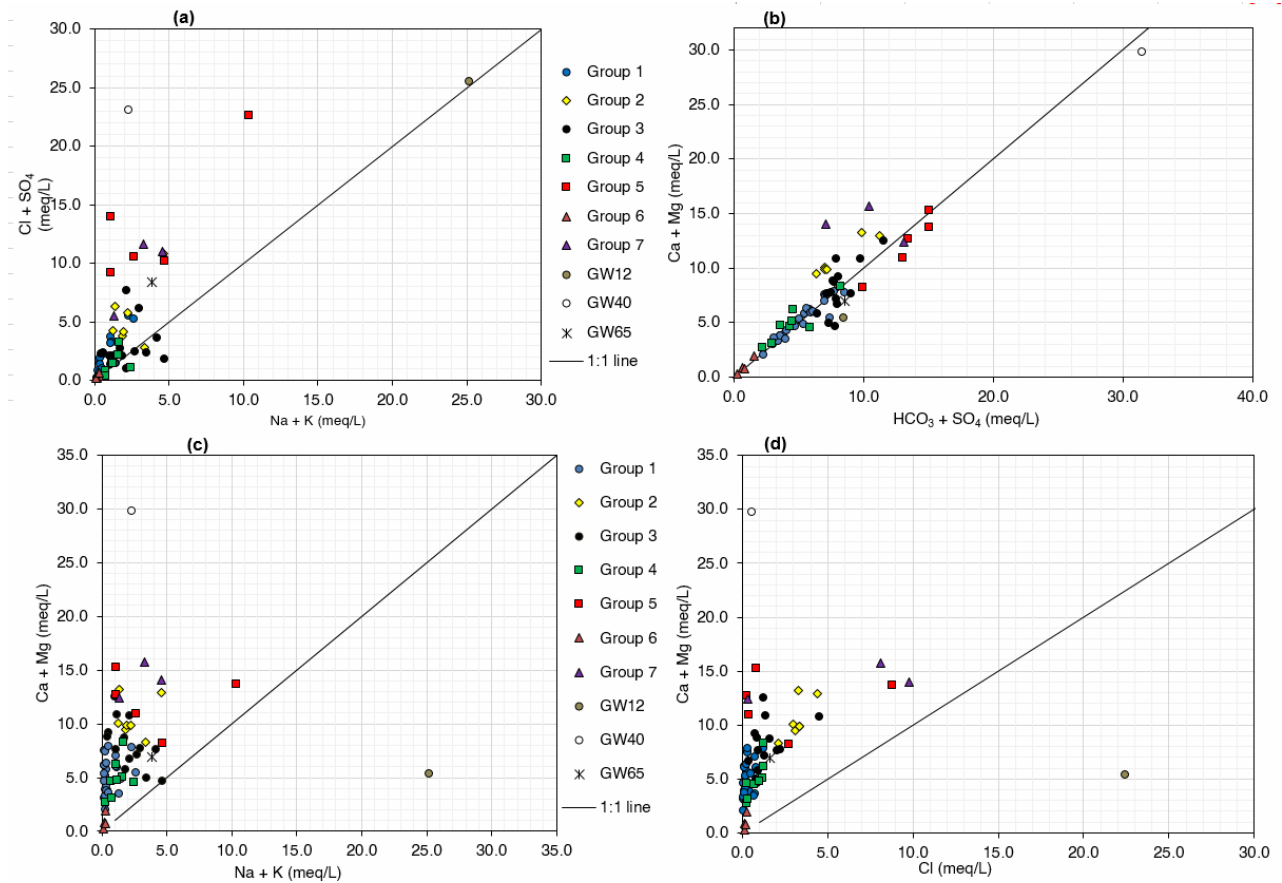


Figure 6.6: Bivariate Plots of major ionic concentration in meq/L that reveal various hydrochemical processes taking place in the Vaal River Basin (a: Na+K versus Cl+SO<sub>4</sub>; b: Ca + Mg vs HCO<sub>3</sub> + SO<sub>4</sub>; c: Ca + Mg vs Na + K and d Ca + Mg versus Cl) (Source: Masindi & Abiye 2018).

The plot of Ca + Mg versus HCO<sub>3</sub> + SO<sub>4</sub> (Figure 6.6(b)) is helpful in identifying if there is ion exchange occurring in the waters. The waters tend to shift to the right of the plot if ion exchange is occurring because of an excess of HCO<sub>3</sub> + SO<sub>4</sub>. In contrast, if carbonate dissolution is taking place, the water plots in the left because of excess Ca + Mg over HCO<sub>3</sub> + SO<sub>4</sub> (Fisher & Mulican, 1997). In this analysis, it can be seen that the waters plot closer to the 1:1 line revealing that there is carbonate weathering in the basin, such as weathering of dolomite, limestone, and gypsum. This is expected

because carbonate rocks in the basin are the most significant aquifers in the VRB and South Africa (SA). The approximately 98% of the waters close to and above the 1:1 line reveals that reverse ion exchange is an important process in the VRB. In addition to the previous plots presented, the plot of  $\text{Ca} + \text{Mg}$  versus  $\text{Cl}$  reveals that there is no linear relationship among  $\text{Ca}$ ,  $\text{Mg}$ , and  $\text{Cl}$ , thereby supporting the suggestion that carbonate dissolution and reverse ion exchange are key hydrochemical processes in the basin.

Another plot of  $\text{Ca} + \text{Mg}$  versus  $\text{Na} + \text{K}$  (Figure 6.6(c)) shows waters clustering to the left of the 1:1 line; this trend reveals dolomite dissolution as a key process in the basin, and to a lesser degree, the occurrence of silicate dissolution. It also supports the earlier suggestion that GW12 could be water from a deep circulating aquifer system that has had a long residence time or groundwater flowing in an evaporative environment, thereby confirming that GW12 is not part of the mine-polluted waters in the basin (Figure 6.2). The plot of  $\text{Ca} + \text{Mg}$  versus  $\text{Cl}$  (Figure 6.6(d)) indicates that carbonate dissolution is a key process over dissolution of ferromagnesian minerals. These observations suggest that the underlying dolomite in the basin has a major influence on the water chemistry.

The principal component analysis (PCA) results are shown in Table 6.3 with loading on the extracted components, and the percentage of variance that each component explains. Only four components explain 81.52% of the total variance in the groundwater chemistry of the basin. The first component accounts for 48.61% of the variance in the hydrochemical data; the fourth component explains only 7.50% of the variance. The residual components that are not included collectively explain 18.48% of the variability in the remaining data. The loadings of the components were helpful in identifying the predominant variable that explains the variability in the data and the factors causing such loading.

Table 6.3: Rotated component matrix for the chemical data for all the groundwater samples  
(Source: Masindi & Abiye 2018).

| Chemical variables                   | Component   |             |             |             |
|--------------------------------------|-------------|-------------|-------------|-------------|
|                                      | 1           | 2           | 3           | 4           |
| TDS                                  | 0.67        | 0.69        |             |             |
| EC                                   | <b>0.74</b> | 0.55        |             |             |
| pH                                   |             | <b>0.81</b> |             |             |
| Ca                                   | 0.51        | <b>0.74</b> |             |             |
| Mg                                   |             | <b>0.79</b> |             |             |
| Na                                   | <b>0.92</b> |             |             |             |
| K                                    | <b>0.79</b> |             |             |             |
| Cl                                   | <b>0.82</b> |             |             |             |
| SO <sub>4</sub>                      | <b>0.72</b> |             |             |             |
| TAL                                  |             | <b>0.89</b> |             |             |
| F                                    | <b>0.76</b> |             |             |             |
| Si                                   |             |             |             | <b>0.71</b> |
| NH <sub>4</sub>                      |             |             | <b>0.85</b> |             |
| NO <sub>3</sub>                      |             |             |             | <b>0.96</b> |
| PO <sub>4</sub>                      |             |             | <b>0.84</b> |             |
| Eigenvalues                          | 7.3         | 2.23        | 1.58        | 1.13        |
| % of variance explained by component | 48.61       | 14.88       | 10.53       | 7.50        |
| Cumulative % of variance             | 48.61       | 63.49       | 74.02       | 81.52       |

High positive loading for Na, Cl, K, F, EC, SO<sub>4</sub> and TDS - in decreasing order - were observed in component 1. This high positive loading suggests that chemical weathering of feldspars, micas, salts, and phosphates have a greater influence in the groundwater chemistry than carbonate dissolution, as highlighted in the previous section. The dissociation of evaporitic minerals is the likely source of Na, K, Cl in the basin. Effluent from industrial and urbanised zones provides additional sources of Na, Cl, K, and Ca.

It is also apparent from Table 6.3 that SO<sub>4</sub> has high loading. The SO<sub>4</sub> is generated through the oxidation of sulphides such as pyrite (FeS<sub>2</sub>), arsenopyrite (FeAsS), cobaltite (CoAsS) and pyrrhotite (FeS), in gold and coal mining tailing dams and mine dumps. The spatial distribution map of SO<sub>4</sub> (Figure 6.7) shows a high SO<sub>4</sub> concentration in the gold mining towns of Carletonville, Orkney, and Klerksdorp. The acidic water from the mine-related activities interacts with pristine water from the dolomitic aquifer, which neutralises the acidic water and results in precipitation of gypsum. The dissolution of gypsum, in turn, releases SO<sub>4</sub> and Ca into the water. The

positive high loading in the first components suggest that a combination of anthropogenic activities and geological materials exert a significant influence on the groundwater chemistry. In the northern part of the VRB around Johannesburg, the  $\text{SO}_4$  concentration is not as high, probably because it is at the water divide, a zone of groundwater recharge. At the recharge zone, there is generally little time for water-rock interaction and the groundwater is relatively pristine.

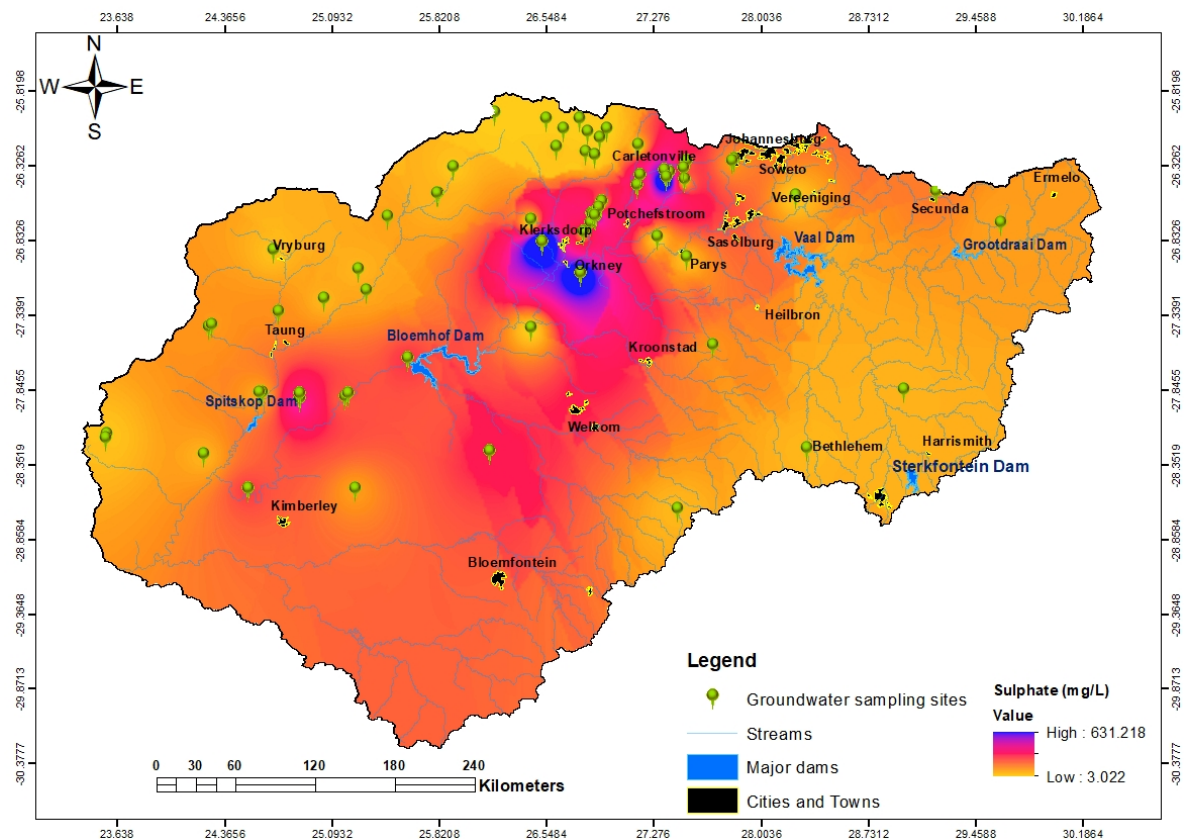


Figure 6.7: Map showing the spatial distribution of sulphate in the study site, with high concentrations notable in mining towns.

The second component accounts for 14.88% of the variance in the water chemistry, with high positive loading for TAL, pH, Mg, Ca, and TDS. The high positive loading in this component suggests that dissolution of carbonates that underlie the northeast and southwest part of the basin is also an important hydrochemical process.

The third component contributes 10% of the variance in the water chemistry. The occurrence of  $\text{PO}_4$  and  $\text{NH}_4$  in the basin is a result of wastewater treatment as well as

industrial and agricultural effluent discharge. Dissolution of granitic rocks probably partially contributes to the  $\text{NH}_4$  and  $\text{PO}_4$ .

The last component accounts for the least (7%) of the variance in the chemical data. Both  $\text{NO}_3$  and Si have high positive loading. This loading suggests that weathering of silica-rich granitic and quartz porphyry rocks and/or sedimentary and meta-sedimentary rocks such as sandstone, conglomerate, and quartzite in the central and northwest part of the basin contribute to the variance in the chemical data. Discharge of sewage from households in the urbanised parts of the basin as well as agricultural return flows, which are sources of  $\text{NO}_3$ , have some influence on the groundwater chemistry variability. The  $\text{NO}_3$  loading is indicative of the impact of human waste disposal on the hydrochemical data, which also threatens the water quality.

## **6.2 Rainfall trend and variability**

The M-K Test and Sen's Slope Estimator results for rainfall are presented in Table 6.4. Data from this table shows that the annual rainfall of selected rain gauges across the basin declined over the entire period. Interestingly, only two rain gauges namely, C2E010 and C4E008 had a statistically significant decreasing trend of -5.466 mm/year and -3.543 mm/year, respectively. The decline in the rainfall amount in the basin over the study period suggests a reduction in terrestrial moisture. This finding is consistent with that of Mackellar et al. (2014) who detected statistically significant decreases in rainfall amounts and increases in minimum and maximum temperatures in the interior of SA for a forty-year period from 1960 to 2010. This explanation may be somewhat limited by the absence of temperature and evaporation analysis because of data scarcity.

Table 6.4: Annual trends of long-term rainfall data obtained by Mann-Kendall Test and Sen's Slope Estimator.

| Rain gauge ID | M-K Test | Sen's Slope Estimator |
|---------------|----------|-----------------------|
| C2E009        | -0.92    | -1.244                |
| C2E001        | 0.00     | -0.003                |
| C2E010        | -2.78    | -5.466**              |
| C4E002        | -1.94    | -2.323                |
| C4E008        | -2.11    | -3.543*               |
| C7E001        | -1.34    | -1.721                |
| C9E003        | -0.03    | -0.045                |

\* Statistically significant trends at the 5% significance level\*\* Statistically significant trends at the 1% significance level

The graphs in Figure 6.8 and Figure 6.9 show the greater annual variability in the rainfall amount across the study area in each rain gauge. Figure 6.8 shows that the annual rainfall patterns in the upper part of the VRB C2E009, C2E010 and C2E001 are dissimilar. In contrast, the rainfall in the lower part of the VRB (Figure 6.9) shows some similarity in peak annual rainfall for some years. For example, rainfall gauges C9E003, C4E002 and C4E008 in the lower part of the VRB recorded the highest rainfall in 1987. The discrepancies among the rain gauges could be a result of large spatial variability in altitude in the upper part of the VRB, whereas in the lower part there are minor variations in altitude. Whilst these findings are more localised, they show that different parts of the VRB will experience water shortages to varying degrees, which has implications for water allocation in the basin.

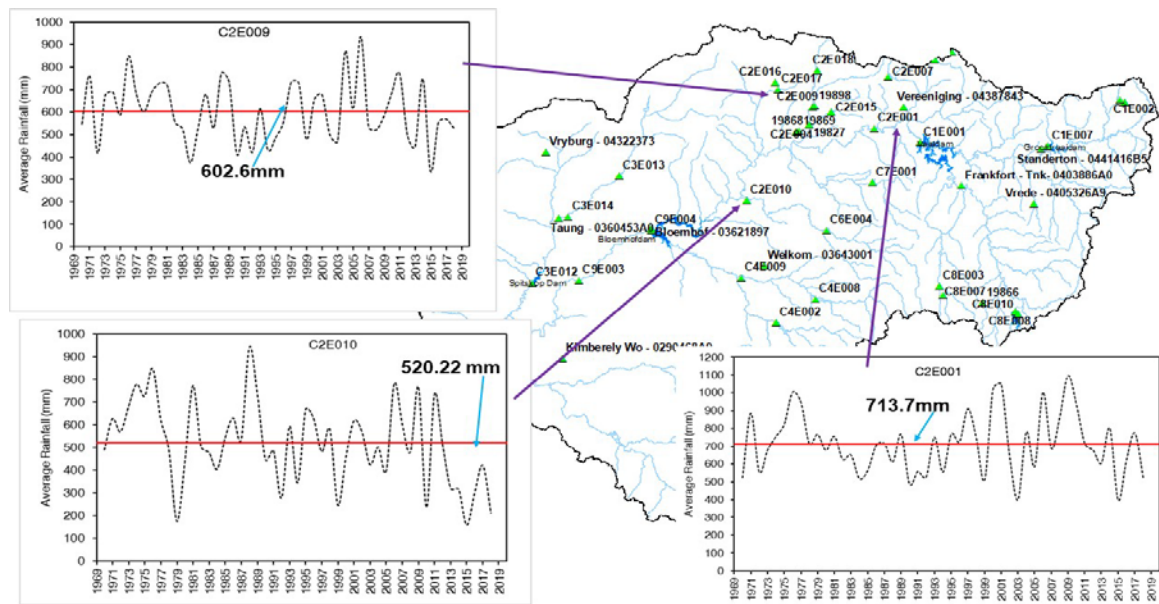


Figure 6.8: The rainfall trends in the upper and central part of the Vaal River Basin.

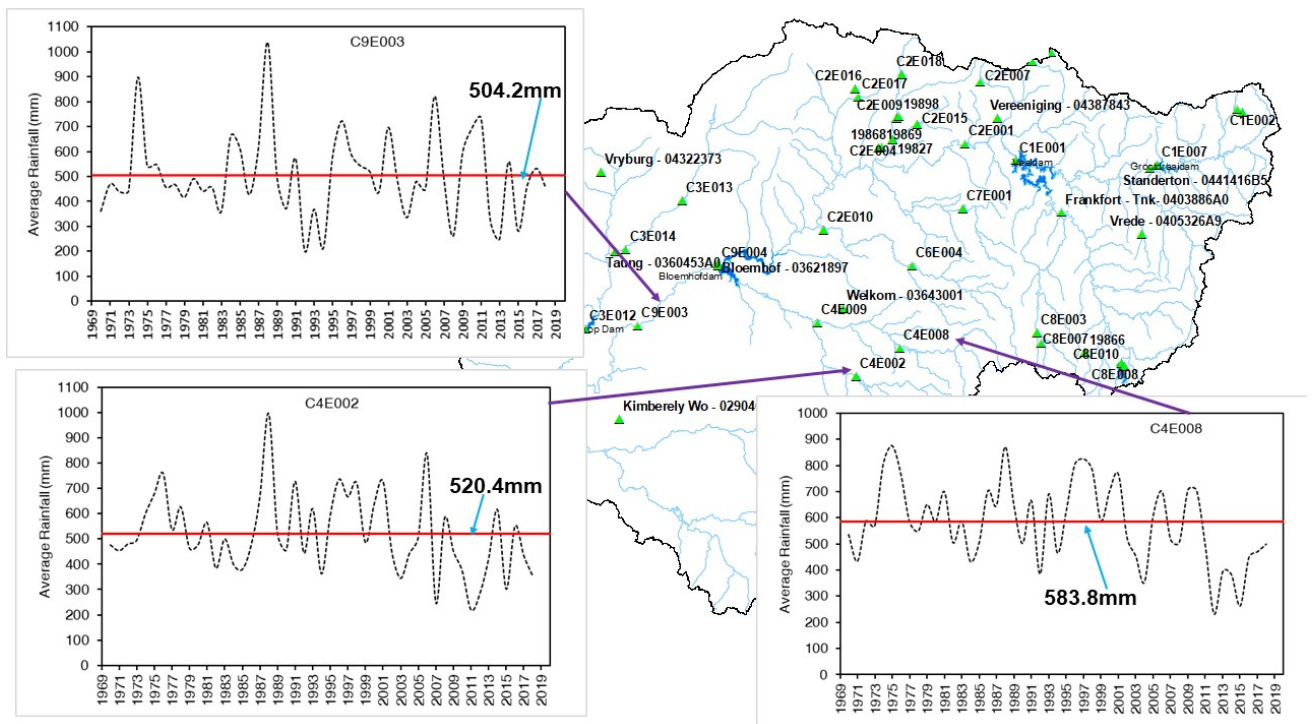


Figure 6.9: The rainfall trends in the lower part of the Vaal River Basin.



On a basin scale, it is apparent from the graph in Figure 6.10 that there is a general pattern of alternating periods of wet and dry years. The variability of the annual rainfall in the graph is much smoother in comparison to the rainfall trend for each station because annual rainfall is the average for the entire basin. The average annual rainfall using the Arithmetic Mean was estimated to be 581.01 mm/year over the entire period. As shown in Figure 6.10, the highest and lowest rainfall amounts were 881.5 mm/year and 313.8 mm/year, recorded in 1988 and 2015, respectively. The overall statistical analysis of the mean annual rainfall shows an insignificant decrease in rainfall amount of -1.968 mm/year.

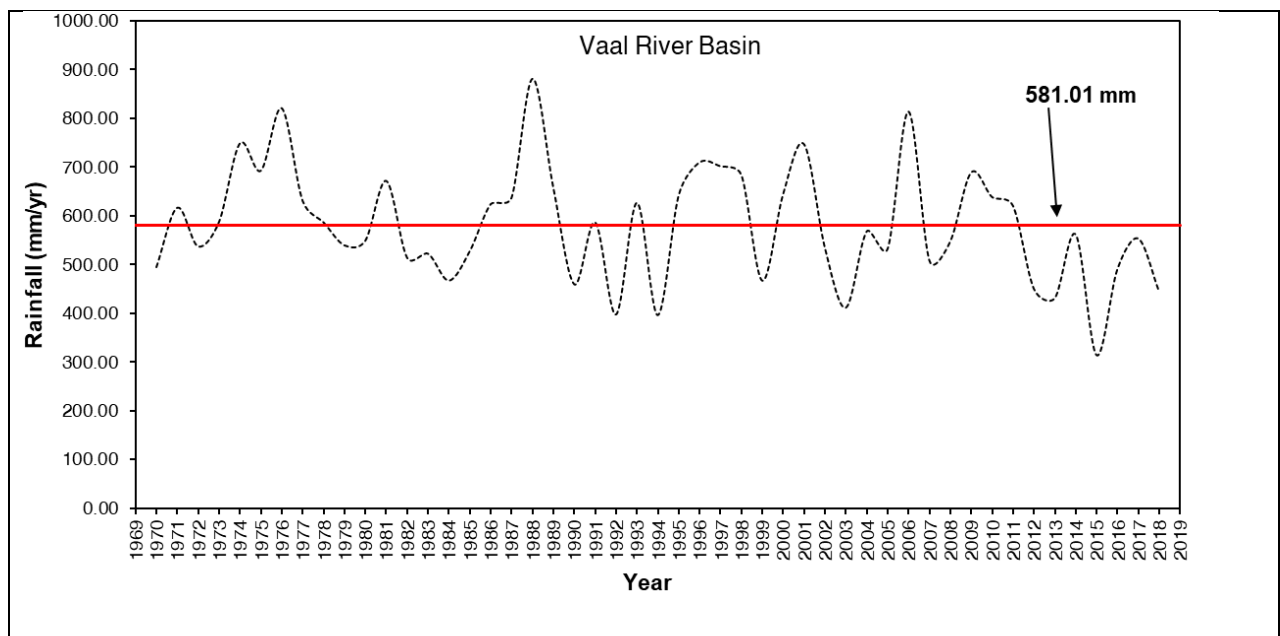


Figure 6.10: Rainfall trend in the Vaal River Basin. The red line is the average annual rainfall over the period 1970 to 2018.

The steady decline in rainfall over the basin implies that less water will be available for terrestrial water storage (TWS). This decline will also affect groundwater availability, because even lesser amounts of water will percolate the soil to reach the aquifer.

### **6.3 Groundwater level trends and variability**

The results of the M-K Test and Sen's Slope Estimator tests for Group 1, Group 2, and Group 3 are discussed sequentially, alongside the cumulative rainfall departure (CRD) plots, below. The Sen's Slope Estimator in the tables below reveal the magnitude of the trend and the asterisk next to the Sen's Slope Estimator values shows the level of significance of the trends.

#### **6.3.1 Group 1 (1970s to 2004)**

The results in Table 6.5 show a statistically significant decreasing trend in six monitoring boreholes and a statistically significant upward trend in one monitoring borehole. The analyses were performed at 0.1%, 1% and 5% significance levels. Of the remaining boreholes, four exhibited insignificant decreasing trends and only one had an increasing, but insignificant trend. The location of monitoring boreholes with statistically significant trends is shown in Figure 6.11. The rise and fall in groundwater levels over the long-term is indicative of volumetric gains and losses in the aquifer caused by a variety of factors. Volumetric changes in the aquifer are helpful in understanding the effects of long-term changes in rainfall and human actions on groundwater resource availability in the basin.

Table 6.5: Results of the statistical analysis of groundwater levels and rainfall for Group 1.

| User ID | DWS ID      | Latitude (°) | Longitude (°) | Avg Depth (mbgl) | Period of data | Trend | Sen's Slope Estimator (m/year) | Total groundwater level change | Total change in rainfall (%) | Rainfall trend |
|---------|-------------|--------------|---------------|------------------|----------------|-------|--------------------------------|--------------------------------|------------------------------|----------------|
| BH35    | 2627BC00051 | -26.2938     | 27.66575      | 20               | 1970-2004      | ↓     | -0.216***                      | -7.127                         | 3.1                          | ↑              |
| BH34    | 2627BC00052 | -26.3087     | 27.66538      | 33               | 1970-2004      | ↓     | -0.200***                      | -6.594                         | 3.1                          | ↑              |
| BH48    | 91          | -26.3198     | 27.6532       | 12               | 1970-2004      | ↑     | 0.038*                         | 1.280                          | 3.1                          | ↑              |
| BH40    | 2627BC00088 | -26.3943     | 27.69643      | 115              | 1970-2004      | ↓     | -2.818***                      | -95.813                        | 3.1                          | ↑              |
| BH38    | 2627AC00175 | -26.2514     | 27.16277      | 12               | 1970-2004      | ↑     | 0.017                          | 0.553                          | -10.6                        | ↓              |
| BH61    | 2627BD00039 | -26.3249     | 27.82261      | 39               | 1973-2004      | ↓     | -0.086                         | -2.746                         | -3.5                         | ↓              |
| BH44    | 1059        | -26.353      | 27.38724      | 77               | 1973-2004      | ↓     | -0.077***                      | -2.392                         | -16.3                        | ↓              |
| BH33    | 2627BD00068 | -26.3011     | 27.81363      | 30               | 1976-2004      | ↓     | -0.067                         | -1.939                         | -5.1                         | ↓              |
| BH46    | 2627BC00024 | -26.2576     | 27.6763       | 14               | 1976-2004      | ↓     | -0.070                         | -2.030                         | -5.1                         | ↓              |
| BH37    | 2627BC00227 | -26.2388     | 27.76044      | 52               | 1976-2004      | ↓     | -0.095**                       | -2.764                         | -5.1                         | ↓              |
| BH36    | 2627BB00001 | -26.2448     | 27.67424      | 12               | 1976-2004      | ↓     | -0.020                         | -0.540                         | -5.1                         | ↓              |
| BH47    | 1111        | -26.3113     | 27.67256      | 59               | 1976-2004      | ↓     | -1.582***                      | -45.890                        | -5.1                         | ↓              |

\* Statistically significant trends at the 5% significance level. \*\* Statistically significant trends at the 1% significance level. \*\*\*

Statistically significant trends at the 1% significance level.

What stands out in Table 6.5 is the substantial decline in total groundwater levels by 95 m and 45 m at a 0.1% significance level in BH40 and BH47, respectively. This translates to a groundwater level decline of 2.818 m/year for BH40 and 1.582 m/year for BH47. Monitoring borehole BH40 recorded the highest reduction in groundwater levels over the study period. It is situated less than 1.5 km from the Twin Shaft South Deep Gold Mine (TSSDGM), and 3 km from agricultural lands in the Westonaria area (Figure 6.11). The monitoring borehole BH47 is approximately 10 km north of BH40 and TSSDGM, at the town of Westonaria (Figure 6.11).

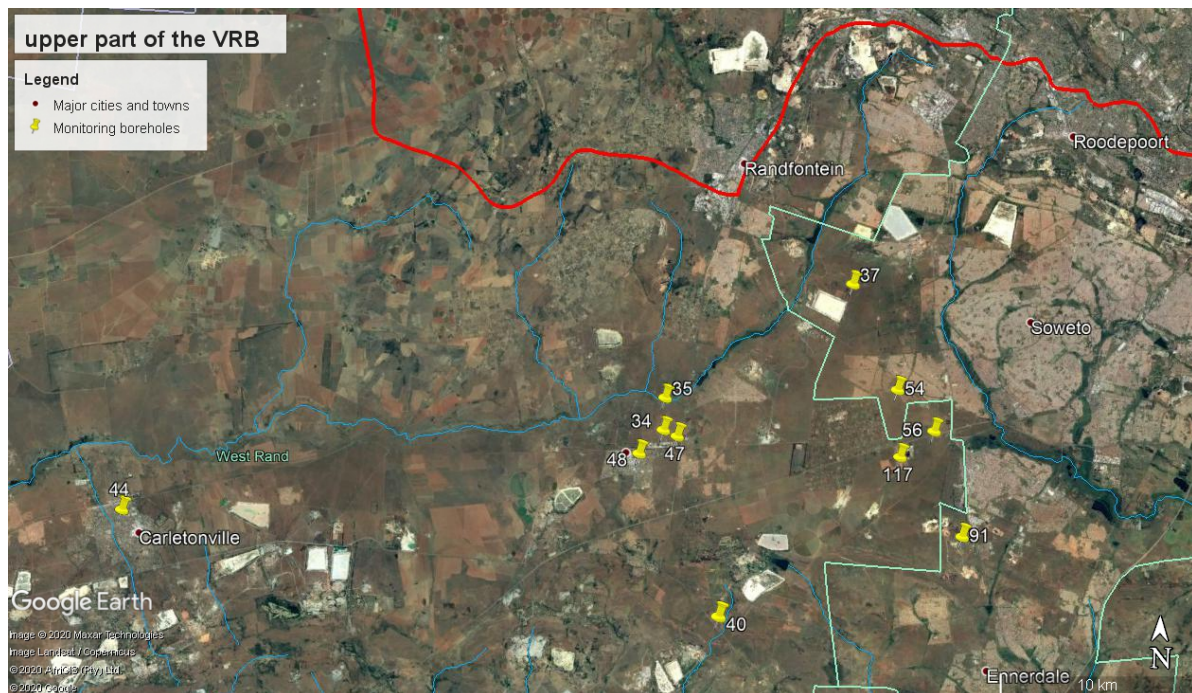


Figure 6.11: Map showing the locality of BH34, BH35, BH37, BH40, BH44, BH47, and BH48 in the Vaal River Basin. The red line is the northern boundary of the basin and the green line is the municipality boundary. (Source: <https://earth.google.com/web>).

Figure 6.12 shows a poor correlation between BH40 and CRD. Rainfall increased by 3.1% in the same period (1970-2004). In contrast, a moderate correlation is apparent between BH47 and CRD with rainfall decreasing by 5.1% over the study period. Monitoring borehole BH47 showed a recovery in response to increases in rainfall in 1996 and a subsequent decline in 1998, with a time lag of approximately 16 months. It is suggested that the dewatering of the dolomite aquifer in the gold mining zone to ensure dry underground working conditions lowers the local water table, which explains the decline in groundwater levels.

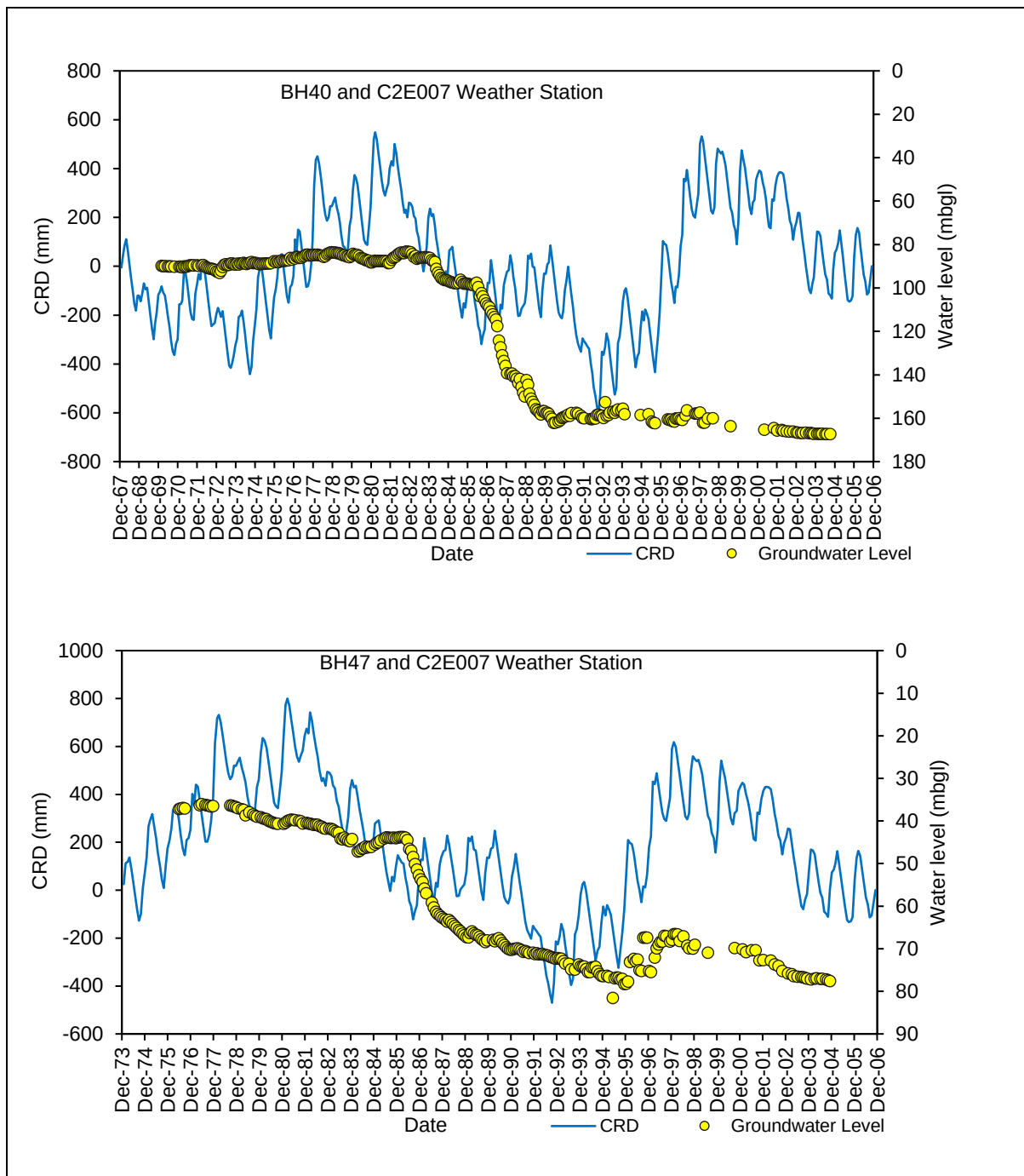


Figure 6.12: Groundwater fluctuation for monitoring boreholes BH40 and BH47 alongside the cumulative rainfall departure plot for rain gauge C2E007.

As displayed in Figure 6.12, groundwater levels dropped by as much as 64.51 m for BH40 and 24.01 m for BH47 in less than four years (between 1986 and 1990). Proximity of BH40 and BH47 to the TSSDGM possibly explains the differences in the

magnitude of the groundwater levels decline, with BH40 being more impacted than BH47, which is further away (see Figure 6.11). A note of caution is due here since there is no dewatering data from the mines. Similar findings were also reported by Swart et al. (2003) who indicated large-scale dewatering of karst aquifers in the mining footprint southwest of Johannesburg as the cause of lowering water levels. Abiye et al. (2018) also attributed the decline in groundwater levels in the Johannesburg area to mining activities, amongst other factors.

The moderate correlation between rainfall and BH47 indicates that rainfall partly contributes to the observed groundwater level changes, but other factors related to human activities probably have the most influence. The possible impact of groundwater abstraction for irrigation on groundwater levels in both boreholes cannot be ruled out. Hence, it can be hypothesised that groundwater systems are more sensitive to human activities than variability and changes in rainfall.

While BH48 is the only monitoring borehole that has an upward statistically significant trend in groundwater levels in Group 1, it also has the highest total rise in groundwater levels by 1.280 m at a rate of 0.038 m/year. BH48 is shallow with groundwater levels at a depth of approximately 12 m below the ground surface. The shallow water table explains the high-frequency oscillation in groundwater levels as set out in Figure 6.13, with zero time lag to CRD.

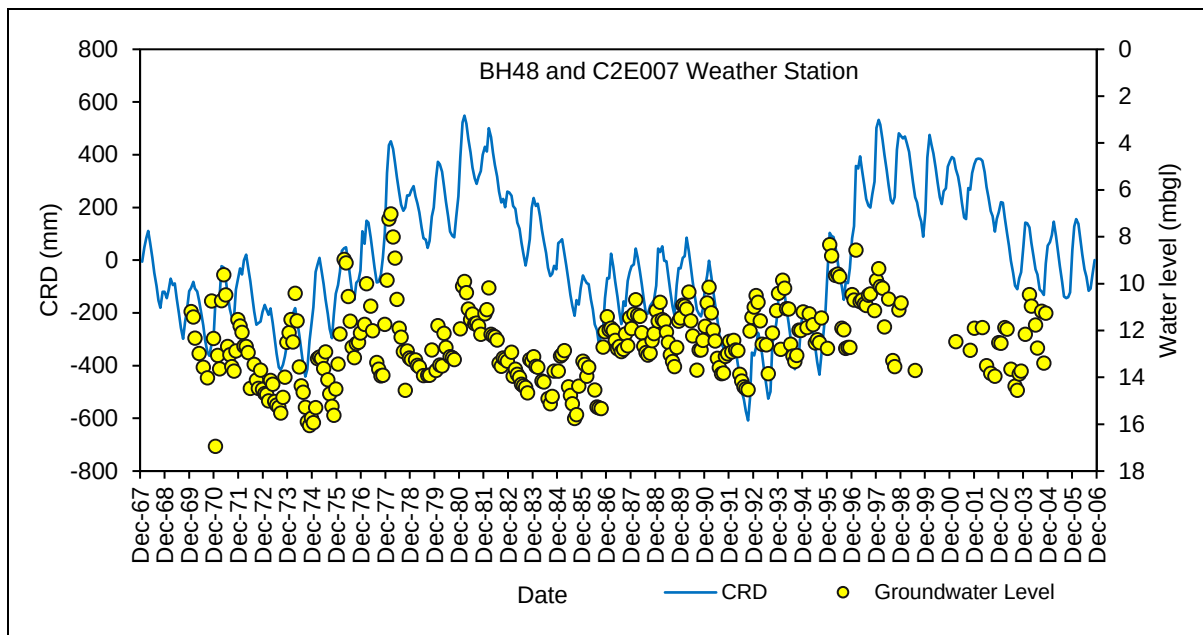


Figure 6.13: Cumulative rainfall departure plot against water level for borehole BH48.

The high-frequency oscillation in BH48 could be a result of daily pumping of groundwater. The rise in groundwater levels is attributed to increases in rainfall by 3.1% and the possible return flow from watering lawns in gardens in the residential blocks. Although BH48 is less than 3 km away from BH47 (see Figure 6.11), it appears to be unaffected by the dewatering activities, which is likely due to the shallow depth of the water levels observed in the monitoring borehole.

Notable statistically significant downward trends ( $\alpha=0.001$ ) in groundwater levels were observed in BH35 and BH34 at a rate of 0.216 m/year (net 7.127 m) and 0.200 m/year (net 6.594 m), respectively. At the same time (1970 to 2004), rainfall increased by 3.1%. These two monitoring boreholes are 1.76 km apart, and are situated in the Westonaria region (Figure 6.11). The groundwater levels versus the CRD plot in Figure 6.14 depicts an upward trend in rainfall and a downward trend in groundwater levels in BH34 and BH35.

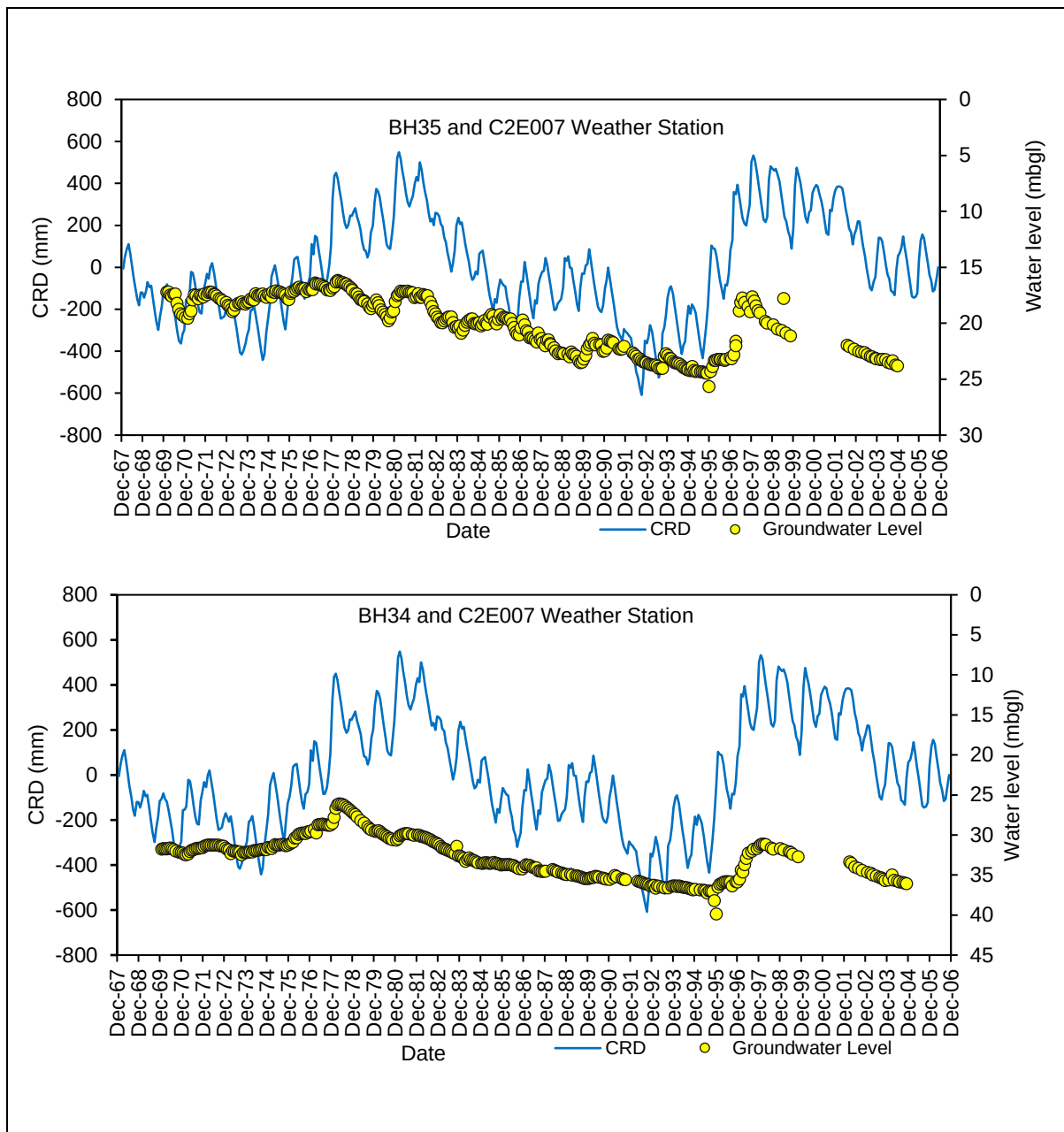


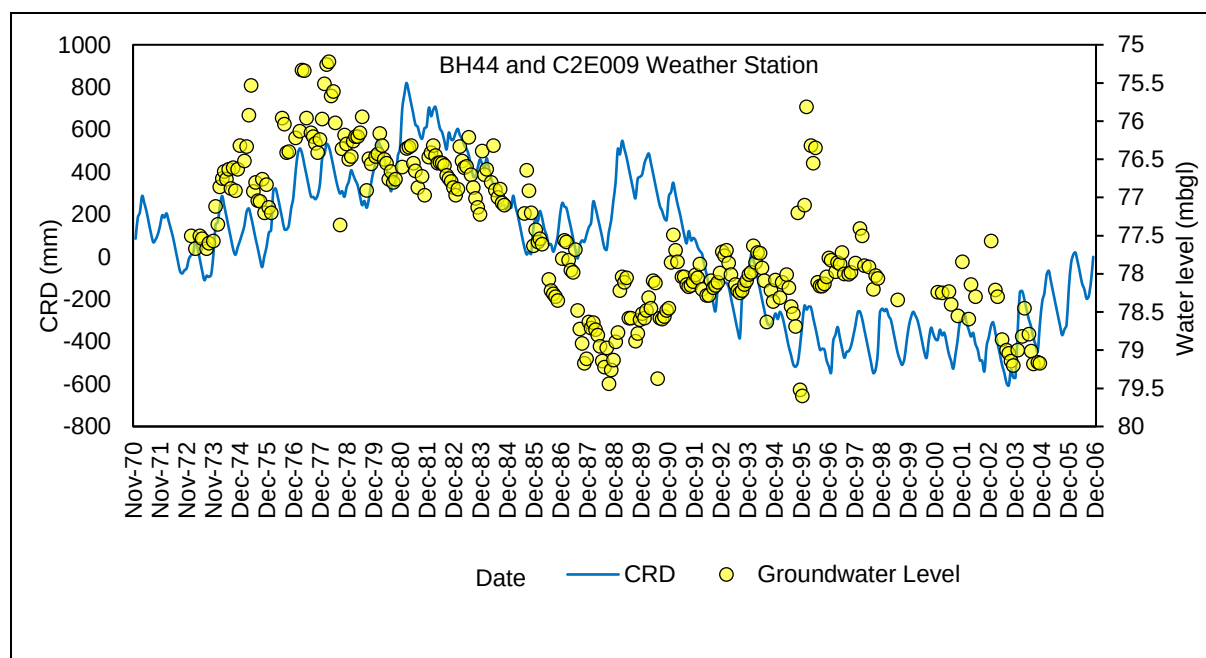
Figure 6.14: Monitoring borehole BH35 and BH34 alongside the cumulative rainfall departure plot.

Despite the opposite trend, moderate correlation exists between rainfall and groundwater levels in BH35 and BH34. There are several explanations for this observation. The moderate correlation implies that rainfall partly influences the groundwater levels; this is evident by a recovery in water levels in 1996 followed by a decline in 1998 due to extreme rainfall events. The rainfall amount over the entire



period is, however, insufficient to cause significant rises in the water table because groundwater discharge exceeds recharge. The response time of groundwater levels to rainfall events is between 0 and 1 month. Nearby farmers use groundwater for irrigation; this practice possibly contributes to the decline in groundwater levels. The monitoring boreholes, BH34 and BH35, are 0.77 km and 2 km northeast of BH47 (see Figure 6.11), which showed a decline in water levels because of dewatering in the mines. Therefore, dewatering could have also partially added to the decreasing groundwater levels.

As shown in Figure 6.15, the groundwater levels in monitoring boreholes BH44 and BH37 declined at a rate of 0.077 m/year ( $\alpha=0.001$ ) and 0.095 m/year ( $\alpha=0.01$ ), respectively. These trends were as a result of the reduction in rainfall by 16.3% and 5.1%, respectively. These boreholes are 40 km apart; BH44 is found in Carletonville Town and BH37 in the Soweto Township (Figure 6.11). They both show a good correlation with the CRD trend as presented in Figure 6.15.



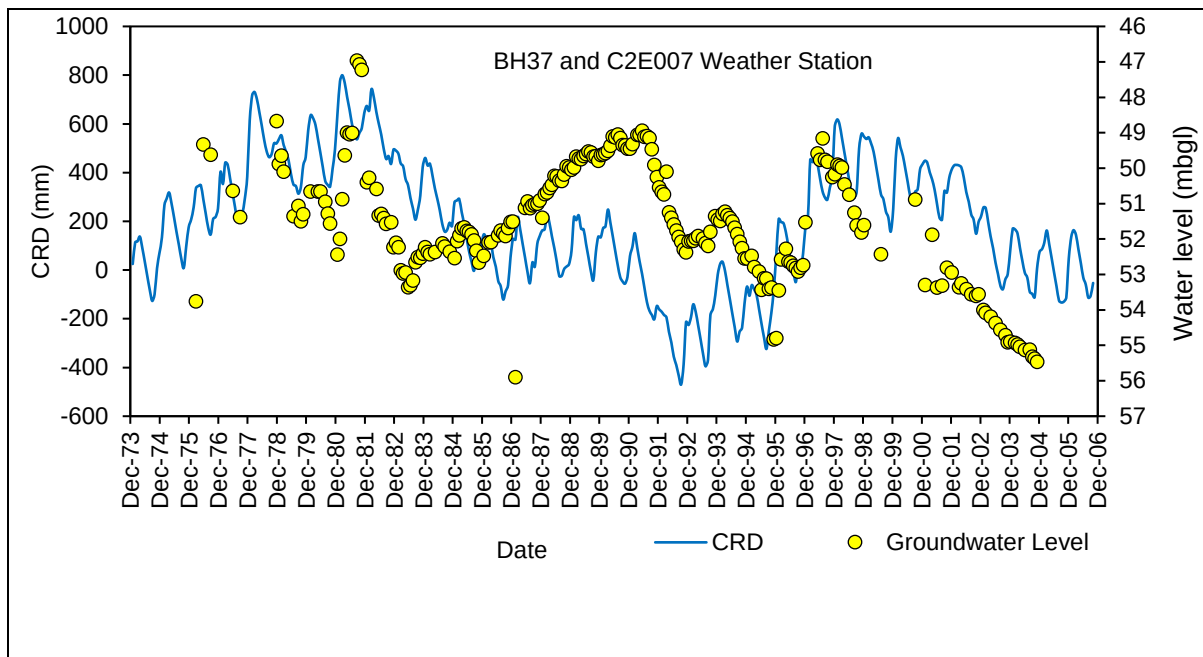


Figure 6.15: Cumulative rainfall departure plot for different rain gauges alongside water levels for monitoring boreholes BH37 and BH44.

Like most of the boreholes in Group 1, groundwater levels in BH44 and BH37 showed a strong recovery in 1996 following increases in rainfall and fell in 1998 after a reduction in rainfall amount at the specific sites. The time lag in response to rainfall events for BH44 is approximately 1 month and that of BH37 is approximately 3 months. The declining water levels of BH37 could be due to groundwater pumping for domestic and agricultural activities.

According to the results presented, it is apparent that there are multiple factors that impact groundwater level variability. The most notable are aquifer dewatering, groundwater abstraction for irrigation, and to a lesser extent, rainfall.

### 6.3.2 Group 2 (1980s to 2004)

The results, as shown in Table 6.6, indicate the presence of an upward statistical trend in groundwater levels for 31% of the monitoring boreholes over the study period.

Table 6.6: Results of the statistical analysis of groundwater levels and rainfall for Group 2.

| User ID                                                                                                                                                                                              | ID          | Latitude (°) | Longitude (°) | Avg Depth (mbgl) | Period of data | GW Trend | Qmed (m/year) | Total groundwater level change | Total change in rainfall (%) | Rainfall trend |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------|--------------|---------------|------------------|----------------|----------|---------------|--------------------------------|------------------------------|----------------|
| BH52                                                                                                                                                                                                 | 31919       | -26.22568    | 27.75613      | 34               | 1980-2004      | ↑        | 0.003         | 0.064                          | 12.7                         | ↑              |
| BH50                                                                                                                                                                                                 | 031937A     | -26.30528    | 27.81559      | 24               | 1980-2004      | ↓        | -0.017        | -0.396                         | 12.7                         | ↑              |
| BH51                                                                                                                                                                                                 | 31923       | -26.26674    | 27.75401      | 65               | 1981-2004      | ↓        | -0.058        | -1.394                         | 17.1                         | ↑              |
| BH76                                                                                                                                                                                                 | 2260        | -26.32838    | 27.78301      | 59               | 1986-2004      | ↑        | 0.011         | 0.212                          | 9.5                          | ↑              |
| BH74                                                                                                                                                                                                 | 2627BD00060 | -26.33524    | 27.79764      | 59               | 1986-2004      | ↑        | 0.261         | 4.966                          | 9.5                          | ↑              |
| BH65                                                                                                                                                                                                 | 2627BD00058 | -26.32701    | 27.77941      | 69               | 1986-2004      | ↑        | 0.262         | 4.973                          | 9.5                          | ↑              |
| BH64                                                                                                                                                                                                 | 2627BD00056 | -26.32662    | 27.78386      | 69               | 1986-2004      | ↑        | 0.264         | 4.752                          | 9.5                          | ↑              |
| BH60                                                                                                                                                                                                 | 1120        | -26.33258    | 27.81049      | 47               | 1986-2004      | ↑        | 0.267         | 5.071                          | 9.5                          | ↑              |
| BH59                                                                                                                                                                                                 | 2627BD00050 | -26.34932    | 27.78235      | 99               | 1986-2004      | ↑        | 0.251         | 4.769                          | 9.5                          | ↑              |
| BH58                                                                                                                                                                                                 | 2627BD00051 | -26.34893    | 27.80644      | 94               | 1986-2004      | ↑        | 0.244         | 4.636                          | 9.5                          | ↑              |
| BH57                                                                                                                                                                                                 | 2627BC00009 | -26.29277    | 27.74674      | 28               | 1986-2004      | ↑        | 0.124         | 2.359                          | 9.5                          | ↑              |
| BH56                                                                                                                                                                                                 | 2627BD00044 | -26.30536    | 27.80453      | 41               | 1986-2004      | ↑        | 0.322*        | 6.131                          | 9.5                          | ↑              |
| BH91                                                                                                                                                                                                 | 2627BD00053 | -26.35359    | 27.82071      | 82               | 1987-2004      | ↑        | 0.346*        | 6.227                          | 8.9                          | ↑              |
| BH90                                                                                                                                                                                                 | 36554       | -26.33475    | 27.90583      | 8                | 1987-2004      | —        | -0.001        | -0.011                         | 8.9                          | ↑              |
| BH88                                                                                                                                                                                                 | 36560       | -26.21773    | 28.02696      | 222              | 1987-2004      | ↑        | 0.093         | 1.666                          | -54.8                        | ↓              |
| BH86                                                                                                                                                                                                 | 37714       | -26.24199    | 28.03915      | 260              | 1987-2004      | ↑        | 0.089         | 1.520                          | -54.8                        | ↓              |
| BH85                                                                                                                                                                                                 | 36592       | -26.42417    | 28.04015      | 52               | 1987-2004      | ↑        | 0.294*        | 5.293                          | -23.8                        | ↓              |
| BH84                                                                                                                                                                                                 | 36593       | -26.41555    | 28.05533      | 50               | 1987-2004      | ↑        | 0.292*        | 5.257                          | -23.8                        | ↓              |
| BH83                                                                                                                                                                                                 | 36590       | -26.41648    | 27.06529      | 45               | 1987-2004      | ↑        | 0.474         | 8.534                          | 13.3                         | ↑              |
| BH80                                                                                                                                                                                                 | 36569       | -26.36378    | 28.24311      | 20               | 1987-2004      | ↑        | 0.104         | 1.769                          |                              |                |
| BH79                                                                                                                                                                                                 | 36582       | -26.34265    | 28.20075      | 17               | 1987-2004      | ↑        | 0.257**       | 4.626                          |                              |                |
| BH77                                                                                                                                                                                                 | 36568       | -26.32676    | 28.29243      | 7                | 1987-2004      | —        | 0.002         | 0.029                          |                              |                |
| BH54                                                                                                                                                                                                 | 31931       | -26.28683    | 27.78506      | 38               | 1987-2004      | ↑        | 0.372***      | 6.702                          | 8.9                          | ↑              |
| BH82                                                                                                                                                                                                 | 36570       | -26.37883    | 28.21708      | 4                | 1987-2004      | ↑        | 0.029         | 0.437                          |                              |                |
| BH104                                                                                                                                                                                                | 37883       | -26.22964    | 28.02558      | 197              | 1988-2004      | ↑        | 0.265         | 4.242                          | -47.5                        | ↓              |
| BH103                                                                                                                                                                                                | 37862       | -26.51665    | 28.00507      | 66               | 1988-2004      | ↑        | 0.230         | 3.902                          |                              |                |
| BH100                                                                                                                                                                                                | 37863       | -26.52353    | 27.98679      | 28               | 1988-2004      | ↑        | 0.248*        | 4.212                          |                              |                |
| BH99                                                                                                                                                                                                 | 37719       | -26.55563    | 27.96182      | 56               | 1988-2004      | ↓        | -0.013        | -0.226                         |                              |                |
| BH98                                                                                                                                                                                                 | 37721       | -26.5693     | 27.96606      | 25               | 1988-2004      | —        | -0.012        | -0.203                         |                              |                |
| * statistically significant trends at the 5% significance level ** statistically significant trends at the 1% significance level *** statistically significant trends at the 0.1% significance level |             |              |               |                  |                |          |               |                                |                              |                |

Table 6.6: Continued...

| User ID | ID          | Latitude (°) | Longitude (°) | Avg Depth (mbgl) | Period of data | GW Trend | Sen's Slope Estimator (m/year) | Total groundwater level change | Total change in rainfall (%) | Rainfall trend |
|---------|-------------|--------------|---------------|------------------|----------------|----------|--------------------------------|--------------------------------|------------------------------|----------------|
| BH97    | 37871       | -26.42961    | 28.04765      | 56               | 1988-2004      | ↑        | 0.318**                        | 5.412                          |                              |                |
| BH96    | 37867       | -26.42213    | 28.05304      | 78               | 1988-2004      | ↑        | 0.316**                        | 5.365                          |                              |                |
| BH95    | 37868       | -26.40868    | 28.05026      | 59               | 1988-2004      | ↑        | 0.312*                         | 4.995                          |                              |                |
| BH94    | 37870       | -26.41211    | 28.05664      | 39               | 1988-2004      | ↑        | 0.303*                         | 4.852                          |                              |                |
| BH92    | 37875       | -26.45869    | 28.06608      | 15               | 1988-2004      | ↑        | 0.236*                         | 4.019                          |                              |                |
| BH102   | 37865       | -26.51395    | 27.98669      | 59               | 1988-2004      | ↑        | 0.247*                         | 4.193                          |                              |                |
| BH101   | 37881       | -26.51062    | 27.97689      | 58               | 1988-2004      | ↑        | 0.164                          | 2.782                          |                              |                |
| BH114   | 2627BC00074 | -26.39811    | 27.64334      | 15               | 1989-2004      | ↑        | 0.002                          | 0.028                          | 4                            | ↑              |
| BH112   | 2627BC00066 | -26.41657    | 27.72205      | 24               | 1989-2004      | ↑        | 0.463                          | 7.414                          | 4                            | ↑              |
| BH110   | 2627BC00055 | -26.44084    | 27.69263      | 30               | 1989-2004      | ↓        | -0.171                         | -2.734                         | 4                            | ↑              |
| BH109   | 2627BC00080 | -26.39193    | 27.73993      | 15               | 1989-2004      | ↑        | 0.127                          | 2.036                          | 4                            | ↑              |
| BH108   | 2627BC00079 | -26.39157    | 27.73402      | 23               | 1989-2004      | ↑        | 0.263                          | 4.204                          | 4                            | ↑              |
| BH107   | 2627BC00077 | -26.38121    | 27.73403      | 76               | 1989-2004      | ↓        | -0.033                         | -0.528                         | 4                            | ↑              |
| BH106   | 37677       | -26.1015     | 28.44925      | 13               | 1989-2004      | ↑        | 0.199                          | 2.979                          | 14                           | ↑              |
| BH116   | 2627BC00274 | -26.39219    | 27.74174      | 7                | 1989-2004      | ↑        | 0.260                          | 4.157                          | 4                            | ↑              |

\* statistically significant trends at the 5% significance level \*\* statistically significant trends at the 1% significance level.

The location of monitoring boreholes with statistically significant trends is shown in Figure 6.17. The monitoring borehole BH54 located south of Johannesburg, and it showed the highest statistically significant rise in groundwater level of 6.7 m over the entire period; this translates into a rise in level of 0.372 m/year ( $\alpha=0.001$ ). A nearby monitoring borehole, BH56, also revealed increases in groundwater levels by 6.1 m or a rate of 0.322 m/year ( $\alpha=0.05$ ). It can also be seen in Figure 6.16 that the groundwater levels in BH54 and BH56 show a poor correlation to the CRD plot. In both cases, the frequency of groundwater fluctuation is very low. It is possible to hypothesise that the poor rainfall response of BH56 and BH54 to C2E007 rainfall is likely due to the overlaying clayey soil that slows down the infiltration and subsequently the recharge to the aquifer.

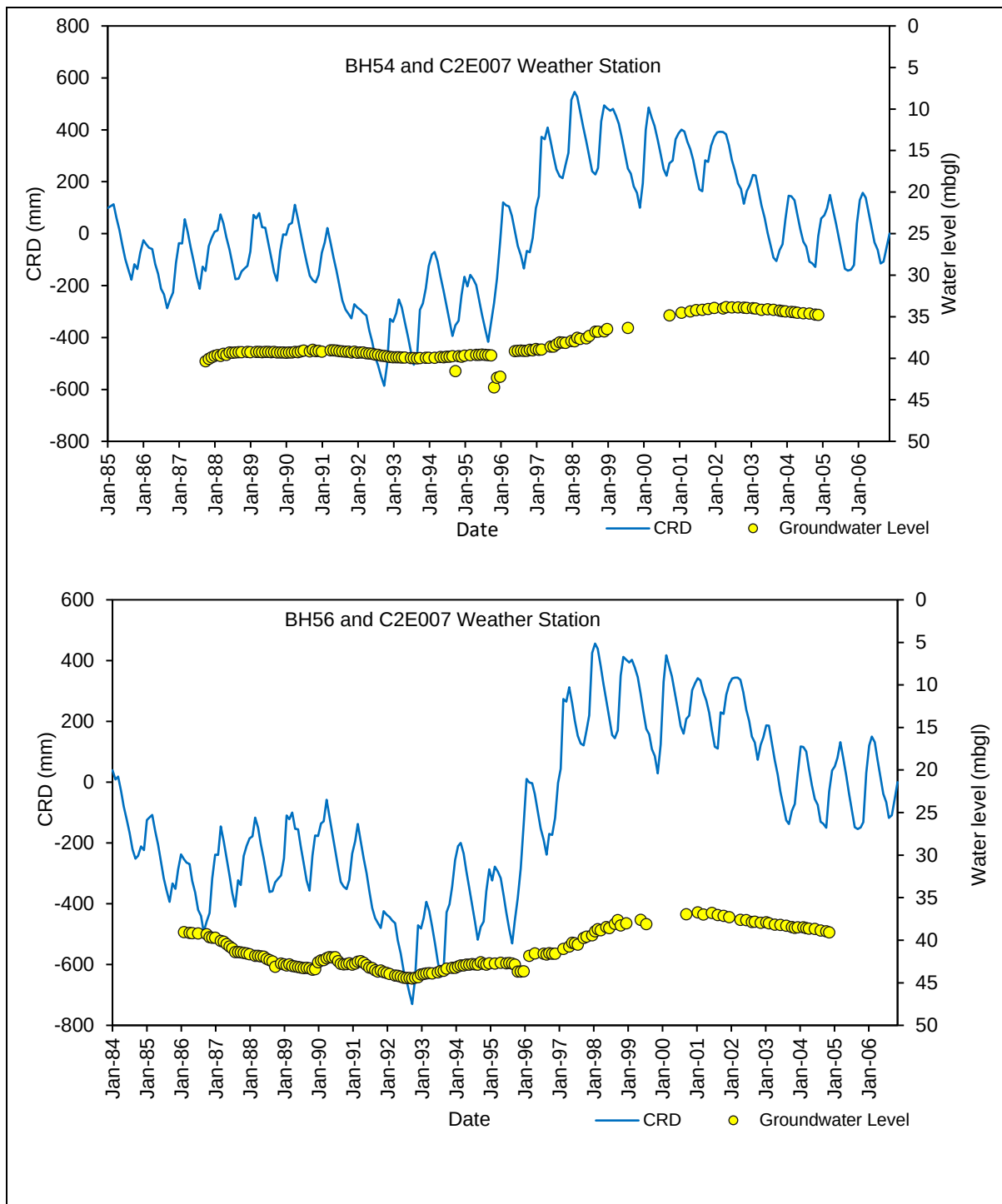


Figure 6.16: Cumulative rainfall departure plot for different rain gauges alongside water levels for monitoring boreholes BH54 and BH56.

The time lag between groundwater level response to CRD varies among the monitoring boreholes, with BH56 responding in about 6 months and BH54 responding

in more than 20 months. The rise in groundwater level in BH54 and BH56 can be explained by increases in rainfall by 8.9% and 9.5%, respectively, over the entire period.

In Johannesburg South, the groundwater levels in BH85 and BH84 increased by 0.294 m/year and 0.292 m/year ( $\alpha=0.05$ ) respectively, over the entire period. Due to the lack of sufficient rainfall data to plot the CRD series for comparison to groundwater levels, it is difficult to explain these results. The depth and locality of the boreholes can provide important insights into the possible mechanisms responsible for groundwater increases. Both monitoring boreholes are found in the Johannesburg South area (Eikenhof), which is mainly characterised by small agricultural holdings bounded by the Klip River in the northwest and southeast direction (Figure 6.17).

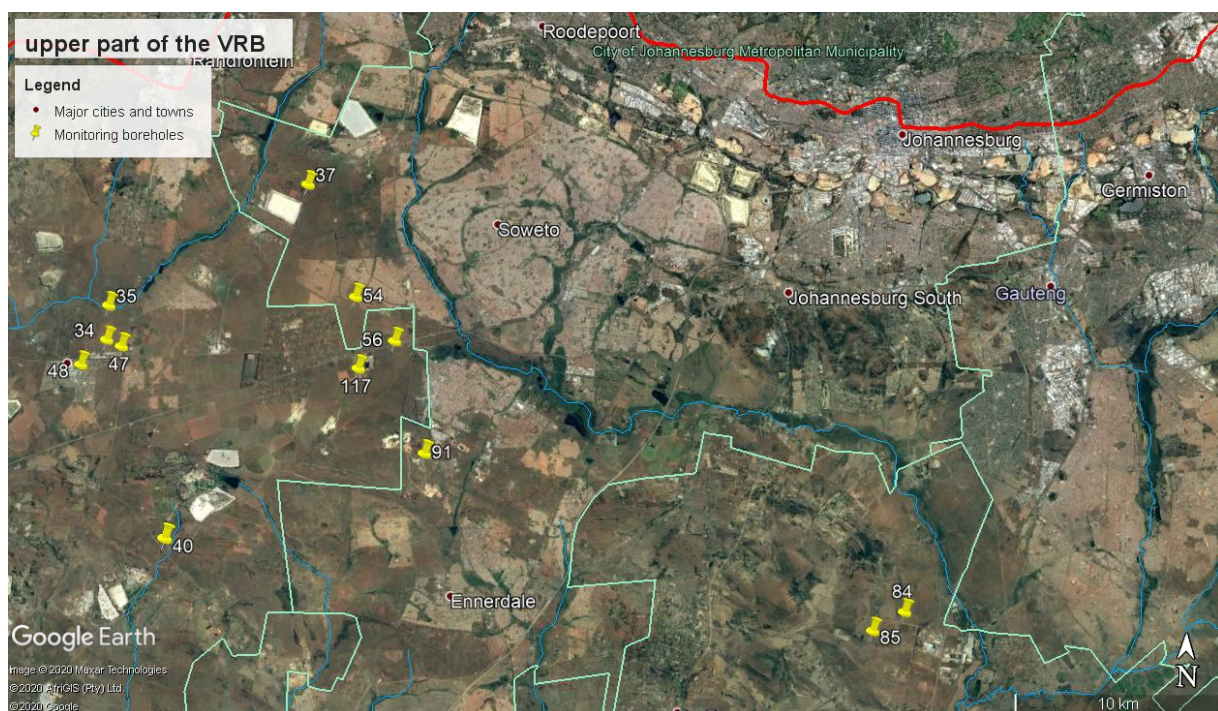


Figure 6.17: Map showing the locality of monitoring boreholes BH54, BH56, BH84, BH85, and BH91. The red line is the northern boundary of the basin and green line is the municipal boundary (source: <https://earth.google.com/web>).

The depth of the water table for BH85 and BH84 is 52 mbgl and 50 mbgl, respectively. It can, therefore, be assumed that the rise in groundwater levels in BH85 and BH84

results from the Klip River losing water to the local groundwater system via the streambed on a continuous basis. The Klip River is among the streams that are a recipient of industrial and domestic effluent, and as a result, flows all year round. This also affect the quality of groundwater. Given that the majority of the monitoring boreholes responded to extreme rainfall events in 1996 and 1998, it is possible that rainfall contributed to the observed trend.

Another notable monitoring borehole that showed a statistically significant increasing trend is BH91; here groundwater levels rose by 0.346 m/year ( $\alpha = 0.05$ ) or a total of 6.22 m over the entire period. The observed correlation between the groundwater levels in BH91 and CRD plot (Figure 6.18) suggests that rainfall is the predominant contributor to the groundwater levels' fluctuations.

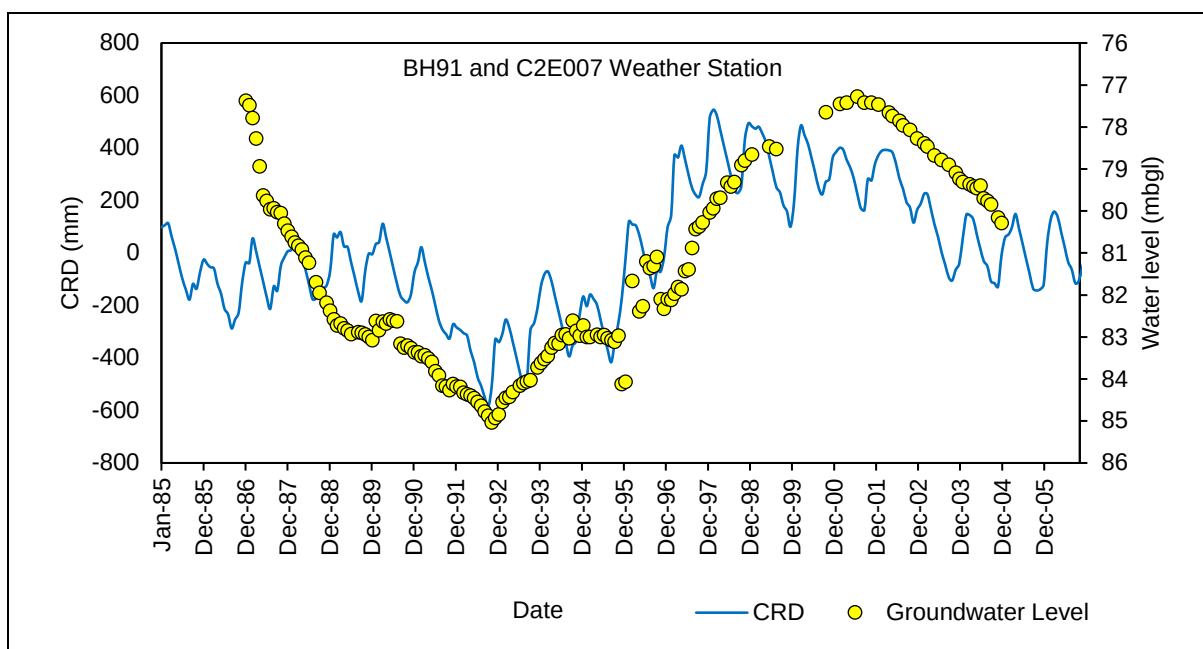


Figure 6.18: Cumulative rainfall departure plot for different rain gauges alongside water levels for BH91.

The borehole is situated in Johannesburg South (Lenasia); it is less than 1.5 km from quarries (Figure 6.17). It is also possible that the inactive quarries act as surface water storages that result in induced recharge thus causing a general increase in

groundwater levels. The groundwater levels in BH91 lag behind major peaks in the CRD plot by approximately 4 months. Between 1992 and 1993, the water table was at its lowest in response to the drought; it experienced a peak in 2001, following high rainfall. This finding broadly supports the work of other studies in this area linking rainfall with groundwater level changes (Meyer, 2005; Abiye et al., 2017).

### 6.3.3 Group 3 (1990s to 2004)

Of the fifteen (15) monitoring boreholes in Group 3, only four revealed a statistically significant groundwater level trend. Half of those boreholes indicated a decreasing trend and the other half an increasing trend in groundwater levels. It was not possible to compare groundwater levels and CRD for three boreholes because of the lack of rainfall data near the monitoring boreholes.

Table 6.7: Results of the statistical analysis of groundwater levels and rainfall for Group 3.

| User ID | ID          | Latitude (°) | Longitude (°) | Average Depth (mbgl) | Period of data | GW Trend | Sen's Slope Estimator (m/year) | Total groundwater level change | Total change in rainfall (%) | Rainfall trend |
|---------|-------------|--------------|---------------|----------------------|----------------|----------|--------------------------------|--------------------------------|------------------------------|----------------|
| BH117   | 2627BD00055 | -26.3177     | 27.78741      | 53                   | 1990-2004      | ↑        | 0.532**                        | 7.983                          | 18.8                         | ↑              |
| BH25    | 39312       | -26.1559     | 26.80614      | 18                   | 1990-2004      | ↑        | 0.071                          | 1.060                          | 19                           | ↑              |
| BH23    | 39308       | -26.0618     | 26.92156      | 66                   | 1990-2004      | ↑        | 0.185*                         | 2.778                          |                              |                |
| BH22    | 39307       | -26.0951     | 26.95295      | 32                   | 1990-2004      | ↓        | -0.626**                       | -9.388                         |                              |                |
| BH21    | 39315       | -26.0408     | 26.37986      | 45                   | 1990-2004      | ↑        | 0.127                          | 1.900                          |                              |                |
| BH20    | 39319       | -26.1659     | 26.57322      | 29                   | 1990-2004      | ↑        | 0.137                          | 2.055                          |                              |                |
| BH19    | 39331       | -25.8771     | 26.53428      | 16                   | 1990-2004      | ↓        | -0.088                         | -1.324                         |                              |                |
| BH18    | 39330       | -25.9589     | 26.5507       | 23                   | 1990-2004      | ↓        | -0.154                         | -2.312                         |                              |                |
| BH14    | 39329       | -26.0463     | 26.39552      | 42                   | 1990-2004      | ↑        | 0.237                          | 3.553                          |                              |                |
| BH13    | 39328       | -25.9887     | 26.38436      | 6                    | 1990-2004      | ↑        | 0.052                          | 0.775                          |                              |                |
| BH12    | 39327       | -25.9169     | 26.42602      | 12                   | 1990-2004      | ↑        | 0.137                          | 2.056                          |                              |                |
| BH11    | 39322       | -25.8874     | 26.28993      | 10                   | 1990-2004      | ↑        | 0.064                          | 0.962                          |                              |                |
| BH10    | 39323       | -25.839      | 26.32989      | 93                   | 1990-2004      | ↑        | 0.118*                         | 1.764                          |                              |                |
| BH9     | 39321       | -25.9217     | 26.23153      | 22                   | 1990-2004      | ↑        | 0.157                          | 2.348                          |                              |                |
| BH8     | 39332       | -26.0268     | 26.29807      | 18                   | 1990-2004      | ↑        | 0.027                          | 0.400                          |                              |                |

\* statistically significant trends at the 5% significance level \*\* statistically significant trends at the 1% significance level.



The location monitoring boreholes with statically significant trend in Group 3 are shown in Figure 6.19. The highest net decrease in groundwater levels is 9.38 m occurring at the rate of 0.626 m/year ( $\alpha=0.01$ ), observed at BH22 situated near the northern boundary of the upper VRB. The decline is considerable given the short span of the data. In contrast, BH23, which is less than 5km from BH22, showed a rise of 2.778 m in the water table over the entire period at the rate of 0.185 m/year ( $\alpha=0.05$ ). Both BH22 and BH23 are within farmland or/and agricultural land with various agricultural landscape (Figure 6.19).

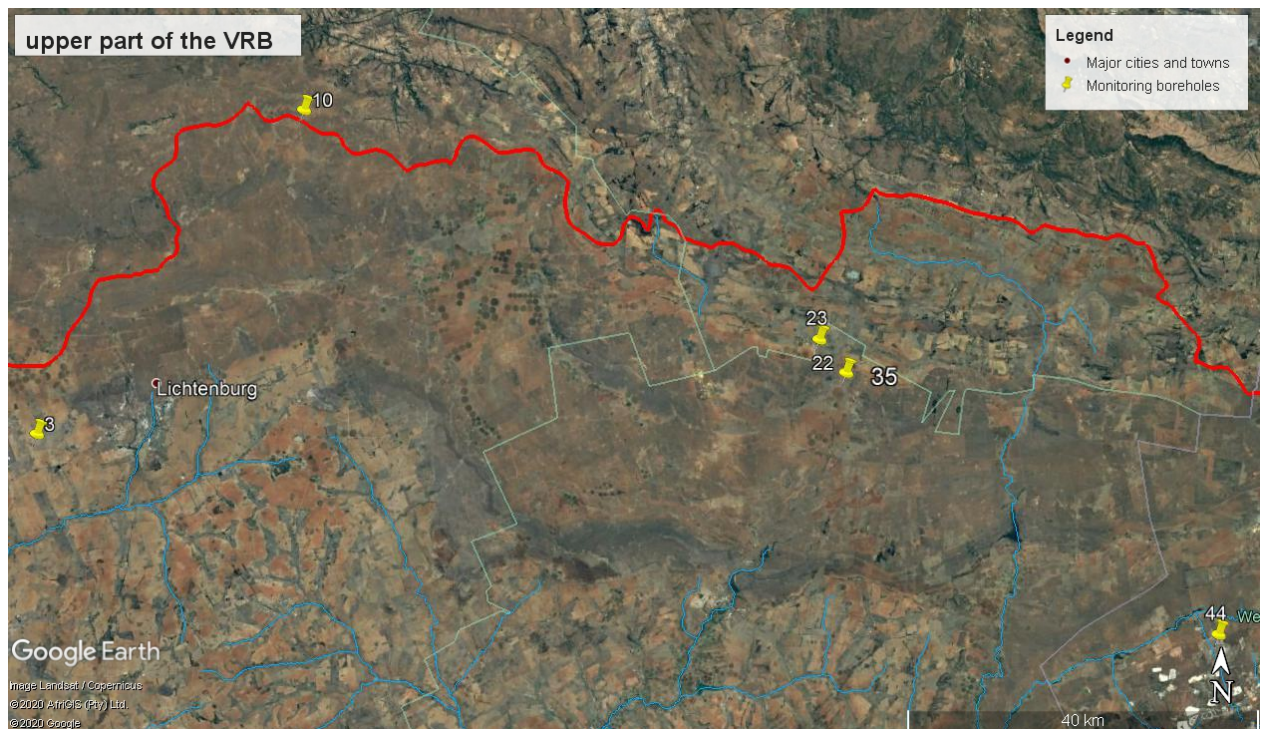


Figure 6.19: Map showing the location of monitoring boreholes BH22, BH23, and BH10 in the Vaal River Basin. The red line is the northern boundary of the basin and the green line is the municipal boundary (source: <https://earth.google.com/web>).

The large-scale groundwater abstraction for irrigation is likely to contribute to the decline in the water table in BH22, whereas the agricultural return flows recharged BH23 leading to a steady increase in groundwater level. Groundwater in the area is a

source of domestic water supply for many households, which also contributes, in part, to groundwater level fluctuations. The difference in groundwater elevation for BH23 (1494.515 mamsl) and BH22 (1508.293 mamsl) has probably resulted in the boreholes being impacted differently.

Monitoring borehole BH10, situated 35 km north northeast of Lichtenburg Town shows an increase in groundwater level which can be partly a result of irrigation return flow recharging the local groundwater system. Although BH23, BH22, and BH10 were not compared to the CRD plot because of the lack of rain gauge in the area, rainfall is suspected to contribute to the groundwater level changes. The highest increase in the groundwater levels was observed in BH117 found in Lenasia, near a brick factory (Figure 6.20). The groundwater levels increased by 7.983 m at a rate of 0.532 m/year ( $\alpha=0.01$ ) over the study period. The rise in water levels in BH117 is most likely due to an increase in rainfall by 18.8% and possibly return flow from the abandoned onsite quarry that acts as a water storage.



Figure 6.20: Map showing the locality of monitoring borehole BH117 in the Vaal River Basin. The monitoring borehole is situated in the brick quarry. C2E007 is the rainfall gauge used to calculate the cumulative rainfall departure (source: source: <https://earth.google.com/web>).

Figure 6.21 shows a poor correlation between CRD plot and groundwater levels. This observation is similar to that observed for BH54 and BH56 that belong to Group 2 (1980s to 2004). These boreholes are in the same area and within an approximately 5 km radius from the C2E007 rain gauge, and both are near the clay brick factory. Thus, the presence of clay soil in the area may explain the observed slow response of groundwater levels to rainfall. This is because clay has low hydraulic conductivity ( $1 \times 10^{-11}$ - $4.7 \times 10^{-9}$  m/s) (Domenico & Schwartz, 1998).

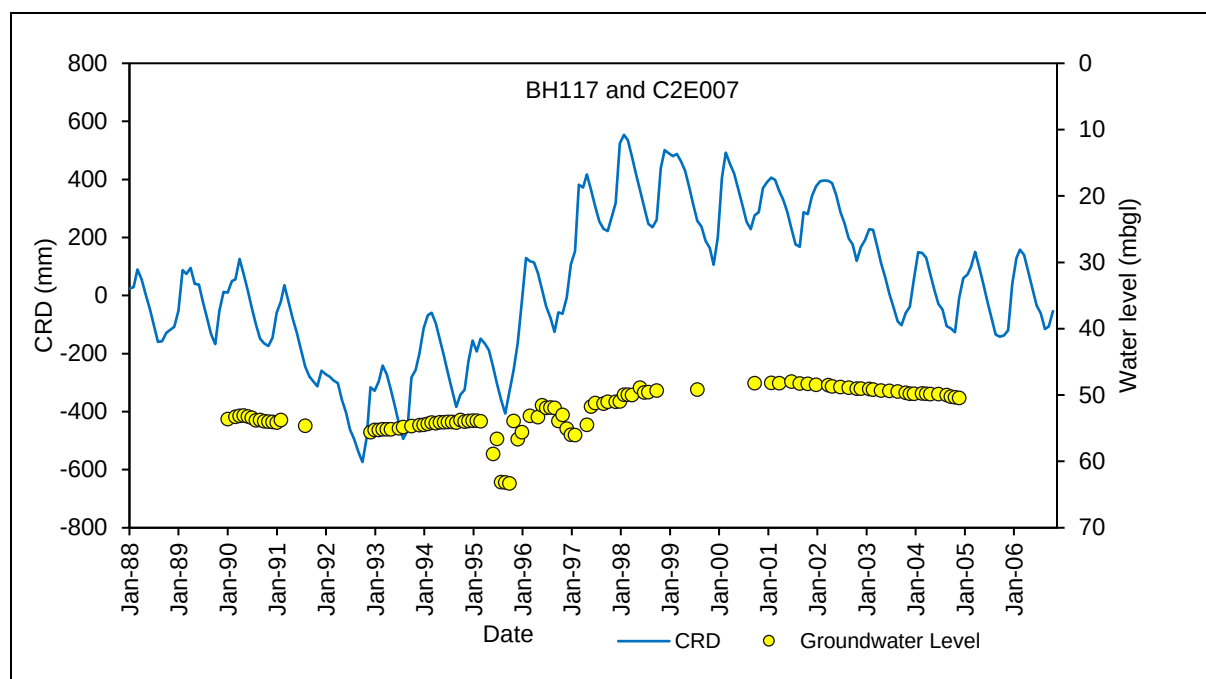


Figure 6.21: Cumulative rainfall departure plot for different rain gauges alongside water levels for BH117.

#### 6.3.4 Groundwater levels changes and depth

Figure 6.22 shows a point plot of groundwater level depth and the slope estimates obtained from analysis from groundwater level data. Figure 6.22 shows that most of the points are clustered near zero; this trend indicates that there are no major increases in groundwater for most boreholes. However, the observation could be a result of sampling bias, because major fluctuations were observed for the same sites for Group 1 (1970s to 2004). The coefficient of determination ( $r^2$ ) for water level and Sen's Slope Estimator is 0.0073. These two data points

illustrate that there is no relationship between groundwater level depth and magnitude of Sen's Slope Estimator.

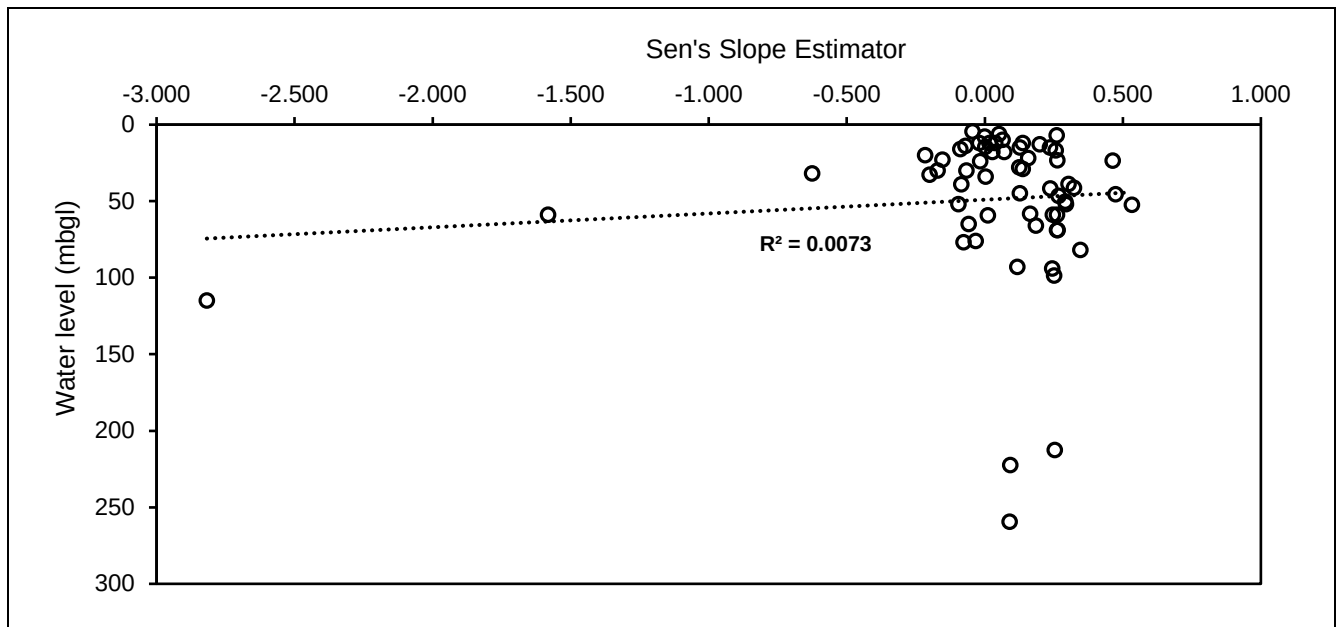
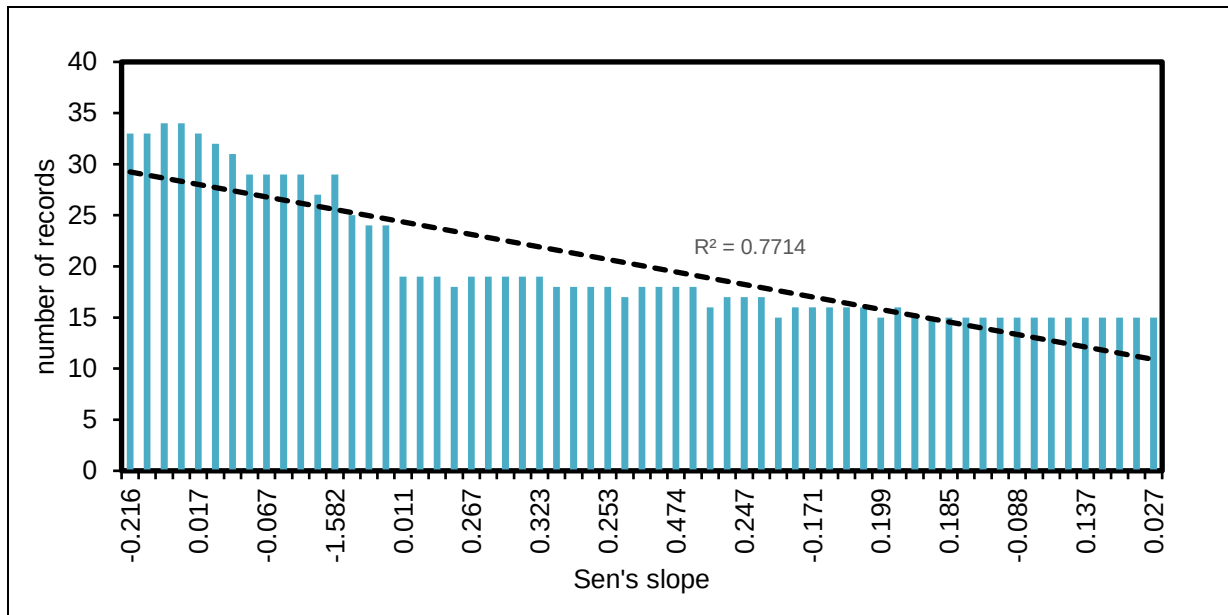


Figure 6.22: Groundwater depth versus the Sen's Slope Estimator. The three anomalous boreholes at a depth greater than 150 m shows that the magnitude of groundwater level trend is not influenced by depth.

Figure 6.23 shows that there is a moderate correlation between the number of records and the observed slope in the data. The results reveal  $r^2=0.771$  for the length of the monitoring period and Sen's Slope Estimator. These suggest that the length of the monitoring records influences the observed groundwater level trends. The monitoring boreholes in Group 1 showed the greatest decline in groundwater levels, whereas the monitoring boreholes in Group 2 and Group 3 revealed the most increase in groundwater levels.





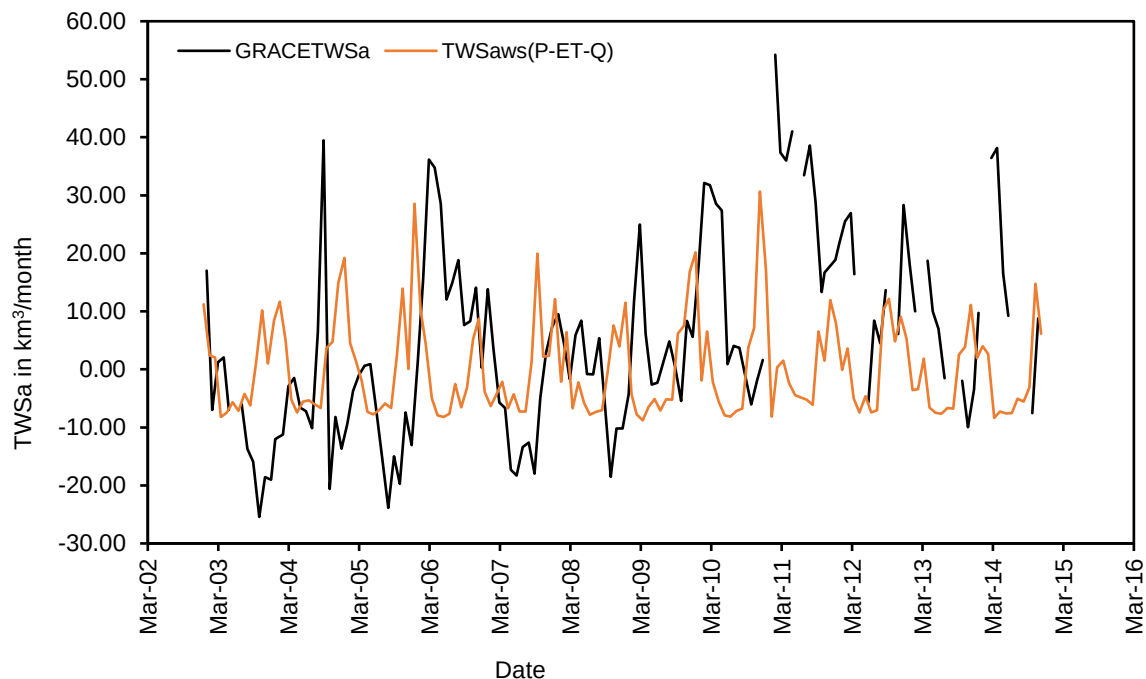


Figure 6.24: A simple comparison of TWS<sub>awb</sub> and GRACETWS<sub>a</sub> from the hydrological budget equation.

A closer inspection of Figure 6.24 shows that both TWS<sub>awb</sub> and GRACETWS<sub>a</sub> exhibit seasonal variability. They also vary by a large magnitude. The peaks and troughs in the TWS anomalies appears to mirror the dry winter months and wet summer months in the VRB. The variability in rainfall and other hydrological units, which govern the redistribution and movement of water masses in the VRB, are possible drivers of TWS, in addition to human-made reservoirs with strong gravimetric signals.

The discrepancy in the magnitude of variation in the GRACETWS<sub>a</sub> and TWS<sub>awb</sub> could be a result of the large spatial coverage of the GRACE satellite. In other words, it can detect water masses outside of the study site. Another possibility could be that the GRACETWS<sub>a</sub> directly captures all water masses; not all water masses are included in the water balance. It can also be seen in Figure 6.24 that there is a poor match between GRACETWS<sub>a</sub> and TWS<sub>awb</sub>. It appears as if GRACETWS<sub>a</sub> and TWS<sub>awb</sub> mimic each other at different times. This could be a result of how data is acquired to estimate

the  $TWS_{awb}$  and  $GRACETWS_a$ . The gaps in the  $GRACETWS_a$  line graph is a result of missing values in some months in the GRACE satellite data. Nonetheless, the  $TWS_{awb}$  and  $GRACETWS_a$  show an increasing trend.

Figure 6.25 shows that the water budget components used in the estimation of  $TWS_{awb}$  show a good match, but have varying magnitude. The water budget components influence the variations in TWS. These components are briefly discussed ahead of the  $GWS_a$  analysis in the next section.

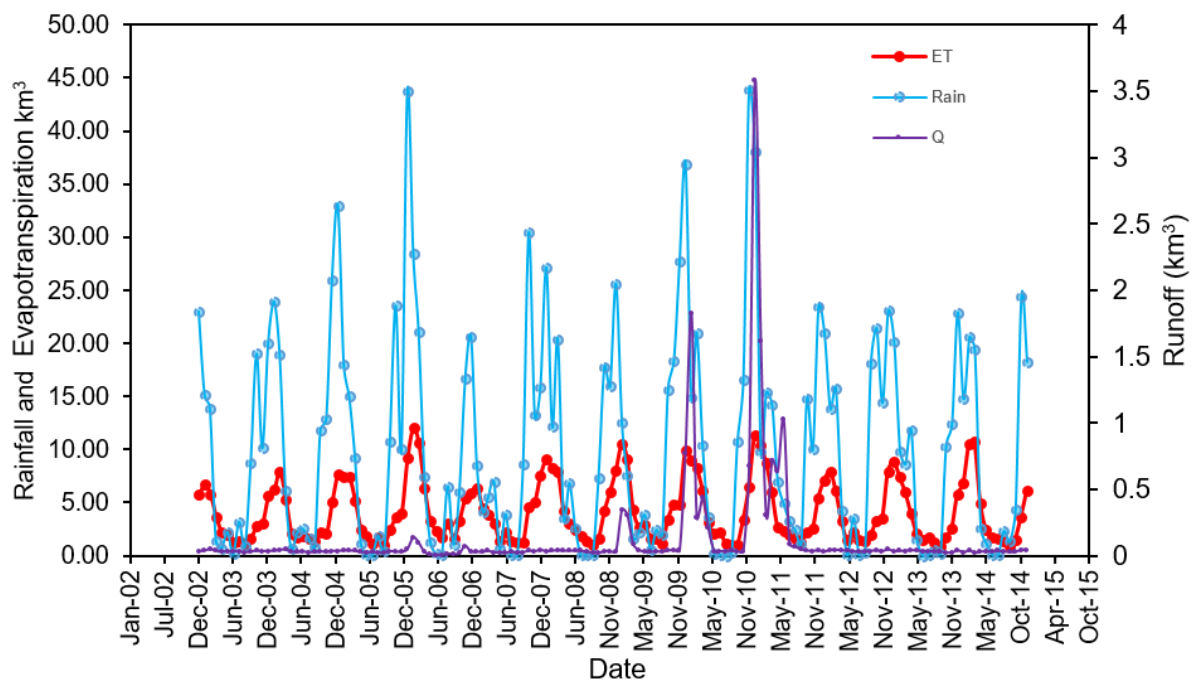


Figure 6.25: A plot of rainfall, evapotranspiration and runoff used in the hydrological budget to estimate terrestrial water storage.

The hydrological budget inputs are indicative of climatic variations in the study area. The minimum rainfall volume of  $0.004907 \text{ km}^3$  was observed in June 2013, and the maximum rainfall of  $43.744 \text{ km}^3$  was noted January 2006. The lowest amount of actual evapotranspiration (AET) is  $0.89 \text{ km}^3$  (September 2014) and the highest is  $12.04 \text{ km}^3$  (February 2006). The discharge volume ranged from  $0.00514 \text{ km}^3$  (June 2006) to  $3.578 \text{ km}^3$  (January 2011). The high magnitude of rainfall signifies that rainfall has the

largest influence on the general water storage in a basin (Scalon et al., 2012). All hydrological components had their highest peak in 2006, which could be the result of excess rainfall. The rising peak in 2006 in hydrological components is not reflected in  $TWS_{awb}$  and  $GRACETWS_a$  estimates.

#### **6.4.2 GRACE-based groundwater storage analysis**

The GRACE-based groundwater storage anomalies ( $GWS_a$ ) were estimated by removing the soil moisture and surface water anomalies from the  $GRACETWS_a$ . The observed negative  $GWS_a$  are indicative of groundwater depletion in the basin, whereas positive  $GWS_a$  values denote groundwater recharge. Trend detection and slope estimation using the M-K Test and Sen's Slope Estimator reveal a statistically significant increasing trend in the  $GWS_a$  estimates of  $3.31 \text{ km}^3$  per year at 0.5% significance level. The total volume gained in groundwater storage over a 12 year period (2003 to 2014) was  $39.72 \text{ km}^3$ . It is apparent from Figure 6.26 that  $GWS_a$  estimates exhibit annual variability. A positive  $GWS_a$  was observed in 2014 ( $41.93 \text{ km}^3$ ); the highest volume loss was in 2005 ( $-10.33 \text{ km}^3$ ).



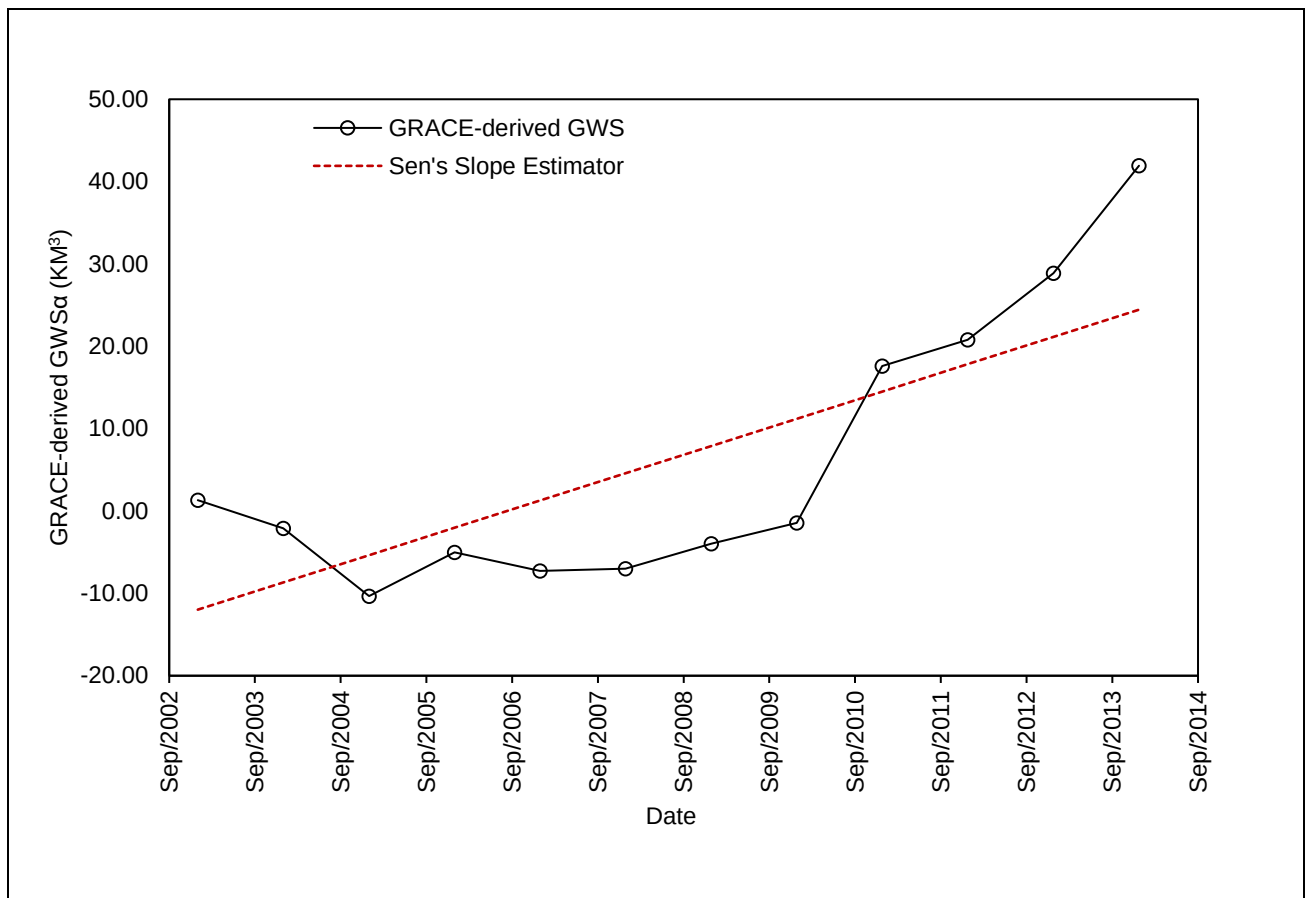


Figure 6.26: Groundwater storage anomaly derived from subtracting the reservoir storage and soil moisture from the GRACE terrestrial water storage. The red line shows groundwater storage trend over the study period.

Figure 6.27 illustrates the spatial variability in the  $GWS_a$  map across the Vaal River Basin (VRB). Figure 6.27 shows that the lower part of the basin gained the most water compared to the upper part of the basin. This trend is not surprising given that dolomite is the predominant aquifer; dolomite has a high storage capacity compared to the crystalline aquifers in the upper part of the basin.

There are several explanations for the observed variability and positive groundwater storage change. Firstly, the variation in  $GWS_a$  is attributed to annual varying hydrological and previous soil moisture conditions in the area, which influence infiltration and subsequently groundwater recharge. The observation of increasing  $GWS_a$  is more likely related to increases in reservoir storage, which facilitates induced

recharge to the aquifers. Another possibility could be related to low consumption of groundwater in the basin, resulting in water gains in the aquifer. Rainfall is one of the most important if not the only hydrological component that drives water mass movement in the region. Since rainfall is the main source of recharge, it was deemed sensible to assess the cause and effect relationship between rainfall and GWS<sub>a</sub>. This relationship is discussed in Section 6.4.3.

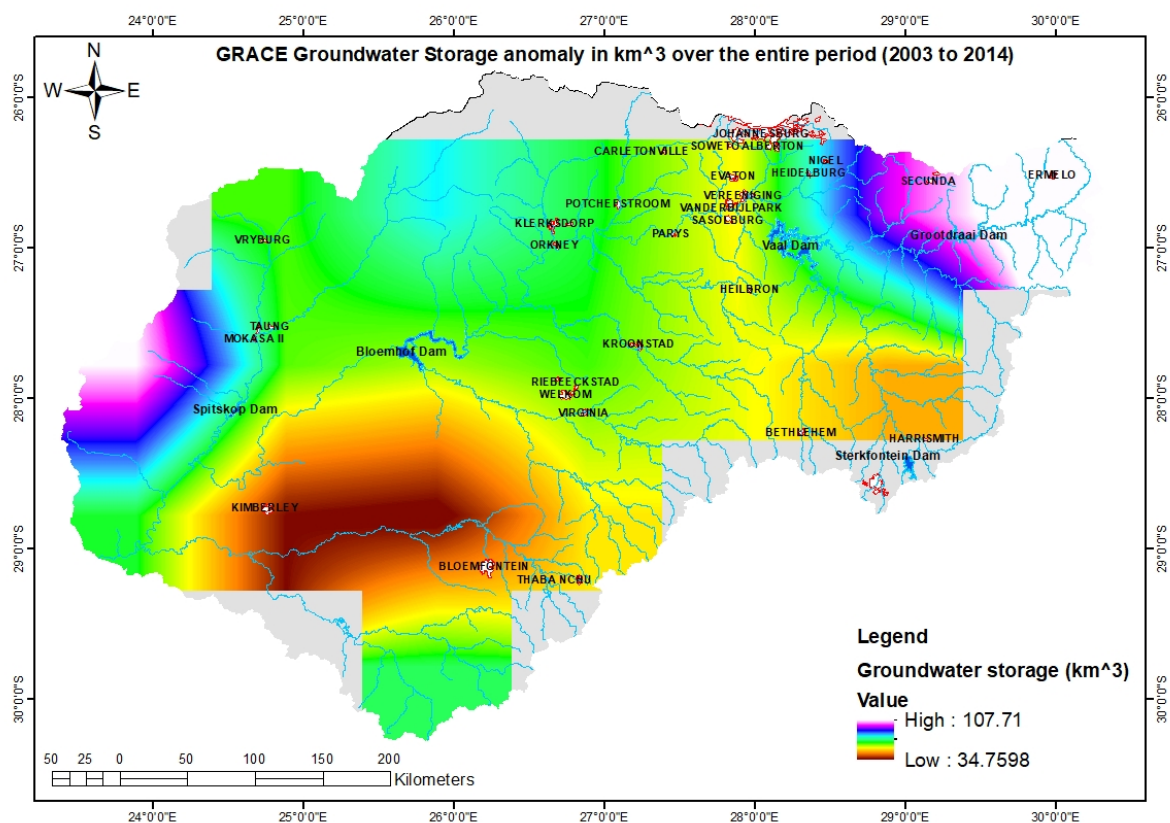


Figure 6.27: Spatial variability in GRACEGWa across the Vaal River Basin.

### 6.4.3 Evaluation of the effect of rainfall on GRACE-based groundwater storage anomalies

Rainfall is the major source of groundwater recharge in the basin. Other possible sources of recharge could be induced recharge by reservoirs and along local streambeds. It can be seen in Figure 6.28 that GWS<sub>a</sub> mimics the total rainfall amount with a time lag response for approximately a year for most parts of 2003 up to 2012. It is important to note that GWS<sub>a</sub> does not respond proportionately to the rainfall

amount. It is also quite clear that not all rainfall amounts have the same effect on the aquifer storage response. For example, GWS<sub>a</sub> showed a weak recovery in 2006, which could be in response to the higher rainfall amount (30.52 km<sup>3</sup>) (Figure 6.28). In contrast, high positive values in GWS<sub>a</sub> were apparent in 2011 following higher rainfall events in 2010 (Figure 6.28). It is likely that the rainfall intensity was sufficiently high and the soil profile conditions moist enough to enable high infiltration rates and facilitate groundwater recharge, which leads to possible gains in groundwater storage.

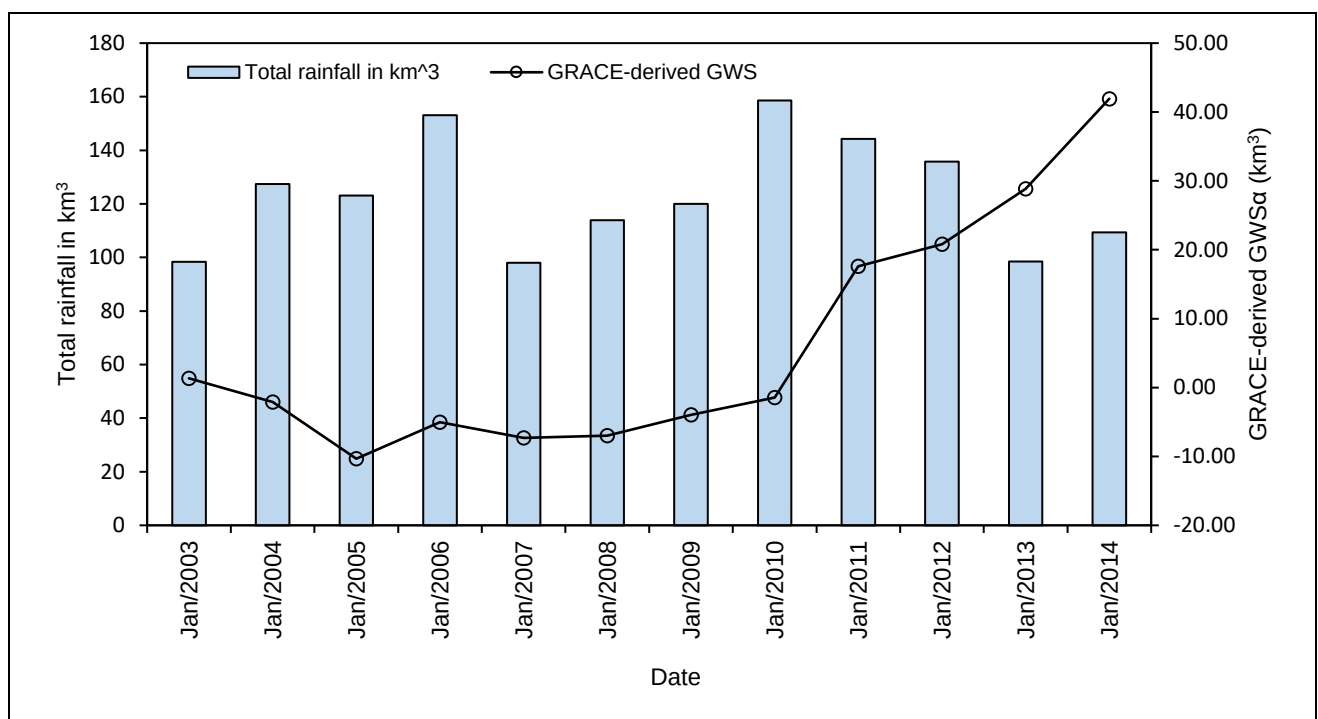


Figure 6.28: Rainfall versus GRACE-derived groundwater storage.

The lag time response in GWS<sub>a</sub> can be explained in several ways. The slow and weak recovery can be a result of insufficient rainfall amounts to cause significant contribution to the soil storage capacity because of drier conditions that prevailed between 2003 and 2005. It is likely that antecedent moisture conditions have a significant influence on the response time. Dry years are likely to increase the time lag because more water is needed to wet the soil, fill the surface storage, and infiltrate to lead, ultimately, to groundwater recharge. Another possibility could be that the rate at which these

processes occur may take hours to years depending on the hydrogeological characteristic and climatic factors that define the study site.

The rainfall anomaly depicts alternating periods of dry and wet spells in the rainfall record. Figure 6.29 shows that over the 12 years, there was a six year wet spell and a six year dry spell. The wet spells from 2004-2006 were succeeded by a dry spell that lasted from 2007-2009 and lastly a wet spell in 2010 and 2012.

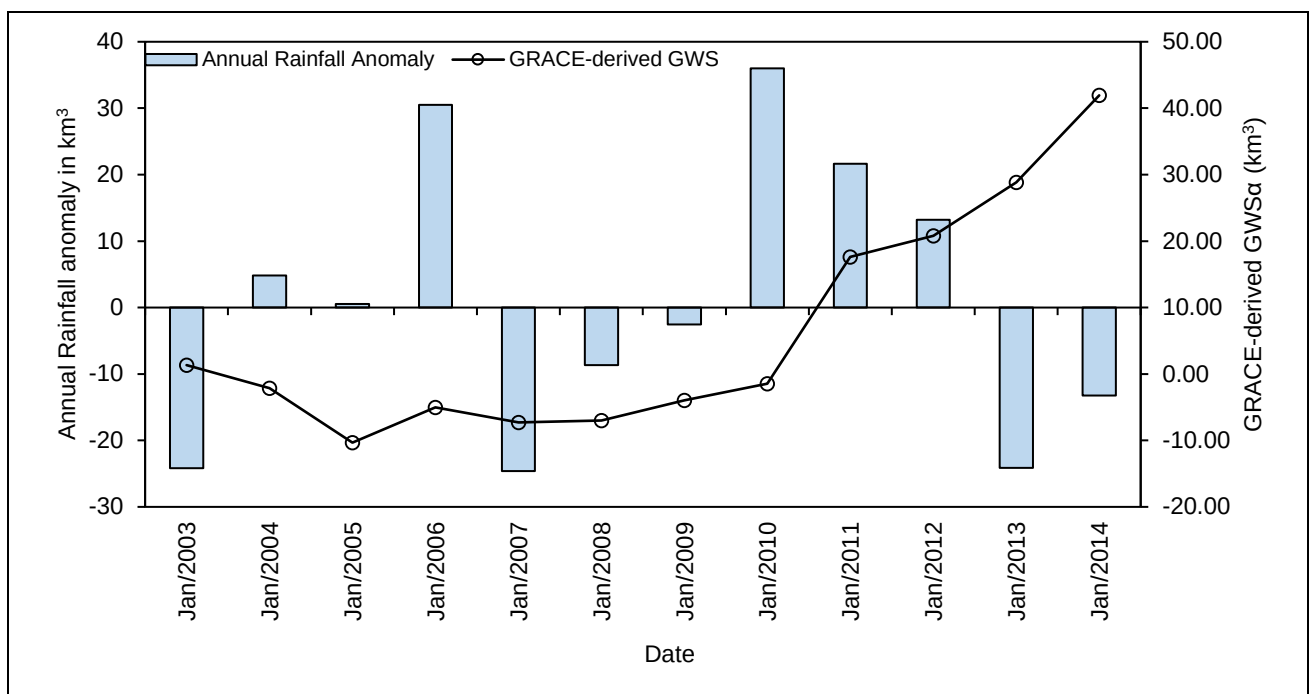


Figure 6.29: Comparison of annual rainfall anomaly and GRACE-based groundwater storage.

The rainfall seasonality and inter-annual variability in the basin is largely influenced by the El Niño Southern Oscillation (ENSO). Thus, aquifer depletion can be attributed to below average rainfall conditions. Above average rainfall has the potential to recharge the aquifer. Nonetheless, recharge must exceed discharge in order to maintain the groundwater storage levels. No statistical and significant trend was detected for the rainfall trend; nonetheless, the rainfall amount remained relatively unchanged with a

minimal net increase of  $0.48 \text{ km}^3$  over the entire period at a rate of  $0.040 \text{ km}^3/\text{year}$ . These data and trends reveal that although rainfall is a major contributor to the  $\text{GWS}_a$ , there could be other natural or human-induced factors contributing to the variability in groundwater storage.

#### 6.4.4 Surface water and soil moisture anomalies

The surface water in the current study refers to the available water in major dam storages in the basin. The surface water and soil moisture are the major components subtracted from GRACETWS when estimating the  $\text{GWS}_a$ . Figure 6.30 shows the surface water storage plotted against  $\text{GWS}_a$ . All surface water, including reservoirs, is the source of water to the soil moisture zone. The surface water storage increased by  $2.72 \text{ km}^3$  over the entire period at a rate of  $0.227 \text{ km}^3/\text{year}$  (Figure 6.30). The surface water storage exhibited similar increases in 2006 to  $\text{SM}_a$  and  $\text{GWS}_a$ . Reservoir storage increased from 2008 to 2017, which is not reflected in the  $\text{SM}_a$  and  $\text{GWS}_a$ . This discrepancy could be a result of human reservoir management such as inter-basin transfer and regulation of flows as part of the Integrated Vaal River System (IVRS) and Lesotho Highlands Water Project (LHWP).

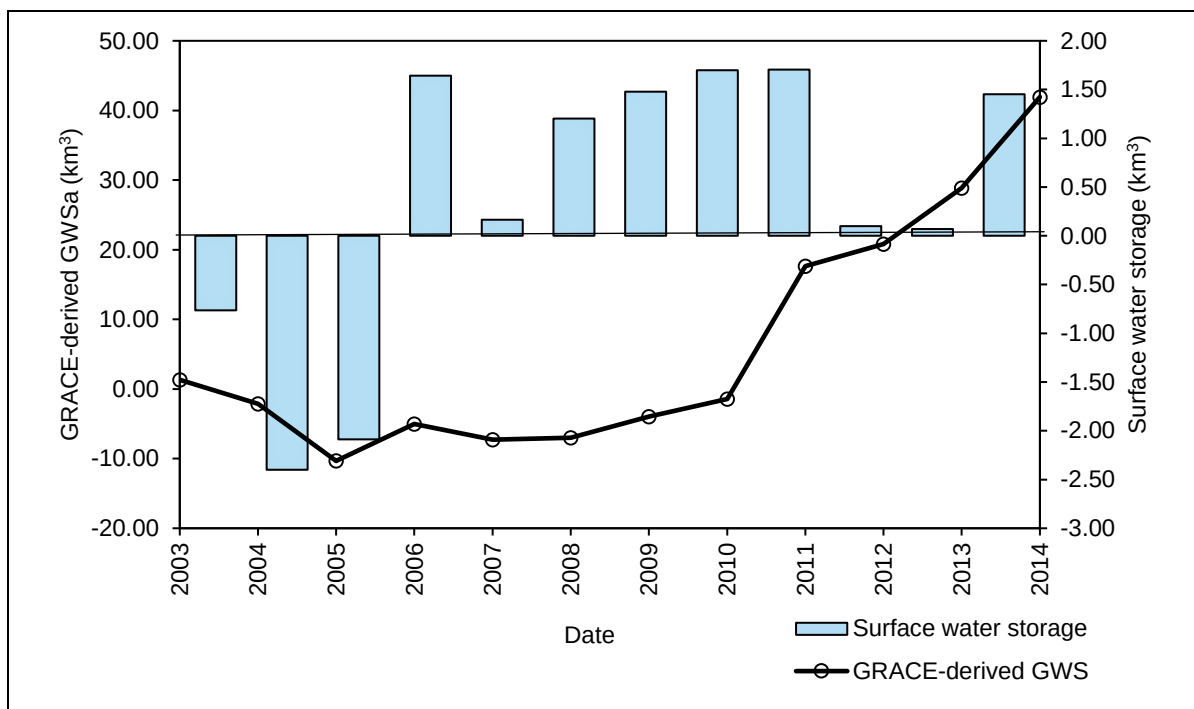


Figure 6.30: Surface water storage versus GRACE-derived groundwater storage.

The rate and amount of infiltration will depend on the soil characteristics. Ultimately, infiltration will add to the soil moisture storage. Some of the water in the soil moisture will effectively recharge the aquifer. The soil moisture storage decreased by 10.5 km<sup>3</sup> over the analysis period at a rate of 0.875 km<sup>3</sup>/year. The decrease is statistically insignificant at  $\alpha = 0.05\%$  and  $0.1\%$ . Notable soil moisture surplus and increases were apparent in 2006, 2010, and 2011 (Figure 6.31). Interestingly, soil moisture storage deficit was apparent in 2012-2014 (Appendix E), which is opposite to the observed increases in GWS<sub>a</sub>. The contrast between soil moisture and GWS<sub>a</sub> post-2012 can be explained by missing values (25%) in the GRACE data. The GWS<sub>a</sub> estimates mimic the soil moisture that was expected because the soil moisture zone is the source of effective recharge for the aquifer. The antecedent soil moisture conditions will determine the amount of surface water that will reach the groundwater storage.

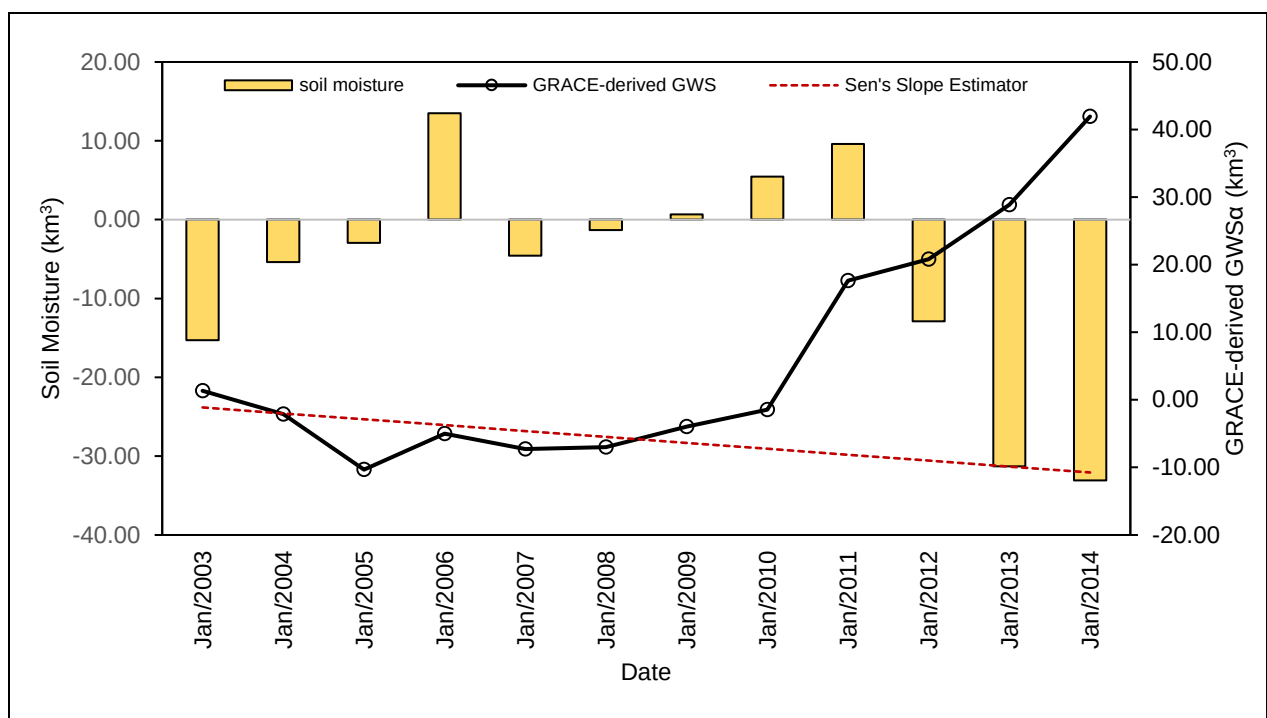


Figure 6.31: Soil moisture versus GRACE-derived groundwater storage.

Figure 6.32 shows that the SMA in the basin has been increasing and decreasing in different parts of the basin. This observation is expected given the variability in soil

thickness and depth, and the different types of soil material found across the VRB. From Figure 6.32, it can be seen that the southern and southwestern part of the VRB experienced a general increase in soil moisture storage. The northern and eastern part of the basin clearly showed a negative soil moisture storage trend over the study period. There are, however, localised regions in the Johannesburg area with net gains in moisture storage between 2003 and 2014, as indicated by a positive trend (Figure 6.32). The SMa map (Figure 6.32) appears to be much clearer, showing more detail because of the high resolution of data compared to the coarse resolution of the GRACE-based GWS<sub>a</sub> map (Figure 6.27).

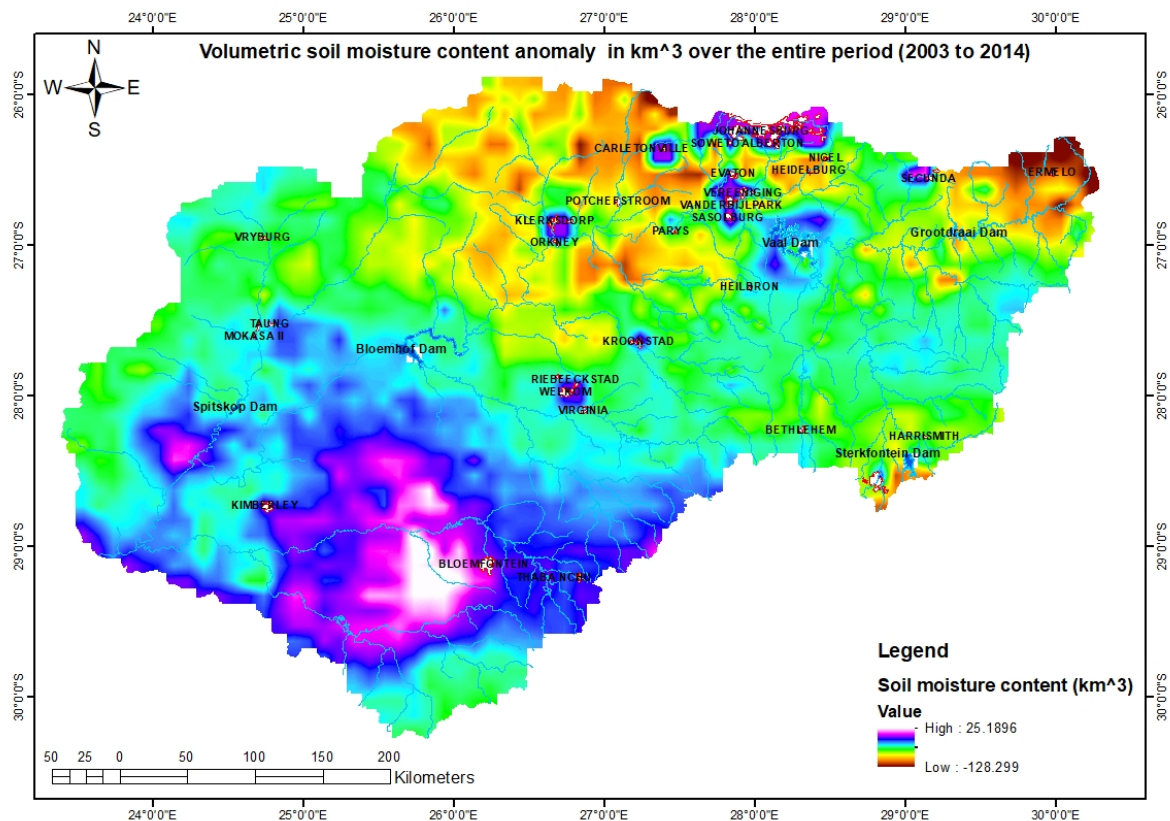


Figure 6.32: Soil moisture anomaly in the Vaal River Basin.

Despite the coarse resolution of GRACE-based GWS<sub>a</sub> and soil moisture storage maps, they reveal information about regional mass water movement in the VRB, which is important for overall water management.

## 6.5 Soil Water Assessment Tool results and implications

### 6.5.1 Calibration

The global sensitivity analysis tool in SUFI-2 identified nine parameters that have the most influence on the hydrological processes. These parameters were further adjusted during calibration in order to create a best fit between the measured and simulated values. Table 6.8 shows the list of the parameters and the values adjusted during the calibration.

Table 6.8: Best parameter estimates in increasing order used in the modelling process.

| Rank | Parameter   | Description                                                                                         | Range (min – max) | Best Parameter Estimate |
|------|-------------|-----------------------------------------------------------------------------------------------------|-------------------|-------------------------|
| 1    | SOL_AWC     | Available water capacity of the soil layer (mm H <sub>2</sub> O/ mm soil)                           | 0 – 0.33          | 0.13                    |
| 2    | HRU_SLP.hru | Average slope steepness (m/m)                                                                       | 0.12 – 0.71       | 0.42                    |
| 3    | CN2.mgt     | Initial SCS run-off curve number for soil moisture condition II                                     | 35 – 67.22        | 54.91                   |
| 4    | OV_N.hru    | Manning's "n" value for overland flow                                                               | 9.04 – 27.26      | 13.69                   |
| 5    | GW_REVAP.gw | Groundwater "revap" coefficient                                                                     | 0.08 – 1.36       | 0.19                    |
| 6    | GWQMN.gw    | Threshold depth of water in shallow aquifer required for return flow to occur (mm H <sub>2</sub> O) | 3223.78 - 5000    | 4996.83                 |
| 7    | SURLAG.hru  | Surface run-off lag coefficient                                                                     | 0 – 1.69          | 0.03                    |
| 8    | USLE_K.sol  | USLE soil erodibility (K) factor                                                                    | 0.25 – 0.75       | 0.43                    |
| 9    | GW_DELAY.gw | The delay time for recharge into groundwater systems                                                | 154.48 – 405.31   | 359.98                  |

The best parameter estimates were used as input in the SWAT model for simulation. Figure 6.33 shows that the SWAT model, to some degree, simulates the peak and low flows in C52F, although the magnitude varies.



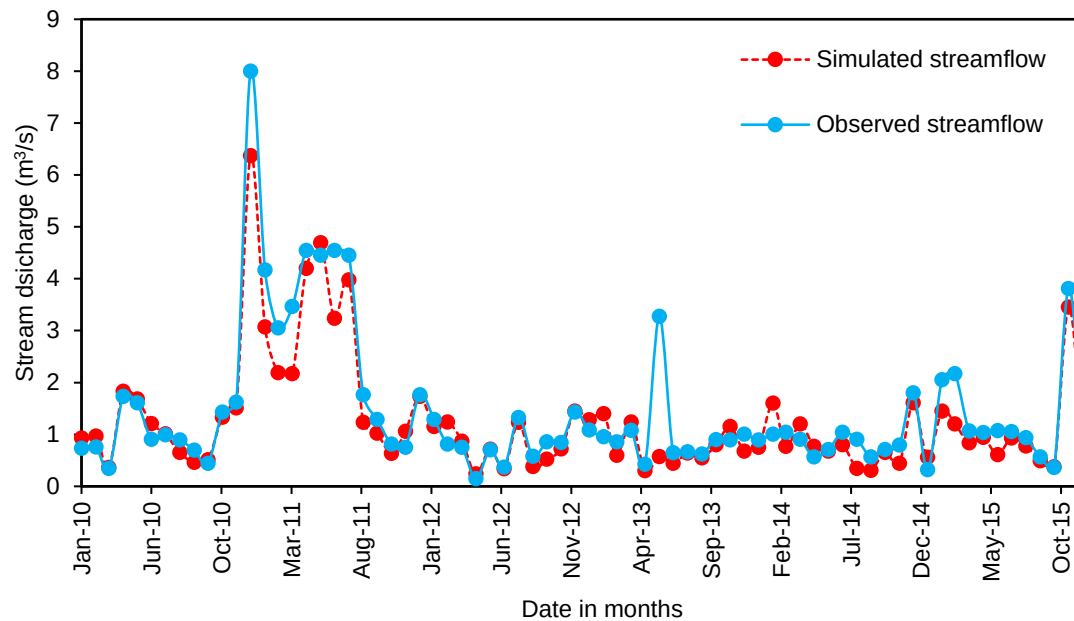


Figure 6.33: Comparison of observed and simulated streamflow values from 01/01/2010 to 31/12/2015.

The simulated values underestimated the streamflow, which could be a result of the sensitivity of the curve number (CN2) and the steepness of the slope. The steepness of the slope influences the amount of excess rainfall that will become runoff. The high sensitivity of the curve number reveals that the soil and land use/land cover (LULC) conditions have a high influence to the streamflow in the watershed. However, it is possible that the simulated flow is an actual representation of the natural flow conditions. This is because in the VRB, the effluent discharge from industries and households contribute significantly to the streamflow. In other words, the observed streamflow is modified, which could explain the high peaks.

### 6.5.2 SWAT Model performance and evaluation

The model results yielded a Nash-Sutcliffe Efficiency (NSE) value of 0.21. The NSE value of 0.21 is out of the acceptable range, which suggests that the observed values are a better predictor of streamflow to environmental change than the simulated values.

(Moriassi et al., 2007). The calculated percent bias (PBIAS) was estimated to be 10.6% is also not acceptable. The implication of NSE value of 0.21 and PBIAS of 10.6% result means that the SWAT model, in this particular context, was not a reliable tool in predicting the impact of changes in rainfall nor the LULC in the hydrological processes of the basin. Thus, the results only focus on how hydrologic processes operate in the basin.

The unsatisfactory performance of the model could be a result of the inadequacy of the digital elevation model (DEM) resolution of 30 m by 30 m to capture the slope and topographical architecture of the basin. Gassman et al. (2014) further support the fact that the weakness in the modelling results is also caused by the problems arising from the input data.

Instead of completely disregarding the modelling exercise the SWAT model water balance does provide useful information that can help understand the hydrological processes taking place in the basin. The components of water balance that are estimated using the SWAT model are evaporation, surface runoff, and percolation of the C52F Quaternary Catchment. The results were visualised using maps, which clearly shows the spatial variation of water balance components between the urbanised and rural parts of the catchment.

### **6.5.3 Visualization of SWAT model outputs and their significance**

Spatial visualisation was used to show how the selected model results, namely evaporation rate, surface runoff and percolation, are distributed across the sub-basins. There were 141 hydrological response units (HRUs) generated from a combination of LULC and soil properties. For practical reasons, the focus was on the sub-basin scale to understand the magnitude of the water balance components in the basin, which will aid in water management. Only five sub-basins were delineated in this study site (Figure 6.35).

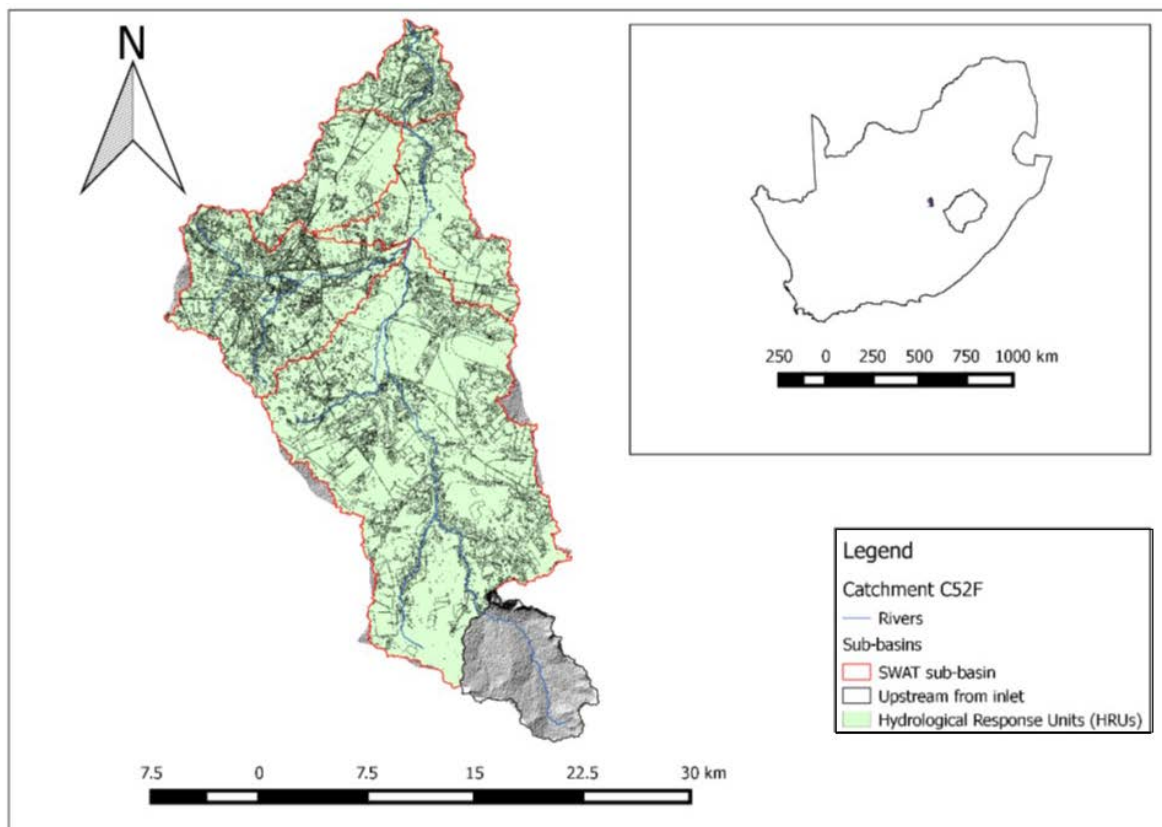


Figure 6.34: Map depicting 141 hydrological response units in the Vaal River Basin for different soil and land use/land cover combinations. The grey block is part of the C52F Quaternary where there was insufficient data.

The model output of the average monthly evapotranspiration (ET) in the catchment C52F ranges from 22.35 mm to 23.02 mm (Figure 6.35). Sub-basin 1, located downstream, has the highest ET. On the other hand, sub-basin 5, which is the northern boundary of sub-basin 1, has the lowest ET. The spatial variation in ET (mm) in the basin is very small, approximately 0.67 mm; this could be a result of minor topographic variation and the use of one meteorological station across the C52F Quaternary Catchment.

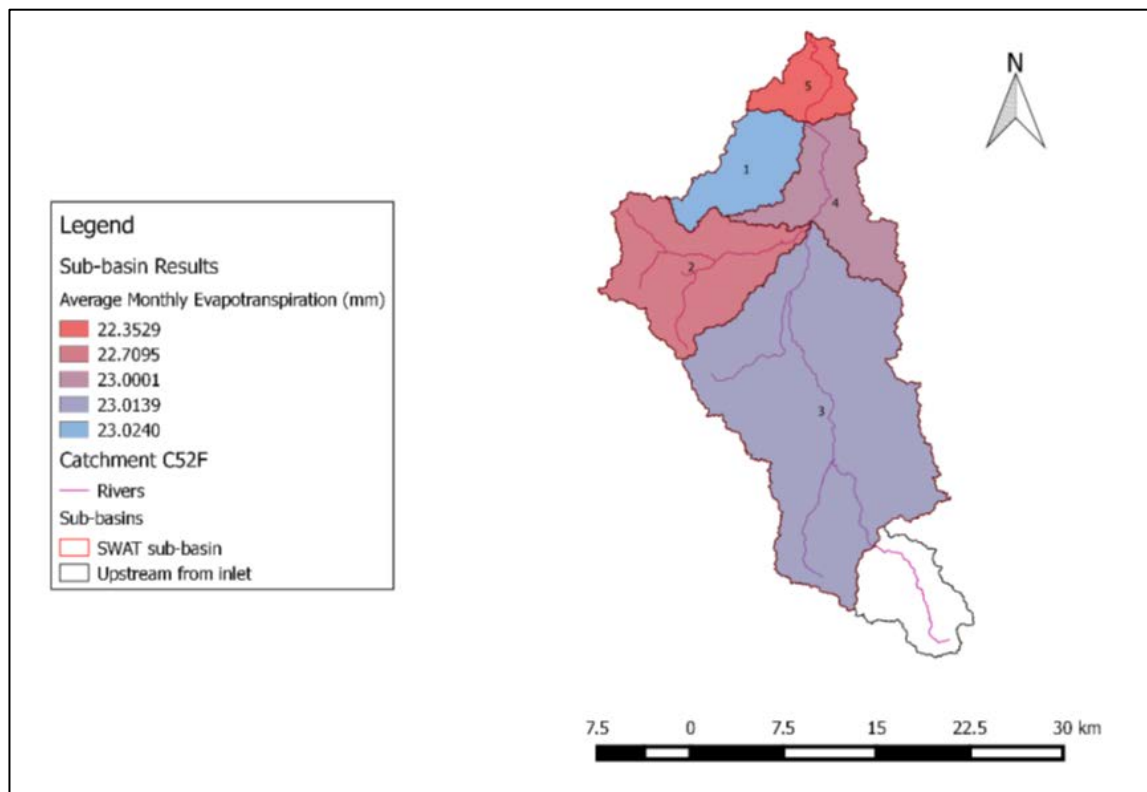


Figure 6.35: Spatial variation map of mean monthly evapotranspiration (mm) in catchment C52F over the period 01/01/2010 to 31/12/2015.

From Figure 6.36 we can see that sub-basin 2 has the lowest mean monthly percolation amount of 12.10 mm in the study site. Sub-basin 2 covers the highly urbanised part of C52 Quaternary Catchment, where Bloemfontein City is located. It could be that sub-basin 1, sub-basin 3, sub-basin 4 and sub-basin 5 have a high percolation amount because they are in rural parts of the study site. The highest percolation amount is at the outlet of C52F, which is in sub-basin 5. Unlike the monthly evaporation rates, the percolation rates shows a marked difference across the C52F. It seems possible that these results are due to the difference in the urban and rural land cover. Pavements and buildings that facilitate surface runoff rather than infiltration mainly cover the urbanised part of C52F. In contrast, large agricultural lands and barren ground surfaces cover the rural area that allows water to infiltrate the top surface, and percolate to groundwater storage. This observation has implications for water that joins groundwater and soil water storages.

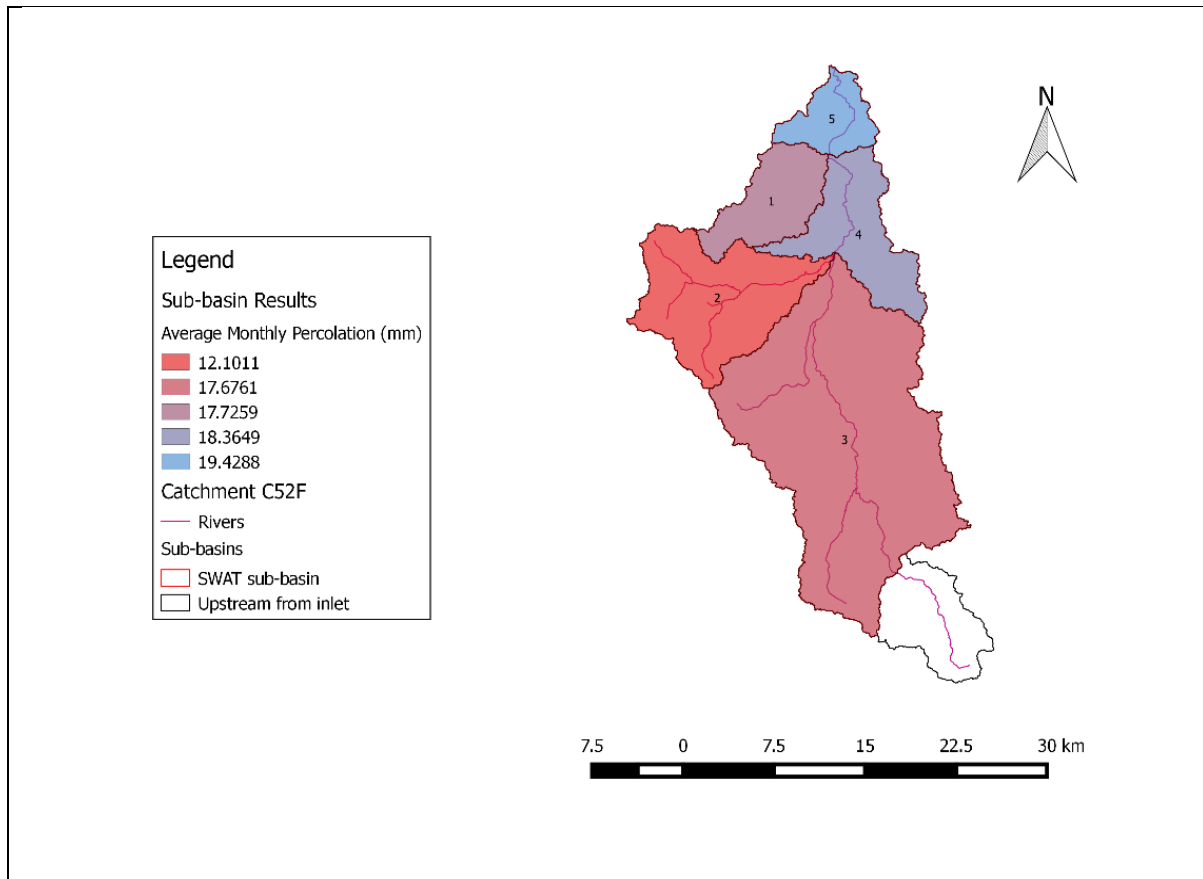


Figure 6.36: Spatial variation map of mean monthly percolation (mm) in catchment C52F over the period 01/01/2010 to 31/12/2015.

Figure 6.37 shows the spatial variation of monthly surface runoff (mm); this hydrological property follows a similar but opposite trend to percolation (Figure 6.36). In this case, sub-basin 2 has the highest surface run-off amount of 9.03 mm and sub-basin 5 has the lowest surface run-off of 1.36 mm. These results are not surprising given that the same basin characteristics that influence percolation also influence surface runoff. The high surface runoff amount in sub-basin 2 is a result of urban paving and building that impede infiltration and favours surface runoff. The rural part is mainly covered with forested and cultivated land which provide conditions favourable for percolation. In this rural part, surface runoff occurs only when the soil moisture capacity is reached.

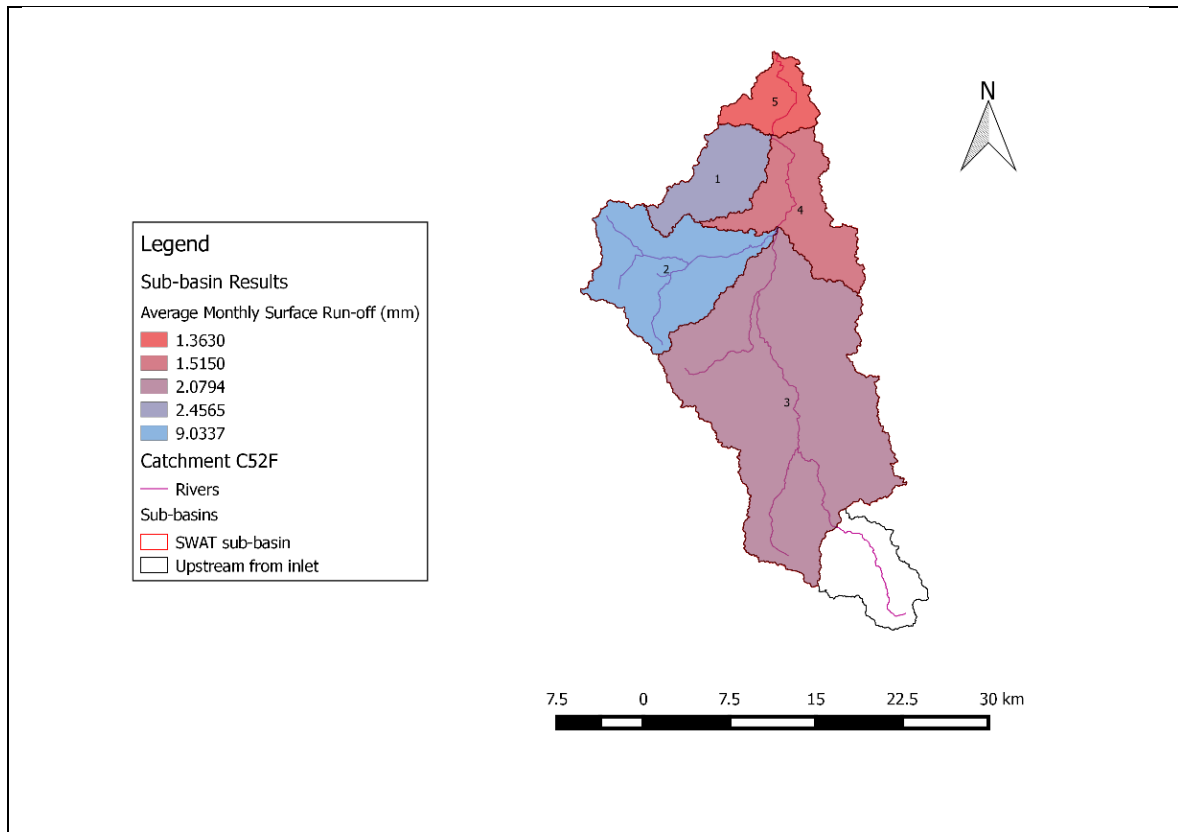


Figure 6.37: Spatial variation map of mean monthly surface run-off (mm) in catchment C52F over the period 01/01/2010 to 31/12/2015.

These findings demonstrate the extent to which LULC can modify the natural functioning of the catchment. Evaporation and surface runoff have a significant influence on the amount of water that adds to the SM, surface water, and groundwater storages. The high percolation in sub-basin 5 implies addition of water in the aquifer, resulting in high groundwater levels downstream. The high groundwater levels could also facilitate surface runoff because the aquifer is fully saturated. Percolation rates are very low in sub-basin 2, which means that urbanisation potentially limits the groundwater recharge rate. These results are encouraging because they help us understand the spatial variability in water balance components that potentially affect the groundwater storage in the sub-basin. Despite these promising results, questions do remain.

## 6.6 Synthesis

Given the broad nature of this study, this section attempts to connect the various parts of the thesis to provide a conceptual understanding of the groundwater system in the VRB. This study set out to improve understanding of the groundwater resources of the VRB using various methods and data from different sources.

Groundwater processes in the VRB are influenced by the interplay of various physical features such as the underlying geology, anthropogenic activities, and rainfall patterns. The anthropogenic activities and rainfall patterns vary naturally on a wide range of temporal and spatial scales across the VRB. The consequence is that this will also influence the groundwater processes and varying scales. The heterogeneity in the geology results in different aquifer types in the study. The analysis of groundwater level trends and variability was limited to the upper part of the VRB. The upper part is underlain mainly by the Transvaal carbonates. On a basin scale, the Transvaal and Griqualand carbonate are found in the southwestern and northeastern part of the study site and are the most significant because of high groundwater productivity. The carbonate rocks occupy only 20% of the VRB and constitute an important source of dependable water supply. In areas underlain by carbonates, there are dense monitoring networks, because of their vulnerability to pollution.

Although rainfall in the basin as a whole has indicated decreasing trends over the time period of this study, the decrease is considered to be insignificant. However, at local scales, massive declines are apparent. These significant localised decreases imply that less water is available to replenish the terrestrial water storages (TWSs). However, without a full understanding of the other climatic variables such as temperature, relative humidity, and wind speed, it is unclear how the groundwater resources will be impacted.

The quality of groundwater in the basin is within drinking standards of the WHO. The groundwater quality varies across the study site with local groundwater within the mining footprint or in the southwest part of the basin having a low water quality. Intense mining, industry, and urbanisation are the source of effluent that pollute the

groundwater system. The pollution is, however, localised. This finding helps in identifying hotspots for aquifer protection and strengthening policy for water users. Despite this, a larger amount of pristine water in the dolomitic aquifer is unpolluted. Thus, if the quality of groundwater in the dolomitic aquifer declines, it will constrain the quantity of groundwater that can be used in the basin.

The groundwater storage changes using GRACE satellite data and ancillary data estimate the change in groundwater storage in the basin to be approximately 3.3 km<sup>3</sup>/year. This gain shows that there is a significant potential to develop groundwater use in the basin. The estimate of GWS<sub>a</sub> in the basin is of renewable groundwater that changes monthly, seasonally, and annually. The GWS<sub>a</sub> on a basin-scale could be attributed to water movement and transfer between large storages such as dams. Since rainfall is the major water input in the basin, it is also expected to contribute to the GWS<sub>a</sub>. At local scales, the GWS<sub>a</sub> are reflected by groundwater level changes in the basin. In some sites, groundwater levels have been dropping, which implies that on a local scale some parts of the basin water quantity are decreasing, which will most likely result in a localised negative GWS<sub>a</sub>. Over-abstraction and mine dewatering cause the lowering of groundwater levels in boreholes in the upper part of the VRB, which are near the mines and agricultural land. On the other hand, the rises in groundwater levels mean that there is a net gain in GWS<sub>a</sub>. The net gain in GWS<sub>a</sub> is limited to the local region where water levels were available. The localised net gain can be linked to excess rainfall, which replenishes the aquifer. Consistent with Meyer's (2005) findings is that drastic rises or recovery in groundwater levels depends on the intensity and duration of rainfall. The changes in groundwater levels and groundwater storage show the extent to which groundwater is renewable at both local and basin scales. The positive GWS<sub>a</sub> is indicative of the accumulation of groundwater, which shows that groundwater recharge exceeds discharge. This also substantiates the view that groundwater is not utilised to its full potential.

The land cover and physical soil properties in the basin influence the rate of percolation and surface runoff. The regions with intense urbanisation favour surface runoff and the percolation rate are low. In rural areas, however, the percolation rate is high and surface runoff is low. These trends also depend on the amount of rainfall in the basin.



On a basin scale, the rainfall amount shows a minor decrease overall but at a local scale, statistically significant decreases in the rainfall amount were observed.

Overall, these findings reveal that human modification of the natural system affects the hydrological processes and exerts more influence on the groundwater system than the climatic factors. The results also reveal that local groundwater systems are more sensitive to human activities and, to some extent, local variability in climate. Thus, groundwater in the basin is of relatively good quality and sufficient quantity to meet future water demands of the VRB - this will also reduce pressure on surface water supplies. These results also show that both quality and quantity considerations are important for groundwater management. Moreover, this study demonstrates that using an integrated approach involving various methods and combining remotely sensed and in-situ data is key in improving the understanding of the groundwater resources at a basin scale, especially where data is scarce.

## 7 CONCLUSIONS AND FUTURE OUTLOOK

### 7.1 Conclusions

This study sets out to study the groundwater storage changes, groundwater trends, and to characterise the groundwater chemistry of the Vaal River Basin (VRB) using an integrated approach. In addition to this, the study intended to estimate water balance components, namely percolation and surface runoff. Integration of various methods and data from various sources was used to achieve the aims and objectives of this research.

The main aim of this study was to use the data from the Gravity Recovery and Climate Experiment (GRACE) mission to estimate the changes in groundwater storage ( $GWS_a$ ) in the VRB, and to identify the drivers of these storage changes. According to the author's knowledge, this is the first study in South Africa to use GRACE-data to evaluate  $GWS_a$ . The assessment of  $GWS_a$  on a large scale is of relevance in the management of groundwater resources in the data-scarce VRB given that the basin is surface water deficit and experiences climate aridity.

Using the GRACE satellite data in combination with ancillary data was found to be valuable in detecting inter-annual variability in groundwater storage. The most interesting finding to emerge is that the ( $GWS_a$ ) in the VRB from 2003 to 2014 showed an increase of approximately  $3.31 \text{ km}^3/\text{year}$  in volumetric storage. The drivers of this increase in  $GWS_a$  are probably due to the input of above-average rainfall events in the basin recharging the groundwater system and induced recharge by the big dams in the VRB. It was noted that  $GWS_a$  lags high rainfall events, which suggests rainfall is probably one of the drivers of  $GWS_a$ . Rainfall is the major input of water in a basin and will vary seasonally, and this will be reflected in the GWS variability. The magnitude of the  $GWS_a$  far exceeds the contribution by soil moisture and surface water, which is indicative of additional drivers of  $GWS_a$ . However, due to the coarse spatial resolution of GRACE satellites, the high  $GWS_a$  magnitude could be a result of leakage along structural discontinuities and flow to or from adjacent basins.

The integration of GRACE satellite data and in-situ data proves to be useful in the assessment of changes in groundwater storage in the data-scarce VRB. The coarse spatial resolution of the GRACE satellite presents a need for downscaling techniques. It was not possible to validate the GWS<sub>a</sub> because of the absence of groundwater levels data across the VRB. Despite the coarse spatial resolution of the GRACE satellite and the absence of groundwater levels, the net gain in GWS<sub>a</sub> is indicative of high a potential of groundwater availability that can augment surface water supply in the VRB.

The study also set out to detect the presence of statistical trends in long-term groundwater levels and to identify key factors causing groundwater level fluctuation. The importance of this statistical analysis of groundwater levels is to improve understanding of the extent of groundwater change over time in the highly industrialised and urbanised VRB.

The Mann-Kendall Test (M-K Test) and Sen's Slope Estimator analysis of groundwater levels showed the presence of both upward and downward statistically significant trends in groundwater levels. The M-K test and Sen's Slope Estimator also reveal that there is no correlation between the groundwater elevation and magnitude of the Sen's Slope Estimator. This study identified aquifer dewatering in active mines and groundwater abstraction for irrigation and communal activities as possible factors resulting in declining water levels in the upper part of the VRB. The reduction in local rainfall contributed in part to the downward trend of groundwater levels in selected monitoring boreholes. The overall increase in rainfall amount, agricultural return flow, and stream loss to the aquifer system contributed to the rise in groundwater levels in the upper part of the VRB. These findings strengthen the idea that on a localised scale the groundwater system is more sensitive to anthropogenic processes than to natural processes such as rainfall. One of the major observation is the massive decline in groundwater levels for monitoring borehole BH40 by 95 m and monitoring borehole BH47 by 45 m, which is attributed to aquifer dewatering in a mining area.

The statistical analysis of groundwater levels and rainfall proved to be useful in identifying causes of groundwater level fluctuation in the upper part of the VRB. The result of this analysis also shows the importance of monitoring and collecting of

hydrological data in the VRB. These findings also confirm the need to assess the impacts of anthropogenic and natural processes at varying scales.

One of the purposes of this study was to characterise the groundwater chemistry to develop insights into the extent of groundwater quality. Analysis of groundwater quality using graphical and multivariate statistical tools revealed the interaction of recently recharged water with mine-polluted water and water in circulation. The main water types identified are Ca-Mg-HCO<sub>3</sub> and Ca-Mg-Cl-SO<sub>4</sub>. Hydrochemical processes such as dolomite dissolution, reverse ion exchange, and silicate and evaporate weathering are active. Mining, as well as industrial and urban water discharge into the environment, threatens the quality of the pristine dolomitic water. Overall, the water is within the World Health Organisation's (WHO) recommended drinking water guidelines, but this analysis did not include metals. The principal controls on groundwater chemistry are both geological and anthropogenic in the VRB. Notwithstanding the relatively limited number of water samples, this research offers valuable insights into the main controls and hydrochemical processes affecting the groundwater quality in the highly industrialised and urbanised sections of the VRB.

The characterisation of the groundwater chemistry in the VRB suggest in general that although land use practices such as mining cover a small surface area, their impact on groundwater quality is high in comparison to cultivation covering a large surface area but with low impact.

Modelling the C52F Quaternary Catchment using the Soil Water Assessment Tool (SWAT) model shows that the measured data are a better predictor of the variance than the simulated values, and that the model underestimates the streamflow. This is validated by measuring the accuracy of the model using the Nash-Sutcliffe Efficiency (NSE) Coefficient and percent bias (PBIAS) that give values of 0.28 and 10.8%, respectively. Overall, these results indicate the necessity of measuring or estimating the amount of synthetic streamflow because streamflow is a recipient of wastewater from urban flow, industrial discharge, and other activities upstream. Nonetheless, these results also show the significance of field measurements of the soil parameters

at a small scale and that the SWAT model is better for modelling at smaller scales rather than for larger areas.

The main weaknesses of this study include the unavailability of groundwater pumping rates, discharge measurements, and point measurements of physical properties of the soils, as well as the limited number of available groundwater quality samples. Despite these limitations, this study certainly contributes to our understanding of groundwater level trends, groundwater storage, and groundwater chemistry in the VRB. It further adds to the growing body of research that seeks to understand the extent to which groundwater – as a resource – is impacted by changes in both anthropogenic and natural processes over time. The findings of this study have a number of practical implications that are highlighted in the Recommendations section 7.2. The outcomes of this study will aid in the protection, and sound management, of groundwater resources in the water-stressed VRB.

## **7.2 Recommendations**

These findings suggest several courses of action for the better management of groundwater resources in the VRB and elsewhere in the country. In particular, better management requires a bottom-up approach together with greater oversight at the national level by the Department of Water and Sanitation (DWS). Further research is still required to improve our understanding of groundwater systems and all the relevant interrelated components. The sections below outline areas that further research might explore as well as practical steps in the management of the groundwater resource in the VRB.

### **7.2.1 Recommendation for further research**

- From the chemical analysis, it is apparent that use of isotopes and artificial tracers need to be incorporated in order to validate the source origin, travel time, and processes of different ions in the VRB. There is also a need to develop an efficient method to treat water from mining tailings dams and inactive mines

before the water is discharged into streams polluting the groundwater resources.

- Further modelling work will have to be conducted in order to determine the anthropogenic impacts on groundwater storage in parts of the basin that are dependent on groundwater resources.
- More emphasis should be placed on studying short-term fluctuation in groundwater levels; these fluctuations can have direct impacts on groundwater-dependent communities on a daily basis.
- Streamflow sensitivity to climate variability and LULC must move beyond the field scale to a watershed scale. This shift in scale is needed to improve our understanding of hydrological processes in the VRB and their impact on groundwater resource availability.
- Remotely sensed data must form an integral part of any hydrogeological investigation, particularly in data-scarce parts of the country.
- There must be a downscaling of space-based observations in order to get better information at a finer resolution.
- Further research should compare the GRACE groundwater storage changes and drought indices to evaluate the effects of climate variability on groundwater storage.

#### **7.2.2 Recommendation for practice or policy**

- A priority should be to continue monitoring and collecting hydro-meteorological data across the VRB, particularly in parts of the basin where significant groundwater resources exist and where there is a high dependency on groundwater.
- Greater efforts are needed to build capacity in local communities to promote management and protection of water resources at local municipality- or district-level. Both capacity building and the management and protection of water resources must be coordinated at a national level by the DWS.

- There is also a need to build capacity in technical skills needed to process and handle space observation data from Earth observation satellites for groundwater management.
- Researchers must raise awareness about groundwater use, depletion, and contamination through public communication of science.

## 8 REFERENCES

- Abiye, T.A. (2011). Provenance of groundwater in the crystalline aquifer of Johannesburg area, South Africa. *International Journal of Physical Science*, 6(1): 98-111.
- Abiye, T.A, Mengistu, H. and Demlie, M.B. (2011). Groundwater resource in the crystalline rocks of the Johannesburg area, South Africa. *Journal of Water Resources and Protection*, 3(4): 199-212.
- Abiye, T.A. (2014). Mine water footprint in the Johannesburg area: A review based on existing and measured data. *South African Journal of Geology*, 117(1): 87-96.
- Abiye, T.A., Masindi, K., Mengistu, H. and Demlie, M.B. (2018). Understanding the groundwater-level fluctuations for better management of groundwater resource: A case in the Johannesburg region. *Groundwater for Sustainable Development*, 7: 1-7.
- Adelana, S.M. and Macdonald, A.M. (2008). Groundwater research issues in Africa. In S.M Adelana and A.M. Macdonald (eds), *Applied groundwater studies in Africa*. London: CRC Press.
- Ahmed, M., Sultan, M., Wahr, J. and Yan, E. (2014). The use of GRACE data to monitor natural and anthropogenic induced variations in water availability across Africa. *Earth-Science Reviews*, 136: 289-300.
- Allison, G. B., & Hughes, M. W. (1983). The use of natural tracers as indicators of soil-water movement in a temperate semi-arid region. *Journal of Hydrology*, 60(1-4): 157-173.
- Altermann, W. and Wotherspoon, J.M. (1995). The carbonates of the Transvaal and Griqualand West Sequences of the Kaapvaal craton, with special reference to the Lime Acres limestone deposit. *Mineralium Deposita*, 30(2): 124-134.
- Anand, B., Karunanidhi, D., Subramani, T., Srinivasamoorthy, K. and Suresh, M. (2019). Long-term trend detection and spatiotemporal analysis of groundwater levels using GIS techniques in Lower Bhavani River basin, Tamil Nadu, India.



*Environment, Development and Sustainability*. Available online at:  
<https://link.springer.com/article/10.1007/s10668-019-00318-3>.

Andersen, O.B., Seneviratne, S.I., Hinderer, J. and Viterbo, P. (2005). GRACE-derived terrestrial water storage depletion associated with the 2003 European heat wave. *Geophysical Research Letters*. Available online at:  
<https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2005GL023574>.

Anhaeusser, C.R., (2006). Ultramafic and mafic intrusions of the Kaapvaal Craton. In Johnson, M.R, Anhaeusser C.R, and Thomas, R.J (eds), *The Geology of South Africa, Johannesburg. Council for Geoscience, Pretoria*:95-134.

Appelo, C.A.J. and Postma, D. (2004). *Geochemistry, Groundwater and Pollution*. Boca Raton, United States: CRC Press.

Armstrong, R.A., Compston, W., Retief, E.A., Williams, I.T. and Welke, H.J. (1991). Zircon ion microprobe studies bearing on the age and evolution of the Witwatersrand triad. *Precambrian Research*, 53(3-4): 243-66.

Arnell, N.W. (1999). Climate change and global water resources. *Global Environmental Change*, 9:S31–S49.

Arnold, J.G., Moriasi, D.N., Gassman, P.W., Abbaspour, K.C., White, M.J., Srinivasan, R., Santhi, C., Harmel, R.D., Van Griensven, A., Van Liew, M.W. and Kannan, N. (2012). SWAT: Model use, calibration, and validation. *Transactions of the American Society of Agricultural and Biological Engineers*, 55(4): 1491-1508.

Arnold, J. G., Srinivasan, R., Muttiah, R. S., and Williams, J. R. (1998). Large area hydrologic modeling and assessment part I: model development 1. *Journal of the American Water Resources Association*, 34(1): 73-89.

Arnold, J. G., and Fohrer, N. (2005). SWAT2000: current capabilities and research opportunities in applied watershed modelling. *Hydrological Processes: An International Journal*, 19(3): 563-572.

Ashouri, H., Hsu, K.L., Sorooshian, S., Braithwaite, D.K., Knapp, K.R., Cecil, L.D., Nelson, B.R. and Prat, O.P. (2015). PERSIANN-CDR: Daily precipitation

- climate data record from multisatellite observations for hydrological and climate studies. *Bulletin of the American Meteorological Society*, 96(1): 69-83.
- Bamford, M.K. (1999). Permo-Triassic fossil woods from the South African karoo Basin. *Palaeontologia Africana*. Available online at: <http://wiredspace.wits.ac.za/handle/10539/16460>.
- Barnard, H.C. (2000). *An explanation of the 1: 500 000 general Hydrogeological map: Johannesburg 2526*. Department of Water Affairs and Forestry.
- Barton, E.S., Compston, W., Williams, I.S., Bristow, J.W., Hallbauer, D.K. and Smith, C.B. (1989). Provenance ages for the Witwatersrand Supergroup and the Ventersdorp contact reef; constraints from ion microprobe U-Pb ages of detrital zircons. *Economic Geology*, 84(7): 2012-19.
- Bates, B. C., Kundzewicz, Z. W., Wu, S., and Palutikof, J. P. (2008). *Climate change and Water Technical Paper of the Intergovernmental Panel on Climate Change*. Available online at: <https://www.ipcc.ch/publication/climate-change-and-water-2/>.
- Bhanja, S.N., Zhang, X. and Wang, J. (2018). Estimating long-term groundwater storage and its controlling factors in Alberta, Canada. *Hydrology & Earth System Sciences*. Available online at: <https://hess.copernicus.org/articles/22/6241/2018/>.
- Blamey, R.C., Kolusu, S.R., Mahlalela, P., Todd, M.C. and Reason, C.J.C. (2018). The role of regional circulation features in regulating El Niño climate impacts over southern Africa: A comparison of the 2015/2016 drought with previous events. *International Journal of Climatology*, 38(11): 4276-95.
- Brandl, G., Cloete, M. and Anhaeusser, C.R. (2006). Archaean greenstone belts. In: Johnson, M.R., Anhaeusser, C.R. and Thomas, R.J. (Eds), *The Geology of South Africa*. Geological Society of South Africa, Johannesburg/Council for Geoscience, Pretoria, 9-56.
- Bredenkamp, D.B., Botha, L.J., Van Tonder, G.J. and Van Rensburg, H.J. (1995). *Manual on quantitative estimation of groundwater recharge and aquifer*

*storativity: based on practical hydrological methods*. Pretoria: Water Research Commission.

Breña-Naranjo, J.A., Kendall, A.D. and Hyndman, D.W. (2014). Improved methods for satellite-based groundwater storage estimates: A decade of monitoring the high plains aquifer from space and ground observations. *Geophysical Research Letters*, 41(17): 6167-73.

Boergens, E., Güntner, A., Dobsław, H. and Dahle, C. (2020). Quantifying the Central European Droughts in 2018 and 2019 with GRACE-Follow-On. *Geophysical Research Letters*. Available online at <https://doi.org/10.1029/2020GL087285>.

Buttrick, D.B., Van Rooy, J.L. and Ligthelm, R. (1993). Environmental geological aspects of the dolomites of South Africa. *Journal of African Earth Sciences (and the Middle East)*, 16(1-2): 53-61.

Callaway, J. M. (2004). Assessing and linking the benefits and costs of adapting to climate variability and climate. In *The benefits of climate change policies* policies, OECD, Paris.

Callaway, J.M. (2004). The Benefits of Climate Change Policies: The Benefits and Costs of Adapting to Climate Variability and Climate Change. OECD.

Cheng, L., Xu, Z. X., Luo, R., and Mi, Y. J. (2009). SWAT application in arid and semi-arid region: A case study in the Kuye River Basin. *Geographical Research*, 28(1): 65-73

Clarke, R., Lawrence, A. and Foster, S. (1996). *Groundwater: A Threatened Resource*. Nairobi, Kenya: United Nations Environment Programme Environment.

Crow, C. and Condie, K.C. (1988). Geochemistry and origin of late Archean volcanics from the Ventersdorp Supergroup, South Africa. *Precambrian Research*, 42(1-2): 19-37.

Crowley, J.W., Mitrovica, J.X., Bailey, R.C., Tamisiea, M.E. and Davis, J.L. (2006). Land water storage within the Congo Basin inferred from GRACE satellite

gravity data. *Geophysical Research Letters*. Available online at: <https://dash.harvard.edu/handle/1/41401418>.

Da Silva, R.M., Santos, C.A., Moreira, M., Corte-Real, J., Silva, V.C. and Medeiros, I.C. (2015). Rainfall and river flow trends using Mann–Kendall and Sen's Slope Estimator statistical tests in the Cobres River Basin. *Natural Hazards*, 77(2): 1205-21.

Department of Water Affairs and Forestry. (2003a). Report No. P WMA 08/000/00/0203. *Upper Vaal Water management area: overview of water resources availability and utilisation*. Pretoria, South Africa.

Department of Water Affairs and Forestry. (2003b). Report No. P WMA09/000/00/0203, *Middle Vaal Water management area: overview of water resources availability and utilisation*. Pretoria, South Africa.

Department of Water Affairs and Forestry. (2005). Groundwater Resource Assessment Phase II - Component 3A - Groundwater recharge. GRA Phase II Project Report, Department of Water Affairs and Forestry, Pretoria.

Department of Water Affairs and Forestry. (2006). *A Guideline for the assessment, planning and management of groundwater resources within dolomitic Areas in South Africa*, vols 1–3. Department of Water Affairs and Forestry, Pretoria.

Devia, G. K., Ganasri, B. P., and Dwarakish, G. S. (2015). A review on hydrological models. *Aquatic Procedia*, 4: 1001-1007.

Dhami, B. S., and Pandey, A. (2013). Comparative review of recently developed hydrologic models. *J. Indian Water Resour. Soc*, 33(3): 34-41.

Dickey, J.O., Bentley, C.R., Bilham, R., Carton, J.A., Eanes, R.J., Herring, T.A., Kaula, W.M., Lagerloef, G.S., Rojstaczer, S., Smith, W.H. and van den Dool, H.M., Wahr, J.M. and Zuber, M.T. (1998). Satellite gravity: insights into the solid earth and its fluid envelope. *Eos, Transactions American Geophysical Union*, 79(20): 237-243.

- Dile, Y.T., Daggupati, P., George, C., Srinivasan, R. and Arnold, J. (2016). Introducing a new open source GIS user interface for the SWAT model. *Environmental Modelling & Software* 85: 129-38.
- Domenico, P. A. and Schwartz, F. W. (1990). *Physical and Chemical Hydrogeology*. New York, NY: Wiley.
- Douglas-Mankin, K. R., Srinivasan, R., and Arnold, J. G. (2010). *Soil and Water Assessment Tool (SWAT) model: Current developments and applications*. *Transactions of the ASABE*, 53(5): 1423-1431.
- Drápela, K. and Drápelová, I. (2011). 'Application of Mann-Kendall test and the Sen's slope estimates for trend detection in deposition data from Bílý Kříž (Beskydy Mts., the Czech Republic) 1997–2010', *Beskydy*, 4(2): 133-46.
- Dunn, C., Bertiger, W., Bar-Sever, Y., Desai, S., Haines, B., Kuang, D., Franklin, G., Harris, I., Kruizinga, G. and Meehan, T. (2003). Instrument of GRACE GPS augments gravity measurements. *GPS world*, 14(2): 16-29
- Duncan, A.R. (1987). The Karoo igneous province—a problem area for inferring tectonic setting from basalt geochemistry. *Journal of Volcanology and Geothermal Research*, 32(1-3): 13-34.
- Duncan, A.R. and Marsh, J.S. (2006). The Karoo igneous province. In Johnson, M.R., Anhaeusser, C.R. and Thomas, R.J. (Eds), *The Geology of South Africa, Johannesburg. Council for Geoscience, Pretoria*. pp: 501-520.
- Durand, J.F. (2012). The impact of gold mining on the Witwatersrand on the rivers and karst system of Gauteng and North West Province, South Africa. *Journal of African Earth Sciences*, 68: 24-43.
- Ericksson, P.G., Altermann, W. and Hartzler, F.J. (2006). The Transvaal Supergroup and its precursors. In Johnson, M.R., Anhaeusser C.R, and Thomas, R.J. (eds), *The Geology of South Africa, Johannesburg. Council for Geoscience, Pretoria*: 237-60.

- Eriksson, P.G. and Altermann, W. (1998). An overview of the geology of the Transvaal Supergroup dolomites (South Africa). *Environmental Geology*, 36(1-2): 179-88.
- Eriksson, P.G., Hattingh, P.J. and Altermann, W. (1995). An overview of the geology of the Transvaal Sequence and Bushveld Complex, South Africa. *Mineralium Deposita*, 30(2): 98-111.
- Famiglietti, J.S., Lo, M., Ho, S.L., Bethune, J., Anderson, K.J., Syed, T.H., Swenson, S.C., de Linage, C.R. and Rodell, M. (2011). Satellites measure recent rates of groundwater depletion in California's Central Valley. *Geophysical Research Letters*, . Available online at: <https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2010GL046442>
- Feng, W., Zhong, M., Lemoine, J.M., Biancale, R., Hsu, H.T. and Xia, J. (2013). Evaluation of groundwater depletion in North China using the Gravity Recovery and Climate Experiment (GRACE) data and ground-based measurements. *Water Resources Research*, 49(4): 2110-18.
- Fisher, R.S. and Mullican III, W.F. (1997). Hydrochemical evolution of sodium-sulfate and sodium-chloride groundwater beneath the northern Chihuahuan Desert, Trans-Pecos, Texas, USA. *Hydrogeology Journal*, 5(2): 4-16.
- Fitts, CR. (2002). Groundwater science. San Diego, California: Academic Press; 2002.
- Forootan, E. (2014). *Statistical signal decomposition techniques for analyzing time-variable satellite gravimetry data* (Unpublished Doctoral dissertation, Universitäts-und Landesbibliothek Bonn).
- Gilbert, R.O. (1987). Statistical Methods for Environmental Pollution Monitoring, Van Nostrand Reinhold, New York.
- Gocic, M. and Trajkovic, S. (2013). Analysis of changes in meteorological variables using Mann-Kendall and Sen's Slope Estimator statistical tests in Serbia. *Global and Planetary Change*, 100:172-82.

- Govender, M. and Everson, C.S. (2005). Modelling streamflow from two small South African experimental catchments using the SWAT model. *Hydrological Processes: An International Journal*, 19(3): 683-92.
- Gassman, P. W., Reyes, M. R., Green, C. H., and Arnold, J. G. (2007). The soil and water assessment tool: historical development, applications, and future research directions. *Transactions of the ASABE*, 50(4): 1211-1250.
- Gassman, P.W., Sadeghi, A.M. and Srinivasan, R. (2014). Applications of the SWAT model special section: overview and insights. *Journal of Environmental Quality*, 43(1): 1-8.
- Grippa, M., Kergoat, L., Frappart, F., Araud, Q., Boone, A., de Rosnay, P., Lemoine, J.M., Gascoin, S., Balsamo, G., Ottlé, C., Decharme, B., Saux-Picart, S., Ramillien, G., (2011). Land water storage variability over West Africa estimated by Gravity Recovery and Climate Experiment (GRACE) and land surface models. *Water Resour. Res.* 47 (5), W05549. <http://dx.doi.org/10.1029/2009WR008856>.
- Güler, C., Kurt, M.A., Alpaslan, M. and Akbulut, C. (2012). Assessment of the impact of anthropogenic activities on the groundwater hydrology and chemistry in Tarsus coastal plain (Mersin, SE Turkey) using fuzzy clustering, multivariate statistics and GIS techniques. *Journal of Hydrology*, 414:435-51.
- Güler, C., Thyne, G.D., McCray, J.E. and Turner, K.A. (2002). Evaluation of graphical and multivariate statistical methods for classification of water chemistry data. *Hydrogeology Journal*, 10(4):.455-74.
- Gupta, H.V., Sorooshian, S. and Yapo, P.O. (1999). Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration. *Journal of Hydrologic Engineering*, 4(2): 135-43.
- Hendriks MR. 2010. Introduction to physical hydrology. Oxford, Oxford University Press.
- Hirsch, R.M., Slack, J.R. and Smith, R.A. (1982). Techniques of trend analysis for monthly water quality data. *Water Resources Research*, 18(1):107-121.

- Hobbs, P., Colvin, C., Maherry, A., Bagan, R., S Clarke, S., Petersen, C., Rose, R. and Carstens, M. (2013). *The Vaal River Management Area* (WRC Project No. K8/969).
- Hobbs, P.J. and Cobbing, J.E. (2007). A hydrogeological assessment of acid mine drainage impacts in the West Rand Basin. *Report No. CSIR/THRIP, Gauteng Province, South Africa*.
- Holland, M. and Witthüser, K.T. (2009). Geochemical characterization of karst groundwater in the cradle of humankind world heritage site, South Africa. *Environmental Geology*, 57(3): 513-24.
- Huang, Z., Yeh, P.J.F., Pan, Y., Jiao, J.J., Gong, H., Li, X., Güntner, A., Zhu, Y., Zhang, C. and Zheng, L. (2019). Detection of large-scale groundwater storage variability over the karstic regions in Southwest China. *Journal of Hydrology*, 569, 409-422.
- Hughes, D.A. (2006). Comparison of satellite rainfall data with observations from gauging station networks. *Journal of Hydrology*, (327): 399-410.
- Humphrey W.A. (1910). *The Geology of the Valley of the Klip River. Report of the Geological Survey (Transvaal) for the year 1909. Union of South Africa Mines Department:91–97*.
- IPCC. *Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core writing team Pachauri, R.K. and Meyer L.A. (eds.)]. Geneva: IPCC, 2014*.
- Jalota, S.K., Vashisht, B.B., Sharma, S. and Kaur, S. (2018). *Understanding Climate Change Impacts on Crop Productivity and Water Balance*. Academic Press.
- Johnson, M.R., van Vuuren, C.J., Visser, J.N., Cole, D.I., Wickens, H.D.V., Christie, A.D., Roberts, D.L. and Brandl, G. (2006). *Sedimentary rocks of the Karoo Supergroup. In Johnson, M.R, Anhaeusser C.R, and Thomas, R.J (eds), The Geology of South Africa, Johannesburg. Council for Geoscience, Pretoria:461-499*.



- Johnson, M.R., Van Vuuren, C.J., Hegenberger, W.F., Key, R. and Show, U. (1996). Stratigraphy of the Karoo Supergroup in southern Africa: an overview. *Journal of African Earth Sciences*, 23(1): 3-15.
- Jolliffe, I. (2011). *Principal component analysis*. In: *International Encyclopedia of Statistical Science*. Springer, Berlin, pp 1094–1096.
- Jovanovic, N., Mu, Q., Bagan, R. D., and Zhao, M. (2015). Dynamics of MODIS evapotranspiration in South Africa. *Water SA*, 41(1): 79-90.
- Kafri, U. and Foster, M.B.J., (1989). Hydrogeology of the malmani dolomite in the Klip River and Natalspruit Basins, South Africa. *Environmental Geology and Water Sciences*, 13(2):153-66.
- Kaiser, H. F. (1959). Computer program for varimax rotation in factor analysis. *Educational and Psychological Measurement*, 19(3): 413-20.
- Kositcin, N. and Krapež, B. (2004). Relationship between detrital zircon age-spectra and the tectonic evolution of the Late Archaean Witwatersrand Basin, South Africa. *Precambrian Research*, 129(1-2): 141-168.
- Kusangaya, S., Warburton, M.L., Van Garderen, E.A. and Jewitt, G.P. (2014). Impacts of climate change on water resources in southern Africa: A review. *Physics and Chemistry of the Earth, Parts A/B/C*, 67:47-54.
- Kuss, A., Brandt, W.T., Randall, J., Floyd, B., Bourai, A., Newcomer, M., Schmidt, C. and Skiles, J.W. (2012). Comparison of changes in groundwater storage using GRACE data and a hydrological model in California's Central Valley. In *ASPRS Ann. Conf., Sacramento, CA*.
- Lakshmi, V. (2016). Beyond GRACE: Using satellite data for groundwater investigations. *Groundwater*, 54(5): 615-18.
- Landerer FW, and Swenson SC (2012). Accuracy of scaled GRACE terrestrial water storage estimates. *Water Resour. Res* 48, W04531, doi: 10.1029/2011WR011453 (2012).

- Lee, J., Kim, S. and Jun, H. (2018). A study of the influence of the spatial distribution of rain gauge networks on areal average rainfall calculation, *Water*, 10(11): 635.
- Lehohla, Pali. (2015). Census 2011: Population dynamics in South Africa, *Statistics South Africa*:1-112.
- Lepono, T., Du Preez, H.H. and Thokoa, M. (2003). Monitoring of water transfer from Katse Dam into the Upper Vaal river system: water utility's perspective. *Water Science and Technology*, 48(10): 97-102.
- Liu, X., Feng, X., Ciais, P. and Fu, B. (2020a). Widespread decline in terrestrial water storage and its link to teleconnections across Asia and eastern Europe. *Hydrology and Earth System Sciences*, 24(7): 3663-3676.
- Liu, W., Park, S., Bailey, R. T., Molina-Navarro, E., Andersen, H. E., Thodsen, H., Nielsen, A., Jeppesen, E., Jensen, J.S., Jensen, J.B. and Trolle, D. (2020b). Quantifying the streamflow response to groundwater abstractions for irrigation or drinking water at catchment scale using SWAT and SWAT–MODFLOW. *Environmental Sciences Europe*, 32(1): 1-25.
- Long, D., Longuevergne, L. and Scanlon, B.R. (2015). Global analysis of approaches for deriving total water storage changes from GRACE satellites. *Water Resources Research*, 51(4): 2574-94.
- Lundin, L.-C., Bergström, S., Eriksson, E. and Seibert, J. (1999). Hydrological models and modelling. L. Lundin (Ed.), *Sustainable Water Management in the Baltic Sea Basin*, The Baltic University Program, Uppsala, Sweden: 129-140.
- MacDonald, M.G., and Harbaugh, A.W. (1988). A modular three dimensional finite difference groundwater flow model. United States Geological Survey (USGS). Reston, Virginia.

- MacDonald, A.M., Bonsor, H.C., Dochartaigh, B.É.Ó. and Taylor, R.G. (2012). Quantitative maps of groundwater resources in Africa. *Environmental Research Letters*, 7(2). Available online at: [https://www.researchgate.net/publication/231116151\\_Quantitative\\_maps\\_of\\_groundwater\\_resources\\_in\\_Africa](https://www.researchgate.net/publication/231116151_Quantitative_maps_of_groundwater_resources_in_Africa).
- MacKellar, N., New, M., and Jack, C. (2014). Observed and modelled trends in rainfall and temperature for South Africa: 1960-2010. *South African Journal of Science*, 110(7-8): 1-13.
- Maggioni, V. and Massari, C. (Eds.). (2019). *Extreme Hydroclimatic Events and Multivariate Hazards in a Changing Environment: A Remote Sensing Approach*. Elsevier.
- Mahed, G., (2016). Gravimetry and its application to geohydrology: a review. *South African Journal of Geomatics*, 5(3): 301-12.
- Makapela, L., Newby, T., Gibson, L.A., Majozi, N., Mathieu, R., Ramoelo, A., Mengistu, M.G., Jewitt, G.P.W., Bulcock, H.H., Chetty, K.T. and Clark, D., (2015). Review of the use of Earth Observations Remote Sensing in Water Resource Management in South Africa. *Water Research Commission, Pretoria, Report KV329/15*.
- Mann, H. B. (1945). Non-parametric test against trend, *Econometrica*, 13,245–259.
- Mare, H. (2007). Review of surface hydrology in the Orange River catchment. *Centurion: ORASECOM/GiZ by WRP Consulting Engineers, Jeffares and Green, Sechaba Consulting, WCE Pty. Ltd. and Water Surveys Botswana Pty. Ltd. ORASECOM*.
- Marsh, J.S. (2006). The Dominion Group. In Johnson, M.R., Anhaeusser, C.R. and Thomas, R.J. (Eds). *The Geology of South Africa. Geological Society of South Africa, Johannesburg. Council for Geoscience, Pretoria*. pp: 149-154.

- Mason, T.R. and Christie, A.D.M. (1986). Palaeoenvironmental significance of ichnogenus *Diplocraterion* torell from the Permian vryheid formation of the Karoo Supergroup, South Africa. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 52(3-4): 249-265.
- Mason, T.R., Stanistreet, I.G. and Tavener-Smith, R. (1983). Spiral trace fossils from the Permian Eccra Group of Zululand. *Lethaia*, 16(4): 241-247.
- Masindi, K., and Abiye, T. (2018). Assessment of natural and anthropogenic influences on regional groundwater chemistry in a highly industrialized and urbanized region: a case study of the Vaal River Basin, South Africa. *Environmental earth sciences*, 77(20):1- 14.
- McCarthy, T. S. (1986). Post-Transvaal structural features of the northern portion of the Witwatersrand Basin. *Trans. Geol. Soc. S. Afr.*, 89, 311-323.
- McCarthy, T.S. (2006). The Witwatersrand Supergroup. In Johnson, M.R, Anhaeusser C.R, and Thomas, R.J (eds), *The Geology of South Africa*, Johannesburg. The Council for Geosciences. Pretoria:155-186.
- McCarthy, T.S. (2011). The impact of acid mine drainage in South Africa. *South African Journal of Science*, 107(5-6): 1-7.
- McNally, A., Arsenault, K., Kumar, S., Shukla, S., Peterson, P., Wang, S., Funk, C., Peters-Lidard, C.D. and Verdin, J.P. (2017). A land data assimilation system for sub-Saharan Africa food and water security applications. *Scientific Data*, 4(1):1-19.
- Meyer, R. (2005). Analysis of groundwater level time series and the relation to rainfall and recharge. WRC Report No. 1323/1/05. Water Research Commission, Pretoria.
- Moiwo, J.P., Yang, Y., Li, H., Han, S. and Hu, Y. (2009). Comparison of GRACE with in situ hydrological measurement data shows storage depletion in Hai River basin, Northern China. *Water SA* 35(5).

- Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D. and Veith, T.L., (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE*, 50(3): 885-900.
- Morris, B.L., Lawrence, A.R.L., Chilton, P.J.C., Adams, B., Calow, R.C., Klinck, B.A. (2003). *Groundwater and its susceptibility to degradation: A global assessment of the problem and options for management. Early warning and assessment report series, RS. 03-3. United Nations Environment Programme, Nairobi, Kenya.*
- Mu, Q., Heinsch, F.A., Zhao, M., and Running, S.W. (2007). Development of a global evapotranspiration algorithm based on MODIS and global meteorology data. *Remote sensing of Environment*, 111(4): 519-36.
- Mu, Q., Zhao, M., and Running, S.W. (2011). Improvements to a MODIS global terrestrial evapotranspiration algorithm. *Remote Sensing of Environment*, 115(8): 1781-1800.
- Naicker, K., Cukrowska, E., and McCarthy, T. S. (2003). Acid mine drainage arising from gold mining activity in Johannesburg, South Africa and environs. *Environmental pollution*, 122(1): 29-40.
- Nanteza, J., De Linage, C.R., Thomas, B.F. and Famiglietti, J.S. (2016). Monitoring groundwater storage changes in complex basement aquifers: An evaluation of the GRACE satellites over East Africa. *Water Resources Research*, 52(12): 9542-64.
- Nash, J.E. and Sutcliffe, J.V. (1970). River flow forecasting through conceptual models part I—A discussion of principles. *Journal of Hydrology*, 10(3): 282-90.
- National Water Resource Strategy, 2nd Edition. (2013). Accessed from: <https://cer.org.za/wp-content/uploads/2013/07/NWRS2-Final-email-version.pdf>.

- Narsimlu, B., Gosain, A. K., and Chahar, B. R. (2013). Assessment of future climate change impacts on water resources of Upper Sind River Basin, India using SWAT model. *Water resources management*, 27(10): 3647-3662.
- Ncube E.J. and Schutte, C.F. (2004). The occurrence of fluoride in South African groundwater: A water quality and health problem. *Water SA*, 31(1): 35-40.
- Ndehedehe, C.E., Awange, J.L., Kuhn, M., Agutu, N.O. and Fukuda, Y. (2017). Analysis of hydrological variability over the Volta river basin using in-situ data and satellite observations. *Journal of Hydrology: Regional Studies*, 12: 88-110.
- Ndlovu, M.S. and Demlie, M. (2018). Statistical analysis of groundwater level variability across KwaZulu-Natal Province, South Africa. *Environmental Earth Sciences*, 77(21): 739.
- Neitsch, S.L., Arnold, J.G., Kiniry, J.R. and Williams, J.R. (2011). *Soil and water assessment tool theoretical documentation version 2009*. Texas Water Resources Institute.
- Nengovhela, A. C., Yibas, B., and Ogola, J. S. (2006). Characterisation of gold tailings dams of the Witwatersrand Basin with reference to their acid mine drainage potential, Johannesburg, South Africa. *Water SA*, 32(4).
- Ngubane, Z. (2017). *Catchment Hydrological Modelling Using ArcSWAT: A Study of the Ingula Pumped Storage Scheme (IPSS) Catchments, South Africa* (Unpublished Doctoral dissertation, University of KwaZulu-Natal, Westville).
- Nguyen, V. T., and Dietrich, J. (2018). Modification of the SWAT model to simulate regional groundwater flow using a multicell aquifer. *Hydrological processes*, 32(7): 939-953.
- Ojha, C., Werth, S. and Shirzaei, M., (2020). Recovery of aquifer-systems in Southwest US following 2012-2015 drought: evidence from InSAR, GRACE and groundwater level data. *Journal of Hydrology*. Available online at <https://doi.org/10.1016/j.jhydrol.2020.124943>.

- Oki, T. and Kanae, S. (2006). Global hydrological cycles and world water resources. *Science*, 313(5790): 1068–1072.
- Partridge, T.C., Botha, G.A. and Haddon, I.G. (2006). Cenozoic Deposits of the Interior. In Johnson, M.R., Anhaeusser, C.R. and Thomas, R.J. (Eds). *The Geology of South Africa*. Geological Society of South Africa, Johannesburg/Council for Geoscience, Pretoria: 585-604.
- Piper, A.M. (1944). A graphic procedure in the geochemical interpretation of water-analyses. *Eos, Transactions American Geophysical Union*, 25(6):914-28.
- Pitman, W. (2011). Overview of water resource assessment in South Africa: Current state and future challenges. *Water SA*, 37, 659–664.
- Pretorius, D.A., (1976). The nature of the Witwatersrand gold-uranium deposits, ch. 2. In *Handbook of strata-bound and stratiform ore deposits; section 2., regional studies and specific deposits*.
- Ragab, R. and Prudhomme, C. (2002). Sw—soil and Water: climate change and water resources management in arid and semi-arid regions: Prospectives and challenges for the 21st century. *Biosystems engineering*, 81(1): 3-34.
- Rahman, K., Maringanti, C., Beniston, M., Widmer, F., Abbaspour, K., and Lehmann, A. (2013). Streamflow modeling in a highly managed mountainous glacier watershed using SWAT: the Upper Rhone River watershed case in Switzerland. *Water resources management*, 27(2): 323-339.
- Reager, J.T. and Famiglietti, J.S. (2009). Global terrestrial water storage capacity and flood potential using GRACE. *Geophysical Research Letters*. Available online at: <https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2009GL040826>.
- Robb, L.J. and Meyer, F.M. (1995). The Witwatersrand Basin, South Africa: Geological framework and mineralization processes. *Ore Geology Reviews*, 10(2): 67-94.
- Robinson, M. and Ward, R., (1990). *Principles of hydrology*. McGraw-Hill, England.

- Rodell, M. and Famiglietti, J.S. (1999). Detectability of variations in continental water storage from satellite observations of the time dependent gravity field. *Water Resources Research*, 35(9): 2705-23.
- Rodell, M. and Famiglietti, J.S. (2001). An analysis of terrestrial water storage variations in Illinois with implications for the Gravity Recovery and Climate Experiment (GRACE). *Water Resources Research*, 37(5): 1327-39.
- Rodell, M., Chen, J., Kato, H., Famiglietti, J.S., Nigro, J. and Wilson, C.R. (2007). Estimating groundwater storage changes in the Mississippi River basin (USA) using GRACE. *Hydrogeology Journal*, 15(1):159-66.
- Rodell, M., Velicogna, I. and Famiglietti, J.S. (2009). Satellite-based estimates of groundwater depletion in India. *Nature*, 460(7258): 999-1002.
- Republic of South Africa [RSA]. (1998) South African National Water Act, Act No. 36 of 1998. *Government Gazette*. Volume 398. Cape Town.
- South African Committee for Stratigraphy [SACS]. (1980). *Stratigraphy of South Africa, Part 1: Lithostratigraphy of the Republic of South Africa, South West Africa/ Namibia and the Republics of Bophuthatswana, Transkei and Venda*. Handbook Geological. Survey of South Africa: 8, 690.
- Salmi, T., Maata, A., Antilla, P., Ruoho Airola, T. and Amnell, T. (2002). *Detecting trends of annual values of atmospheric pollutants by the Mann–Kendall test and Sen’s slope*. Finnish Meteorological Institute, Helsinki. Report code: FMI-AQ-31:36.
- Scanlon, B.R., Longuevergne, L. and Long, D. (2012). Ground referencing GRACE satellite estimates of groundwater storage changes in the California Central Valley, USA. *Water Resources Research*, 48(4):
- Schmidt, R., Schwintzer, P., Flechtner, F., Reigber, C., Güntner, A., Döll, P., Ramillien, G., Cazenave, A., Petrovic, S., Jochmann, H. and Wünsch, J. (2006). GRACE observations of changes in continental water storage. *Global and Planetary Change*, 50(1-2): 112-26.



- Schoeller, H. (1965). Qualitative evaluation of groundwater resources. *Methods and techniques of groundwater investigations and development*. UNESCO, 5483.
- Sen, P.K. (1968). Estimates of the regression coefficient based on Kendall's tau. *Journal of the American Statistical Association*, 63(324):1379-89.
- Sharma, M.L. (1986). Measurement and prediction of natural groundwater recharge an overview. *Journal of Hydrology*, 25:86–94.
- Shiklomanov, I.A. (1993). World fresh water resources, in *Water in Crisis: A Guide to the World's Fresh Water Resources*. Edited by P.H. Gleick, P.H. Oxford Univ. Press, New York:13-24.
- Siderius, C., Gannon, K.E., Ndiyoi, M., Opere, A., Batisani, N., Olago, D., Pardoe, J. and Conway, D. (2018). Hydrological response and complex impact pathways of the 2015/2016 El Niño in Eastern and Southern Africa. *Earth's Future*, 6(1): 2-22.
- Singh, V.P. and Chowdhury, P.K. (1986). Comparing some methods of estimating mean areal rainfall. *Journal of the American Water Resources Association*, 22(2): 275-82.
- Sishodia, R. P., Shukla, S., Graham, W. D., Wani, S. P., and Garg, K. K. (2016). Bi-decadal groundwater level trends in a semi-arid south indian region: Declines, causes and management. *Journal of Hydrology: Regional Studies*, 8, 43-58.
- Swart, C., Stoch, E., van Jaarsveld, C. and Brink, A. (2003). The lower Wonderfontein Spruit: An exposé. *Environmental Geology*, 43(6): 635-53.
- Swenson, S. and Wahr, J. (2002). Methods for inferring regional surface-mass anomalies from Gravity Recovery and Climate Experiment (GRACE) measurements of time-variable gravity. *Journal of Geophysical Research: Solid Earth*, 107(B9): ETG-3.

- Swenson, S., Wahr, J. and Milly, P.C.D. (2003). Estimated accuracies of regional water storage variations inferred from the Gravity Recovery and Climate Experiment (GRACE). *Water Resources Research*, 39(8).
- Syed, T.H., Famiglietti, J.S., Rodell, M., Chen, J. and Wilson, C.R. (2008). Analysis of terrestrial water storage changes from GRACE and GLDA. *Water Resources Research*, 44(2).
- Thavhana, M.P., Savage, M.J. and Moeletsi, M.E. (2018). SWAT model uncertainty analysis, calibration and validation for runoff simulation in the Luvuvhu River catchment, South Africa. *Physics and Chemistry of the Earth, Parts A/B/C*, 105: 115-24.
- Todd, D.K. and Mays, L.W. (2005). Groundwater hydrology edition. *Welly Inte*, 891.
- Tutu, H., McCarthy, T. S., and Cukrowska, E. (2008). The chemical characteristics of acid mine drainage with particular reference to sources, distribution and remediation: The Witwatersrand Basin, South Africa as a case study. *Applied Geochemistry*, 23(12): 3666-3684.
- van der Westhuizen, W.A. and De Bruijn, H. (2000). High temperys ature ash flow–wet sediment interaction in the Makwassie Formation, Ventersdorp Supergroup, South Africa. *Precambrian Research*, 101(2-4): 341-51.
- van der Westhuizen, W.A., De Bruijn, H. and Meintjes, P.G. (1991). The Ventersdorp supergroup: An overview. *Journal of African Earth Sciences (and the Middle East)*, 13(1): 83-105.
- van Tonder, G. (1999). Groundwater management under the new National Water Act in South Africa. *Hydrogeology Journal*, 7(5): 421-22.
- van Vuuren, L. (2008). Start saving or start paying, river studies warn. *Water Wheel*, 7(3): 15.
- Vegter, J.R., (1995). Groundwater resources of the Republic of South Africa: an explanation of a set of national groundwater maps. *Water Research Commission report no. TT/74/95, August, Pretoria*.

- Vegter, J.R. (2001). *Groundwater Development in South Africa and an Introduction to the Hydrogeology of Groundwater Regions: Prepared for the Water Research Commission*. Pretoria, South Africa Water Research Commission.
- Vörösmarty, C. J., Green, P., Salisbury, J., and Lammers, R. B. (2000). Global water resources: vulnerability from climate change and population growth. *Science*, 289(5477): 284-288.
- Voss, K.A., Famiglietti, J.S., Lo, M., De Linage, C., Rodell, M. and Swenson, S.C. (2013). Groundwater depletion in the Middle East from GRACE with implications for transboundary water management in the Tigris-Euphrates-Western Iran region. *Water Resources Research*, 49(2): 904-14.
- Wahr, J., Molenaar, M. and Bryan, F. (1998). Time variability of the Earth's gravity field: Hydrological and oceanic effects and their possible detection using GRACE. *Journal of Geophysical Research: Solid Earth*, 103(B12): 30205-229.
- Wahr, J., Swenson, S., Zlotnicki, V. and Velicogna, I. (2004). Time-variable gravity from GRACE: First results. *Geophysical Research Letters*, 31(11).
- Wahr, J., Swenson, S., and Velicogna, I. (2006). Accuracy of GRACE mass estimates. *Geophysical Research Letters*, 33(6).
- Wang, X., de Linage, C., Famiglietti, J. and Zender, C.S. (2011). Gravity Recovery and Climate Experiment (GRACE) detection of water storage changes in the Three Gorges Reservoir of China and comparison with in situ measurements. *Water Resources Research*, 47(12).
- Wang, H., Sun, F., Xia, J., and Liu, W. (2017). Impact of LUCC on streamflow based on the SWAT model over the Wei River basin on the Loess Plateau in China. *Hydrology and Earth System Sciences*, 21(4): 1929-1945.
- Weber, K. and Stewart, M. (2004). A critical analysis of the cumulative rainfall departure concept, *Ground Water*, 42(6/7): 935.

- Wheater, H. S. (2010). Hydrological processes, groundwater recharge and surface-water/groundwater interactions in arid and semi-arid areas. *Groundwater Modeling in Arid and Semi-Arid Areas, 1st ed.*; Cambridge University Press: Cambridge, UK: 5-37.
- Wentzel, L.K. (1936). Several methods of studying of groundwater levels. *Transactions of the American Geophysical Union*, 17.
- World Health Organisation [WHO]. (2004). *Guidelines for drinking water quality. Vol 1 recommendations*, 3rd ed. WHO, Geneva: 540.
- Winsemius, H.C., Savenije, H.H.G., Van De Giesen, N.C., Van Den Hurk, B.J.J.M., Zapreeva, E.A. and Klees, R. (2006). Assessment of Gravity Recovery and Climate Experiment (GRACE) temporal signature over the upper Zambezi. *Water Resources Research*, 42(12).
- Winter, H. de la R. (1976). A lithostratigraphic classification of the Ventersdorp succession. *Transactions of the. Geological Society of South Africa*, 79: 31-48.
- Winter, T.C. (1999). Relation of streams, lakes, and wetlands to groundwater flow systems. *Hydrogeology Journal*, 7(1): 28-45.
- Winter, T.C. (2001). The concept of hydrologic landscapes 1. *Journal of the American Water Resources Association*, 37(2): 335-49.
- Woodford, A., Rosewarne, R. and Girman, J. (2006). How much groundwater does South Africa have? [http://www.srk.co.uk/groundwater/PDFs/1\\_A\\_Woodford.pdf](http://www.srk.co.uk/groundwater/PDFs/1_A_Woodford.pdf).
- Xu, Y. and Beekman, H.E. (eds.) (2003). Groundwater recharge estimation in Southern Africa.
- Xu, Y. and Van Tonder, G.J. (2001). Estimation of recharge using a revised CRD method. *Water SA*, 27(3): 341-43.

- Yetemen, O., Istanbuluoglu, E. and Vivoni, E.R. (2010). 'The implications of geology, soils, and vegetation on landscape morphology: Inferences from semi-arid basins with complex vegetation patterns in Central New Mexico, USA', *Geomorphology*, 116(3-4): 246-63.
- Yue, S. and Hashino, M. (2003). Long term trends of annual and monthly precipitation in Japan 1. *JAWRA Journal of the American Water Resources Association*, 39(3): 587-596.

## APPENDICES

### A. List of the rain gauges used in the spatial interpolation of rainfall in the study site

| Station Name | Latitude (°) | Longitude (°) | MAP        | Source | Station Name2                  | Latitude3 (°) | Longitude4 (°) | MAP5       | Source6 |
|--------------|--------------|---------------|------------|--------|--------------------------------|---------------|----------------|------------|---------|
| C1E001       | -26.88439    | 28.11081      | 675.064    | DWS    | Bethlehem Wo - 03315859        | -28.249       | 28.334         | 703.039474 | SAWS    |
| C1E002       | -26.47503    | 29.94667      | 718.353061 | DWS    | Bloemhof - 03621897            | -27.651       | 25.621         | 443.066667 | SAWS    |
| C1E007       | -26.90256    | 29.29033      | 782.386842 | DWS    | Ermelo Wo - 0479870X           | -26.497       | 29.983         | 711.879167 | SAWS    |
| C2E001       | -26.76272    | 27.68292      | 702.403448 | DWS    | Frankfort - Tnk-0403886A0      | -27.267       | 28.494         | 667.813158 | SAWS    |
| C2E004       | -26.73377    | 27.08297      | 640.17541  | DWS    | Jhb Bot Tuine - 04758790       | -26.156       | 27.999         | 652.809375 | SAWS    |
| C2E007       | -26.30083    | 27.81381      | 684.613559 | DWS    | Johannesburg Int Wo - 04763990 | -26.143       | 28.234         | 737.037931 | SAWS    |
| C2E009       | -26.57133    | 27.118        | 602.559184 | DWS    | Kimberely Wo - 0290468A9       | -28.8         | 24.767         | 401.471053 | SAWS    |
| C2E010       | -27.40694    | 26.50416      | 520.22449  | DWS    | Standerton - 0441416B5         | -26.93        | 29.23          | 566.251852 | SAWS    |
| C2E015       | -26.61653    | 27.29192      | 657.375    | DWS    | Taung - 0360453A0              | -27.55        | 24.767         | 452.6875   | SAWS    |
| C2E016       | -26.35147    | 26.77528      | 621.654762 | DWS    | Vereeniging - 04387843         | -26.569       | 27.958         | 640.115385 | SAWS    |
| C2E017       | -26.41678    | 26.79633      | 597.028571 | DWS    | Vrede - 0405326A9              | -27.422       | 29.169         | 489.24     | SAWS    |
| C2E018       | -26.24575    | 27.16208      | 523.516667 | DWS    | Vryburg - 04322373             | -26.954       | 24.652         | 462.418421 | SAWS    |
| C3E012       | -28.12541    | 24.50375      | 428.221951 | DWS    | Welkom - 03643001              | -27.994       | 26.666         | 396.97037  | SAWS    |
| C3E013       | -27.17658    | 25.331        | 546.3      | DWS    | 19827                          | -26.7333336   | 27.08333397    | 622.01     | ARC-SCW |
| C3E014       | -27.53906    | 24.8507       | 451.652174 | DWS    | 19868                          | -26.79157     | 26.9685        | 618.967327 | ARC-SCW |
| C4E002       | -28.50136    | 26.77551      | 519.847541 | DWS    | 19866                          | -28.3142      | 28.70859       | 732.704762 | ARC-SCW |
| C4E008       | -28.29111    | 27.14361      | 577.091228 | DWS    | 19869                          | -26.78983     | 26.99633       | 587.583607 | ARC-SCW |
| C4E009       | -28.10079    | 26.45158      | 507.8125   | DWS    | 19898                          | -26.56142     | 27.13528       | 554.336667 | ARC-SCW |
| C6E004       | -27.67545    | 27.24966      | 611.69375  | DWS    | 30459                          | -26.07512     | 28.39705       | 609.339    | ARC-SCW |
| C7E001       | -27.24694    | 27.66861      | 616.907843 | DWS    |                                |               |                |            |         |
| C8E003       | -28.16709    | 28.29969      | 669.989655 | DWS    |                                |               |                |            |         |
| C8E007       | -28.31291    | 28.70804      | 729.325    | DWS    |                                |               |                |            |         |
| C8E008       | -28.38791    | 29.01638      | 705.775556 | DWS    |                                |               |                |            |         |
| C8E010       | -28.41152    | 29.04277      | 579.373077 | DWS    |                                |               |                |            |         |
| C9E003       | -28.10875    | 24.94126      | 490.461429 | DWS    |                                |               |                |            |         |
| C9E004       | -27.67128    | 25.61628      | 491.770833 | DWS    |                                |               |                |            |         |

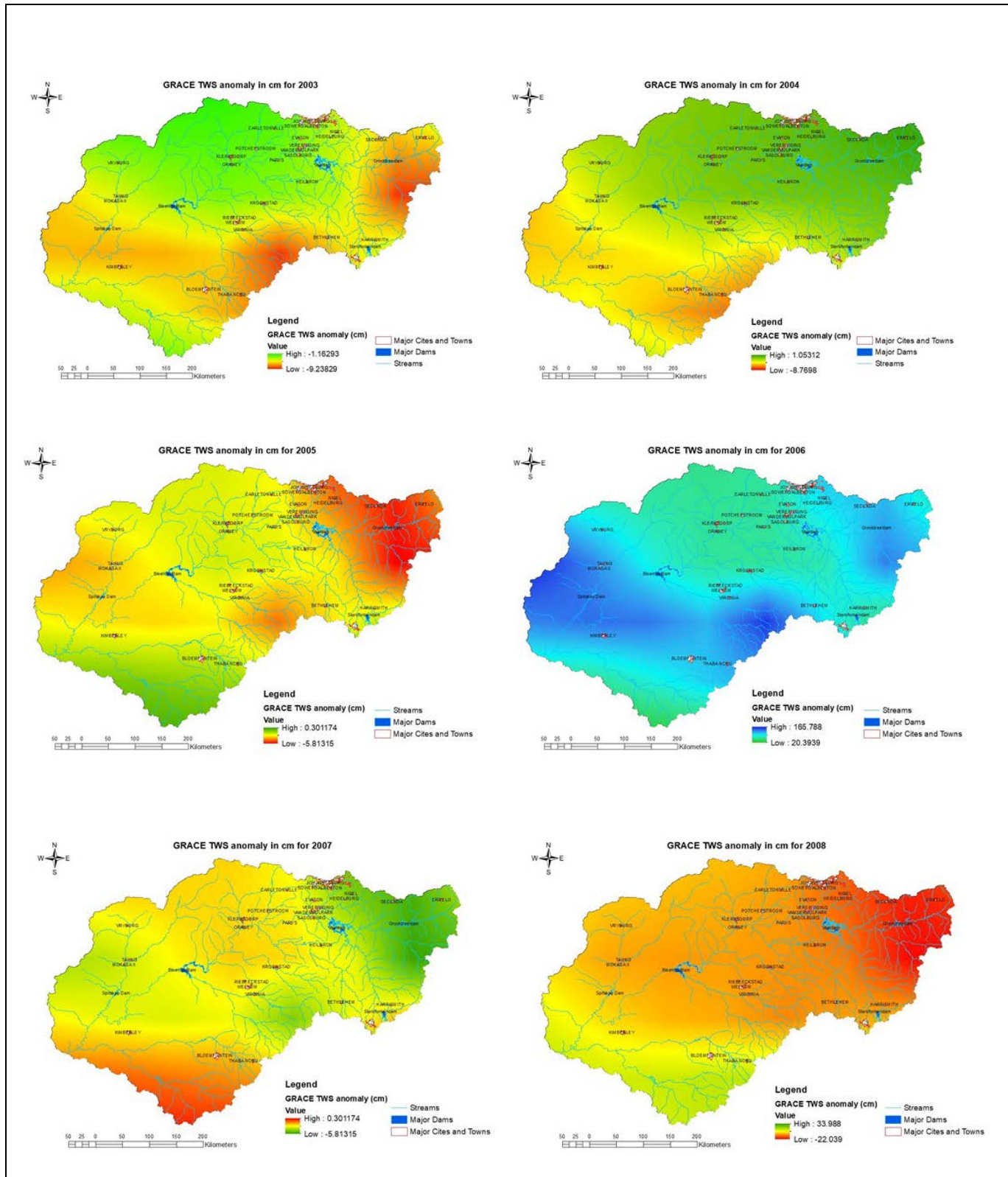
## B. Temperature data used in the spatial interpolation

| Station Name                   | Latitude (°) | Longitude (°) | Tmin (°C) | Tmax (°C) | Tavg (°C) |
|--------------------------------|--------------|---------------|-----------|-----------|-----------|
| Bethlehem Wo - 03315859        | -28.249      | 28.334        | 6.479588  | 22.26814  | 14.37386  |
| Bloemhof - 03621897            | -27.651      | 25.621        | 9.83114   | 26.83625  | 18.3337   |
| Ermelo Wo - 0479870X           | -26.497      | 29.983        | 9.072853  | 21.62397  | 15.34841  |
| Frankfort - Tnk-0403886A0      | -27.267      | 28.494        | 6.714211  | 24.37262  | 15.54341  |
| Jhb Bot Tuine -04758790        | -26.156      | 27.999        | 9.514096  | 23.16959  | 16.34184  |
| Johannesburg Int Wo - 04763990 | -26.143      | 28.234        | 10.04081  | 22.46573  | 16.25327  |
| Kimberely Wo - 0290468A9       | -28.8        | 24.767        | 10.1421   | 26.64927  | 18.39568  |
| Standerton - 0441416B5         | -26.93       | 29.23         | 7.453215  | 23.25051  | 15.35186  |
| Taung - 0360453A0              | -27.55       | 24.767        | 10.95226  | 28.02566  | 19.48896  |
| Vereeniging - 04387843         | -26.569      | 27.958        | 9.120505  | 24.74131  | 16.93091  |
| Vrede - 0405326A9              | -27.422      | 29.169        | 7.506034  | 23.05491  | 15.28047  |
| Vryburg - 04322373             | -26.954      | 24.652        | 9.407583  | 27.40872  | 18.40815  |
| Welkom - 03643001              | -27.994      | 26.666        | 10.37737  | 26.18205  | 18.27971  |
| 19827                          | -26.73333    | 27.083334     | 9.127407  | 25.25143  | 17.18942  |
| 19868                          | -26.79157    | 26.9685       | 9.602045  | 25.78443  | 17.69324  |
| 19866                          | -28.3142     | 28.70859      | 6.75734   | 22.03386  | 14.3956   |
| 19869                          | -26.78983    | 26.99633      | 10.01859  | 25.62308  | 17.82083  |
| 19898                          | -26.56142    | 27.13528      | 9.973361  | 25.15439  | 17.56388  |
| 30459                          | -26.07512    | 28.39705      | 9.132165  | 23.52467  | 16.31092  |

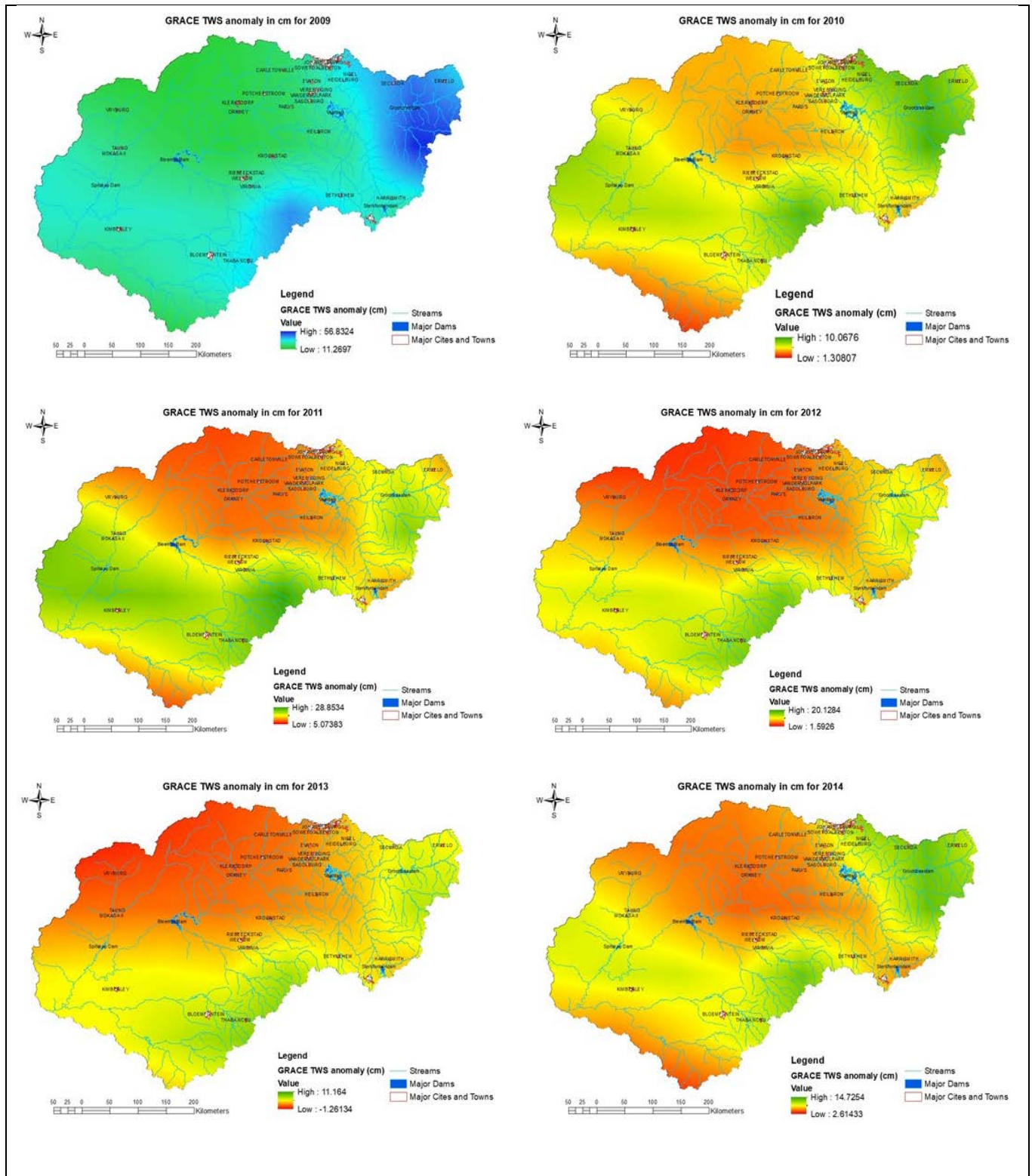
## C. Evaporation in mm used in the spatial interpolation

| Station Name | Latitude (°) | Longitude (°) | Evaporation in mm |
|--------------|--------------|---------------|-------------------|
| 19827        | -26.7333     | 27.08333      | 2118.603          |
| 19868        | -26.7916     | 26.9685       | 1914.942          |
| 19869        | -26.7898     | 26.99633      | 1935.509          |
| C1E001       | -26.8844     | 28.11081      | 1643.101          |
| C1E002       | -26.475      | 29.94667      | 1417.804          |
| C1E007       | -26.9026     | 29.29033      | 1908.276          |
| C2E001       | -26.7627     | 27.68292      | 1496.044          |
| C2E004       | -26.7338     | 27.08297      | 1657.278          |
| C2E007       | -26.3008     | 27.81381      | 1472.72           |
| C2E009       | -26.5713     | 27.118        | 1676.716          |
| C2E010       | -27.4069     | 26.50416      | 1960.667          |
| C2E015       | -26.6165     | 27.29192      | 1854.78           |
| C2E016       | -26.3515     | 26.77528      | 1856.929          |
| C2E017       | -26.4168     | 26.79633      | 1867.45           |
| C2E018       | -26.2458     | 27.16208      | 1336.274          |
| C3E012       | -28.1254     | 24.50375      | 2143.139          |
| C3E013       | -27.1766     | 25.331        | 1906.048          |
| C3E014       | -27.5391     | 24.8507       | 1949.922          |
| C4E002       | -28.5014     | 26.77551      | 1970.69           |
| C4E008       | -28.2911     | 27.14361      | 1861.128          |
| C4E009       | -28.1008     | 26.45158      | 2161.897          |
| C6E004       | -27.6755     | 27.24966      | 2099.816          |
| C7E001       | -27.2469     | 27.66861      | 1869.373          |
| C8E003       | -28.1671     | 28.29969      | 1488.585          |
| C8E007       | -28.3129     | 28.70804      | 1625.756          |
| C8E008       | -28.3879     | 29.01638      | 1785.471          |
| C8E010       | -28.4115     | 29.04277      | 1693.088          |
| C9E003       | -28.1088     | 24.94126      | 2004.824          |
| C9E004       | -27.6713     | 25.61628      | 1912.09           |

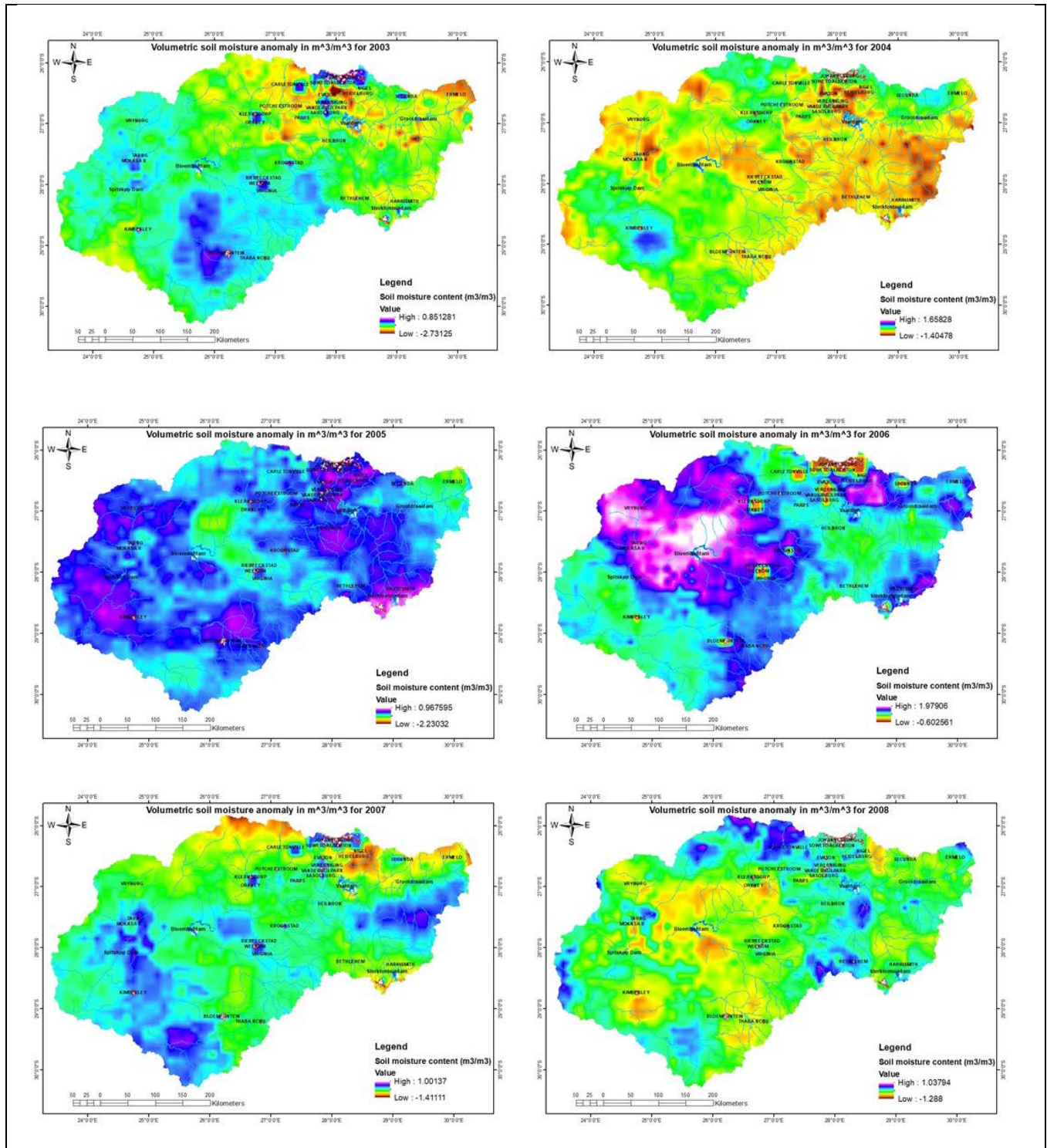
# D. GRACE terrestrial water storage anomaly yearly maps from 2003 to 2014



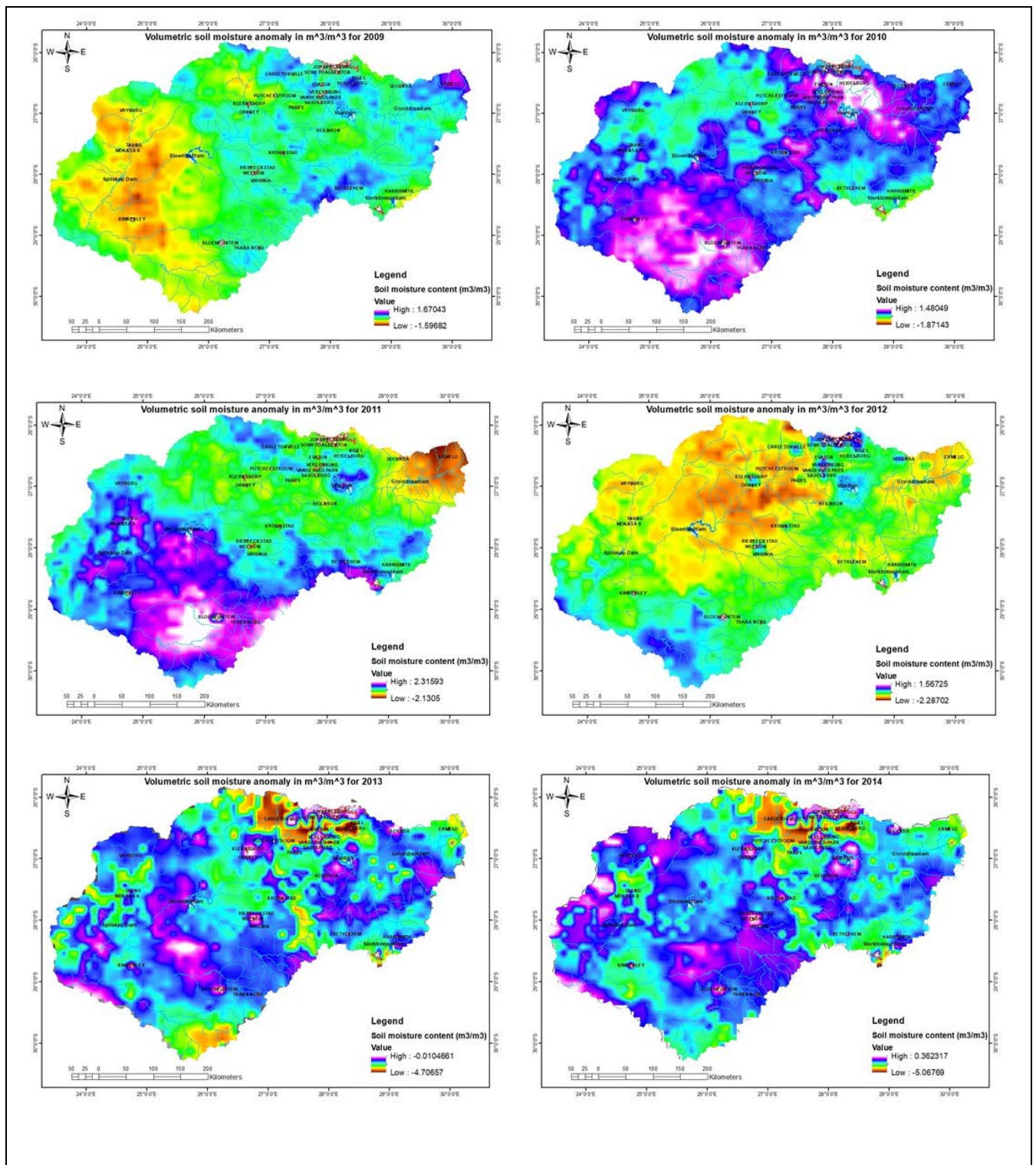




# E. Soil moisture anomaly yearly maps from 2003 to 2014







F. Publication – Journal of Environmental Earth Sciences

Masindi, K. and Abiye, T., 2018. Assessment of natural and anthropogenic influences on regional groundwater chemistry in a highly industrialized and urbanized region: a case study of the Vaal River Basin, South Africa. *Environmental Earth Sciences*, 77(20): 1-14.7



## Assessment of natural and anthropogenic influences on regional groundwater chemistry in a highly industrialized and urbanized region: a case study of the Vaal River Basin, South Africa

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### Abstract

The Vaal River Basin is an economically significant area situated in the interior of South Africa (SA), where mining, industrial, domestic and agricultural activities are very intense. The purpose of the study was to assess the influence of geology and anthropogenic activities on groundwater chemistry, and identify the predominant hydrochemical processes in the basin. Data from seventy groundwater sites were retrieved from the national database, and attention was paid to fifteen water quality parameters. Groundwater samples were clustered into seven hydrochemically distinct groups using Hierarchical Cluster Analysis (HCA), and three samples treated independently. A Piper plot revealed two major water types, Ca–Mg–HCO<sub>3</sub> and Ca–Mg–SO<sub>4</sub>–Cl, which were linked to dissolution of the underlying geology and mine pollution. The Ca + Mg vs HCO<sub>3</sub> + SO<sub>4</sub> plot indicated that reverse ion exchange is an active process than cation exchange in the area. Principal component analysis (PCA) was used to identify the main natural and anthropogenic processes causing variation in groundwater chemistry. Four principal components were extracted using PCA that explains 82% of the total variance in the chemical parameters. The PCA results can be categorized by four components: (1) evaporites and silicates weathering enrichment of Na, K, Cl, SO<sub>4</sub> and F, and anthropogenic Cl; (2) dissolution of dolomite, limestone and gypsum; (3) agricultural fertilizers (4) wastewater treatment. This study reveals that both natural and anthropogenic activities are the cause of groundwater variation in the basin.

**Keywords** Principal component analysis · Hierarchical cluster analysis · Groundwater · Vaal River Basin

### Introduction

The arid and semi-arid regions of the world generally rely on groundwater resources as the main source of dependable water supply because of low rainfall and the limited occurrence of surface water bodies. As rainfall in many of these regions is likely to decline because of global climate change and due to a fast growing population, groundwater dependency in these regions is likely to increase (Arnell 1999; Vörösmarty et al. 2000; Green et al. 2011). The availability of sufficient good quality groundwater is important in meeting agricultural, domestic and industrial demand to ensure food security and improve livelihoods (Calow et al.

2010; Green et al. 2011; Taylor et al. 2013). Understanding of the groundwater chemistry is important in regions experiencing increasing groundwater use driven by rapid urbanization and industrialization, which threatens both the water quality and quantity.

Across the world, land use practices have been found to impact groundwater resources. In China, Qin et al. (2013) and Huang et al. (2018) found that agricultural activities and urbanization were the cause of high nitrate concentration in groundwater in the Liaohe River Plain and Pearl River Delta, respectively. Silicate weathering, simple dissolution and evaporation were identified as the predominant hydrochemical process in Delhi, India (Kumar et al. 2006). Güler et al. (2012) reported the influence of both anthropogenic activities and natural process on groundwater in Tarsus Coastal Plain, Turkey.

Conventional and multivariate techniques namely, Hierarchical Cluster Analysis (HCA) and Principal Component Analysis (PCA) have been widely used in groundwater chemistry investigations, for instance, in Algeria (Belkhiri

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et al. 2010), China (Qian et al. 2016), Ghana (Yidana et al. 2018), South Africa (Adams et al. 2001), and Nigeria (Okiongbo and Douglas 2015). According to Dalton and Upchurch (1978) conventional techniques such as the use of Piper (Piper 1944), Durov and Schoeller plots are limited to assessing the composition of major ions in groundwater and excludes minor constituents for instance, nitrate and fluoride that when present in elevated levels could have adverse effect on human health (Güler et al. 2002; Ncube and Shutte 2005). In contrast, PCA and HCA are capable of handling and analysing all water parameters in an analytical suite through data reduction and classification (Dalton and Upchurch 1978; Suk and Lee 1999; Güler et al. 2002). HCA provides a way for the classification of large datasets based on the level of similarity of parameters and results are presented in the form of a dendrogram. Although, the classes produced by this analysis are subjective, they can often be linked to same geological source or/and land use practices. On the other hand PCA, a data reduction technique, is useful in revealing principal components that explains the variation in the water chemistry data (Usunoff and Guzmán-Guzmán 1989; Suk and Lee 1999; Furi et al. 2012). Interpretations are based on the extracted components loading that show the relationships between the chemical parameters. The causation of these relationships are inferred in order understand

the hydrochemical processes and factors controlling groundwater chemistry.

The Vaal River Catchment (VRB) is a densely urbanized and industrialized region (Fig. 1) with the highest density of mining activities situated in the interior of South Africa (Braune and Rogers 1987). It is regarded as the economic hub of South Africa (SA), contributing more than 25% of the GDP (DWA 2003a, b). Anthropogenic activities such as industrial effluent discharge and mining activities have among other things caused the deterioration of surface water quality rendering it unfit for use (Braune and Rogers 1987). Nonetheless, increasing water demands driven by growing population and economic expansion, and the recurrence of drought has put pressure on surface water supply in the region (Rouault and Richard 2005; Wepener et al. 2011). As a consequence of these factors, groundwater has received attention as an alternative to surface water supply, particularly during drought conditions.

Presently, the main user of groundwater in the region is the agricultural sector and to a lesser extent the urban centres, particularly in the southwestern part of the basin (DWA 2003b). Small towns situated in the drier northwestern and southwestern parts of the VRB also rely on groundwater for domestic water use. Braune and Rogers (1987) recognized the need for groundwater development in the region to

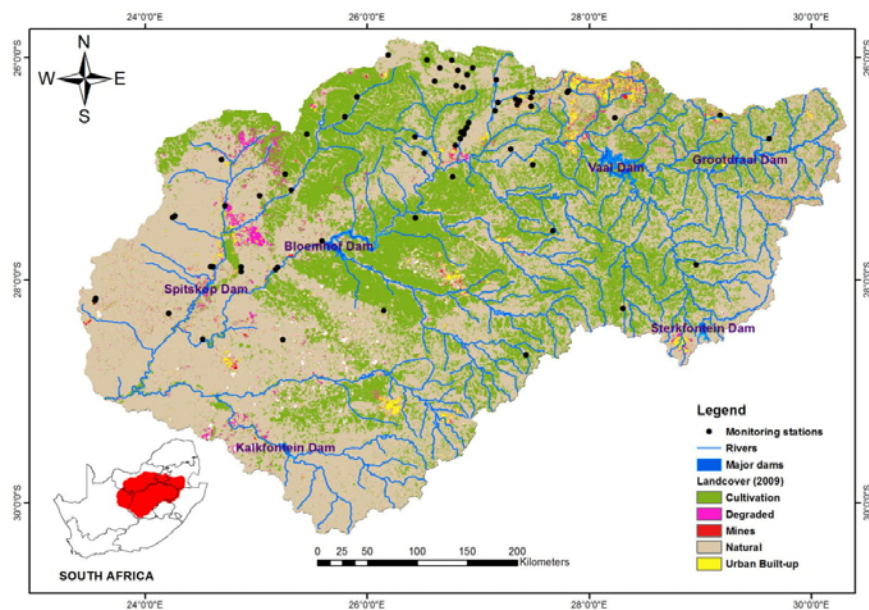


Fig. 1 Map showing the Vaal River Basin with different land uses



reduce pressure on surface waters, and the need for groundwater protection from pollution.

Researchers have not treated groundwater in much detail as surface water quality in the VRB. This is mainly because surface water is the main source of water supply. It is beyond the scope of this study to examine surface water quality and interested readers are referred to Braune and Roger (1987) and Du Plessis (2017) for more information about this issue. Vegter (1995) produced a national map showing trends and variation of groundwater quality using Piper plot and salinity ratio. The study was more descriptive in nature. Hobbs et al. (2013) examined groundwater chemistry trends in the VRB using a Piper diagram, geological information and descriptive statistics to provide an overview of groundwater chemistry. Previous published studies are limited to local surveys and have mainly focused on the impacts of acid mine drainage (AMD) on water resources (Naicker et al. 2003; Nengovhela et al. 2006; Tutu et al. 2008; Durand 2012; Abiyeh 2014). Data from such studies suggest that acid mine drainage and tailing dumps are polluting water resources in the vicinity of mines. However, there have been few empirical and multi-approach investigations into groundwater chemistry in the basin. This work attempts to generate fresh insights into the hydrochemical characteristics of groundwater chemistry in the VRB.

The purpose of this paper is to assess the impacts of natural and anthropogenic activities on groundwater and to determine hydrochemical processes that influence groundwater quality in the basin. A combination of graphical techniques and multivariate statistics, PCA and HCA were used to examine the groundwater chemistry. These methods provided a means to robustly interpret the results with a high degree of confidence rather than in a speculative manner. This work provided an important opportunity to advance the understanding of the regional groundwater chemistry in the highly urbanized and industrialised VRB.

### Geographical conditions

The VRB is situated in the interior of South Africa, covering an area of approximately 198,000 km<sup>2</sup>. The Vaal River originates from the Drakensberg escarpment in the north-eastern part of the basin. It flows 900 km in a southwesterly direction where it joins the Senqu River from Lesotho and forms Orange River and discharges into the Atlantic Ocean. A water divide runs along the catchment boundary in a northeasterly to northwesterly direction which separates the Orange River Basin and Limpopo Basin. The topography varies from nearly level in the northwestern and southwestern parts of the study area, to very hilly in the Vredefort Dome and Johannesburg area.

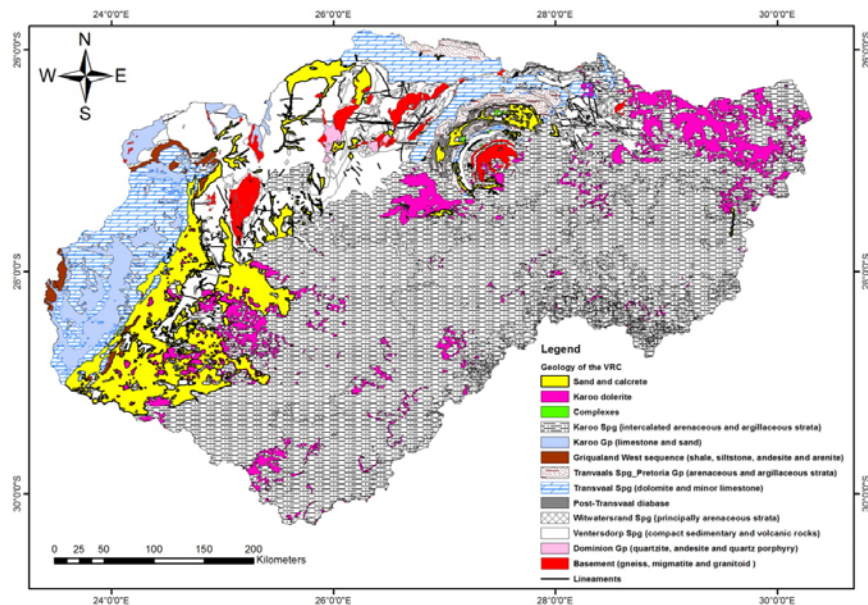
Climatic factors like rainfall and temperature are highly variable in space and time in the VRB, which is a result of a combination of different factors such as elevation and moisture source (Middleton and Bailey 2005). The mean annual precipitation decreases from the east (800 mm) to west (500 mm) (Middleton and Bailey 2005). Rainfall is strongly seasonal and often occurs as convective thunderstorms in the late evening and early morning in the summer season (October to March). In winter it is relatively dry and there is little or no rainfall with the exception of light snow in mountainous parts of the region. Evaporation as measured by A-Pan also exhibits a similar but opposite trend, ranging from 1900 mm/year in the east to 2400 mm/year in the western part of the region. High evaporation in the southwestern part of the basin is evident by the occurrence of salt pans. The average annual temperature also increases from 14 °C on the eastern side to 17.9 °C in the western side of the region (Middleton and Bailey 2005).

### Land use activities

The VRB lies in the Witwatersrand Basin, famously known for the rich gold and uranium deposits, the mining of which has underpinned development in the basin (Robb and Meyer 1995). Major industries include, but are not limited to: power and fuel generation; manufacturing; steel production and agriculture (Braune and Rogers 1987; DWAF 2003a, b). Based on field surveys, coal mining activities are located mainly in the northeastern part of the Basin. Gold and Uranium mines are scattered across the northwestern to the southwestern parts of the study area. Agricultural activities are mainly in the eastern and the southwestern parts of the study site. A high number of salt pans were observed during the field survey between Spitskop Dam and Kalkfontein Dam in the southwestern part of the basin, some are being mined for salt. Other notable industries include manufacturing of petro-chemical products from coal in upper part of the basin.

### Geological and hydrogeological setting

The VRB consists of a wide variety of rock types including volcano-sedimentary, igneous and metamorphic rocks that covers the entire geological record from the Early Archaean to late Mesozoic (Fig. 2). More than two-third of the basin is covered by the Late Carboniferous to Early Jurassic Karoo Supergroup. It is composed of fine to coarse-grained sandstone, tillite and mud rocks that underlies the far eastern to the southwestern part of the basin (Johnson et al. 1996, 2006). In some localities, the sedimentary rocks are intruded by dolerite dykes and covered by basaltic lava.



**Fig. 2** A simplified geological map of the VRB (from the 1:1,000,000 geological map of South Africa prepared by the Council for Geosciences). The predominant rocks associated with a particular strati-

graphic unit are included in the legend. Note: Spg and Gp refer to Supergroup and Group, respectively

The granitoids and gneisses are exposed in a few localities in the northern part of the basin. These basement rocks are unconformably and conformably overlain by meta-sedimentary rocks such as quartzite, shale and conglomerate that belong to the Witwatersrand Group (Robb and Meyer 1995; McCarthy et al. 2006). The quartzite makes up the prominent ridges in the northern part of the basin. The Late Archaean Ventersdorp Supergroup consists of volcano-sedimentary rocks that are mainly found in the northwestern part of the region (van der Westhuizen et al. 1991; van der Westhuizen and Bruijn 2000). The volcano-sedimentary rocks include andesite, quartz porphyry, conglomerate and tuff. The Transvaal Supergroup (Neo-Archaean to Palaeo-Proterozoic age) overlies the Ventersdorp Supergroup (Eriksson et al. 1995; Eriksson and Altermann 1998). The Transvaal Supergroup is exposed along the upper northeastern boundary to the southwestern boundary of the basin. The predominant rock types are dolomite, conglomerate, quartzite, sandstone, shale, and andesite (Eriksson and Altermann 1998). The dolomite is intercalated with chert layers, and majority of the boreholes have been sited along this unit, including the limestone in the southwestern edge of the basin.

From a hydrogeological point of view, the dolomite formations that belong to the Transvaal Supergroup

are the most significant aquifers, because of their high groundwater productivity. The dolomites are situated in the northeastern to southwestern parts of the VRB. In the explanatory notes compiled by Barnard (2000) of the 2526 Johannesburg map, four hydrogeological units were defined namely: (1) intergranular aquifers in the alluvial covered area; (2) karst aquifers in the Transvaal Supergroup carbonates; (3) fractured-rock aquifers in the Witwatersrand Supergroup; and (4) intergranular and fractured-rock aquifers in the Dominion Group, Klipriviersberg Formation and Karoo Supergroup.

The Malmani Subgroup dolomite can be classified as an extensive fractured and karstic rock aquifer. It is an unconfined system and comprises an extensive soil cover and weathering products underlain by karstic dolomite aquifer. Buttrick et al. (1993) and DWAF (2006), reported high storativity values (9.7%) and transmissivity values (30,000 m<sup>3</sup>/day) for the dolomitic aquifer. The younger Karoo Sequence (sandstone, shale, tillite and clay) fills the valley topography in the dolomitic terrain and in some parts the dolomite is flanked by quartzite ridges (Kafri and Foster 1989). In general, the dissolution cavities, fissures and fracture network act as conduits for groundwater movement and as recharge zones (Holland and Withüser 2009; Abiye et al. 2011).



There are WNW-ESE trending faults (e.g., Rietfontein Fault) and major fractures post-Transvaal tensional tectonics that have penetrated the whole sequence of the Malmani Subgroup and the Ventersdorp lava into the underlying Witwatersrand Supergroup (Swart et al. 2003; Hobbs and Cobbing 2007). Abiye et al. (2011) showed the significance of fractures in regulating groundwater recharge in the crystalline rocks of Johannesburg. The fractured and granular aquifer have a low to moderate groundwater productivity with a borehole yield of less than 2 l/s (Barnard 2000). Hobbs and Cobbing (2007) reported relatively low to modest transmissivity values ( $< 10 \text{ m}^2/\text{d}$ ) and low storativity values ( $< 1\%$ ) for the fractured-rock aquifers. Heterogeneity prevails over homogeneity in the aquifer system not all fractures are permeable.

## Methodology

### Data collection

Water chemistry data for existing wells in the VRB were obtained from the Department of Water and Sanitation (DWS) of South Africa. The DWS has a database that contains both surface and ground water chemistry data spanning more than a decade. The water chemistry data included both chemical and physical parameters. Trace element concentration and groundwater temperature records were discarded because of inconsistency and paucity in the measurement records. To ensure quality

control of the datasets only physico-chemical measurements from monitoring stations with more than 5 years of chemistry data (1995 to 2016) were used in the study. The quality of the chemical analysis was verified by calculating the charge balance error (CBE) as part of quality assurance. The CBE value of less than  $\pm 5\%$  is regarded as the best analytical estimation, and the threshold CBE value is  $\pm 10\%$ , which is the acceptable error (Güler et al. 2002; Appelo and Postma 2004). The chemical analysis with CBE values greater than  $\pm 10\%$  are associated with the errors in the sampling and measurement procedures. In this study, 84% of the samples were below  $\pm 5\%$ , and few samples (16%) were greater than  $\pm 5\%$  but less than  $\pm 10\%$ , which means that the chemical analysis are reliable. Physical parameters such as total dissolved solids (TDS) amount was verified by calculating the total sum of major constituent, and comparing them to reported values. These values showed an agreement, which increases confidence on the use of the data. Table 1 show mean values of physico-chemical parameters from 70 groundwater monitoring stations (59 wells, 9 springs and 2 mine-water discharges) that were used in the study. Following the quality assurance of the chemistry data, data were averaged over the entire period for each monitoring station to get representative values which were used for graphical and statistical analysis, and interpretation. Averaging the data removes seasonal effects on water chemistry, which allows for identification of major hydrochemical process and of the determination of the key factors that govern the evolution of groundwater quality.

**Table 1** Summary statistics of the physico-chemical parameters for the groups determined from HCA. Mean concentrations (mg/L), pH (standard units), electrical conductivity ( $\mu\text{S}/\text{Cm}$ )

| Parameter       | Mean   | SD     | WHO (2004) | Group 1 | Group 2 | Group 3 | Group 4 | Group 5 | Group 6 | Group 7 | GW12    | GW40    | GW65   |
|-----------------|--------|--------|------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|--------|
| $n^a$           |        |        |            | 26      | 7       | 14      | 8       | 5       | 4       | 3       | 1       | 1       | 1      |
| pH              | 8.02   | 0.38   | 6.5–8.5    | 8.20    | 8.01    | 8.13    | 8.03    | 7.91    | 6.99    | 7.90    | 7.87    | 7.53    | 7.58   |
| TDS             | 648.39 | 385.53 | 5          | 427.51  | 892.52  | 739.72  | 453.93  | 1075.46 | 90.77   | 1148.95 | 1949.39 | 2168.20 | 732.35 |
| EC              | 92.85  | 57.98  |            | 58.44   | 136.40  | 103.79  | 78.55   | 142.89  | 14.07   | 164.92  | 327.49  | 248.68  | 102.16 |
| Ca              | 72.16  | 44.41  |            | 52.14   | 109.83  | 73.41   | 45.81   | 136.62  | 8.41    | 145.18  | 50.66   | 257.43  | 72.20  |
| Mg              | 44.46  | 30.30  |            | 30.70   | 61.48   | 53.50   | 31.89   | 64.90   | 6.49    | 82.76   | 34.58   | 205.84  | 40.57  |
| Na              | 41.99  | 74.59  | 200        | 13.66   | 52.08   | 47.59   | 25.42   | 88.51   | 4.17    | 62.03   | 574.06  | 48.00   | 82.37  |
| K               | 3.36   | 3.00   |            | 1.68    | 3.21    | 3.24    | 4.06    | 4.24    | 1.17    | 13.42   | 7.82    | 7.88    | 9.32   |
| Cl              | 58.49  | 112.59 | 250        | 13.86   | 114.39  | 50.67   | 27.16   | 91.78   | 6.26    | 216.07  | 796.80  | 19.44   | 58.37  |
| SO <sub>4</sub> | 112.76 | 183.26 | 250        | 50.47   | 106.11  | 68.82   | 29.50   | 515.31  | 8.07    | 157.78  | 146.48  | 1083.80 | 326.29 |
| TAL             | 235.58 | 108.90 |            | 208.11  | 297.59  | 340.21  | 197.53  | 131.41  | 33.47   | 350.54  | 273.89  | 447.11  | 90.07  |
| Si              | 12.62  | 6.46   |            | 8.36    | 20.74   | 12.60   | 22.94   | 10.90   | 6.16    | 18.32   | 9.85    | 10.46   | 6.79   |
| F               | 0.30   | 0.30   |            | 0.17    | 0.37    | 0.49    | 0.21    | 0.23    | 0.10    | 0.42    | 2.02    | 0.17    | 0.23   |
| NH <sub>4</sub> | 0.12   | 0.43   |            | 0.05    | 0.04    | 0.06    | 0.04    | 0.29    | 0.04    | 0.07    | 0.08    | 0.05    | 3.58   |
| NO <sub>3</sub> | 5.81   | 6.16   | 50         | 2.47    | 18.59   | 4.42    | 11.04   | 3.08    | 3.29    | 9.37    | 0.64    | 0.08    | 4.73   |
| PO <sub>4</sub> | 0.08   | 0.31   |            | 0.02    | 0.02    | 0.11    | 0.02    | 0.07    | 0.02    | 0.02    | 0.01    | 0.02    | 2.50   |

<sup>a</sup>Number of water samples within the groups

### Graphical and multivariate statistical methods

Statistical analysis was performed using SPSS software (version 25). The first step before analysis of the datasets was to perform a test for normality on the hydrochemical data using a Shapiro–Wilk (SK) and Kolmogorov–Smirnov (KS) test to assess how the datasets are distributed. Both tests for normality showed that most of the variables were not normally distributed.

The non-normal distributed datasets were then grouped according to similarity/dissimilarity in physico-chemical parameters, to reveal the relationship among the water samples. We assumed that the water samples that fall within the same cluster indicate a common source, and indicate similar hydrochemical processes. The squared Euclidean distance was used as a similarity/dissimilarity measurement with the Ward's method for linkage such that the clusters are linked (Güler et al. 2002). The physico-chemical parameters were standardized using z-scores because they are not of the same scale and magnitude. The water samples within the groups are more similar to others within the group and dissimilar with water samples outside the groups. Grouping the raw data using HCA proved to be useful, because outliers were detected. The outliers were not discarded because the water chemistry measurements are not just random numbers but provide important information about the groundwater quality in the study area. The water samples within the groups were presented using Piper plot, Schoeller diagram and bivariate graphs.

A Piper diagram (Piper 1944) was used to classify the water types and evaluate possible mixing trends. Bivariate plots of major ions were plotted along the  $x$ – $y$  coordinates to validate key hydrochemical processes taking place. Schoeller diagram was used to visualise the distinct groups and their associated water samples. Although the datasets were in mg/L with the exception of EC and pH, the unit of measurements that was used is Meq/L for Piper plot, Schoeller diagram and bivariate plots. The axis were converted to a logarithmic scale to discern patterns in the hydrochemical datasets.

One of the assumption of multivariate statistics method such as PCA is that the data must be normally distributed (Jolliffe 2011), which is not the case in this study as indicated by the KS-SK tests. For that reason, the datasets were log transformed to reduce the skewness in the distribution of the variables. By log transforming the data the level of normality of the datasets is improved, which consequently improves the reliability of the datasets.

Furthermore, we tested the suitability of the datasets for PCA by determining the Kaiser–Meyer Olkin (KMO) measure of sampling adequacy, and performing Bartlett's test of sphericity. The former gives an indication of how the dataset is well conditioned for PCA, whereas the latter tests whether

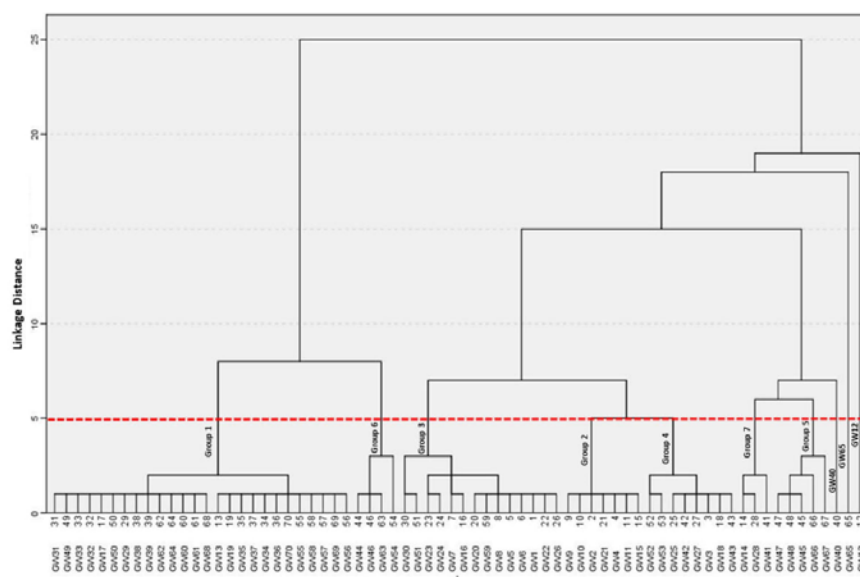
the correlation matrix of the dataset is significantly different from an identity matrix. In this study, the KMO value is 0.756, in the middling range (in the 0.70 s) according to Kaiser (1959), which means that the dataset is moderately suitable for PCA. The Bartlett's test of sphericity tests the null hypothesis that the correlation matrix is an identity matrix. The significance value is less than 0.05 ( $p < 0.05$ ), and therefore, we reject the null hypothesis that the correlation matrix is an identity matrix. This confirms that PCA is suitable for the datasets. The statistical tests indicate that PCA is applicable to the dataset and that it will be useful in the study. Factor analysis was performed on the normalized dataset and the components were extracted using PCA. Only components with eigenvalues greater than 1 were extracted, because they account for at least one variable in the dataset. The extraction communalities for the variables were greater than 0.6, which suggest a greater level of extraction. The principal components were rotated using a Varimax rotation with Kaiser Normalization (1959) to maximize the loading of each variable on one of the components, whilst minimizing the loading on all other components (Güler et al. 2002, 2012). The higher the communalities the better because of a greater level of extraction.

### Results and discussion

An HCA assessment was performed on the raw chemical data. HCA outputs are in the form of a dendrogram (Fig. 3) and the statistical summary of the data is presented in Table 1 and were plotted on a Schoeller diagram (Fig. 4). Seven clusters were recognized from the HCA analysis (Fig. 3). Outlier were detected, and were included because they represent a relevant group that could have probably been under-sampled in the VRB. Groundwater samples 12, 40 and 65 were dissimilar to the groups and to each other, and were referred herein as GW12, GW40 and GW65, respectively.

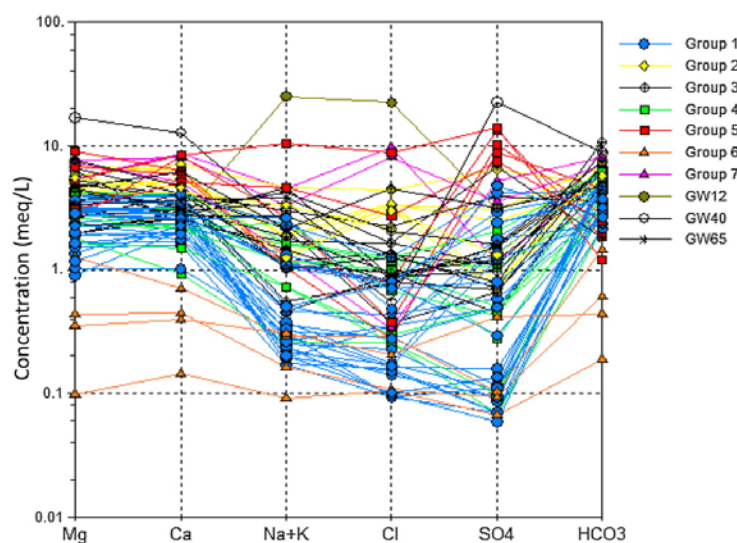
It can be seen from Table 1 that the mean values for the physico-chemical parameters for the groups are highly variable, which could be a result of heterogeneity in the geology and various land use activities in the basin. Lines connecting to the points in the Schoeller diagram (Fig. 4) visually illustrate the compositional trends in different samples. The pH of groundwater groups is generally alkaline in nature with the exception of Group 6, which is slightly acidic (6.99). The high pH could be a result of dissolution of the underlying carbonate aquifer, which is the major aquifer-type in the VRB.

Group 6 has the lowest values for chemical parameters (Fig. 4), a characteristic of water in recharge areas. Groups (5 and 7) and GW samples (12, 40 and 65) are highly mineralized waters (TDS > 1000 mg/L), with high sulphate



**Fig. 3** Dendrogram from the HCA for the 70 water samples. The red line of asterisks was chosen as the limit to select the number of groups

**Fig. 4** A Schoeller diagram showing the relative proportion of major ions for groundwater samples from the VRB



concentrations ( $> 140$  mg/L). The high TDS and  $\text{SO}_4$  are consistent with characteristics of mine-polluted waters in the basin, which means that Groups (5 and 7) and GW

samples (40 and 65) are mine-polluted waters except for GW12. GW12 has a seawater geochemical signature with a much higher Na (574.06 mg/L) and Cl (796.80 mg/L)



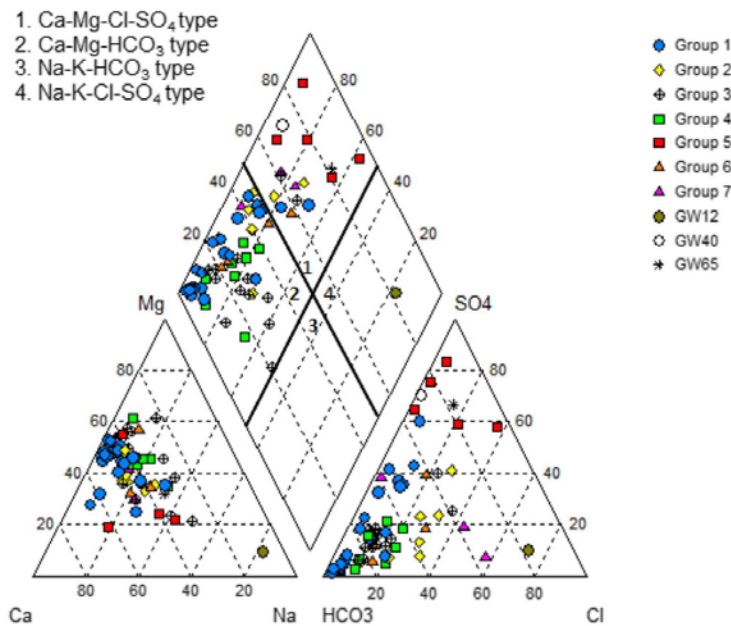
concentrations than all other samples. The high degree of mineralization of GW12 may be explained by deep circulating water that has had a long residence time. It could also be a result of the higher evaporation in the southwestern part of the basin, which increases the soil salinity. The samples belonging to Group 1, 2, 3 and 4 have relatively similar mean values for the physico-chemical variables; we can infer that this is water in circulation (Fig. 4). Group 2 has a notably high  $\text{NO}_3$  concentration (18.59 mg/l), which is evident of impacts of agricultural activities and urbanization on groundwater chemistry.

A comparison of water alongside the WHO (2004) drinking water guidelines reveals that the groundwater is below the guidelines with the exception of group (5 and 7) and GW samples. This does not take into account the bacteriological characteristics of groundwater which is an important consideration in drinking water.

The major ions were plotted in a Piper plot (Piper 1944) (Fig. 5), to discern the plausible genesis of the sample groups and the hydrochemical facies to which each sample belongs. The Piper plot shows that the groundwater is dominated by alkaline earths (Ca and Mg) over alkalis (Na and K) and that weak acids ( $\text{HCO}_3$ ) exceed strong acids ( $\text{SO}_4$  and Cl). The water samples within the groups can be broadly classified into two water types, namely: Ca–Mg– $\text{SO}_4$ –Cl and Ca–Mg– $\text{HCO}_3$ . The composition Ca–Mg– $\text{HCO}_3$  is the predominant water type corresponding to the following

groups: 1, 2, 3, 4 and 6. These observations suggest that groundwater is draining diverse geological materials, in particular, dolomite and volcanic rocks in the western part of the basin. These findings are consistent with Hobbs et al. (2013) who showed that Ca–Mg– $\text{HCO}_3$  represents pristine water from the dolomitic aquifer. The highly mineralized water, Groups (5 and 7) and GW (40 and 65), are clustered in the Ca–Mg– $\text{SO}_4$ –Cl field, and are likely to be indicative of pollution from multiple source, particularly from mining and urbanization. This is supported by previous studies by McCarthy (2011), Durand (2012) and Abiye (2014) who demonstrated that mining pollution is the main cause of  $\text{SO}_4$  enrichment in groundwater in the region. The Ca–Mg– $\text{SO}_4$ –Cl water type probably evolved from the interaction of recharge water in circulation and acidic water from the mines, and water from the shallow aquifers that has been polluted by highly soluble chloride compounds from the highly urbanized area. In their study Hobbs et al. (2013) reported possible mixing of groundwater from pristine dolomitic aquifers with mining water resulting in a Ca– $\text{SO}_4$  water type. The cation ternary plot shows that the bulk of water samples have no dominant ions. These could be explained by mixing of water from different sources, cation exchange between Mg–Ca–Na and the replacement of  $\text{HCO}_3$  by  $\text{SO}_4$ . Groundwater sample GW12 has Na–Cl water composition which confirms that it is not mining related.

**Fig. 5** Piper diagram showing the hydrochemical facies of groundwater. The ternary plots show the abundance of major cation and anion in decreasing order:  $\text{Ca} > \text{Mg} > \text{Na}$  and  $\text{HCO}_3 > \text{SO}_4 > \text{Cl}$



The results of the correlation analysis are presented in Table 2. Pearson correlations reveal statistical relationships between two or more variables, and no causal relationship is assumed between the variables. For most correlations among the variables the significance values were less than 0.05 ( $p$  value  $< 0.05$ ), which implies that there is a statistical significant relationship among the chemical variables. We also found that a high number of variables have correlation coefficient values ( $r$ ),  $p < 0.05$ , that exceeds the critical value ( $R$ ) which is 0.24. The  $R$  value is obtained from the critical value table, at the intersection between the degrees of freedom (68) and the level of significance (0.05). The  $R$  is low because of a higher degree of freedom (68). In this study, we assume that correlation among variables with  $r \geq 0.5$  are practical and meaningful. The strength of the correlation among the variables is described as follows weak ( $r$  0.00–0.49), moderate ( $r$  0.50–0.69), strong ( $r$  0.70–0.79) and very strong ( $r$  0.80–1).

What stands out in the table is a very strong correlation between TDS and EC, which are both moderately to very strongly correlated to the major ions and F. These observations indicate that the major ions and F contributes significantly to groundwater salinization and mineralisation in the basin. It is not surprising that TAL is strongly correlated to Mg and Ca in the basin. This could be a result of chemical weathering of carbonate minerals, which releases  $\text{CO}_3$  and  $\text{HCO}_3$  in the groundwater system. Another possible source of  $\text{CO}_3$  and  $\text{HCO}_3$  is rainfall, which is slightly acidic, and carbon dioxide from the soil. The moderate correlation between TAL and pH could be an indication that

the groundwater has a high buffering capacity, which could also explain the neutral to basic pH values observed earlier in Table 1.

There is a very strong positive correlation between Ca and Mg ( $r = 0.90$ ). We suggest that the dissolution of dolomite ( $\text{CaMg}(\text{CO}_3)_2$ ) which underlies a large part of the north-western and southwestern part of the region, and to a lesser extent limestone ( $\text{CaCO}_3$ ) is the major source of Ca and Mg. The metasedimentary and volcanic rocks found in the central and northern part of the basin contain ferromagnesian minerals including but not limited to hornblende, biotite, mica, talc, chloritoid and feldspars that could be the additional source of Mg and Ca. We observed correlations between the cations Na–K (0.72), Na–Ca (0.59), and Mg–Na (0.50). The possible explanation might be ion exchange processes and silicate weathering.

The most surprising aspect of the data is the moderate to strong correlation between sulphate and all other major ions Na– $\text{SO}_4$  (0.73), Ca– $\text{SO}_4$  (0.67), Cl– $\text{SO}_4$  (0.61), Mg– $\text{SO}_4$  (0.60) and K– $\text{SO}_4$  (0.53). The known source of  $\text{SO}_4$  is primarily the dissolution of sulphate precipitates such as gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ), anhydrite ( $\text{CaSO}_4$ ) and magnesium sulphate ( $\text{MgSO}_4$ ) found largely in mining tailing dumps, they are also sources of Ca and Mg. This is supported by Naicker et al. (2003) and Tutu et al. (2008) who reported elevated proportions of pyrite and other minor metallic sulfides in tailing dumps, which on dissolution pollutes groundwater in the basin.

There is also a very strong correlation between Na and Cl ( $r = 0.85$ ). This relationship may be partly explained by the dissolution of evaporites minerals such as halite (NaCl) and

**Table 2** Correlation matrix of the 15 physico-chemical variables

|               | TDS  | EC   | pH   | Ca   | Mg   | Na   | K    | Cl   | $\text{SO}_4$ | TAL    | F    | Si     | $\text{PO}_4$ | $\text{NO}_3$ | $\text{NH}_4$ |
|---------------|------|------|------|------|------|------|------|------|---------------|--------|------|--------|---------------|---------------|---------------|
| TDS           | 1.00 |      |      |      |      |      |      |      |               |        |      |        |               |               |               |
| EC            | 0.94 | 1.00 |      |      |      |      |      |      |               |        |      |        |               |               |               |
| pH            | 0.42 | 0.29 | 1.00 |      |      |      |      |      |               |        |      |        |               |               |               |
| Ca            | 0.94 | 0.86 | 0.44 | 1.00 |      |      |      |      |               |        |      |        |               |               |               |
| Mg            | 0.92 | 0.84 | 0.45 | 0.90 | 1.00 |      |      |      |               |        |      |        |               |               |               |
| Na            | 0.74 | 0.78 | 0.13 | 0.59 | 0.50 | 1.00 |      |      |               |        |      |        |               |               |               |
| K             | 0.58 | 0.61 | 0.04 | 0.48 | 0.42 | 0.72 | 1.00 |      |               |        |      |        |               |               |               |
| Cl            | 0.70 | 0.77 | 0.08 | 0.59 | 0.54 | 0.85 | 0.62 | 1.00 |               |        |      |        |               |               |               |
| $\text{SO}_4$ | 0.70 | 0.72 | 0.03 | 0.67 | 0.60 | 0.73 | 0.53 | 0.61 | 1.00          |        |      |        |               |               |               |
| TAL           | 0.74 | 0.64 | 0.65 | 0.72 | 0.77 | 0.34 | 0.27 | 0.34 | 0.21          | 1.00   |      |        |               |               |               |
| F             | 0.59 | 0.59 | 0.22 | 0.40 | 0.36 | 0.75 | 0.51 | 0.66 | 0.39          | 0.46   | 1.00 |        |               |               |               |
| Si            | 0.41 | 0.47 | 0.15 | 0.39 | 0.43 | 0.39 | 0.38 | 0.45 | 0.10          | 0.41   | 0.30 | 1.00   |               |               |               |
| $\text{PO}_4$ | 0.21 | 0.18 | 0.06 | 0.21 | 0.18 | 0.23 | 0.20 | 0.23 | 0.30          | – 0.01 | 0.16 | – 0.17 | 1.00          |               |               |
| $\text{NO}_3$ | 0.15 | 0.23 | 0.11 | 0.17 | 0.23 | 0.12 | 0.02 | 0.39 | – 0.09        | 0.14   | 0.02 | 0.58   | 0.02          | 1.00          |               |
| $\text{NH}_4$ | 0.30 | 0.24 | 0.00 | 0.25 | 0.22 | 0.34 | 0.33 | 0.24 | 0.47          | – 0.10 | 0.14 | – 0.28 | 0.60          | – 0.09        | 1.00          |

$N = 70$ . Correlation is significant at the 0.05 level (2-tailed)

$r(68) = 0.5, p < 0.05$

sylvite (KCl) in the salt pans during recharge, which are the sources of Na, Cl and K. This may also explain the moderate correlation observed between Cl and K (0.62). Another explanation of the association between these ions is likely to be deposition of marine-derived salts in the rain. The moderate correlation between Cl–F (0.66), Ca–Cl (0.59) and Mg–Cl (0.54) could be related to industrial discharge in the basin. DWA (2003a) reported the discharge of wastewater by industries and household that contains highly soluble salts (ClF,  $\text{MgCl}_2$ ,  $\text{CaCl}_2$  and NaF) which infiltrates and join the groundwater system. The soluble salts are anthropogenic and are a source of F, Cl, Ca and Na. The granites, sandstone, quartzites and mudstones in the study area contain; albite, anorthite and apatite which could contribute to Ca, Na and F enrichment in groundwater on dissolution.

Strong correlation between Na and F ( $r=0.75$ ) exists. The fluoride in groundwater is most likely derived from the weathering of basement rocks in the VRB and the concentration of this ion in groundwater is likely to be limited by the solubility of fluorite and common-ion effect caused by elevated calcium ion concentrations in some water samples. Ncube and Schutte (2004) reported high F concentration in the northwest province, which suggests that there is a geogenic source of fluoride in this part of the basin.

The observed correlation between  $\text{NH}_4$  and  $\text{PO}_4$  in groundwater is likely to be a result of runoff from agricultural activities and sewage sludge that seeps to the subsurface. This finding is consistent with that of DWA (2003a, b) which showed the impact of urbanization and industrialization on water quality. Phosphate could also be sourced from the weathering of basement granitic rocks, which contain the mineral apatite [ $\text{Ca}_5(\text{PO}_4)_3(\text{F,Cl,OH})$ ]. The  $\text{NO}_3$  and Si are moderately correlated. We suggest that groundwater interaction with the meta-sediments and dolomite intercalated with chert is the major source for Si. Agricultural return flows and domestic wastewater discharge to streams are possible sources for nitrate in groundwater system. Nitrate could also be partially sourced from the oxidation of ammonium ions.

### Ionic ratios

Geochemical variations in major ions were plotted in an  $x$ – $y$  coordinate (Güler et al. 2002) to investigate possible geochemical processes that influence the chemistry of groundwater in the region. From Fig. 6a plot of  $\text{Na} + \text{K}$  vs  $\text{Cl} + \text{SO}_4$ , it is apparent that about 85% of the samples plots above the 1:1 line indicating the dominance of Cl and  $\text{SO}_4$ . The Cl and  $\text{SO}_4$  are most probably derived from the oxidation of sulphide ores as a result of human disturbances such as mining activities and urbanization in the basin. Group 5 samples plot above all the samples, which is indicative of mining pollution.

The plot of  $\text{Ca} + \text{Mg}$  vs  $\text{HCO}_3 + \text{SO}_4$  (Fig. 6b) is useful in revealing the likely chemical reactions in groundwater, particularly the extent to which ion exchange reactions influence groundwater quality. In case of ion exchange the samples will tend to shift to the right on this plot as a result of excess of  $\text{HCO}_3 + \text{SO}_4$ . On the other hand, samples will tend to shift to the left due to an excess of  $\text{Ca} + \text{Mg}$  over  $\text{HCO}_3 + \text{SO}_4$  (Fisher and Mulican 1997). The samples that are clustered closer to the 1:1 line indicate that the dissolution of calcite, dolomite and gypsum is the predominant hydrochemical process influencing groundwater quality. Nearly 98% of the samples are clustered around and above the 1:1 line, which shows that reverse ion exchange is significant in the basin. Furthermore, the plot of  $\text{Ca} + \text{Mg}$  vs Cl (Fig. 6d) shows that Ca and Mg do not increase with increasing salinity, which could be further evidence of carbonate weathering and an indication of reverse ion exchange.

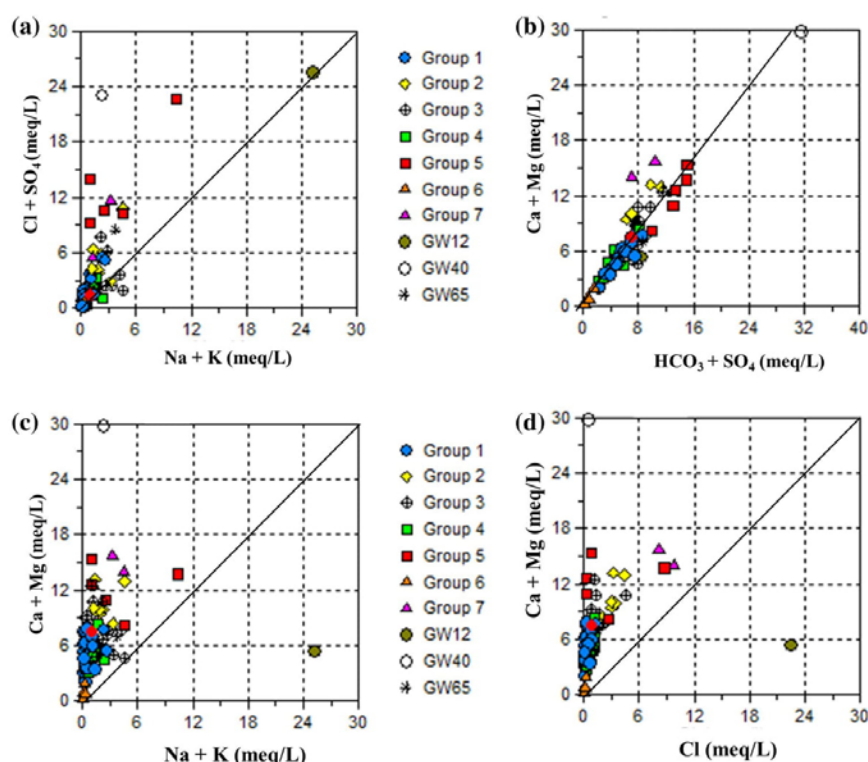
The plot of  $\text{Ca} + \text{Mg}$  vs  $\text{Na} + \text{K}$  (Fig. 6c) is useful in identifying the importance of chemical weathering of carbonates and silicates. The graph shows that the sample are clustered to the left of the 1:1 line, which means that carbonate dissolution is more important than silicate weathering. Furthermore, the plot supports the suggestion that GW12 is derived from dissolution of evaporates or a result of deep circulating groundwater with a long residence time, and it is not polluted by mine activities.

Table 3 indicates the loading of the variables on each principal component, and the percentage of variance that the variables accounted for in the regional groundwater chemistry data. Four components that accounted for 81.52% of the total variance were extracted using the PCA method. The first component accounts for the most variation in the data, and so are the other remaining components for the residual data. The seventeen variables were treated independently to reveal interrelationships. The principal components were used to explain and infer predominant hydrochemical processes related to man-made and natural factors in the VRB.

### Component 1

The first component accounts for 48.61% of the variance in the chemical analysis. The first component has a high positive loading of Na, Cl, K, F, EC,  $\text{SO}_4$  and TDS in decreasing order. The high positive loading of the ions with EC shows that they are major contributors to groundwater salinity. We suggest that the dissolution of feldspars, micas, salts and phosphates bearing rocks in the study area is a possible sources of Na, K, F and Ca enrichment in groundwater. Enrichment of Na, K, Cl could also be related to soil salinity due to direct evaporation of rainfall and preferential dissolution particularly in the arid parts of the basin. This confirms that dissolution of soil and geological material and the dissociation of evaporites are





**Fig. 6** Graphs showing the plot of Na + K vs Cl + SO<sub>4</sub> (a), Ca + Mg vs HCO<sub>3</sub> + SO<sub>4</sub> (b), Ca + Mg vs Na + K (c) and Ca + Mg vs Cl (d). The solid line represents the 1:1 line

active processes in the VRB. The occurrence of Na, Cl, K and Ca could also be linked to industrial effluent, domestic wastewater and fertilizers. The high loading of SO<sub>4</sub> is indicative of anthropogenic disturbances in the environment particularly gold, coal and uranium mining. The oxidation of sulphide ores such as pyrite (FeS<sub>2</sub>), arsenopyrite (FeAsS), cobaltite (CoAsS) and pyrrhotite (FeS) in mine tailing dumps and abandoned mines releases SO<sub>4</sub> to the environment. The SO<sub>4</sub> is latter removed from the water by addition of lime to neutralize the acidic water in the mine site and/or interaction of dolomitic water with the SO<sub>4</sub> rich water. These results in the precipitation of sulphate salts, which on dissolution by carbonic acid from rain or inflow of more acidic water will generate SO<sub>4</sub>, K, Mg, Ca, and Na. Both human activities such as mining and industrial activities, and dissolution of rocks have a considerable influence on the groundwater chemistry.

### Component 2

This component has a high positive loading for TAL, pH, Mg, Ca and TDS, explaining 14.88% of the variance in the remaining water chemistry data. The second component shows that dissolution of the underlying dolomitic aquifer is a major hydrochemical process. The dissolution of dolomite, gypsum and anhydrite by circulating water recharging the groundwater system releases mainly Ca, Mg, CO<sub>3</sub> and SO<sub>4</sub>, which affects the pH and contributes to TAL and TDS of the water. The plot of Ca + Mg vs HCO<sub>3</sub> + SO<sub>4</sub> (Fig. 6b) also illustrated the predominance of carbonate dissolution over weathering of ferromagnesian minerals which contain Mg and Ca. Therefore, the geology exerts some control on the regional groundwater chemistry and not all groundwater is impacted by human activities, particularly in areas underlain by dolomites outside of the mining footprint.

**Table 3** Rotated component matrix of hydrochemical data of all groundwater samples

| Chemical variables                   | Component |       |       |       |
|--------------------------------------|-----------|-------|-------|-------|
|                                      | 1         | 2     | 3     | 4     |
| TDS                                  | 0.67      | 0.69  |       |       |
| EC                                   | 0.74      | 0.55  |       |       |
| pH                                   |           | 0.81  |       |       |
| Ca                                   | 0.51      | 0.74  |       |       |
| Mg                                   |           | 0.79  |       |       |
| Na                                   | 0.92      |       |       |       |
| K                                    | 0.79      |       |       |       |
| Cl                                   | 0.82      |       |       |       |
| SO <sub>4</sub>                      | 0.72      |       |       |       |
| TAL                                  |           | 0.89  |       |       |
| F                                    | 0.76      |       |       |       |
| Si                                   |           |       |       | 0.71  |
| NH <sub>4</sub>                      |           |       | 0.85  |       |
| NO <sub>3</sub>                      |           |       |       | 0.96  |
| PO <sub>4</sub>                      |           |       | 0.84  |       |
| Eigenvalues                          | 7.3       | 2.23  | 1.58  | 1.13  |
| % of variance explained by component | 48.61     | 14.88 | 10.53 | 7.50  |
| Cumulative % of variance             | 48.61     | 63.49 | 74.02 | 81.52 |

### Component 3

Phosphates and ammonia have the highest positive loading, explaining less than 10% of the variance in the chemical data. The presence of PO<sub>4</sub> and NH<sub>4</sub> in groundwater in the study area is mainly due to sewage sludge, industrial wastewater discharge, and agricultural return flows across the basin. Although the breaking down of organic matter in the soil and the chemical weathering process of granitic rocks in the study area could partly contribute to NH<sub>4</sub> and PO<sub>4</sub>, human activities play a much more significant role in influencing the chemistry of groundwater.

### Component 4

NO<sub>3</sub> and Si have a high positive loading, which accounts for the remainder of the variation (7%) in groundwater chemistry. Si is derived from the weathering of sandstone, granite, conglomerate, quartz porphyry, and quartzite mainly in northern, northwest and central part of study area. Nitrate in the study area is largely a result of disposal of sewage in the Vaal River and its tributaries, which ends up joining the shallow groundwater system. Another human induced possible source of NO<sub>3</sub> is agricultural return flows. Natural contribution of ammonia could be the oxidation of ammonium to nitrate. These findings further support the idea of

geogenic and human induced activities on hydrochemical composition of groundwater.

### Conclusion

The purpose of the current study was to assess both man-made and geological factors that influence the chemical composition of groundwater and to identify the predominant hydrochemical processes. A combination of graphical and multivariate statistics was used in the study. One of the most significant findings to emerge from this study is that the groundwater chemistry is principally controlled by both geological and human induced activities. It was found that the relative abundance of ions is highly variable among the different groups, which was indicative of recently recharged water, mine-polluted water and water in circulation. The main water types were Ca–Mg–HCO<sub>3</sub> type and Ca–Mg–Cl–SO<sub>4</sub> type. Human activities such as gold mining and industrialization are likely to be the major sources of higher sulphate and some other ions such as chlorides that pollute the dolomitic groundwater. A comparison of the water chemistry measurements with the WHO water guidelines indicate that the water is below the WHO standards on a regional scale. However, other constituents of public health and environmental concern were not tested. The dissolution of dolomite and gypsum is the main source of ion abundance in groundwater. To a lesser extent dissolution of sulphate salts and evaporites contribute to the TDS. The process of reverse ion exchange is more active than cation exchange. Anthropogenic activities such as agricultural return flows, wastewater treatment discharge and industrial wastewater discharge are possibly significant sources of ammonia, nitrates and phosphates in the groundwater system. Notwithstanding the relatively limited water samples, this work offers valuable insights into the hydrochemical processes and factors that govern evolution of groundwater quality in a geological complex region with various land uses. A natural progression of this work is to analyse isotope to pinpoint the exact source of origin and processes of different ions in the basin. Greater efforts are needed to safeguard the groundwater quality for sustainable use in the future.

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### Compliance with ethical standards

**Conflict of interest** The authors declare no conflict of interest.



## References

- Abiye TA (2014) Mine water footprint in the Johannesburg area: a review based on existing and measured data. *S Afr J Geol* 117(1):87–96
- Abiye TA, Mengistu H, Demlie MB (2011) Groundwater resource in the crystalline rocks of the Johannesburg area, South Africa. *J Water Resour Protect* 3(4):199–212
- Adams S, Titus R, Pietersen K, Tredoux G, Harris C (2001) Hydrochemical characteristics of aquifers near Sutherland in the Western Karoo, South Africa. *J Hydrol* 241(1–2):91–103
- Altermann W, Wotherspoon JM (1995) The carbonates of the Transvaal and Griqualand West Sequences of the Kaapvaal craton, with special reference to the Lime Acres limestone deposit. *Miner Deposita* 30(2):124–134
- Appelo CAJ, Postma D (2004) *Geochemistry, groundwater and pollution*. CRC press, Boca Raton, United States
- Armstrong RA, Compston W, Retief EA, Williams IT, Welke HJ (1991) Zircon ion microprobe studies bearing on the age and evolution of the Witwatersrand triad. *Precamb Res* 53(3–4):243–266
- Arnell NW (1999) Climate change and global water resources. *Global Environ Change* 9:S31–S49
- Barnard HC (2000) An explanation of the 1: 500,000 general Hydrogeological map: Johannesburg 2526. Department of Water Affairs and Forestry
- Belkhir L, Boudoukha A, Mouni L, Baouz T (2010) Application of multivariate statistical methods and inverse geochemical modeling for characterization of groundwater—a case study: Ain Azel plain (Algeria). *Geoderma* 159(3–4):390–398
- Braune E, Rogers KH (1987) The Vaal River System: Problems and research needs. A report for the committee for Inland Water Ecosystems National Programme for Ecosystems Research. South African National Scientific Programme Report, (143)
- Buttrick DB, Van Rooy JL, Ligthelm R (1993) Environmental geological aspects of the dolomites of South Africa. *J Afr Earth Sc* 16(1–2):53–61
- Calow RC, MacDonald AM, Nicol AL, Robins NS (2010) Ground water security and drought in Africa: linking availability, access, and demand. *Groundwater* 48(2):246–256
- Dalton MG, Upchurch SB (1978) Interpretation of hydrochemical facies by factor analysis. *Groundwater* 16(4):228–233
- Du Plessis A (2017) *Freshwater challenges of South Africa and its Upper Vaal River*. Springer, New York
- Durand JF (2012) The impact of gold mining on the Witwatersrand on the rivers and karst system of Gauteng and North West Province, South Africa. *J Afr Earth Sc* 68:24–43
- DWAF (Department of Water Affairs and Forestry) (2003a) Report No P WMA 08/000/00/0203. Upper Vaal Water management area: overview of water resources availability and utilisation
- DWAF (Department of Water Affairs and Forestry) (2003b) Report No. P WMA09/000/00/0203. Middle Vaal Water management area: overview of water resources availability and utilisation
- DWAF (Department of Water Affairs and Forestry) (2006) A Guideline for the assessment, planning and management of groundwater resources within dolomitic Areas in South Africa, vols 1–3. Department of Water Affairs and Forestry, Pretoria
- Eriksson PG, Altermann W, Hartzler FJ (2006) The transvaal supergroup and its precursors. In: Johnson MR, Anhaeusser CR The geology of South Africa, pp 237–260
- Eriksson PG, Altermann W (1998) An overview of the geology of the Transvaal Supergroup dolomites (South Africa). *Environ Geol* 36(1–2):179–188
- Eriksson PG, Hattingh PJ, Altermann W (1995) An overview of the geology of the Transvaal Sequence and Bushveld Complex, South Africa. *Miner Deposita* 30(2):98–111
- Fisher RS, Mullican WF (1997) Hydrochemical evolution of sodium-sulfate and sodium-chloride groundwater beneath the northern Chihuahuan Desert, Trans-Pecos, Texas, USA. *Hydrogeol J* 5(2):4–16
- Fitts CR (2002) *Groundwater science*. Elsevier, Amsterdam
- Furi W, Razack M, Abiye TA, Kebede S, Legesse D (2012) Hydrochemical characterization of complex volcanic aquifers in a continental rifted zone: the Middle Awash basin, Ethiopia. *Hydrogeol J* 20(2):385–400
- Green TR, Taniguchi M, Kooi H, Gurdak JJ, Allen DM, Hiscock KM, Treidel H, Aureli A (2011) Beneath the surface of global change: Impacts of climate change on groundwater. *J Hydrol* 405(3–4):532–560
- Güler C, Thyne GD, McCray JE, Turner KA (2002) Evaluation of graphical and multivariate statistical methods for classification of water chemistry data. *Hydrogeol J* 10(4):455–474
- Güler C, Kurt MA, Alpaslan M, Akbulut C (2012) Assessment of the impact of anthropogenic activities on the groundwater hydrology and chemistry in Tarsus coastal plain (Mersin, SE Turkey) using fuzzy clustering, multivariate statistics and GIS techniques. *J Hydrol* 414:435–451
- Hobbs PJ, Cobbing JE (2007) Hydrogeological assessment of acid mine drainage impacts in the West Rand Basin, Gauteng Province
- Hobbs P, Colvin C, Maherry A, Bugan R, Clarke S, Petersen S, Rose C, Carstens M (2013) The Vaal River Management Area (WRC Project No. K8/969)
- Holland M, Witthüser KT (2009) Geochemical characterization of karst groundwater in the cradle of humankind world heritage site, South Africa. *Environ Geol* 57(3):513–524
- Huang G, Liu C, Sun J, Zhang M, Jing J, Li L (2018) A regional scale investigation on factors controlling the groundwater chemistry of various aquifers in a rapidly urbanized area: A case study of the Pearl River Delta. *Sci Total Environ* 625:510–518
- Johnson MR, Van Vuuren CJ, Hegenberger WF, Key R, Show U (1996) Stratigraphy of the Karoo Supergroup in southern Africa: an overview. *J Afr Earth Sc* 23(1):3–15
- Johnson MR, van Vuuren CJ, Visser JNJ, Cole DI, Wickens HdeV, Christie ADM, Roberts DL, Brandl G (2006) Sedimentary rocks of the Karoo Supergroup. In: Johnson MR, Anhaeusser CR, Thomas R The geology of South Africa, pp 461–499
- Jolliffe I (2011) Principal component analysis. In: International encyclopedia of statistical science. Springer, Berlin, pp 1094–1096
- Kafri U, Foster MJB (1989) Hydrogeology of the malmani dolomite in the Klip River and Natalspruit Basins, South Africa. *Environ Geol Water Sci* 13(2):153–166
- Kaiser HF (1959) Computer program for varimax rotation in factor analysis. *Educ Psychol Meas* 19(3):413–420
- Kumar M, Ramanathan AL, Rao MS, Kumar B (2006) Identification and evaluation of hydrogeochemical processes in the groundwater environment of Delhi, India. *Environ Geol* 50(7):1025–1039
- McCarthy TS (2011) The impact of acid mine drainage in South Africa. *S Afr J Sci* 107(5–6):01–07
- McCarthy TS, Johnson MR, Anhaeusser CR, Thomas (2006) The witwatersrand supergroup. In: The geology of South Africa, 155:186
- Middleton BJ, Bailey AK (2005) Water Resources of South Africa, 2005 (WR2005) Version 1. Water Research Commission Project, (K5/1491)
- Naicker K, Cukrowska E, McCarthy TS (2003) Acid mine drainage arising from gold mining activity in Johannesburg, South Africa and environs. *Environ Poll* 122(1):29–40
- Ncube EJ, Schutte CF (2005) The occurrence of fluoride in South African groundwater: a water quality and health problem. *Water SA* 31(1):35–40
- Nengovhela AC, Yibas B, Ogola JS (2006) Characterisation of gold tailings dams of the Witwatersrand Basin with reference to their

- acid mine drainage potential, Johannesburg, South Africa. *Water SA*, 32(4)
- Okiongbo KS, Douglas RK (2015) Evaluation of major factors influencing the geochemistry of groundwater using graphical and multivariate statistical methods in Yenagoa city, Southern Nigeria. *Appl Water Sci* 5(1):27–37
- Piper AM (1944) A graphic procedure in the geochemical interpretation of water-analyses. *Eos Trans Am Geophys Union* 25(6):914–928
- Qin R, Wu Y, Xu Z, Xie D, Zhang C (2013) Assessing the impact of natural and anthropogenic activities on groundwater quality in coastal alluvial aquifers of the lower Liaoh River Plain, NE China. *Appl Geochem* 31:142–158
- Qian J, Wang L, Ma L, Lu Y, Zhao W, Zhang Y (2016) Multivariate statistical analysis of water chemistry in evaluating groundwater geochemical evolution and aquifer connectivity near a large coal mine, Anhui, China. *Environ Earth Sci* 75(9):747
- Robb LJ, Meyer FM (1995) The Witwatersrand Basin, South Africa: geological framework and mineralization processes. *Ore Geol Rev* 10(2):67–94
- Rouault M, Richard Y (2005) Intensity and spatial extent of droughts in southern Africa. *Geophys Res Lett* 32(15)
- Suk H, Lee KK (1999) Characterization of a ground water hydrochemical system through multivariate analysis: clustering into ground water zones. *Groundwater* 37(3):358–366
- Swart CJU, James AR, Kleywegt RJ, Stoch EJ (2003) The future of the dolomitic springs after mine closure on the Far West Rand, Gauteng, RSA. *Environ Geol* 44(7):751–770
- Taylor RG, Scanlon B, Döll P, Rodell M, Van Beek R, Wada Y, Longuevergne L, Leblanc M, Famiglietti JS, Edmunds M, Konikow L (2013) Ground water and climate change. *Nat Clim Change* 3(4):322
- Tutu H, McCarthy TS, Cukrowska E (2008) The chemical characteristics of acid mine drainage with particular reference to sources, distribution and remediation: the Witwatersrand Basin, South Africa as a case study. *Appl Geochem* 23(12):3666–3684
- Usunoff EJ, Guzmán-Guzmán A (1989) Multivariate analysis in hydrochemistry: an example of the use of factor and correspondence analyses. *Groundwater* 27(1):27–34
- Van der Westhuizen WA, De Bruijn H (2000) High temperature ash flow–wet sediment interaction in the Makwassie Formation, Ventersdorp Supergroup, South Africa. *Precamb Res* 101(2–4):341–351
- Van der Westhuizen WA, De Bruijn H, Meintjes PG (1991) The Ventersdorp supergroup: an overview. *J Afr Earth Sc* 13(1):83–105
- Vegter J (1995) Groundwater resources of South Africa: an explanation of a set of national groundwater maps. Water Research Commission
- Vörösmarty CJ, Green P, Salisbury J, Lammers RB (2000) Global water resources: vulnerability from climate change and population growth. *Science* 289(5477):284–288
- WHO (2004) Guidelines for drinking water quality. Vol 1 recommendations, 3rd ed. WHO, Geneva
- Wepener V, Van Dyk C, Bervoets L, O'Brien G, Covaci A, Cloete Y (2011) An assessment of the influence of multiple stressors on the Vaal River, South Africa. *Phys Chem Earth Parts A/B/C* 36(14–15):949–962
- Yidana SM, Bawoyobie P, Sakyi P, Fynn OF (2018) Evolutionary analysis of groundwater flow: application of multivariate statistical analysis to hydrochemical data in the Densu Basin, Ghana. *J Afr Earth Sci* 138:167–176