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A HYDROGEOLOGICAL INVESTIGATION OF GRAHAMSTOWN, ASSESSING BOTH THE DYNAMICS AND QUALITY OF THE LOCAL GROUNDWATER SYSTEM

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Thesis submitted to Rhodes University in fulfilment of the requirements for the degree of Master of Science

Submitted in March 2018

DECLARATION

I declare that this thesis, titled "A hydrogeological investigation of Grahamstown, assessing both the dynamics and quality of the local groundwater system", is my own work, and information from other publications is adequately referenced. It is being submitted in fulfilment of the requirements for the degree of Master of Science through the Institute for Water Research (IWR), Rhodes University.

Kyle Norman Smetherham ________________

Name of candidate Signature

Signed on the **25th** day of **March** 2018

ABSTRACT

In many parts of South Africa, complete allocation of surface water reservoirs together with current drought conditions has led to serious water shortages and subsequent awareness regarding the importance to save water. Grahamstown is no different, with water problems relating to low supply and high demand being compounded by insufficient treatment capacity and aging infrastructure. Groundwater is an alternative water resource that could potentially act as a supplementary and/or emergency supply to the town, reducing the reliability on surface reservoirs. Groundwater however, is a hidden resource and requires an understanding of various aquifer properties and continuous monitoring and modelling so not to permanently disrupt the natural system but rather achieve sustainable management.

Grahamstown is situated towards the northern extent of the Cape Fold Belt (CFB) system, within a synclinal fold structure. The local geology forms two local aquifer systems beneath Grahamstown that directly influence both the dynamics and quality of the groundwater. These underground reservoirs are the Witpoort and Dwyka aquifers and can be described as a semi-confined, fractured, quartzitic sandstone aquifer and an unconfined, fractured, tillite aquifer, respectively. Separating these aquifer systems is a shale aquitard, although due to the fractured nature of the rocks in the region there is most likely some groundwater interaction between them. Evaluation of geological formations together with the monitoring of 31 local boreholes presented a valuable conceptualisation of the local system and allowed for the application of methods to estimate recharge.

Recharge estimation is one of the most crucial factors when managing aquifer systems as it can be used to determine what proportion of rainfall contributes to the subsurface reservoir and therefore, the sustainable amount that can be extracted. Various methods have been developed to estimate recharge, however due to the uncertainty surrounding groundwater systems, especially fractured aquifers, it was important to apply multiple methods to validate results. The water-table fluctuation (WTF) and cumulative rainfall departure (CRD) are two methods that were used in the present study to determine recharge. These methods rely on water-table changes in boreholes and specifically how they respond to rainfall events. Along with the WTF and CRD methods, a modelling approach was also used to estimate recharge which focused on the dynamics of a natural groundwater outlet, termed the Fairview Spring.

This natural spring system is located just outside the main town of Grahamstown, within the Witpoort aquifer system, and is an important water resource to many residents due to poor supply and quality of municipal water. Monitoring the discharge of this spring allowed for the development of a model which attempts to recreate the discharge conditions observed. Along with groundwater recharge, other processes added to the model include evapotranspiration, storage, interflow spring outflow and groundwater outflow. Several different model simulation scenarios provided valuable insight into the greater groundwater dynamics.

In terms of groundwater quality, nine borehole samples and one spring sample were analysed for major ions (Ca, Na, K, Cl, Mg, SO_4, HCO_3), metals (Cu, Fe, Mn) as well as pH and electrical conductivity. Overall electrical conductivity levels and major ion concentrations were lower in the Witpoort aquifer indicating a better groundwater quality compared to that of the Dwyka aquifer. Of the three metals included in the analysis, Mn proved to be the most significant and the highest concentrations were produced for samples that intersected the shale aquitard unit, suggesting that Mn-containing groundwater is drawn from this geological layer.

Development of a supplementary and/or emergency groundwater supply requires careful consideration of the geology, quantity, quality, and recharge in the study site. All these aspects were assessed as well as deliberation into the potential infrastructural costs involved. Through conceptualisation of the system; evidence gathered during basic monitoring; and a simple spring model, the current study aimed to explore certain management strategies and recommend potential options going forward.

The hidden nature of the resource together with the heterogeneity of fracture networks creates an inevitable uncertainty surrounding the system. Proper development and management of the aquifer can only be achieved if the system is continually monitored, modelled and utilised sustainably.

ACKNOWLEDGEMENTS

In writing this section it signifies the end of a richly rewarding learning experience that has been a constant thought on my mind for the last two years. The submission of this thesis represents a massive achievement in my life as I officially end my 7-year academic career at Rhodes University!

Having said that I would like to take this opportunity to extend my thanks to all those that have contributed to the completion of this thesis.

To all my mates, especially the stooges I lived and worked with at St Andrews Prep, thank-you for all the constant moral support and general “I back you” aimed in my direction. A big thanks to James Bursey and Kashka Crampton for taking the odd spring measurement when I was not in town and a special mention and huge thanks to Wouter van der Walt for taking the time to share some of his extensive ArcGIS knowledge with me.

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As I soon came to realise, data is everything in research! Thank-you to all the borehole owners for allowing me to visit and take water-level measurements on a regular basis. All were hugely supportive and always interested in my work, I look forward to sharing the results with you all!

To my supervisors, Denis Hughes and Jane Tanner, thank-you for everything! Denis, your knowledge of hydrological models is unlike anyone I have met before and I really enjoyed and learnt tremendously from you during the development of the Fairview Spring Model. To Jane, your patience, guidance and willingness to help has always been hugely appreciated, thank-you!

I would like to say the biggest thank-you to my loving family whom without, none of this would have been possible. Stew and Ali, thank-you for always being such amazing role models in my life, I have learnt so much from both of you! To my incredible mother, thank-you for your constant love and never-ending support throughout, I would not have been able to come this far without you! Lastly to my late father, Rob Smetherham, I would like to dedicate this work to you. You are never gone and continue to live through me.

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LIST OF ABBREVIATIONS

CFB - Cape Fold Belt

CRD – Cumulative Rainfall Departure (method)

DWS – Department of Water and Sanitation

EC – Electrical Conductivity

ET – Actual evaporation

GWh – Groundwater height

GWL – Groundwater level

GWR – Groundwater recharge

GWQ – Groundwater discharge/outflow

IQ – Interflow discharge/outflow

IWRM – Integrated Water Resource Management

JKTW – James Kleynhans Treatment Works

K - Hydraulic conductivity

MAP – Mean annual precipitation

masl – Metres above sea level

MWTS – Mobile water treatment systems

NGS – National Groundwater Strategy

NSS – Near surface storage

NWA – National Water Act

P – Daily rainfall

RIB – Rainfall Infiltration Breakthrough (method)

RO – Reverse osmosis

S – Storativity

SGWCA – Subterranean Government Water Control Areas

SRTM – Shuttle Radar Topography Mission

T – Transmissivity

TDS – Total Dissolved Solids

TMG – Table Mountain Group

WTF – Water-table fluctuation (method)

WTW – Waainek Treatment Works

CHAPTER 1. BACKGROUND

1.1. Overview of study

South Africa is considered a semi-arid country with an average annual rainfall of 464 mm, compared to the world average of 860 mm, placing large pressure on water resources (Braune *et al*., 2014). Surface water is scarce, limited and completely allocated in many areas. The country's demand for potable water is increasing and its surface water supply is under pressure. Supplementary water resources need to be appropriately utilised to advance sustainably, one such alternative is groundwater. Currently groundwater is recognised as a strategic resource for meeting the requirements of rural needs, urban supply, food security and the environment (Braune *et al*., 2014). Although groundwater has and continues to be an important water resource to many communities, a lack of long-term monitoring and adequate modelling has resulted in poor, unsustainable management in many regions. Grahamstown does utilise groundwater but primarily as a private resource. The current research will explore whether groundwater has the potential to act as a supplementary addition to the current stressed municipal water supply.

1.2. Summary of study site

Grahamstown is situated in the Eastern Cape Province of South Africa and was the primary study site for this research project (Figure 1).

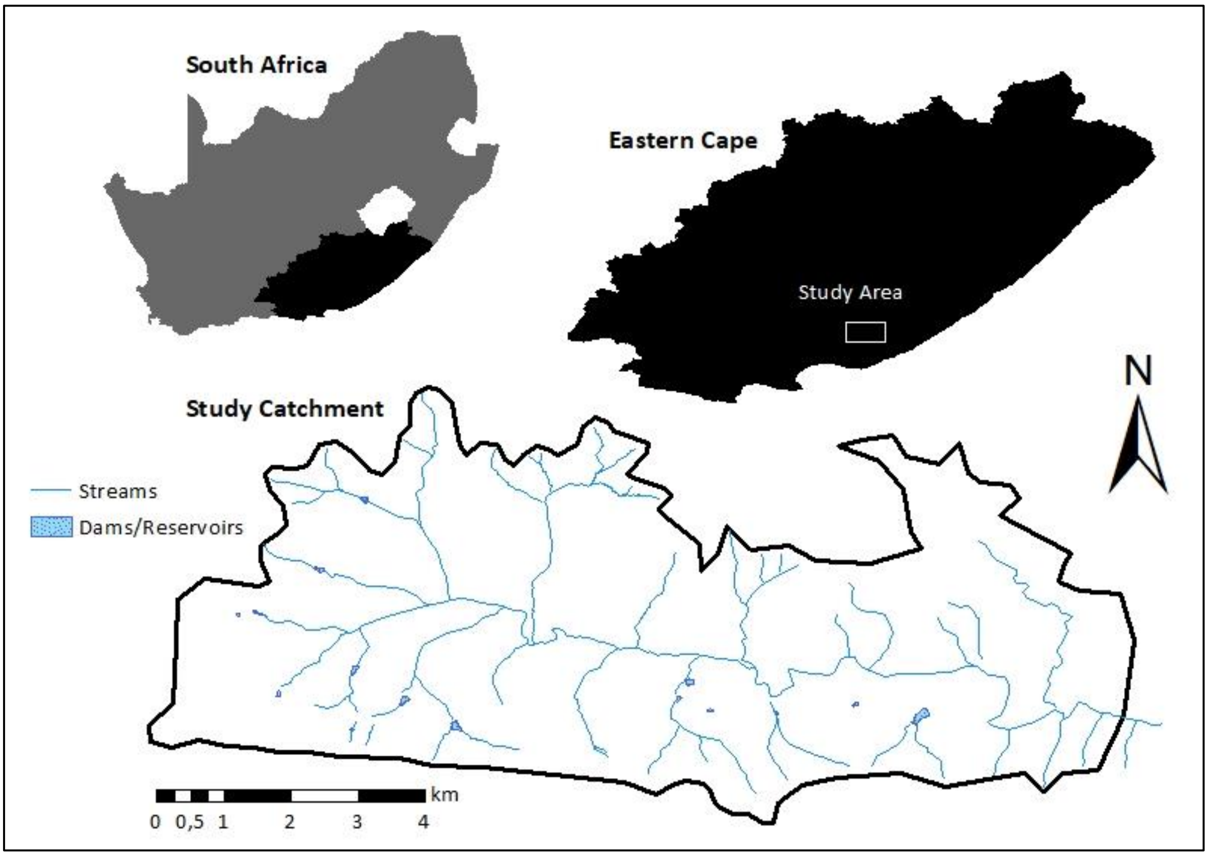


Figure 1 The position of the study area and catchment relative to South Africa.

The Grahamstown area (Figure 2) has moderate weather and has received a mean annual precipitation (MAP) of ~740 mm y^{-1} since 1997 (based on rainfall data collected by D. A. Hughes). The annual rainfall during 2016 was much lower than this average and amounted to 560 mm, the lowest since 1999, while over the 2017 period an annual rainfall of 669 mm occurred, also below this average. The lower rainfall resulted in drought conditions. Grahamstown's current water supplies are stored in reservoirs that are fed by two separate rivers systems, namely the Kariega and Orange Rivers, however high demand together with aging infrastructure are putting pressure on these primary water resources.

Groundwater beneath the study site moves and is stored in local aquifers made up of Cape and Karoo Supergroup sediments that were folded and fractured during intense crustal forces as the Cape Fold Belt system developed. The fractures increase hydraulic conductivity in aquifer systems as they form secondary permeability through which groundwater can flow. Fractured networks are abundant in the local geology and enhance the uncertainty involved with various aquifer dynamics, since they significantly increase aquifer heterogeneity. The current study could potentially be the first step in devising a long-term development and management plan that will provide a basis for more sustainable management strategies to develop.

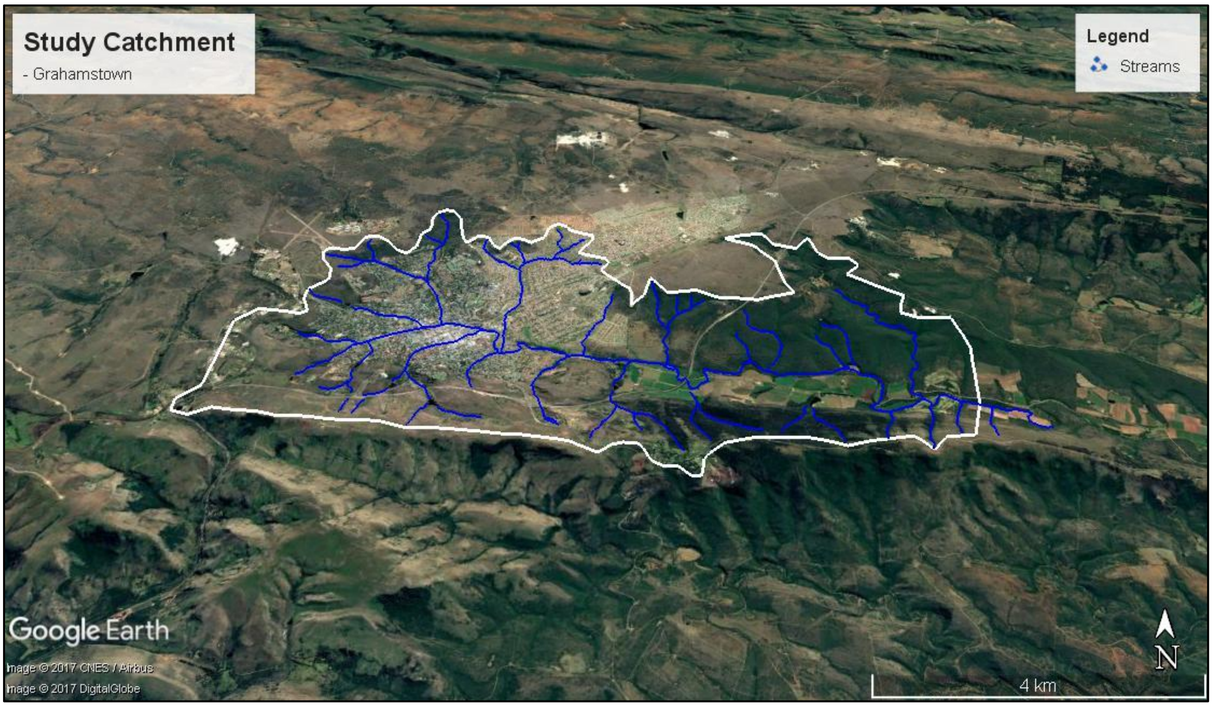


Figure 2 Google Earth^{PRO} image highlighting the Grahamstown study catchment.

1.3. Aims and associated objectives

1. Aim:

To develop a conceptual model of the local groundwater system to better understand dynamics and aid in applying appropriate recharge methods.

Associated objectives

- Investigate local geology to define aquifer systems.
- Map groundwater elevations from monitored boreholes to determine groundwater flow patterns.
- Examine structural characteristics of aquifers to evaluate groundwater movement.

- Assess abstraction and use from hydro-census completed by borehole owners.

2. Aim:

To reliably estimate the amount of recharge entering the groundwater system in Grahamstown.

Associated objectives:

- To monitor borehole water levels on a monthly basis.
- Compare the relationship between water-table fluctuations and rainfall events.
- Estimate specific yield/storativity for the study area.
- Use the conceptual model to assist in the selection of appropriate recharge estimation methods.

3. *Aim:*

To investigate if the groundwater quality within Grahamstown is appropriate for human use and whether treatment would be necessary if it were to be used as a supplementary water resource to residents.

Associated objectives:

- One-off collection of nine borehole samples and one spring water sample that can be analysed for major anions and cations as well as certain metals.
- Compare ion and metal concentrations to recommended water guidelines.

4. Aim:

To develop a small-scale water balance model of the Fairview Spring to aid in better understanding the greater Grahamstown groundwater dynamics.

Associated objectives:

- Monitor discharge rate at the Fairview Spring.
- Develop a conceptual model of the spring functioning.
- Apply a modified daily time-step version of the integrated Pitman Model to model the observed data.

- Form and test assumptions and explain their implications through model simulation.

5. *Aim:*

To produce an up-to-date record of Grahamstown's groundwater resources and provide the initial step to long-term monitoring and better management of the groundwater system.

Associated objectives:

- Examine the groundwater report compiled by Andrew Stone in 1985/86.
- Recommend a long-term management strategy which includes a monitoring plan and a potential drill site for supply boreholes.

1.4. Research problem

In many parts of South Africa, complete allocation of surface water reservoirs has led to serious water shortages and subsequent strict monitoring of potable water use. Grahamstown is no different as dam levels continue to drop while water consumption needs continue to grow. The problem is compounded by ongoing issues surrounding corroded water pipes, impacting both quantity and quality. An alternative water resource could act as a supplementary supply to the town, reducing the reliance on surface reservoirs, this resource could be groundwater. Groundwater use however, requires careful management to ensure the resource is protected in the long-term and remains sustainable. Recharge estimation is one of the most crucial factors when managing aquifer systems as it can be used to determine what proportion of rainfall contributes to the subsurface reservoir and therefore, the sustainable amount that can be extracted. Various methods have been developed to estimate recharge, however it is important to have a good conceptual understanding of the aquifer before applying a method. These methods can only be implemented if sufficient data is available, emphasising the need for reliable long-term monitoring of the aquifer systems. Pressure transducers should be installed within monitoring wells across key aquifers in relevant towns and cities in order to properly manage the groundwater reservoirs. Financial constraints make this difficult in the short-term and therefore, as in the present study, physical monitoring methods must bridge the initial gap.

1.5. Previous work

By the late 1960's geophysics was recognised as a common method used in the mining industry and the development of these techniques initiated an increase in training programs. The University of Pretoria led the way through the addition of a geophysics course to their post-graduate geology degree (Nel, 2013). Rhodes University was the only other establishment to offer groundwater training at the time and this was spear-headed by Andrew Stone, who presented the course through the Department of Geography (Nel, 2013). During 1985-1986 Andrew Stone produced a report titled the "Assessment of groundwater resources in the Grahamstown municipal area". The need for the report was prompted by an increasing water demand in the town due to drought conditions during 1983-1985. Although further surface water development was planned for the long-term via the development of a water transfer scheme from the Orange River via the Great Fish River, the project was only scheduled to be completed in 1992, hence the need for the investigation into the potential use of groundwater resources. The idea was that groundwater could 1) be used as an interim augmentation source until the water transfer scheme was properly established and 2) be developed as a supplementary/emergency supply post 1992.

It was decided that the groundwater investigation would incorporate three primary phases:

Phase 1: An initial phase to determine all existing groundwater sources in Grahamstown

Phase 2: A drilling and test pumping phase to determine the productivity of the groundwater reservoir within the municipal boundaries. This phase also included a chemical analysis of certain borehole water samples to examine groundwater quality.

Phase 3: An extended investigation of groundwater sources in the immediate surroundings of the town. This phase was not undertaken.

A total of 120 boreholes were located during the phase 1 survey on existing groundwater supplies and, according to Stone (1986), 25% of Grahamstown's water supply was of a groundwater origin. This seems to be an over-exaggeration, however a lower population and the lack of surface water storage and distribution infrastructure (particularly to the township) at the time may have increased the reliance on groundwater, therefore supporting this approximation. Furthermore, the evaluation could have included the groundwater volume pumped for playing-field irrigation purposes and thus elevating the overall proportion supplied.

During phase 2 it was found that most of the groundwater sources could not be used for domestic consumption due to elevated levels of total dissolved solids (TDS), limiting the use of groundwater to irrigational needs. Not all groundwater tested was of poor drinking quality and water samples from boreholes located on the high-lying ridge that runs adjacent to Grahamstown showed to have low TDS. Apart from the groundwater quality issues in certain area the overall groundwater supply was construed as positive, and it was suggested that the resource held "considerable untapped potential". This interpretation of groundwater quantity was assessed through several single-well pumping tests which were also conducted during this phase and provided insights into the sustainable yields through inspection of drawdown and recovery at that immediate area of the aquifer. Other aquifer properties namely, hydraulic conductivity (K), transmissivity (T) and storativity (S) were not added into the report (Stone, 1985).

Phase 3 does not seem to have developed any further.

In August 1985, a report was developed by Stewart, Sviridov and Oliver Consulting Engineers termed the "Report on underground water supply". This report focused on the infrastructure that would be necessary to accommodate the addition of groundwater into the Council's reticulation system. The recommendations in this report were based on Andrew Stone's initial results and information relating to the quantity and quality of the groundwater. These results would later be included in his full report which he completed the following year (Stone, 1986).

At the time when this infrastructural report was being compiled a total of ten boreholes had been drilled, of which four were said to have poor yields while six had yields that were worth developing. Three boreholes were chosen for pumping tests to better evaluate their sustainable yields which ranged from 2.4 $l\ s^{-1}$ to 6.8 $l\ s^{-1}$. In terms of quality, the same three boreholes were chemically analysed for major ions and certain metals. The test showed that two of the boreholes had elevated levels of dissolved solids, averaging 2000 mg l^{-1} and although one showed much lower dissolved solids at only 200 mg l^{-1}, the iron content of 7.5 mg l^{-1} was well above the recommended limit of 1 mg l^{-1}. The main issues were therefore associated with high salinity in certain areas and excess iron in others. The solution proposed was to dilute the high salinity groundwater by either pumping it into one of the Council's surface reservoirs where it could mix with water already treated at Waainek or otherwise diluting at the borehole somehow. Regarding the groundwater with high iron levels it was suggested that, although saline dilution was not required, the excess iron would still need to be removed before it could join the reticulation system. The most economical solution proposed was to pump the water directly to the ‘Town Filters’ (Waainek treatment works) and by allowing some air into the pump the iron could oxidise. The precipitated iron could then be filtered out by the filters and the water chlorinated thereafter.

Although many residents have resorted to drilling boreholes on their property for personal needs, the infrastructural plans that were suggested in the report have not been implemented by the municipality and it remains a relatively private water resource in the town.

CHAPTER 2. INTRODUCTION

2.1. Groundwater systems in South Africa

2.1.1. Aquifer types

South Africa boasts rich sources of underground water stored within primary, secondary and dolomitic aquifer systems which are classified into major, minor and poor aquifer systems (Parsons and Conrad, 1998) (Table 1). Primary aquifers store and move groundwater through intergranular pore spaces which develop during rock formation, while secondary aquifers store and move groundwater through fractures and other conduits formed after the rock lithified. Dolomite is essentially an impermeable sedimentary carbonate rock, however, through structural and weathering processes a combination of faults, fractures, joints and solution cavities have formed in which groundwater can flow and be stored. The ability of water to move in these aquifers, namely the permeability, has developed as geological and hydrological forces alter the rock over time. Furthermore, the variability of physical structures and chemical composition between different rocks can influence aquifer properties. The Department of Water and Sanitation (DWS) has classified the aquifer systems in South Africa as major, minor and poor aquifers (Table 1).

Table 1 Aquifer classification in South Africa (revised from DWS, 2016).

	AQUIFER TYPE	**GENERAL LOCATION**
MAJOR AQUIFERS (18% coverage)	Primary	Along coastal areas
	Dolomite	Areas in Gauteng, Mpumalanga, Northern Cape and North West Province
	Primary and/or secondary	Table Mountain Group rocks, Parts of Karoo Supergroup
MINOR AQUIFERS (67% coverage)	Primary and/or secondary - variable yield and quality	Occur extensively – supply small towns such as Nylstroom, Richmond and **Grahamstown**
POOR AQUIFERS (15% coverage)	Primary and/or secondary - low yielding, poor quality	Vital to smaller communities and common in dry northern and western parts of South Africa

2.1.2. Governance

Prior to the amendments made to the 1998 National Water Act (NWA) there was no need for private groundwater users to supply the Department with groundwater use, level and quality information, unless they were situated within the Subterranean Government Water Control Areas (SGWCA). This led to the development of the National Groundwater Strategy (NGS) in the early 2000's. The strategy formed on the view that groundwater should be considered a resource that can open numerous benefits and should be managed as part of Integrated Water Resource Management (IWRM). The resource has played and continues to play an integral part in providing and meeting basic needs for all, although overall management should be improved (Pietersen *et al*., 2011).

2.1.3. Utilisation

In terms of registering and licensing groundwater use it should be noted that individuals do not need permission to simply drill and install a borehole. However, if the borehole is successful and the usage exceeds certain limits then it is necessary to register this water use with the DWS (Bertram, 2016). The following utilisation guideline is used to establish whether the registration and licensing of a borehole is necessary:

Schedule 1: The National Water Act (NWA) allows a land owner the right to use a 'reasonable' amount of groundwater from an aquifer on their property without requiring registration or licensing (Bertram, 2016). The reasonable amount can be defined under Schedule 1 as:

- Normal domestic use
- Irrigation of a small garden
- Water for animals which graze within the capacity of the land (Bertram, 2016).

The above mentioned is likely to vary from owner to owner, however if a person is using more than 10 000 litres per day their utilisation should be registered (Bertram, 2016).

General Authorisation: General Authorisation alleviates the need to issue water licenses and allows permission for common, but low-impact, water use. Although the water use may still require registration.

Above General Authorisation: For users that exceed the General Authorisation limit a licence is required (Bertram, 2016).

2.1.4. Quality

The DWS has developed a groundwater quality map for South Africa based on electrical conductivity (EC) measurements. Electrical conductivity is a measure of the water's ability to transmit electrical flow and is directly proportional to ions within the water. Generally, the higher the electrical conductivity the poorer the quality of water. According to this DWS map most groundwater in South Africa has an electrical conductivity ranging between 0-150 milliSiemens per metre (mS m^{-1}), and is predominantly found in central parts, extending to the northern and western borders. Groundwater within this EC range is considered good quality with no significant health effects, although a slightly salty taste may be present if EC levels are at the upper extent of this range. Grahamstown is portrayed on the map to have relatively high EC levels starting from 370 mS m^{-1} and even exceeding 520 mS m^{-1} in areas, which represents extremely salty and bitter groundwater quality. Due to the extensive area covered by this map, the levels may be generalised to a degree and don't necessarily provide an accurate representation of the local groundwater quality.

2.1.5. Groundwater characteristics of other places with similar geology to study site

Dwyka Group

The Dwyka Group is not looked at as an ideal groundwater aquifer and in general it is considered a poor target for groundwater exploitation. The nature of its deposition and chemical components both negatively affect its quantity and quality. An assessment of the Umkomazi area in Kwa-Zulu Natal revealed that the Dwyka Tillite produced water with the highest concentration of ions out of all units in the study site (Sherman, 1998). However, this quality varies with location and according to Bond (1946), groundwater from Dwyka Group aquifers is significantly higher in the Western Cape and North West areas compared to those found in Natal. On average Dwyka groundwater in the Kwa-Zulu Natal Province had average total dissolved solids of 440 mg l^{-1}, in contrast to 1500 mg l^{-1} in areas outside of Natal. Two explanations for this are firstly, higher and more frequent rainfall in Natal and secondly, the Dwyka Group outside of Natal may have been deposited in brackish water or perhaps experienced some sort of sea flooding post formation (Bond, 1946). In a study which focused on the eastern Kalahari region the Dwyka Group was characterised as 'fractured sedimentary rock'. The primary porosity and permeability are extremely low in this unit and without the presence of secondary induced porosity they would be considered aquitards. According to King (1995) these fractured Dwyka tillites are rated as one of the best development potentials to target in Kwa-Zulu Natal. Transmissivity values of the Dwyka Group vary from 5 m^2 d^{-1} to 22 m^2 d^{-1} in fractured units (Dondo *et al*., 2010). Similarly, borehole yields are generally low and range from 0.1-2.0 l s^{-1} in unfractured units but are higher, between 2.0-5.0 l s^{-1}, when secondary porosity and permeability are present (van Veelen *et al*., 2009; Dondo *et al*, 2010).

Witpoort Formation

The quartzitic lithology and fractured nature of the Witpoort Formation make it comparable to that of the Table Mountain Group (TMG), however its groundwater potential has been largely ignored, perhaps due to the ease and low cost of developing coastal aquifers (Mouton, 2004). During a groundwater study along the Albany Coast in the Eastern Cape, an analysis of 272 boreholes, drilled into the Witpoort Formation, indicated an average yield of 0.49 l s^{-1}, with 10% producing yields of more than 2.8 l s^{-1} (Mouton, 2004). Higher yields, between 15-25 l s^{-1}, have also been recorded in the area and highlight the potential that this aquifer system holds (Mouton, 2004). Several abstraction schemes from the TMG in the Western Cape have also yielded positive results, all ranging from between 20-50 l s^{-1} (Parsons, 2002; Weaver *et al*., 1999; Rosewarne, 2002). Natural springs, such as the Kariega Spring, are also commonly associated with the Witpoort Formation (Mouton, 2004). This spring is thought to tap fracture networks and produce yields of 15-20 l s^{-1} (Mouton, 2004). In terms of quality, the Witpoort Formation has been known to hold water that is slightly acidic and iron-rich. The low pH often causes issues with piping due to corrosive action (Mouton, 2004). According to Smart and Tredoux (2002) average EC levels of TMG groundwater are low and range between 20 and 50 mS m^{-1}. Generally, the TMG has been known to hold high quality groundwater with low salinity and, like the Witpoort Formation, this is attributed to the quartzitic lithology and abundance of fracture networks.

2.2. Regional geology

About 550 - 330 million years ago (Ma), during the Cambrian-Ordovician periods a rift valley developed on the southern margin of Gondwana (Figure 3). The rift formed due to north-south extensional forces causing a depression in the land surface that flooded and established the Agulhas Sea. Over time sediment was deposited and accumulated in this sea, forming the Cape Supergroup sedimentary sequence (McCarthy and Rubidge, 2005).

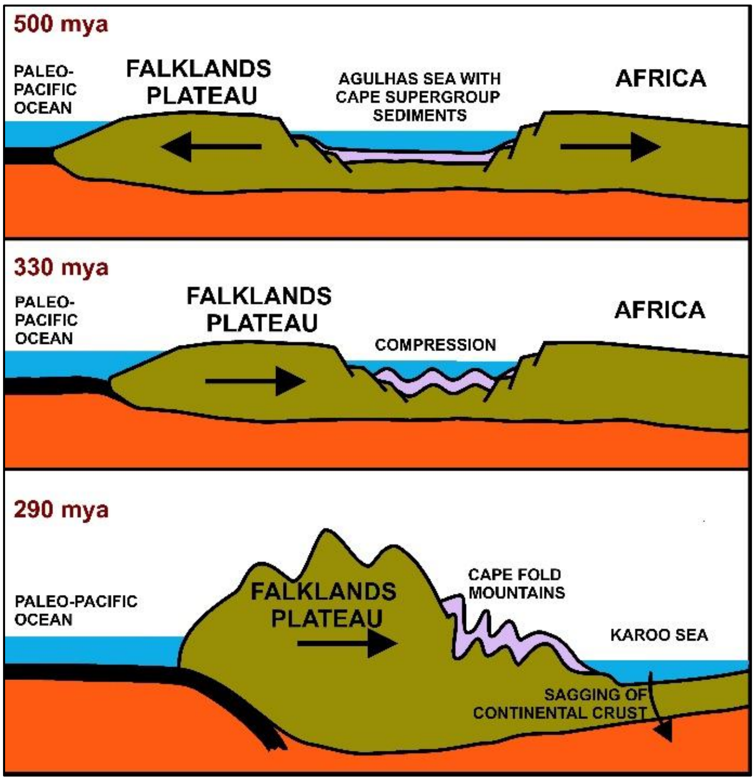


Figure 3 Geological time series highlighting the major events that formed and shaped the Cape and Karoo Supergroups (McCarthy and Rubidge, 2005).

Starting 330 Ma a subduction zone developed south of Gondwana and subsequently initiated closure of the rift valley (Figure 3) (McCarthy and Rubidge, 2005). The shift to compressional forces caused Cape Supergroup sediments to uplift forming the Cape Fold Belt (CFB) (Compton, 2004). The increased crustal weight caused the southern portion of Gondwana to sag, depressing the land surface just north of the CFB and creating the Karoo Sea (Catuneanu, 2004).

Between 300 - 200 Ma Karoo sediments were deposited and accumulated in this sea forming the Karoo Supergroup sedimentary sequence (Catuneanu, 2004) (Figure 3). Following the formation of the Karoo Sea, south Gondwana drifted as a continental mass over the South Pole zone and a major ice sheet formed over the Karoo in place of the sea (McCarthy and Rubidge, 2005; Truswell, 1977). As it melted over time, sediments were deposited and accumulated to form the Dwyka Group (McCarthy and Rubidge, 2005; Truswell, 1977). The landscape we see in and around the study area has been shaped by these ancient geological events and represents the current erosional surface after years of weathering and transport of younger, overlying strata (Figure 4).

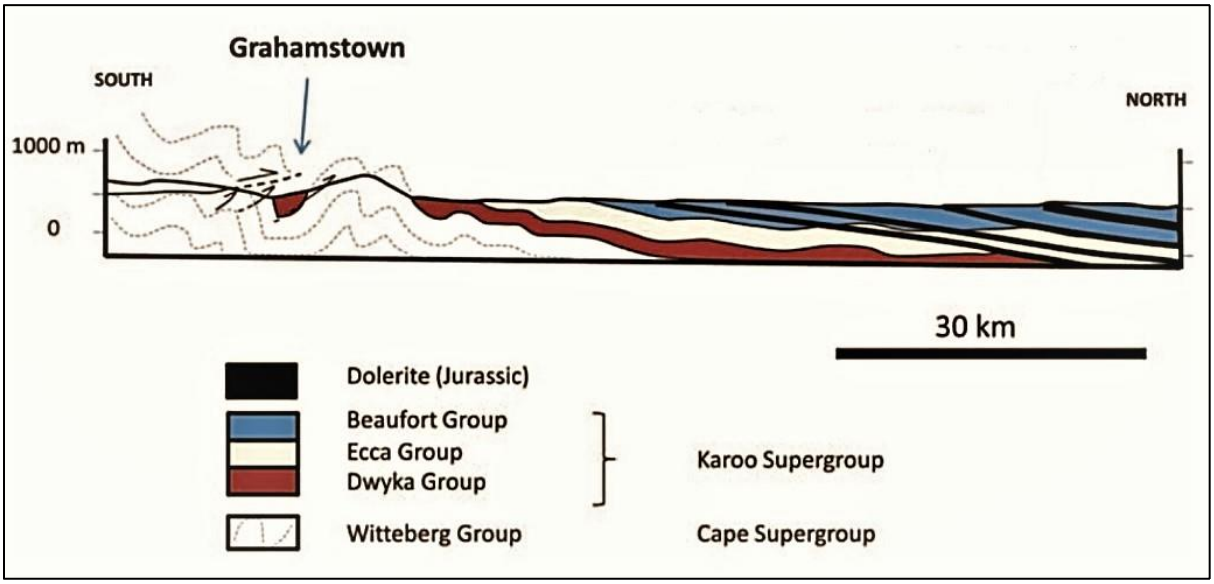


Figure 4 Cross-sectional sketch indicating the northernmost compressional extent experienced during the development of the Cape Fold Belt (Booth and Goedhart, 2014).

Grahamstown is positioned at the northern extent of the Cape Fold Belt and the compressional forces that were present during formation of this system are evidenced by the folding nature of the rocks in the region (Figure 4).

2.3. Regional hydrogeology

A considerable amount of South Africa's groundwater occurs and flows within fractures and fissures of consolidated hard rocks considered to be 'fractured' aquifers. The deformation processes, namely the orogenesis of the CFB and subsequent continental uplift, weathering and erosion all contributed to the development of the regional groundwater environment in relation to the study site. During the orogenesis event, more competent rocks containing significant arenaceous material underwent brittle deformation, creating fractures and fissures as they folded, while certain incompetent layers, namely shales, behaved in a more plastic manner during the deformation and were therefore less inclined to fracture. The competent contrast between various rock types characterises permeable and impermeable units, namely aquifers and aquitards. Furthermore, the intense pressures of the event led to the metamorphism and subsequent brittle deformation of certain rocks, altering the way by which groundwater moves through them.

There is evidence that Eastern Cape groundwater systems have regional processes of recharge and flow. The TMG, which is comparative to the Witpoort Group found in the study site, is one of three major regional aquifers in South Africa along with dolomite and the Karoo dolerite. There is a common understanding that TMG fractured aquifers are highly anisotropic on both regional and local scales due to the complexity of various hydraulic properties. Therefore, TMG related groundwater projects have tended to focus on more site-specific and local approaches to avoid this uncertainty (Lin, 2007). The lack of information and complexity around considering a regional system steered the current study to assume a closed groundwater system within a surface water boundary.

2.4. Fractured aquifers

Fractures occur in all rocks, both subsurface and surface, and are common features of many aquifers (Kuchuk *et al*., 2014), especially in South Africa. Other types include 'intergranular' and 'fractured/intergranular' aquifers. Major geological events generate forces capable of exerting immense stress on rocks to the point where strain occurs to produce secondary porosity. The degree of secondary porosity depends on the rock type and stress involved, nevertheless rocks with a higher fracture density will result in higher yielding groundwater zones (David *et al*., 2014). Generally, in a fold system, anticlines are zones of tension while synclines are zones of compression. Typically tension zones will have more open fractures to store and transmit groundwater. The fractured network may form due to stresses such as intense crustal weight, high fluid pressure, tectonic activity as well as thermal loading (Kuchuk *et al*., 2014). Consequently, a variety of fractures may form at multiple scales ranging from microscopic to continental (Kuchuk *et al*., 2014). Fractured aquifers can store and transmit important quantities of fresh water resources however, these aquifers are complex, consisting of numerous components that may differ independently from system to system and are therefore known to be highly heterogeneous (Wang *et al*., 2016; Zha *et al*., 2015; David *et al*., 2014). The heterogeneity is caused by inconsistencies in hydraulic properties as the fractures generally have a higher permeability than the surrounding matrix. Furthermore, the connectivity of fractures is often inconsistent from one area to the next and it is not uncommon that the distribution of groundwater, even over proximal regions, may be largely different (David *et al*., 2014; Zha *et al*., 2015). As a result, fractured aquifer systems are often difficult to characterise accurately, allowing for a degree of inevitable uncertainty (Zha *et al*., 2015). Understanding the location, distribution and connectivity of fractures in an area will help to make realistic predictions regarding the groundwater system dynamics (Wang *et al*., 2016).

2.4.1. Classification of fractured reservoirs

Fractures refer to multiscale joints, faults, fissures and other discontinuities within a lithologic unit (Lin *et al*., 2012). Depending on certain properties, namely geometric or physical, these fractures can either enhance groundwater flow by creating conduits, or otherwise restrict flow, acting as barriers that limit groundwater flow (Lin *et al*., 2012). Connectivity is a key parameter in controlling how groundwater moves in a fractured aquifer (Lin *et al*., 2012). To accurately conceptualise fractured groundwater systems it is important that one gains a comprehensive understanding of both the pores and fracture corridors of the specific aquifer environment (Kuchuk *et al*., 2014). This is a complex task and cannot be achieved by a single observation or measurement however, Kuchuk *et al*., (2014) describe four fractured aquifer categories to help ease interpretation. These are as follows:

1. *Continuously fractured reservoirs*

The fractures are all interconnected and continuous, producing a relatively high hydraulic conductivity. Furthermore, the surrounding matrix has a primary porosity which can store most of the groundwater. Consequently, the aquifer will have both fracture and matrix components that have distinct porosities and permeability's (Kuchuk *et al*., 2014).

2. *Discretely fractured reservoirs*

The fractures in this case are not entirely connected and only a limited number are able to form a continuous network. The matrix also has a primary porosity and once again is key is determining the overall storage capacity. Formations that consist of alternating fractured and non-fractured layers should also be included in this category (Kuchuk *et al*., 2014).

3. *Compartmentalised reservoirs*

The fractures are isolated and do not have the ability to transmit groundwater. The permeability and storage capacity are both principally controlled by the primary porosity of the matrix (Kuchuk *et al*., 2014).

4. Unconventional basement reservoirs

The fractures are all hydraulically connected while the matrix has no permeability or porosity. Therefore, the fractures control the groundwater flow and dynamics entirely (Kuchuk *et al*., 2014).

2.4.2. Characterising fractures

Fitts (2013) highlights the difficulty when interpreting flow in fractured rocks as the distribution and properties of discrete fractures are relatively unknown. This together with the flow in larger fractures being generally turbulent as opposed to laminar, limit the use of Darcy's law which is a fundamental basis in hydrogeology. Fitts (2013) describes two separate approaches that may be used when considering groundwater movement in fractured rocks, either to assess the flow in discrete fractures or otherwise to treat the fractured system as a continuum. The discrete fracture approach is better used in more site-specific situations where the fracture spacing is similar in scale to the scale of the study focus area. It is necessary to identify all fracture characteristics as a key step when evaluating geotechnical problems such as rock slope stability and seepage related issues. Alternatively, the continuum approach does not focus on specific fractures but rather considers the aquifer to have a homogenous medium with relatively equal hydraulic conductivities. Fitts (2013) adds that when the continuum approach is used the problem at hand should be of a larger, macroscopic scale. Due to the limited availability of certain instruments for the present study a continuum approach may be more relevant although analysis of fracture characteristics, where possible, will only benefit the overall understanding of the system and therefore should be incorporated.

A degree of heterogeneity is present in all aquifer investigations and can impact the dynamics of the system. When examining fractured aquifer formations, the fundamental stem of heterogeneity arises from large variation in spatial hydraulic conductivity which directly relates to groundwater flow rate. Hypothetically water within a certain fractured aquifer may flow through the conduits with high velocity however, it is possible that the fractures only make up a small part of the otherwise impermeable aquifer, therefore making overall average volumetric flow rates low (Fitts, 2013).

2.4.3. Fracture classification

“All aquifers can be considered to fall on a continuum between porous media systems and conduit systems” (Akoachere and van Tonder, 2009). At the porous end, heterogeneity in groundwater flows derive from differences in grain size creating preferential flow paths, an example being tillite such as that of the Dwyka Group. Heterogeneity at the extreme fractured end has already been mentioned above relating to spatial variability in hydraulic conductivity (Fitts, 2013). In attempting to reduce uncertainty in fractured aquifers it is useful to investigate the characteristics of fractures. Outcrops provide visual examples of fracture networks in an area however, it is important to consider that firstly, stress release may have influenced surface rocks but not necessarily subsurface rocks and secondly, outcrops are limited which may form a biased outlook when applied to the whole study site. Nevertheless, Cook (2003) states that classification should include some or all the following fracture features:

Number of sets:

A set is a group of fractures that all have a preferred orientation. Combining fractures into sets will make it easier to make general assumptions about the overall fracture system.

Orientation:

When investigating fracture orientation, the most applied method is to compare core fracture logs with geophysical borehole results however, in the present study core and geophysical data is not readily available. In highly fractured rocks the orientation of fractures may vary quite significantly, and it may be more useful to describe the orientation in relation to the bedding planes.

Spacing:

Fracture spacing refers to the perpendicular distance between two parallel fractures in a set.

Fracture length:

It is difficult to obtain an exact measurement of fracture length due to unknown variations along strike and dip. Consequently, the measurement may only provide an apparent fracture length compared to the true length which will impact the reliability of the results.

Fracture connectivity:

Groundwater flow is greatly affected by the interconnectedness of fractures. An increase in fracture length and/or fracture density will increase the connectivity of fractures by enhancing the probability of fractures intersecting. The connectivity can be represented as ratios of three different fracture types:

1. Individual fractures that end in the rock matrix (blind fractures)
2. Fractures that cross-cut other fractures
3. Fractures that share a common edge with other fractures

Aperture:

Aperture relates to the distance between rock walls of an open fracture. This can be filled by air, water or precipitated minerals. Accurate examination of fracture aperture may be difficult due to stress release caused by erosional removal of overburden pressures. Aperture observation can therefore be unreliable and misleading depending on the outcrop.

Surface roughness:

It is uncommon for fracture walls to be flat smooth surfaces. Often these surfaces are irregular and possess a certain roughness. These irregularities can reduce fluid flow leading to preferential flow paths. Surface roughness is assessed by comparing an exposed, unaltered fracture wall to a set of predetermined profiles, therefore assigning the fracture (set) a joint roughness coefficient, ranging from 0 to 20.

2.5. Aquifer recharge

Recharge is broadly described as the process by which water enters or increments the groundwater system, it is the fundamental driver influencing aquifer dynamics (Healy and Cook, 2002; Gleeson *et al*., 2009). According to Beekman and Xu (2003) there are four main types of recharge:

1. Downward percolation of water through the unsaturated zone and into the groundwater reservoir.
2. Flow within the aquifer, either laterally or vertically.

3. Water exiting surface water bodies and entering the saturated zone. Proximal groundwater extraction may accelerate this process (induced recharge).
4. Artificial recharge either by injection of water into boreholes or ponds designed to allow for downward infiltration.

The first mode mentioned is generally the most common in arid and semi-arid climatic zones and accounts for sources such as rainfall, surface water bodies and irrigation-related water losses (Beekman and Xu, 2003). Quantification of recharge is essential for proper resource modelling, planning, management and use as it offers a calculated approach regarding sustainable groundwater extraction from an aquifer system (Healy and Cook, 2002; Beekman and Xu, 2003; Ahmadi *et al*., 2014; Rivard *et al*., 2013). This is particularly relevant in semi-arid countries such as South Africa where evapotranspiration is high and recharge rates are generally low (Beekman and Xu, 2003; Sun *et al*., 2013; Ahmadi *et al*., 2014). Recharge estimation however, is difficult to determine accurately and requires that multiple methods be applied to enhance credibility (Beekman and Xu, 2003). Several recharge estimation methods exist, though not all can be applied in every case due to certain advantages and drawbacks associated with each (Healy and Cook, 2002; Rivard *et al*., 2013). Furthermore, certain methods require data that is not always available and accessible. It is important to develop a concise conceptual model of an area so that appropriate methods can be used.

2.5.1. Recharge complexity

The heterogeneity of fractured rock aquifers makes it complicated to accurately determine recharge as variable fracture flows, unknown fracture connectivity, matrix transmissivity and differing hydraulic responses all contribute uncertainty (Cai and Ofterdinger, 2016; Gleeson *et al*., 2009). Fractured aquifers seldom reveal a uniform water-table enhancing the difficulty in determining local groundwater flow paths (Lin *et al*., 2012). Nevertheless, any discrepancies together with field evidence should provide indications into certain fracture properties and distribution. It is important that a combination of recharge estimation methods along with pumping tests and hydrogeochemical data, if available, are used when examining and interpreting fractured aquifer networks and other hydraulic properties (Cai and Ofterdinger, 2016; David *et al*., 2014).

2.5.2. Recharge methods

Numerous methods have been formed to estimate recharge, though no single method holds enough authority to produce a completely accurate estimation. It therefore becomes necessary to use a multitude of methods when attempting to determine recharge in the hope that results will be consistent. The methods cover a vast range, from differing temporal and spatial scales to variations in complexity and cost, highlighting the importance of applying appropriate methods (Healy and Cook, 2002). Various recharge methods used in Southern Africa as well as related references are summarised in Table 2 below. The methods are separated into four zones, namely the surface water, unsaturated, saturated-unsaturated and saturated zones. The present study will focus of methods related to the saturated-unsaturated zone, in other words the zone where fluctuations in the water-table occur and can be measured.

Table 2 Summary of recharge estimation methods used in arid parts of Southern Africa taken from Beekman and Xu, 2003.

Zone	Approach	Method	Principle	References
Surface Water	Physical	HS	Stream hydrograph separation: outflow, evapotranspiration and abstraction balances recharge	10
		CWB	Recharge derived from difference in flow upstream and downstream accounting for evapotranspiration, in- and outflow and channel storage change	4
		WM	Numerical rainfall-runoff modelling; recharge estimated as a residual term	5
Unsaturated	Physical	Lysimeter	Drainage proportional to moisture flux / recharge	2
		UFM	Unsaturated flow simulation e.g. by using numerical solutions to Richards equation	2, 4
		ZFP	Soil moisture storage changes below ZFP (zero vertical hydraulic gradient) proportional to moisture flux / recharge	2, 3, 6
	Tracer	CMB	Chloride Mass Balance – Profiling: drainage inversely proportional to Cl in pore water	1, 2, 3, 6
		Historical	Vertical distribution of tracer as a result of activities in the past (^{3}H)	1, 2, 3, 6
Saturated – Unsaturated	Physical	CRD	Water level response from recharge proportional to cumulative rainfall departure	2, 9
		EARTH	Lumped distributed model simulating water level fluctuations by coupling climatic, soil moisture and groundwater level data	3, 7
		WTF	Water level response proportional to recharge / discharge	2
	Tracer	CMB	Amount of Cl into the system balanced by amount of Cl out of the system for negligible surface runoff / runon	1, 2, 3, 6
Saturated	Physical	GM	Recharge inversely derived from numerical modeling groundwater flow and calibrating on hydraulic heads / groundwater ages	2, 3
		SVF	Water balance over time based on averaged groundwater levels from monitoring boreholes	2
		EV-SF	Water balance at catchment scale	2
	Tracer	GD	Age gradient derived from tracers, inversely proportional to recharge; Recharge unconfined aquifer based on vertical age gradient (^{3}H, CFCs, $^{3}H/^{3}He$); Recharge confined aquifer based on horizontal age gradient (^{14}C)	1, 6, 8

HS:	Hydrograph Separation – Baseflow	**EARTH**:	Extended model for Aquifer Recharge and Moisture Transport through Unsaturated Hardrock
CWB:	Channel Water Budget		
WM:	Watershed Modelling	**WTF**:	Water Table Fluctuation
UFM:	Unsaturated Flow Modelling	**GM**:	Groundwater modelling
ZFP:	Zero Flux Plane	**SVF**:	Saturated Volume Fluctuation
CMB:	Chloride Mass Balance	**EV-SF**:	Equal Volume - Spring Flow
CRD:	Cumulative Rainfall Departure	**GD**:	Groundwater Dating

[1]Beekman et al., 1996	[4]Lerner et al., 1990	[7]Van der Lee and Gehrels, 1997	[10]Xu et al., 2002
[2]Bredenkamp et al., 1995	[5]Sami and Hughes, 1996	[8]Weaver and Talma, 1999	
[3]Gieske, 1992	[6]Selaolo, 1998	[9]Xu and Van Tonder, 2001	

A rise in the water-table is direct evidence that groundwater recharge has occurred in some form (van Wyk *et al*., 2011). The water-table fluctuation (WTF) and cumulative rainfall departure (CRD) methods rely on the postulation that rainfall events are the primary cause of water-table fluctuations and it is this relationship that is used to estimate recharge (van Wyk *et al*., 2011). They are ideal methods to apply in the current study as they are cost effective, require few data sets and have previously been applied to fractured aquifers in South Africa, namely the Table Mountain Group sandstone.

When a precipitation event occurs, there are several factors at play which determine the portion of rainfall, if any, that infiltrates down into the subsurface and reaches the saturated zone. These factors may include, rainfall intensity and duration, surface topography, geology, moisture content, hydraulic conductivity as well as others. Once all these components have been accounted for it becomes extremely difficult and complex to produce an accurate recharge result and therefore recharge estimates based on infiltration and unsaturated zone studies are less favoured. For this reason, hydrogeologists generally investigate the direct relation between rainfall and the rise and fall of the water-table. Depending on the level of the water-table in relation to the land surface there may be cases where the water-table responds rapidly and other cases where it takes several days, months or years. Thus, it is vital that any fluctuation in the water level can be positively related to the rainfall event/s that caused the change.

2.5.3. Groundwater storage

Water within an aquifer is affected by changes in both the effective stress and pore water pressures in the subsurface. The effective stress relates to the expansion and contraction of the solid rock matrix while the pore water pressure involves the expansion and contraction of the water within the pore spaces. These two parameters determine the amount of water stored in the groundwater reservoir and vary with fluctuations in hydraulic head and associated water pressure that occur during transient flow. According to Fitts (2013) these two parameters are the only processes that can change the amount of water stored within a confined aquifer and is termed the elastic storage. Unconfined aquifers are slightly different because of their part saturated, part unsaturated property and therefore a third parameter accompanies the matrix and water compressional forces. The third force involves the rise and fall of the water boundary between the saturated and unsaturated zones and is known as water-table storage or phreatic storage (Fitts, 2013).

The present study will focus on the second type involving water-table storage within unconfined aquifers in the hope that it will form a basis for determining aquifer recharge. The storativity within an unconfined aquifer is known as the specific yield (S_y) which can be defined as the decrease in water volume stored within a column of water per unit decline in head and can be expressed as either a ratio or percentage of the aquifer volume. Capillary forces hold water onto mineral surfaces in the unsaturated zone above the water-table and therefore the water that is drained when there is a decrease in head will always be less than the porosity of the rock matrix (Fitts, 2013). Having said this, specific yield can be simply interpreted as the difference in water contents between the saturated and unsaturated zones.

The heterogeneity of fractured aquifers will provide limitations in determining an accurate storativity estimate however, if the fracture networks are abundant and well connected it may be useful to assume a uniform porosity to provide an initial estimate of the storativity of the aquifer. Due to the prominent secondary porosity of the quartzitic sandstone aquifer in the study site, it is suggested that groundwater movement will be focused through these fractures, limiting water remaining on mineral surfaces when the head falls. Therefore, specific yield will assumedly be the same or just less than the averaged porosity of the fractured aquifer. Due to the geologic nature of the Dwyka aquifer, it is proposed to have a higher storativity compared to the Witpoort aquifer as groundwater can move though both openings between rock fragments as well as fractures. The current study investigates system dynamics of the Fairview Spring of which near surface storativity is an important parameter within the unsaturated and saturated zones. The weathered nature of the rocks in the unsaturated zone would increase the primary porosity and therefore storativity in this zone compared to the saturated zone, where water mainly moves though fractured networks.

2.6. Hydrogeochemistry

Hydrogeochemistry is a sub-discipline of hydrogeology and deals with the chemical composition and properties of groundwater. This could be referred to as the quality of the groundwater which may vary quite significantly depending of certain variables, either interacting together or independently in the subsurface.

2.6.1. Recharge water

The main source of recharge to an aquifer is precipitation. As it falls it will interact with atmospheric CO^2 before reaching the Earth's surface. The result of this interaction is a slightly more acidic precipitation that, depending on CO^2 levels, will affect the geology and associated groundwater, in diverse ways. Dissolution of basic minerals will decrease the acidity of the groundwater and increase the dissolved solids over time. The recharge will slowly flow through the subsurface, all while interacting with mineral phases, before reaching the saturated zone and/or discharging as surface water or natural springs (Fitts, 2013). If the local geology is fractured, it may increase the infiltration rate in certain areas and create local recharge zones.

2.6.2. Interaction between water and soil

Leaching is a term used to describe the process of water infiltrating through soils in the unsaturated zone and subsequently removing soluble substances such as natural salts, pesticides and chemical fertilisers. Their concentration in the leached groundwater depends of the amount and rate of water passing through which directly relates to soil permeability, water-table conditions and/or hydraulic loading (Fitts, 2013). If ideal leaching conditions occur over an extended period it can cause rocks to weather chemically as in Grahamstown, where leaching of silica from tillite and shale has formed a silica rich silcrete (Grahamstown Formation) and produced an underlying kaolinitic clay residue.

2.6.3. Soil-gas interactions

Gas is capable of existing in pore spaces between soil particles. Primarily nitrogen, carbon dioxide and oxygen are the dominant gases however, atmospheric methane and radon can also be present. As groundwater moves through the vadose zone, these soil gases may dissolve and become soluble, impacting the chemical composition of the water (Fitts, 2013).

2.6.4. Water-rock interactions

Groundwater typically interacts quite intimately with solid mineral phases at it moves through the subsurface. These mineral-solute reactions are generally slow and equilibrium between groundwater and the surrounding rock is uncommon due to numerous mineral assemblages that the groundwater encounters in the system. Groundwater can either dissolve minerals or, if conditions are favourable, may precipitate certain minerals as veins, therefore adding to the matrix (Fitts, 2013).

2.6.5. Residence time

The residence time is the average amount of time that a water molecule will spend in an aquifer system before moving onto another reservoir or otherwise being pumped. It is possible for deep groundwater systems to have residence times up to and exceeding 20 000 years, however this may be significantly less for certain shallow aquifers. The longer groundwater migrates through the subsurface the more minerals it is likely to encounter and dissolve, therefore becoming more enriched in total dissolved solids (TDS) (Fitts, 2013). The same can be said for EC which is directly proportional to TDS. Consequently, TDS and EC levels in can be used as important indicators of groundwater residence time and its associated flow path.

2.7. Natural spring dynamics

Natural groundwater fed springs form in areas where the hydraulic head of an aquifer intersects the land surface elevation and a visible outflow appears (Kresic, 2010; Fitts, 2013). It is common for a spring to develop at the base of a steep slope and many occur where fractures or the base of an aquifer are positioned in such a way that they intersect the land surface on a slope (Fitts, 2013). The point of discharge is known as the spring orifice, although in scenarios where the output flow is not observed but rather the land surface is saturated the discharge is known as a seep (Kresic, 2010). A seepage spring commonly describes discharge from unconsolidated sediments, namely loose sand and gravel (Kresic, 2010). A fracture spring is formed in fractured rock terrains through directed flow by bedding planes, joints, cleavage, faults and other openings (Kresic, 2010). Tubular or cave springs are characteristic of karst environments where discharge is from large openings in the rock (Kresic, 2010). Furthermore, natural springs may develop in areas where groundwater discharges from perched aquifers as underlying rock units prevent the downward percolation of infiltrating water and rather direct the water laterally until it meets the land surface. According to Kresic (2010) natural springs can be separated into two main groups:

1. Gravity springs, which appear in unconfined aquifers where the water-table meets the land surface, also called descending springs.
2. Artesian springs, which are generated under pressure due to confined conditions, also called ascending and/or rising springs.

When investigating any spring system, it is valuable to form a conceptual understanding of the dynamics as it will aid in determining certain parameters that can then be modelled. Modelling spring operations can provide important clues regarding spring sustainability and because springs are essentially groundwater discharge systems, they can provide insights into local aquifer dynamics. Springs can provide valuable sources of potable water for communities, and many towns in South Africa were established in areas with adequate water supplies from natural springs. The Fairview Spring of Grahamstown was first described in the 1860’s by British Royal Engineers and has since been developed into an important drinking water supply for many residents.

CHAPTER 3. STUDY SITE

3.1. Physiography

3.1.1. Climate and rainfall

Grahamstown is positioned at the south-eastern fringe of the arid Karoo and on the eastern extents of the Mediterranean climate zone that is characteristic of the southern Cape. Subsequently the climate of Grahamstown can be quite variable but, generally the weather is hot and dry during summer months, cold and wet during winter months. Grahamstown has received an average annual rainfall of ~740 mm y^{-1} since 1997, although this amount is less for both the 2016 and 2017 periods. This lack of rainfall has caused the current drought conditions.

3.1.2. Surface drainage

All catchments develop a natural drainage system through many years of runoff and erosion. The characteristics of an area such as the topography, geology, climate and vegetation will all have an influence on the input, exit and transport of water and sediment in an area. Depending on the geological formations and structure of the region a specific drainage pattern will form over time. Common drainage patterns include: dendritic, rectangular, trellis and parallel (Zhang and Guilbert, 2012). In the study site, a trellis pattern is evident where the main stream is parallel to the E-W trending ridges with a number of tributaries joining at right angles. The folded nature of the Cape Supergroup observed in and around Grahamstown is the primary cause of such a pattern. Additionally, there are signs of a rectangular pattern at certain stages of the main stream. Rectangular patterns usually develop in fractured areas and is further evidence of the fractured nature of the geology in the study site.

3.1.3. Surface water

The primary water source for Grahamstown residents is obtained by two separate river systems that supply three main surface water reservoirs. The first river system is the Kariega River which flows into the Settlers and Howiesons Poort reservoirs before being pumped to the Waainek treatment works (WTW) where the water is processed and distributed to Grahamstown West (Figure 5). The second river system is the Orange River which flows into the Gariep Dam before being tunnelled and piped south to the Fish River where it continues its journey until eventually it is piped to the Glen Melville reservoir. This water is then pumped to the James Kleynhans treatment works (JKTW), situated in the Ecca valley, where it is processed and pumped to Grahamstown East (Figure 5) (O'Keeffe, 2011). The Waainek and James Kleynhans treatment works supply Grahamstown with approximately 8 000 m^3 d^{-1} and 12 000 m^3 d^{-1} of treated water, respectively. Currently, low supply to the Waainek treatment works together with over demand and lack of processing capacity at the James Kleynhans treatment works is placing serious pressure on Grahamstown's water supply. Additionally, piping infrastructure is aging and unreliable causing water leakage.

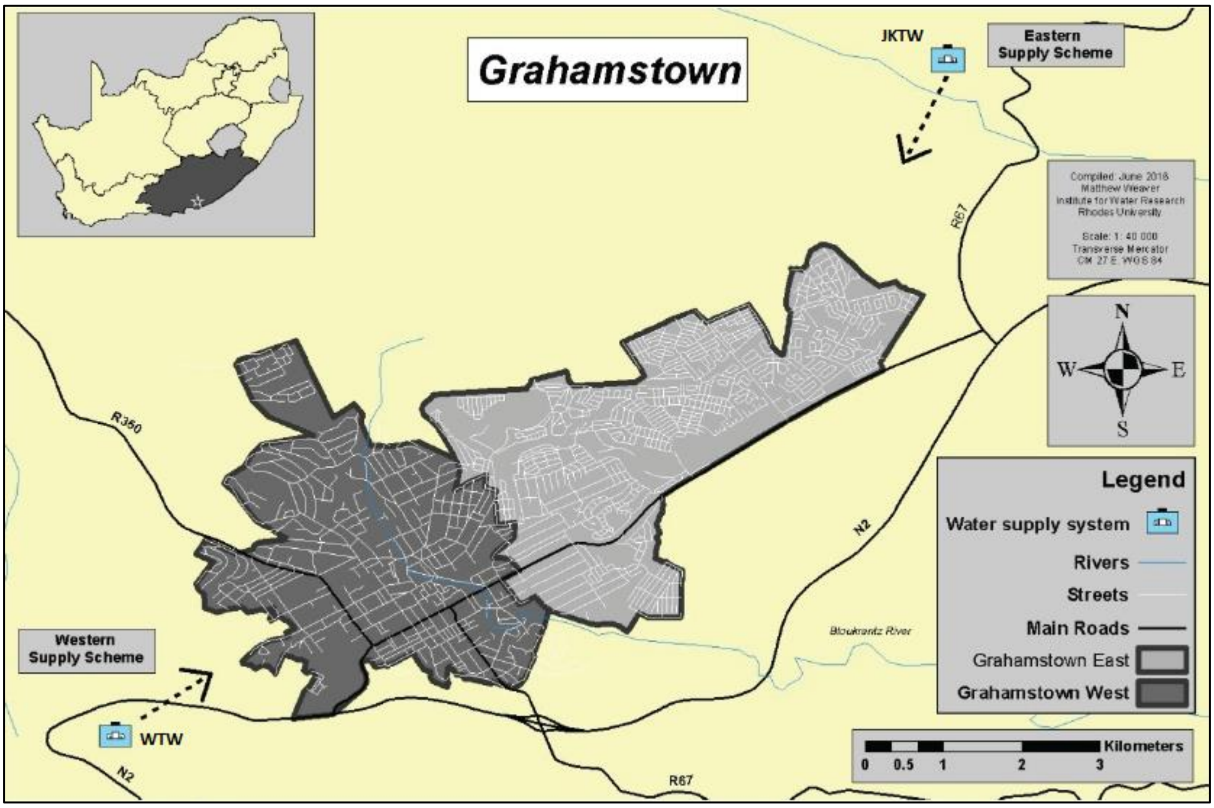


Figure 5 The Waainek and James Kleynhans treatment works and their associated water distribution zones in the study area. (Taken from Weaver *et al*., 2017).

3.1.4. Geomorphology

The local synclinal fold structure has influenced erosional processes in such a way that a bowl type landscape has developed in which much of urban Grahamstown is situated. Harder, more resistant Witteberg quartzitic sandstone rocks have been better preserved over time and are observed as high-lying, E-W trending ridges which border the southern margin of the town. The less resistant Dwyka tillite and Witteberg shales have eroded at a faster rate and are generally found in the low-lying areas (Figure 6).

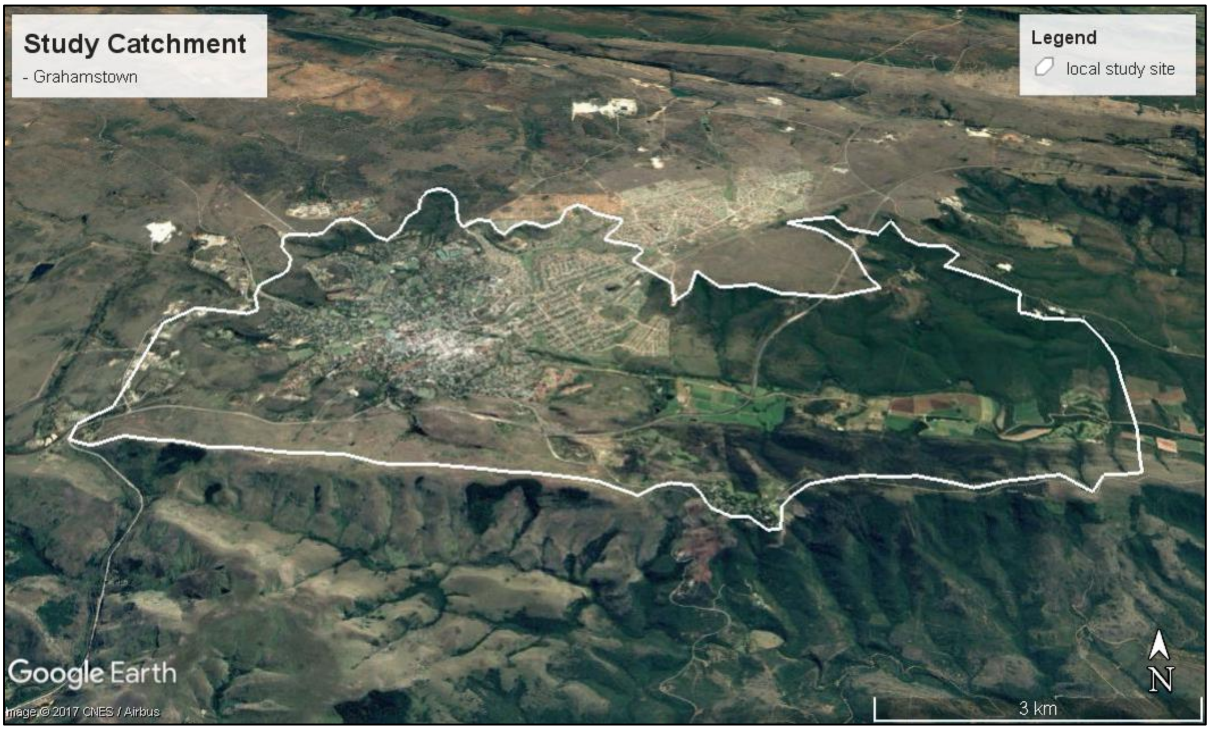


Figure 6 Google Earth[PRO] image highlighting the Grahamstown study catchment.

3.2. Geology

3.2.1. Local geology

Grahamstown and its surrounding area comprise of geological formations that belong to the Cape and Karoo Supergroups as well as young Cenozoic deposits. The occurrence of past magmatic events is evidenced by numerous intrusive dolerite dykes and sills in certain regions, although these do not outcrop in the study site. The Cape Supergroup is subdivided into three primary groups, namely the Table Mountain, Bokkeveld and Witteberg Groups, from oldest to youngest respectively (McCarthy and Rubidge, 2005). The Cape Supergroup in the study area is represented by the Bokkeveld and Witteberg Groups however, the Bokkeveld is predominantly overlain by Witteberg quartzites and shales. The Bokkeveld Group consists of mudrock, quartzitic sandstones and marine invertebrate fossils occur in the lower beds (McCarthy and Rubidge, 2005). These rocks are extensively folded and fractured, however, due to their limited exposure at the surface it is difficult to clearly differentiate between them and rocks of the overlying Witteberg Group as well as attain an accurate thickness. The Witteberg Group is separated into various subgroups and formations, however, the Grahamstown area specifically includes the Witpoort, Kweekvlei and Waaipoort Formations (Hiller and Taylor, 1992). The Witpoort Formation is found extensively along the southern margin of the study catchment (Figure 7) and comprises siliceous quartzitic sandstone with interbedded subordinate carboniferous shale and mudstone (Hiller and Taylor, 1992). Dark grey to grey-red lenticular shales as well as grey-black massive shales make up the Kweekvlei Formation, while the Waaipoort formation comprises dark grey lenticular and massive shales with subordinate fine-grained sandstones (Hiller and Taylor, 1992). The Kweekvlei and Waaipoort Formations are difficult to differentiate, but as both are principally shale lithologies they were combined during the present study and referred to as the upper Witteberg Group (Figure 7). Succeeding the Cape Supergroup are younger Karoo sediments, which include the Dwyka, Ecca, Beaufort, Stormberg and Drakensberg Groups from youngest to oldest respectively (Smith *et al*., 1993), although only the Dwyka Group tillites and minor Ecca Group deposits can be found in the Grahamstown region (Figure 7). The Dwyka Group is recognized by poorly sorted, massive tillite deposits that were deposited by glacial action (Smith *et al*., 1993). The remnants of the Ecca Group lithology are found in a small portion of the study, perhaps this represents the hinge line of the fold structure in which Grahamstown is situated? It is hard to distinguish the Ecca Group into an exact formation and is therefore referred to as the Lower Ecca Group in the present study (Figure 7).

The kaolinic clays found in and around the Grahamstown area are related to the Grahamstown Formation silcrete (Jacob *et al*., 2004). This silcrete is a remnant of a widespread peneplain that developed on the slightly concave erosional surface during the time between the Cretaceous and Tertiary periods (Jacob *et al*., 2004). Portions of the Witteberg Group shale and Dwyka Group tillite have both been subject to extended periods of deep chemical weathering and have developed these clay deposits through the breakdown of feldspars (Jacob *et al*., 2004). These deposits are common along the western and northern margins of the study catchment (Figure 7). Due to the close relation between these clay deposits and the silcrete they have both been grouped together as the Grahamstown Formation in Figure 7.

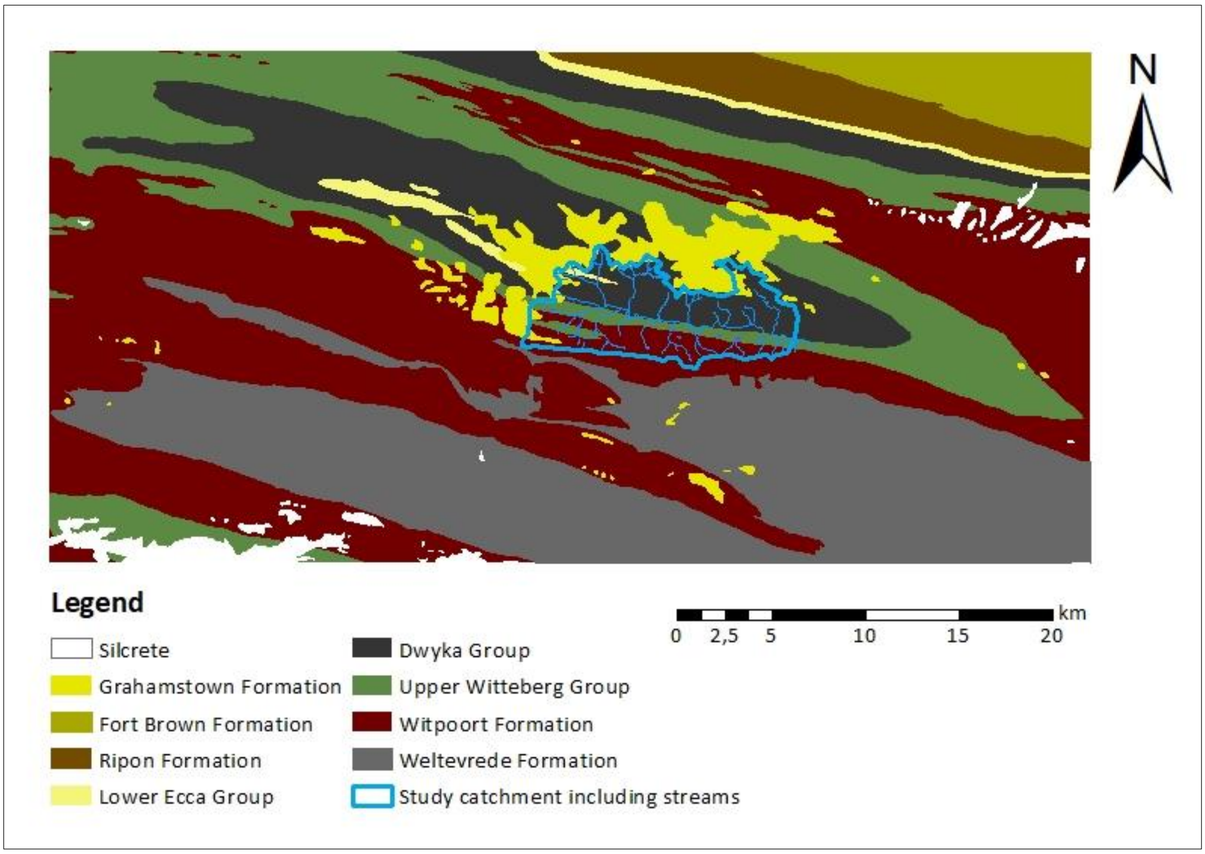


Figure 7 The local geology of the study catchment and surrounding area.

The Cape and Karoo Supergroup sediments in the study catchment were deposited during the late-Devonian, Carboniferous and early-Permian geological times periods, between 370-290 Ma, while the Grahamstown Silcrete Formation is much younger is age and formed during the late-Cretaceous to early Tertiary periods, around 66 Ma (Figure 8).

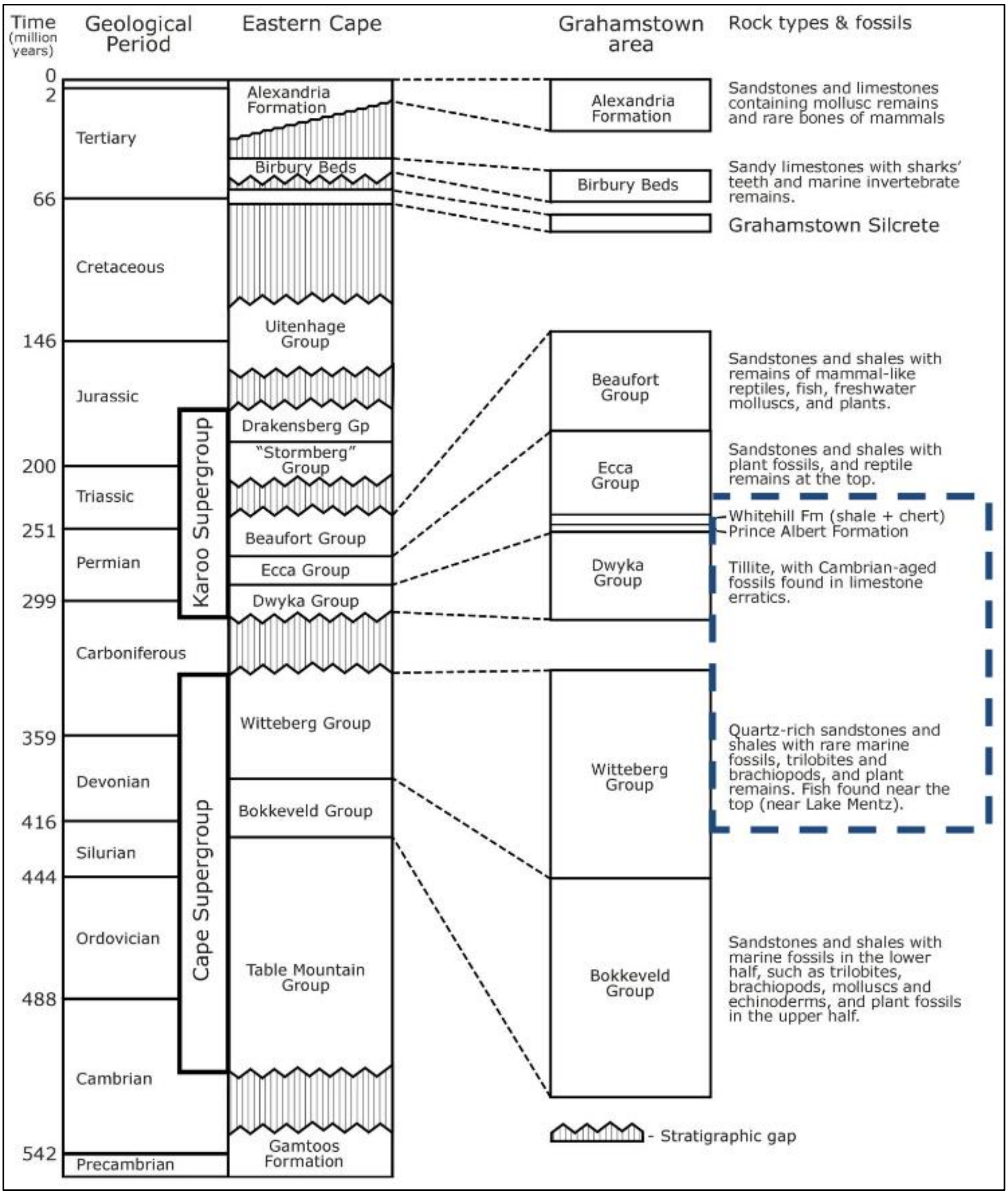


Figure 8 A stratigraphic section highlighting the rocks that are present in the study site (emphasised by blue dashed lines). Modified from Hiller (1992).

3.2.2. Structures

The overall shape of Grahamstown's natural water drainage system was formed predominantly due to the fold structures in underlying rock units. The synclinal fold structure in which Grahamstown is situated directs all water towards the middle low-lying areas and depending on the local aquifer it either discharges into the main stream or otherwise passes underneath and continues eastwards as groundwater. The environment in which the Cape Sediments were deposited and lithified have produced predominant bedding planes that are suggested to act as primary groundwater pathways within the Witpoort aquifer. Other structures such as faults, fractures, joints are common in both the Witpoort and Dwyka aquifers and assumedly provide important fluid pathways for groundwater to flow.

3.3. Hydrogeology

3.3.1. Local aquifers

The geology beneath Grahamstown creates two prominent groundwater systems, namely the Witpoort and Dwyka aquifers (Figure 9):

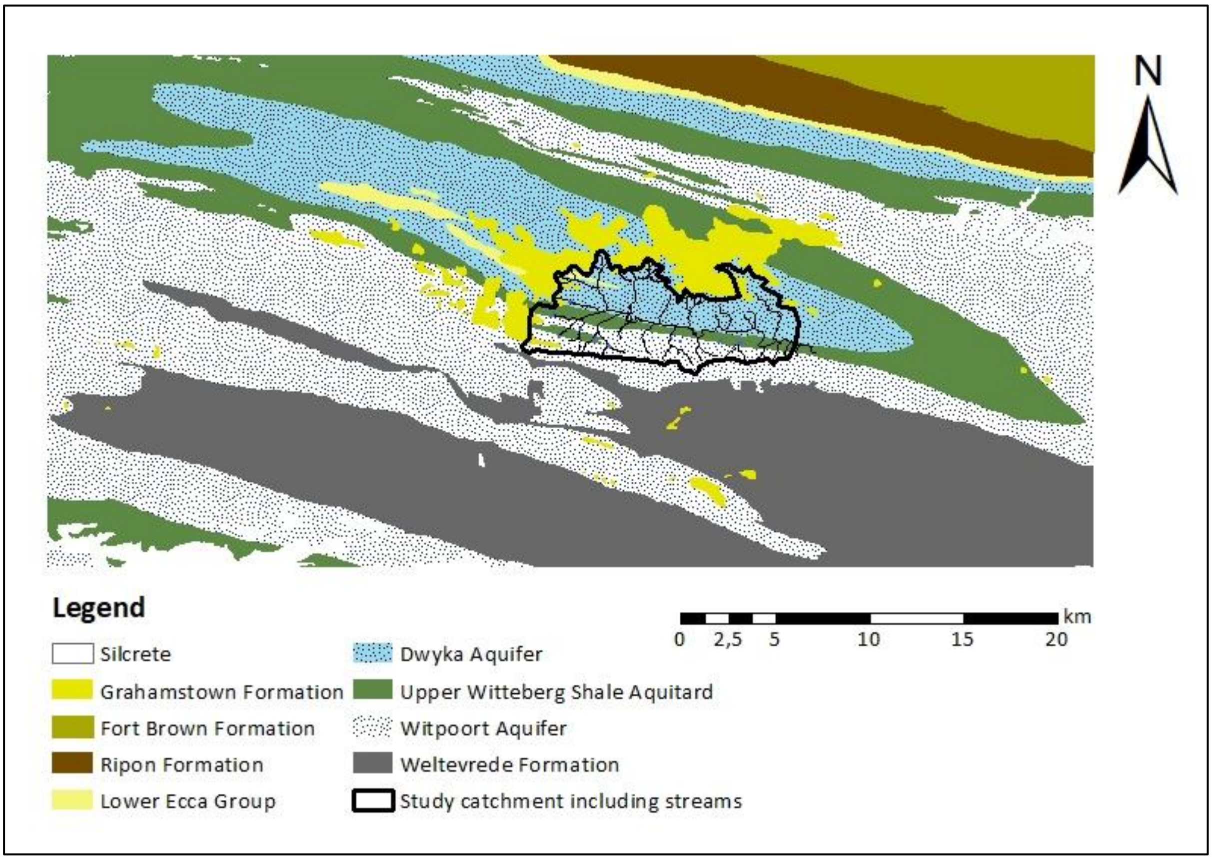


Figure 9 Study area geology, indicating the aquifer systems found within the study catchment.

Witpoort aquifer:

The Witpoort Formation is approximately 850 m thick and is predominantly made up of quarzitic sandstones with interbedded carboniferous minor shale units. The southern limb of the synclinal fold structure borders the town to the south and extends north, underneath the town, where it resurfaces at Botha's Ridge. According to Meyer (1998) the Witpoort Formation has an arenaceous: argillaceous ratio of 94:6. The highly arenaceous nature of this formation improves yield potential and borehole yields exceeding 2 l s^{-1} are common, while in the overlying, more argillaceous formations of the Witteberg Group borehole yields seldom exceed 2 l s^{-1} (Meyer, 1998). Competent contrasts within the Witpoort Formation suggest a higher fracture abundance within the quartzitic sandstone compared to that of the interbedded carboniferous shale. These interbedded shale units have low permeability and are suggested to form perched aquifers which direct infiltrating water back to the surface, a potential process occurring at the Fairview Spring.

Dwyka aquifer:

The Dwyka Group tillite and shale is a poorly sorted, dense formation with little primary pore spaces. These properties create resistance for groundwater flow and typically this formation has low permeability, often forming perched aquifers when overlain by other deposits. It is characteristically a poor recharge material and underlying aquifers are generally at minor risk of becoming contaminated by surface sources (Meyer, 1998). Joints and fractures provide a secondary porosity and are thought to play a key role in groundwater storage and movement in the Dwyka aquifer system. It is suggested that recharge to this local aquifer system occurs through a combination of two processes, firstly from the underlying quartzitic sandstone aquifer pushing groundwater up under artesian mechanisms, and secondly, through river beds which are believed to act as dominant recharge zones during rainfall events, raising the water-table along these water channels. The former however, is likely to be limited due to the upper Witteberg Group shale which separates the two aquifer systems.

3.3.2. Groundwater dynamics

The high lying quartzitic sandstone ridges at the southern border of the study site are believed to be primary recharge zones due to factors relating to elevation and structural controls within the rock. Similarly to that of the surface water, groundwater movement is suggested to flow down gradient towards the main stream. Depending on which aquifer the groundwater is in and the amount of water in the system, it may either discharge as surface water in this low-lying area or remain in the saturated zone and ultimately exit beneath Grahamstown to the east.

3.3.3. Hydrogeochemistry

A clear difference in groundwater quality exists between the two aquifer systems based on both qualitative and quantitative data. Principally, the Witpoort aquifer holds better quality water to that of the Dwyka aquifer. The main difference is the high salt content and many residents with boreholes that extract groundwater from the Dwyka aquifer limit their use to irrigation of gardens or otherwise utilise filtration systems to purify the water. Groundwater pumped from the Witpoort aquifer generally holds groundwater with electrical conductivity less than 100 mS m^{-1} and seldom exceeds unsafe limits for human consumption (Meyer, 1998).

Groundwater quality is negatively impacted by the upper Witteberg Group shale aquitard where electrical conductivity levels in groundwater can range between 200 – 700 mS m^{-1} and major ions such as sodium, magnesium, chloride and sulphate often exceed the recommended limits (Meyer, 1998). Having said this, there may be a chance that any borehole placed close to or through this aquitard unit may be at risk of poor quality groundwater being drawn through the fractures (Meyer, 1998).

CHAPTER 4. METHODOLOGY

4.1. Remote sensing

4.1.1. Aerial photographs

Aerial photographs provided an initial evaluation into the dynamics of the local catchment, including the position of water bodies and how water flows and drains through stream channels. Continuous flow of surface water, even during dry spells, often indicates an interaction with the saturated zone and can provide clues as to where the groundwater is closest to the surface.

4.1.2. Geological maps

The current study made use of physical and digital geological map data. Dynamics within local aquifer systems are primarily influenced by the geological lithologies through which the groundwater is stored and flows. Understanding the type of rock present in the study site as well as its structural characteristics allowed for conceptual understanding into local aquifer properties. ArcGIS 10 software made use of digital geological data to create maps that helped visualise and better understand the positions of local aquifer systems.

4.1.3. Hydrogeological maps

Hydrogeological maps contain valuable information regarding groundwater dynamics over South Africa. The maps are generalised to a certain degree and may not represent exact conditions, but as an initial evaluation they were very useful and allowed for a basic understanding of regional groundwater dynamics and quality.

4.2. Field work

4.2.1. Fracture observations

Secondary porosity is a vital component of the local groundwater system and determines aquifer properties such as specific yield. Investigative approaches to understanding the secondary porosity involved examining the characteristics of geological structures such as bedding planes, faults, fractures and joints. Certain well-exposed outcrops were used to examine the secondary porosity. Various outcrop sites were photographed and examined, primarily focusing on abundance and connectivity properties of fracture networks. The heterogeneity however, means that quantifying specific yield and other aquifer properties is uncertain.

4.2.2. Borehole monitoring

The water-table level of 31 private boreholes was monitored over a year long time-series which extended from July 2016 to July 2017. To initially locate the boreholes, a message was placed on an emailing list, Grahamstown Parents Network (GPN), requesting permission from owners to allow monitoring and possible sampling data to be acquired and added to the project. Based on the owner's insight they were asked to complete a hydrocensus regarding the age, depth, use and quality of their borehole (APPENDIX 1). Borehole water level measurements were obtained using a water level meter on a monthly basis (Figure 10a). Measurements from actively pumped boreholes were taken at least 24 hours after any pumping as to allow for sufficient water-table recovery. The measurements were compared to rainfall to investigate any correlations and if clear relations were observed then water-table fluctuation methods were applied to estimate recharge.

Figure 10ab Two boreholes that were monitored during the study period.

Water-table fluctuation (WTF) method

Healy and Cook (2002) derived a mathematical expression (Eq. 1) to determine recharge to an unconfined aquifer. The method relies on the degree of water-table response to a specific rainfall event (Figure 11).

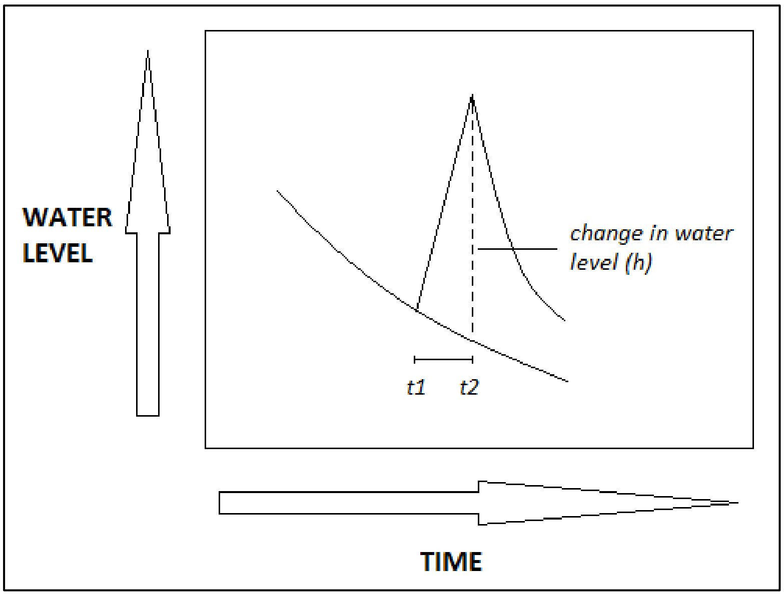


Figure 11 Sketch illustrating the water-table fluctuation (WTF) method.

Initial specific yield estimates were based on a previous study (Sun *et al*., 2013), while change in water level (Δh) and change in time (Δt) vary according to borehole response. An estimation of recharge can be determined by the following equation (Eq. 1):

$$\mathrm{r} = \mathrm{S_y} \times \frac{\Delta \mathrm{h}}{\Delta \mathrm{t}} \qquad \text{(Eq. 1)}$$

Where,

r = recharge

S_y = specific yield

Δh = change in water-table elevation

Δt = time interval between rainfall and water-table response

The cumulative rainfall departure (CRD) method

The cumulative rainfall departure (CRD) method was first proposed by Bredenkamp *et al.* (1995) and later revised by Xu and van Tonder (2001). The general approach assumes that aquifer conditions have adjusted over time so that rates of discharge and recharge are in equilibrium. Through this premise it can be inferred that any fluctuation in the water-table is directly related to specific rainfall recharge events or lack thereof. This physical method utilises data from the unsaturated-saturated zone and has commonly been used in many recharge estimate studies over South Africa. Fractured aquifers generally have low storativity and respond rapidly to rainfall events allowing for relatively accurate estimates of recharge, provided that reliable estimates of storativity can be determined. The method makes use of the following equation (Eq. 2):

$$\mathrm{CRD} = \sum_{n=1}^{i} \mathrm{R_n} - \mathrm{k} \sum_{n=1}^{n} \mathrm{R_{av}} \quad \text{(Eq. 2)}$$

Where,

R = Rainfall amount with 'i' indicating the i-th time scale and 'av' the average, while 'n' is the start of the time series. If pumping does not occur then k = 1, while k > 1 if pumping and/or natural outflow does take place. Although many of the monitored boreholes are actively used, the water-table measurements were always done at least 24 hours after any pumping as to allow for proper recovery of the static water level. Therefore 'k' was assumed to be 1, although, ideally the methods should be limited to boreholes that are not pumped but rather strictly used for monitoring purposes.

The method assumes that under natural conditions any water-table fluctuations will have a linear relationship with recharge to the groundwater reservoir. In other words, the relationship between recharge (r), storativity (s) and the change in rainfall from its average (CRD) can be related to the observed change in water level from its average (Δh). This relationship can be expressed by the following equation (Eq. 3):

$$\Delta \mathrm{h_i} = \frac{\mathrm{r}}{\mathrm{s}} \times \mathrm{CRD} \quad \text{(Eq. 3)}$$

Where,

△h = simulated water-table fluctuation

r = percent CRD that results in recharge

s = storativity/specific yield

By adjusting the values of r and s an attempt was made to simulate the observed water-table fluctuations measured in certain monitored boreholes.

4.2.3. Water quality sampling

Ten groundwater samples were collected and sent to the Aquatico Labs in Pretoria for analysis. Samples were extracted from nine selected boreholes and one from the Fairview

Spring. It was required that 500 ml containers be used with as little trapped air as possible. Before the collection of samples could be done it was necessary to properly sterilize the containers as to make sure no contamination affected the results. Each container was taken through an acid wash which involved the following procedure:

- An initial rinse with tap water
- A thorough wash with 5% Extran (a phosphate free soap)
- A second rinse with tap water
- Soaked in 10% hydrochloric acid (HCL) for 10 minutes
- A third rinse with tap water
- Three times rinsed with boiling tap water
- Three times rinsed with deionized water
- Finally left to drip dry
- Ready for use

To prevent the collection of stagnant groundwater, the samples were collected at the end of a pumping cycle. As a rule of thumb, it is required that three times the borehole volume be pumped before a sample is collected. From a pure groundwater outlet, a bucket was rinsed three times before being filled, the sample bottles were dipped in the bucket and the cap closed to avoid air in the container.

Schoeller plot

A French hydrogeologist by the name of Henri Schoeller established a graphical method to investigate the chemistry of groundwater using the concentrations of six fundamental chemical parameters, namely Mg, Ca, Na+K, Cl, SO_4 and HCO_3+CO_3 (Brassington, 2007). The technique was applied in the present study although a conversion was necessary to change milligrams per litre (mg l^{-1}) to milli-equivalents per litre (mEq l^{-1}). This was achieved by dividing the concentration of each ion in mg l^{-1} by its atomic weight over the valence. A conversion factor, used by Brassington (2007), was applied before the ions were plotted.

Piper plot

A popular graphical method to characterise groundwater chemistry is to plot certain cations and anions onto a Piper diagram. The Piper plot is divided into various zones and depending on where the sample plots will define the groundwater quality type.

4.2.4. Past pumping tests

Andrew Stone's 1986 report contains the results of three independent borehole pumping tests which formed part of his field work. Through these tests an estimate of localised aquifer yield was made. Most pumping tests include the monitoring of proximal observation boreholes during the drawdown and recovery periods. This was not the case when Andrew Stone performed the tests and instead single borehole pumping tests were done that excluded any water-table fluctuations at observation wells. Nevertheless, the maximum sustainable yields of the specific boreholes were estimated and included in his report. This yield information was used to provide important insight regarding the current conditions.

4.2.5. Fairview Spring monitoring

Collection of spring discharge data

An initial investigation was done to locate any natural springs in the study area that could be monitored accurately and on a consistent basis. Certain springs were not considered due to either their locality outside of the study site or complete lack of discharge during dry periods. Therefore, only the Fairview Spring was considered due to its accessibility, continuity and localised output. A simple method was used to measure discharge where a 25-litre container was filled, and the time recorded (Figure 12abc). Measurements were taken on a regular basis (~weekly) and compared to rainfall events to evaluate any response trends.

Figure 12abc Public water collection point at the Fairview Spring. Photographs by K. Smetherham.

Building a Fairview Spring model

A spreadsheet model of the Fairview Spring was set-up by forming assumptions and using certain parameters applied in the daily time-step version of the modified Pitman Model (Hughes, 2004). The primary objective of the model was to simulate spring outflow that closely resembles the known discharge curve observed at the Fairview Spring while ensuring the simulated physical processes in the model correlated with the understanding of reality and also the conceptual model.

CHAPTER 5. RESULTS

5.1. Information from hydrogeological maps

The components and records summarised in Table 3 were gathered from past hydrogeological maps (DWS, 2012). Although the maps were published in 1995, the information is a useful baseline to compare results obtained during the current study.

Table 3 Summary of hydrogeological characteristics for the Grahamstown area. Information gathered from hydrogeological maps produced by the DWS (2012).

COMPONENT	RECORDS
Storage medium	Pores in disintegrated, partly decomposed rock + fractures which are primarily restricted to zone below groundwater level
Probability of drilling a successful borehole (Accessibility)	40-60%
Probability of successful borehole yielding greater than 2 l/s (Exploitability)	10-20%
Factors restricting harvest potential	Volume of effective storage. Recharge occurs regularly most years but cannot be fully absorbed due to low storage capacity.
Mean depth to groundwater level	20-30 m
Average borehole yield	0.4 – 0.6 l/s
Mean annual recharge	25-37 mm (3 - 5 % MAP)
Groundwater component to baseflow (river flow)	0-10 mm
Groundwater quality	1000-1500 mg l^{-1} (TDS)
Hydrogeochemical types	Na^{+} and/or $K^{+)}$ (dominant cations) Cl^{-} and/or SO_4^{-} (dominant anions). Salty/brackish taste

5.2. Structural evidence

5.2.1. Folds

The representation of local rock units on geological maps is typical of a folding environment. A cross sectional sketch through the study catchment reveals this folded environment (Figure 13 and Figure 14).

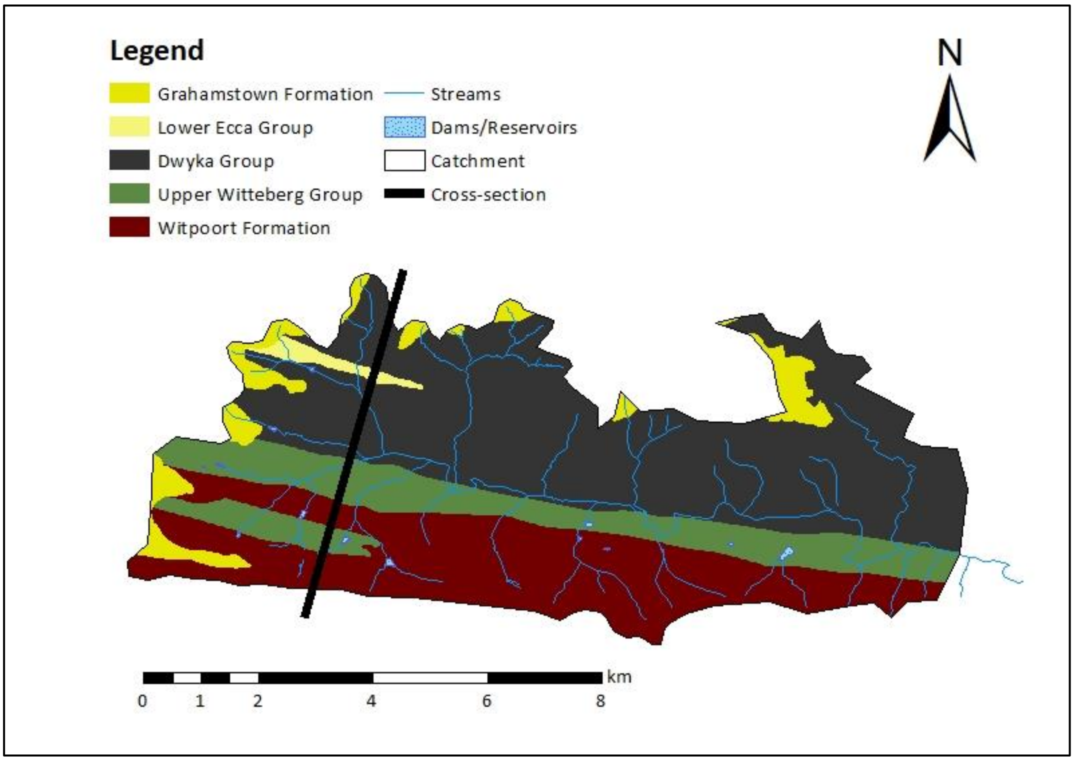


Figure 13 Study catchment displaying position of cross-sectional line.

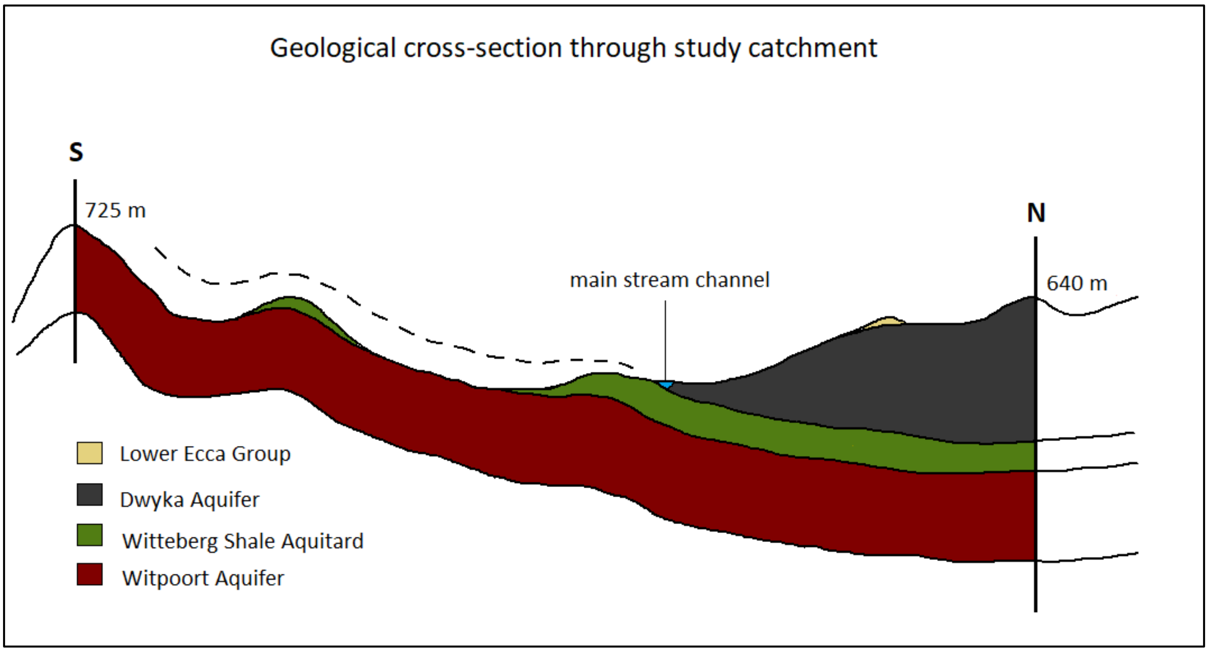


Figure 14 Geological cross-sectional sketch through study catchment.

5.2.2. Fracture networks

The compressional forces that folded these local rock units simultaneously caused numerous fractures to develop and in some areas fault zones are present, indicating that movement along a fracture plane occurred. Due to the heterogeneity of fracture networks observed in the study site, as well as the scale of the study site, certain specific fracture characteristics, namely the number of sets, orientation, length, aperture and surface roughness were not comprehensively assessed and instead a focus was placed on fracture abundance and connectivity.

Witpoort aquifer

Road-cuttings can provide an important portal into the subterranean environment and in the study catchment the Witpoort Formation is commonly intersected by this type of construction. At first inspection of these outcrops it becomes clear that numerous fracture networks exist within the Witpoort Formation. Mapping the fracture networks on photographs confirms this abundance and reveals that fracture connectivity is high (Figure 15abcd).

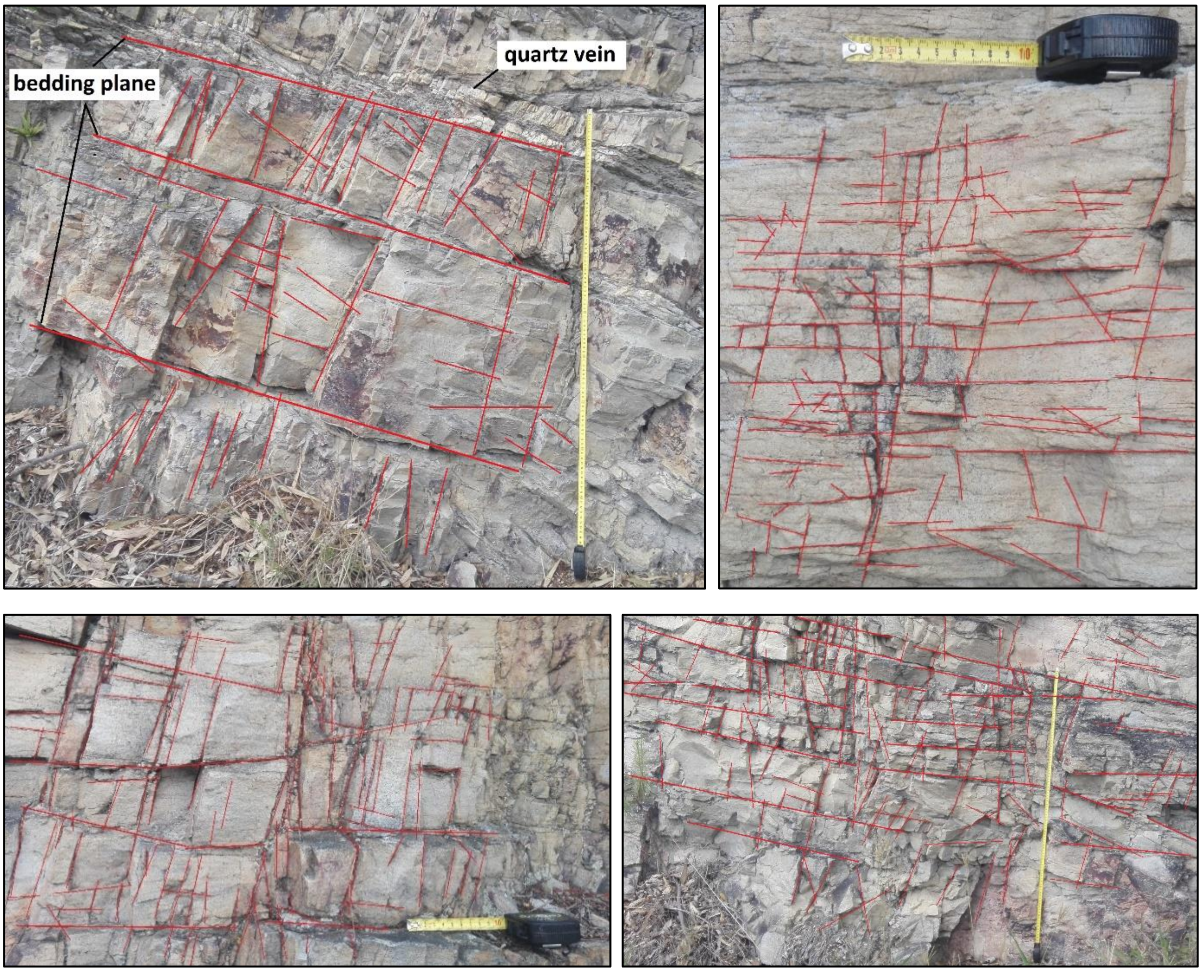


Figure 15abcd Observations from a road-cutting through the Witpoort Formation highlighting the connectivity and abundance of the fracture networks. Tape measure (1m and 10cm) for scale.

Bedding planes are common in the Witpoort Formation and are believed to act as dominant groundwater flow paths, although observational evidence suggests that fractures, joints and fault zones play a significant role in increasing the connectivity and overall abundance of the secondary porosity (Figure 15abcd).

Dwyka aquifer

The Dwyka Group does not outcrop in the study catchment, but it is suggested that fractures also play a key role in groundwater movement within this aquifer system. The evidence was observed during local drilling projects where the presence of quartz veins was often accompanied by a water strike. Figure 16 and Figure 17 show the drill piles from two separate private drilling operations into the Dwyka aquifer. The quartz vein fragments are not visible in these figures but appeared concurrently with the water strikes.

Figure 16 Drill piles form a borehole sunk into the Dwyka aquifer.

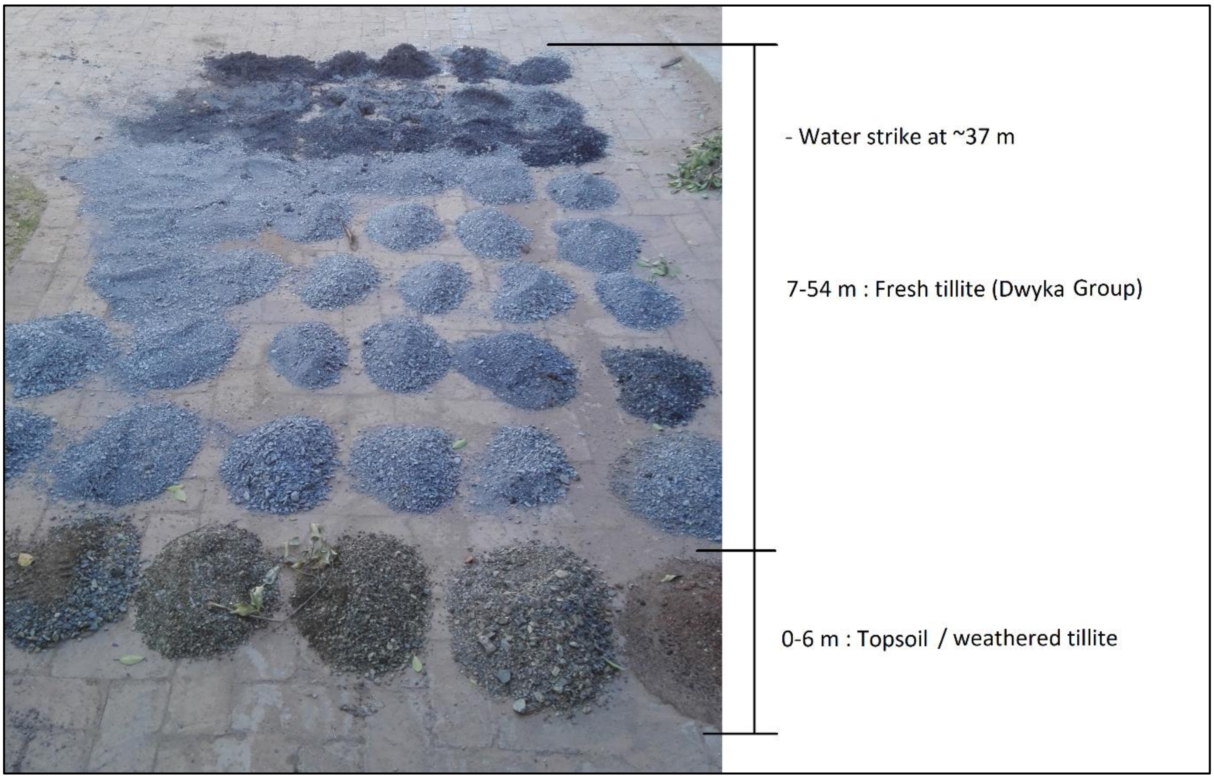


Figure 17 Drill piles from a borehole sunk into the Dwyka aquifer.

5.3. Boreholes

Boreholes provide an important portal into the groundwater reservoir and allow for direct interaction with system dynamics. The boreholes in the current study have been categorised into three groups (Figure 18):

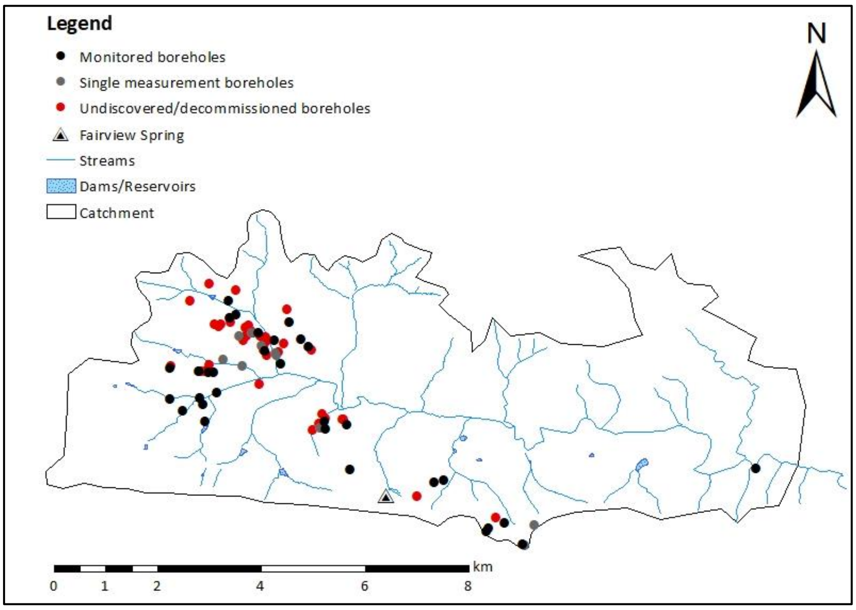


Figure 18 The locations of the monitored, single measurement and undiscovered/decommissioned boreholes within the study catchment.

1. Monitored boreholes: These are boreholes that were involved in the monitoring series. Based on their positions across the study site, nine boreholes were selected for quality testing.
2. Single measurement boreholes: Refers to nine boreholes that were only discovered after the monitoring period had started and therefore only a single water level measurement was obtained (with the aim to enhance the accuracy of the groundwater elevation map) (Figure 20).
3. Undiscovered/decommissioned boreholes: Boreholes used in previous groundwater report that either could not be found or have since been decommissioned.

5.3.1. Conceptual flow model

To initially gauge an understanding regarding the groundwater dynamics a comparison was made between water-table elevation and land surface elevation at the position of each measured borehole as well as the Fairview Spring (Figure 19).

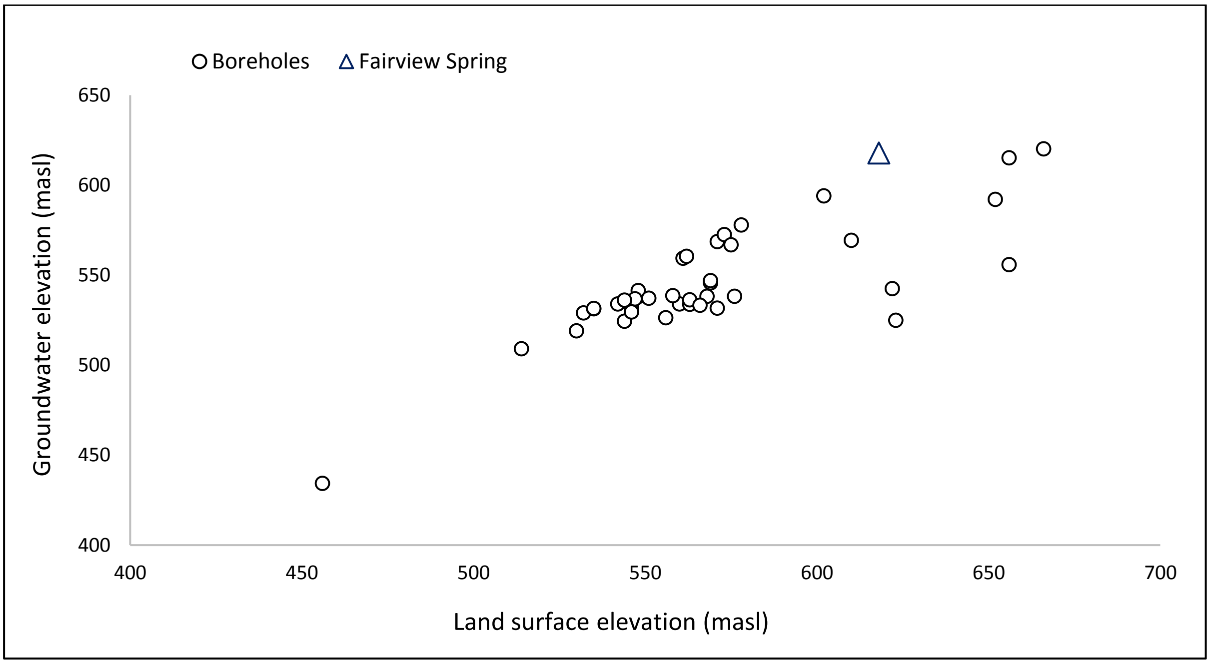


Figure 19 illustrates the relationship between water-table elevation and land surface elevation of each borehole as well as the Fairview Spring.

Time-series measurements of water-table elevations obtained from the monitored boreholes were averaged and Shuttle Radar Topography Mission (SRTM), through Google Earth, was used to determine their respective surface elevations. Single measurement boreholes were also included in Figure 19. Comparison of these two variables reveals a relatively positive relationship between them.

To evaluate groundwater flow patterns a simple elevation map was generated using ArcGIS 10. Elevation values were determined by averaging the water-table measurements, in metres above sea level (masl), from individual boreholes over the entire monitoring period. Single water-table measurements were taken for boreholes discovered after the monitoring period began and were also included in the groundwater elevation map (Figure 20).

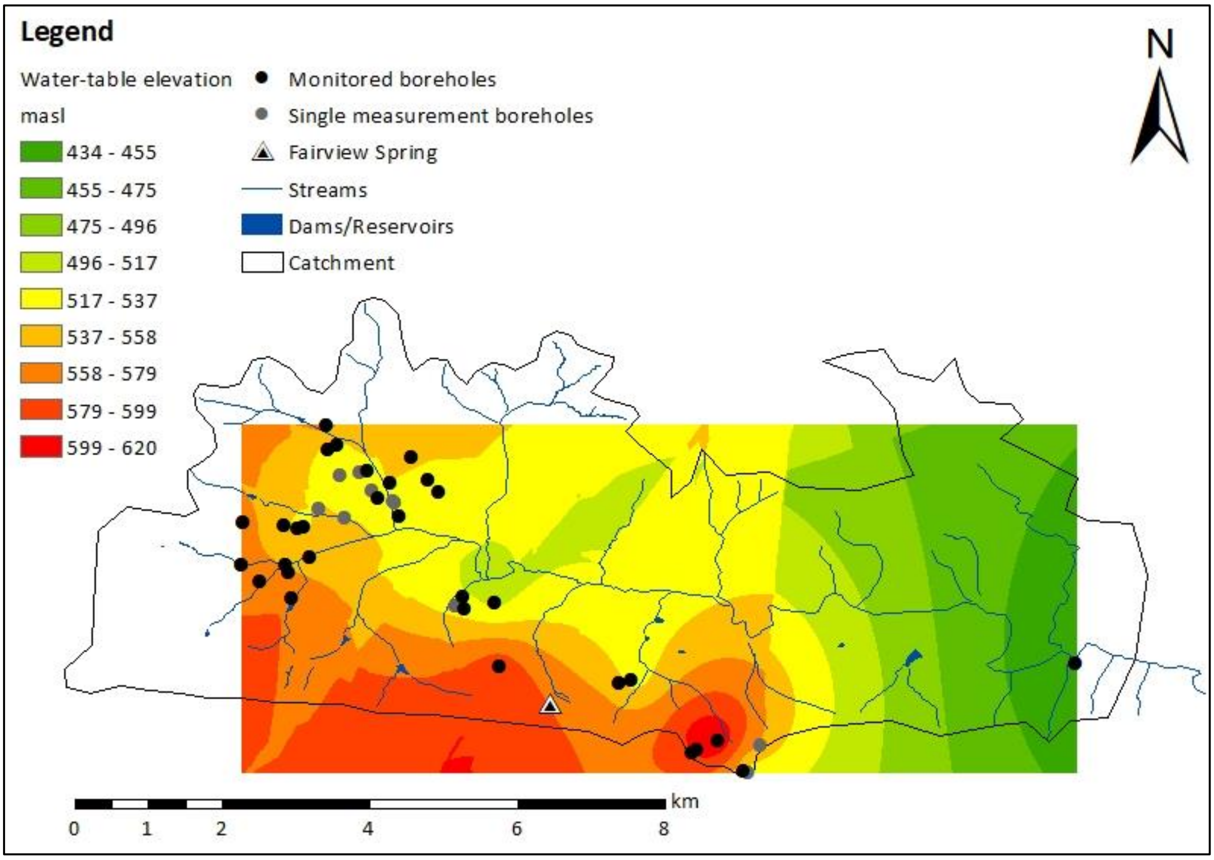


Figure 20 Groundwater elevation map indicating the local groundwater flow pattern.

Groundwater will always prefer to flow from high to low hydraulic head as shown by red and green respectively (Figure 20). Water-table elevation in the study catchment ranged between 620 masl to 434 masl, a difference of 186 metres. The map was produced purely based on gathered borehole data and there is a clear disjointedness towards the eastern side due to a lack of boreholes in that area of the study site.

5.3.2. Borehole monitoring

The positions of the 31 monitored boreholes were overlain onto a map of the local geology to gain perspective regarding the aquifer system into which they were drilled (Figure 21). A detailed summary of individual borehole characteristics can be found in APPENDIX 2.

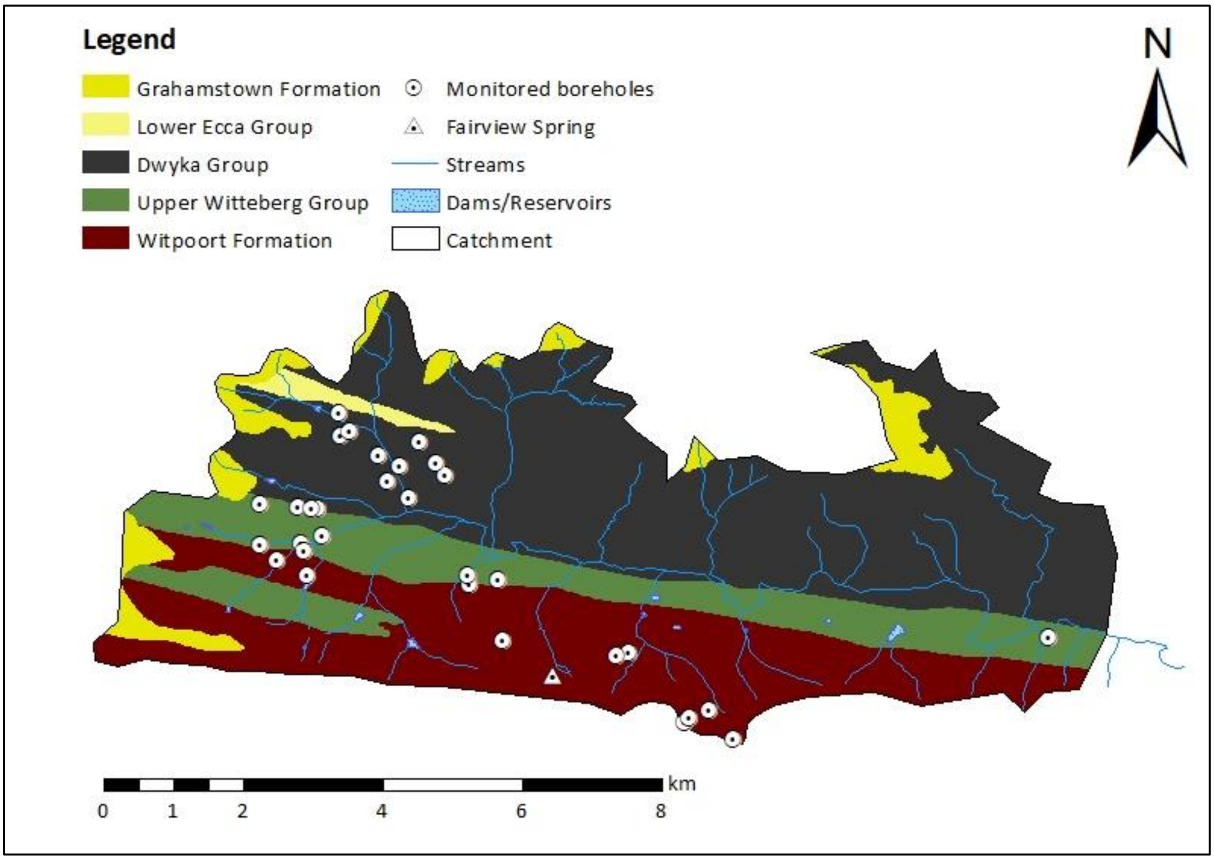


Figure 21 Locations of the 31 monitored boreholes in relation to local geology.

It is important to remember however, that locations of the monitored boreholes in Figure 21 indicate the land surface geology and may not necessarily represent the rock formation from which groundwater is being extracted. For example, boreholes located on the upper Witteberg Group shales were most likely drilled through this layer into the underlying water-bearing quartzitic sandstone of the Witpoort Formation (Figure 21).

The borehole monitoring period provided an opportunity to observe the way in which the water-table fluctuates over time. An important trend, observed in numerous boreholes, occurred after a series of rainfall events and caused a sudden rise in the water-table during November/December 2016 (Figure 22). Interestingly, this exact rainfall series was also responsible for one of the sudden discharge spikes observed at the Fairview Spring.

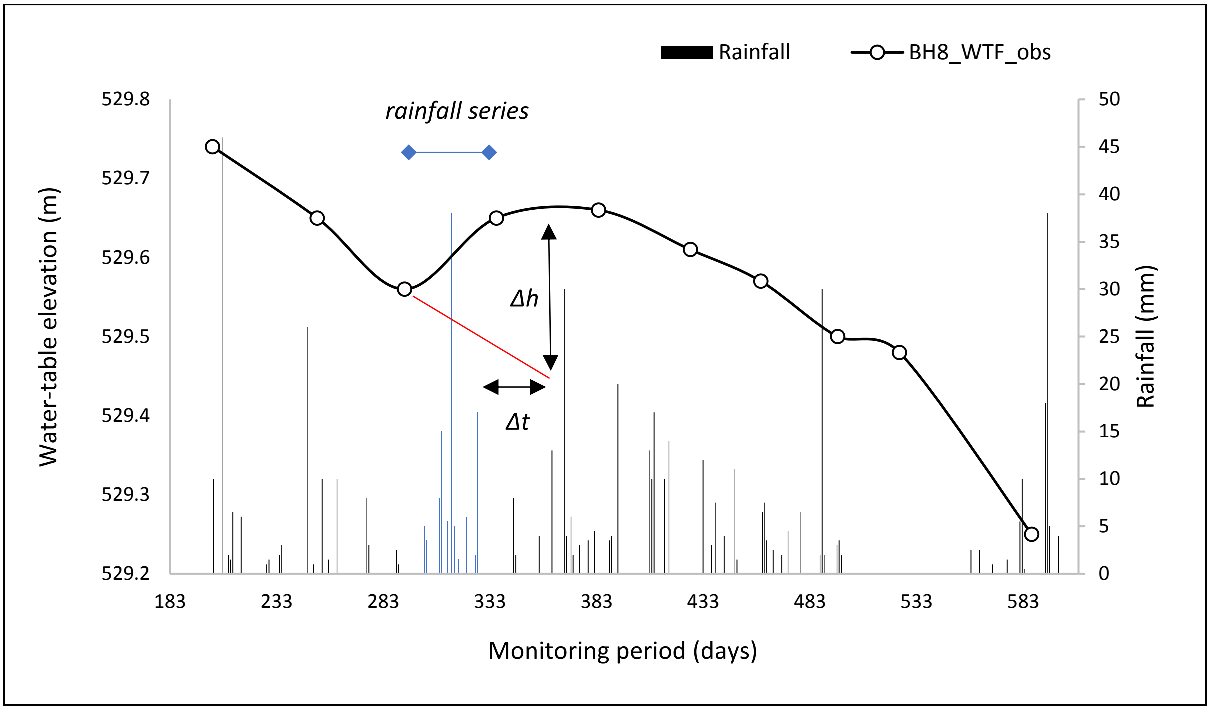


Figure 22 Water-table fluctuation that occurred in BH8 (Figure 23) following a recharge event. This sudden response allowed for the application of the WTF method to estimate recharge.

5.3.3. Water-table fluctuation (WTF) method

Using basic extrapolation and regression, the WTF method was applied to any boreholes that showed a clear and positive response following the rainfall series highlighted in Figure 22. For that reason, the calculated recharge values only represent the percent recharge that infiltrated during that specific rainfall series. Nevertheless, the method delivered an initial estimate of recharge which could then be used as a baseline comparison for methods that followed. Of the 31 monitored boreholes, nine exhibited this water-table fluctuation and were subsequently used to estimate recharge (Figure 23).

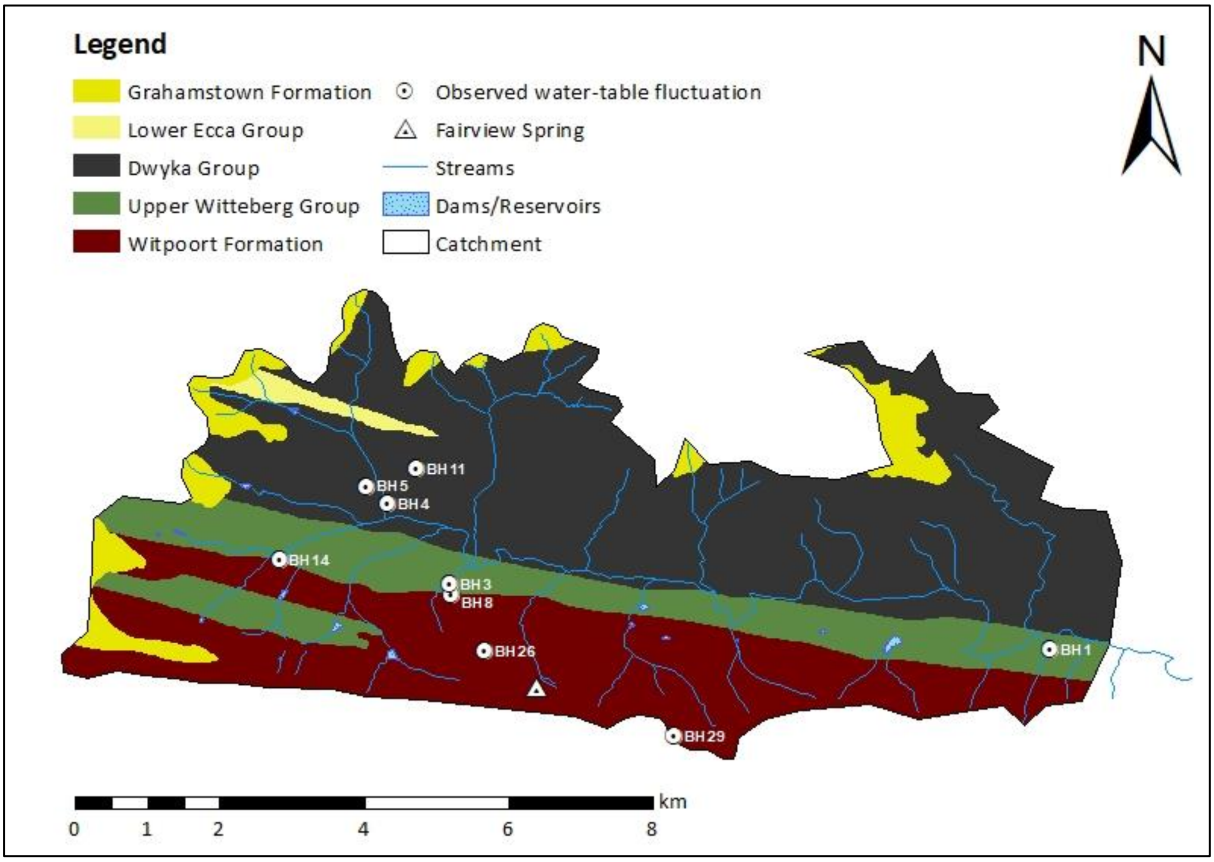
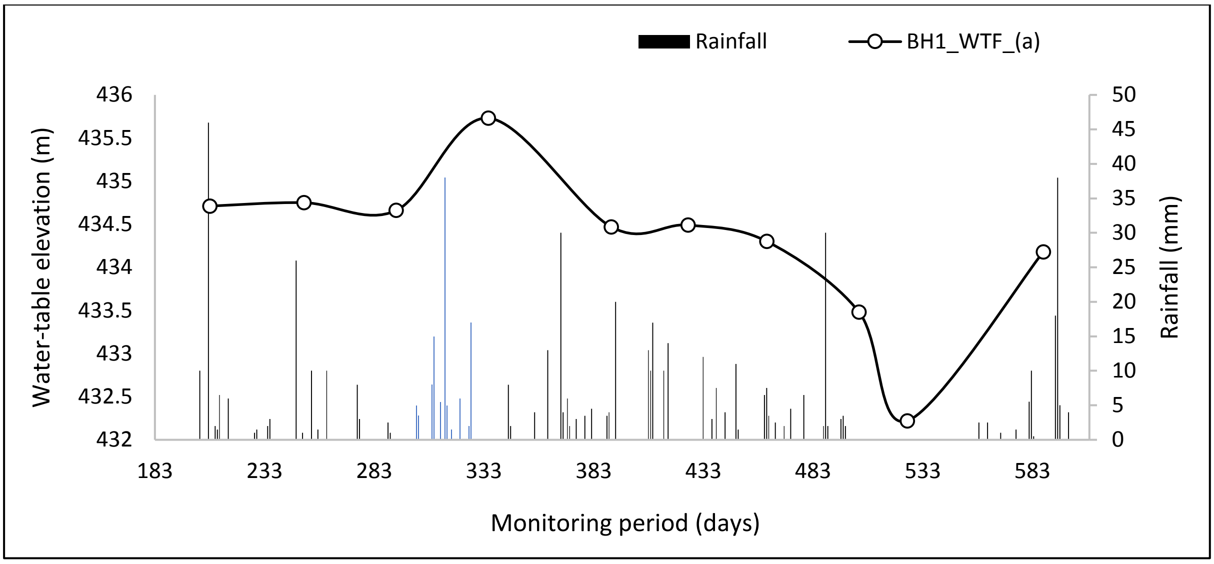
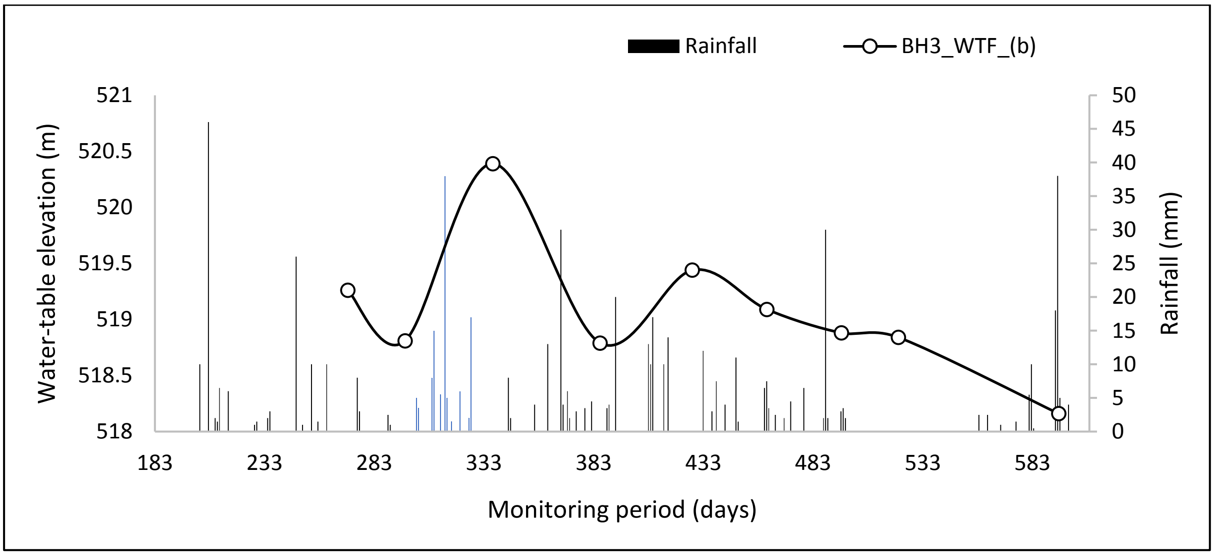


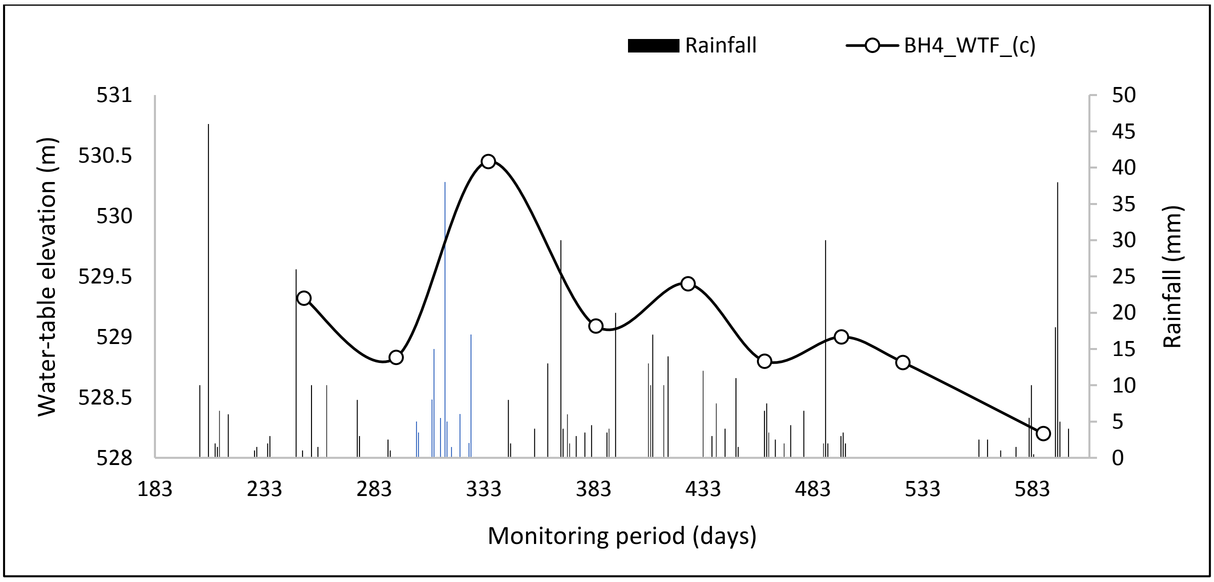
Figure 23 Monitored boreholes that showed a positive water-table fluctuation following a specific rainfall series (recharge event).

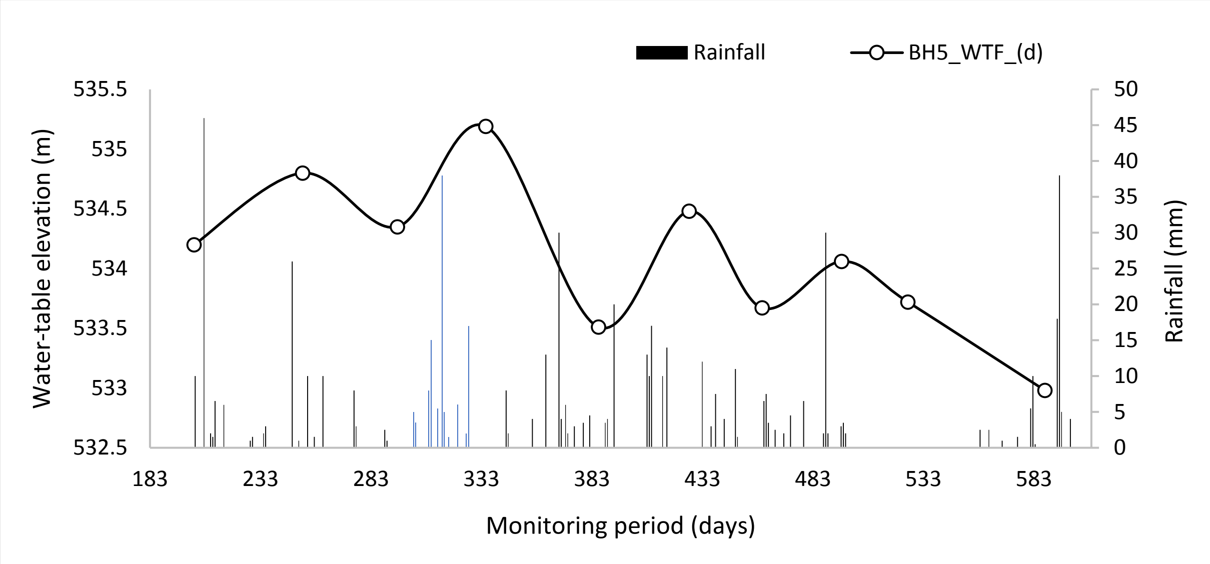
The nine boreholes were scattered across both aquifer systems although it is likely that those situated on the shale aquitard are drilled through into the Witpoort Formation. This assumption suggests that six of the nine boreholes, therefore the majority, are drilled into this fractured quartzitic sandstone, indicating its potential as a groundwater recharge zone. The three boreholes drilled into the Dwyka aquifer are situated in residential areas where street runoff may play a part in recharge dynamics, effecting some boreholes more than others depending on the location of storm water drains and steam channels. BH11 is situated on a school property and surrounded by large sports fields which may also encourage regular recharge following rainfall events.

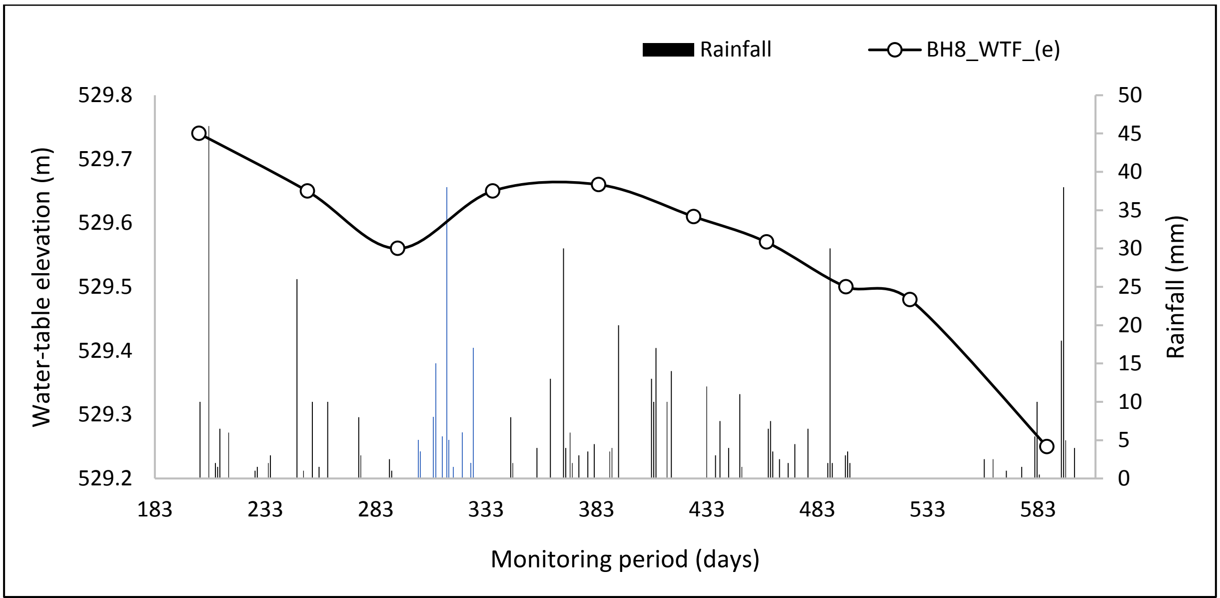
The following graphs display this specific water-table fluctuation observed for the nine monitored boreholes. The sudden rise in water-table suggests a definite recharge event following a series of rainfall events that occurred from the 28/10/2016 to the 22/11/2016 and amounted to 106.5 mm. This targeted rainfall series has been highlighted in blue for each of the graphs (Figure 24a-i).

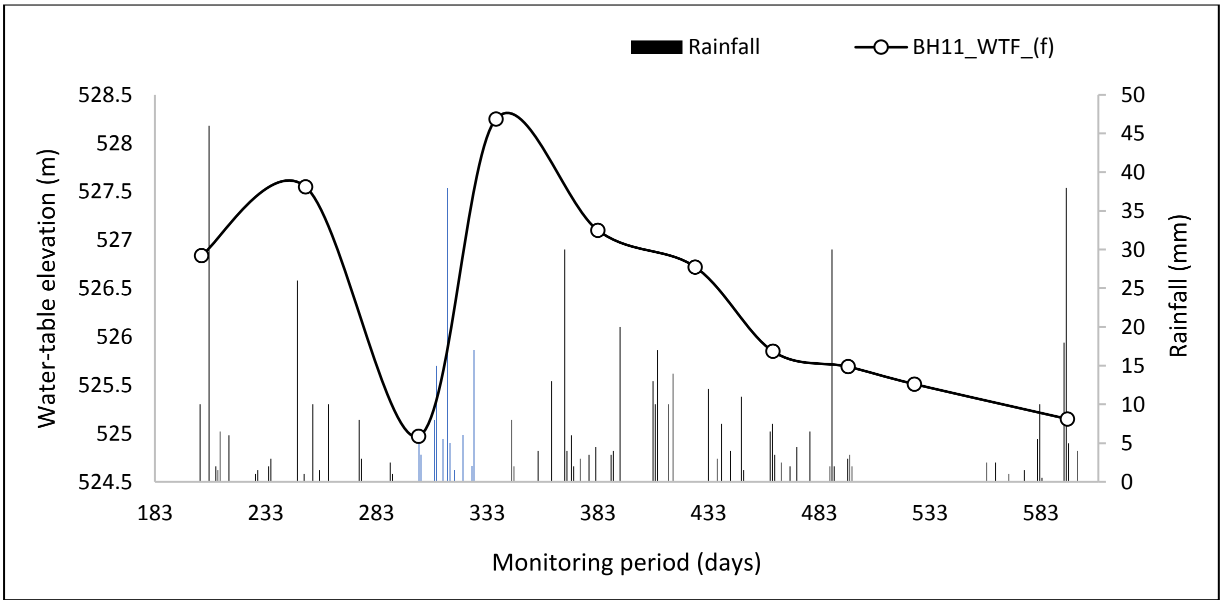

Rainfall
BH1_WTF_(a)
Water-table elevation (m)
436
435.5
435
434.5
434
433.5
433
432.5
432
Rainfall (mm)
50
45
40
35
30
25
20
15
10
5
0
183
233
283
333
383
433
483
533
583
Monitoring period (days)

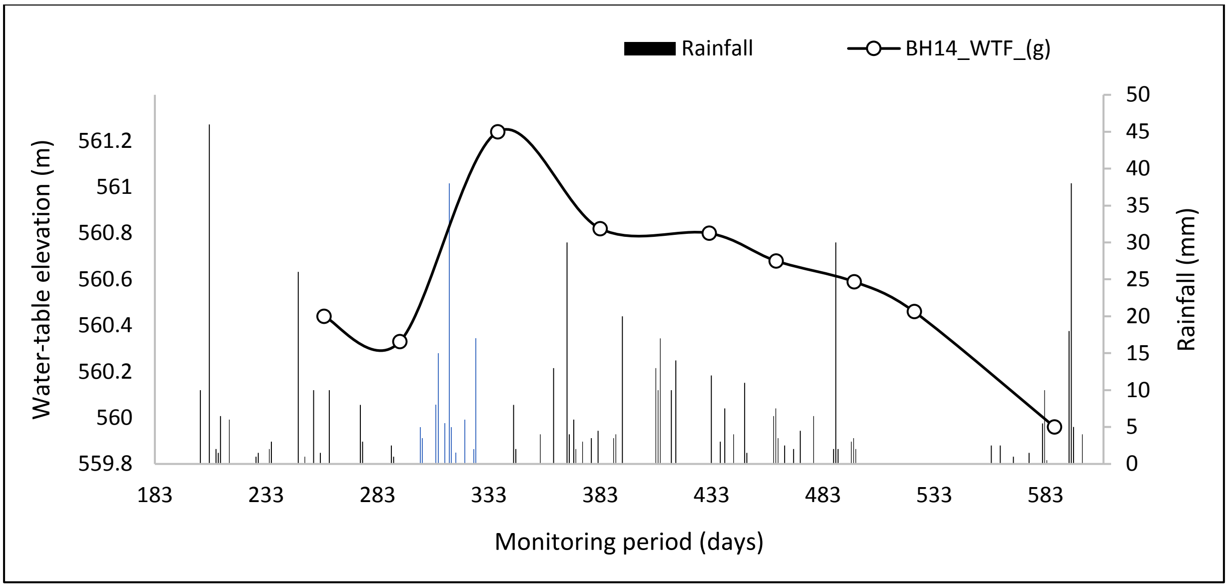

Rainfall
BH3_WTF_(b)
Water-table elevation (m)
521
520.5
520
519.5
519
518.5
518
Rainfall (mm)
50
45
40
35
30
25
20
15
10
5
0
183
233
283
333
383
433
483
533
583
Monitoring period (days)

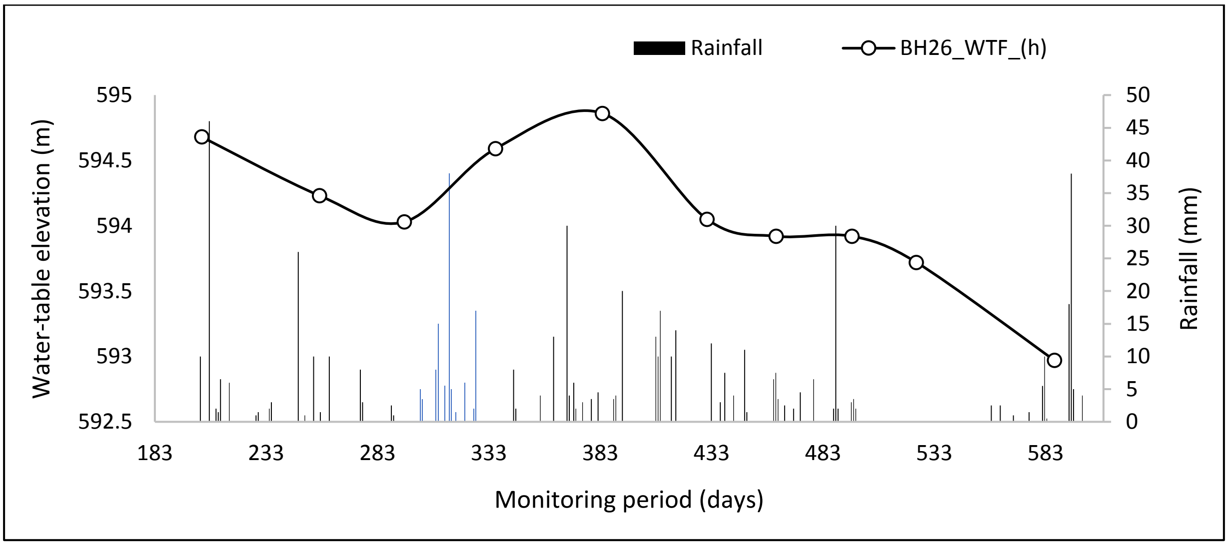

Rainfall
BH4_WTF_(c)
Water-table elevation (m)
531
530.5
530
529.5
529
528.5
528
Rainfall (mm)
50
45
40
35
30
25
20
15
10
5
0
183
233
283
333
383
433
483
533
583
Monitoring period (days)


Rainfall
BH5_WTF_(d)
Water-table elevation (m)
535.5
535
534.5
534
533.5
533
532.5
Rainfall (mm)
50
45
40
35
30
25
20
15
10
5
0
183
233
283
333
383
433
483
533
583
Monitoring period (days)


Rainfall
BH8_WTF_(e)
Water-table elevation (m)
529.8
529.7
529.6
529.5
529.4
529.3
529.2
Rainfall (mm)
50
45
40
35
30
25
20
15
10
5
0
183
233
283
333
383
433
483
533
583
Monitoring period (days)


Rainfall
BH11_WTF_(f)
Water-table elevation (m)
528.5
528
527.5
527
526.5
526
525.5
525
524.5
Rainfall (mm)
50
45
40
35
30
25
20
15
10
5
0
183
233
283
333
383
433
483
533
583
Monitoring period (days)





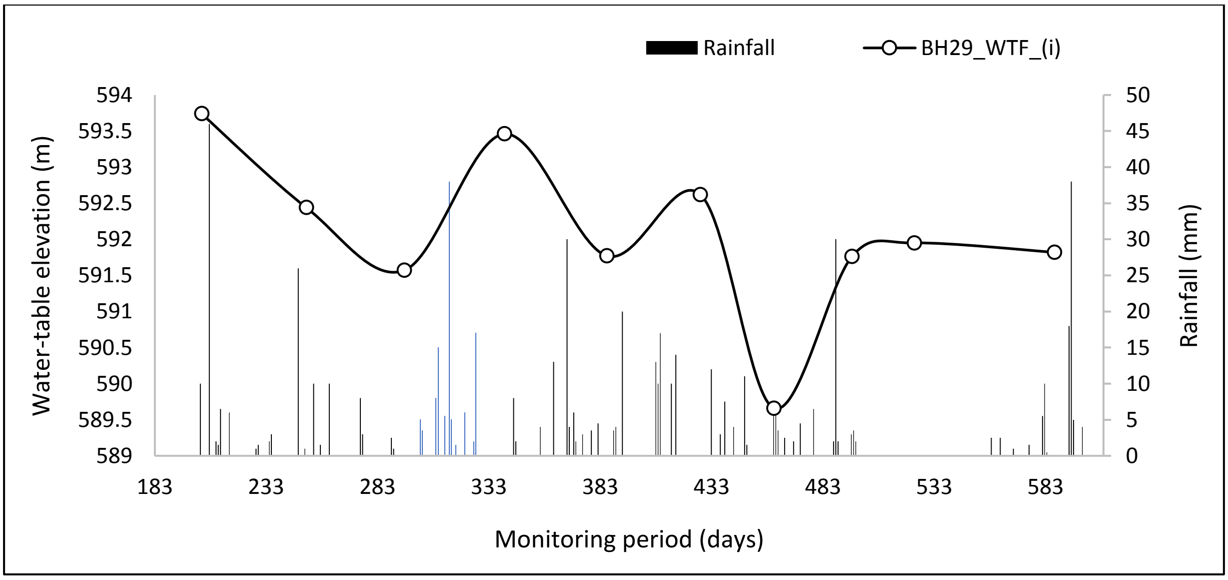


Figure 24a-i Observed water-table fluctuation from nine monitored boreholes following a targeted rainfall series, which is highlighted in blue.

Due to the inevitable uncertainty surrounding specific yield (S_y), the values were based on estimates from a study by Sun *et al*. (2013) involving Cape Supergroup sediments and consequently simulated at 0.002, 0.02 and 0.2 (Table 4).

Table 4 Estimates of recharge (R), for the targeted rainfall series, using the water-table fluctuation (WTF) method. Specific yield (Sy) simulated at 0.002, 0.02 and 0.2.

BH No.	Δh (mm)	Δt (days)	S_y	R (mm)	R (%)	S_y	R (mm)	R (%)	S_y	R (mm)	R (%)
1	1214	18	0.002	2.4	2.3	0.02	24.3	22.8	0.2	242.8	228.0
3	1970	20	0.002	3.9	3.7	0.02	39.4	37.0	0.2	394.0	370.0
4	1998	18	0.002	4.0	3.8	0.02	40.0	37.5	0.2	399.6	375.2
5	1191	15	0.002	2.4	2.2	0.02	23.8	22.4	0.2	238.2	223.7
8	2369	26	0.002	4.7	4.4	0.02	47.4	44.5	0.2	473.8	444.9
11	3552	24	0.002	7.1	6.7	0.02	71.0	66.7	0.2	710.4	667.0
14	1042	19	0.002	2.1	2.0	0.02	20.8	19.6	0.2	208.4	195.7
26	1360	14	0.002	2.7	2.6	0.02	27.2	25.5	0.2	272.0	255.4
29	2822	20	0.002	5.6	5.3	0.02	56.4	53.0	0.2	564.4	530.0

Realistic recharge values, ranging from 2 - 6.7 % of the targeted rainfall series, were calculated for a specific yield of 0.002 and therefore this value was used as a baseline estimate for following methods (highlighted in Table 4). Specific yield values of 0.02 and 0.2 were ignored as they produced inappropriate recharge estimates that were unrealistically high, ranging from 19.6 - 66.7 % and 195.7 - 667 %, respectively.

5.3.4. Other observed water-table fluctuation trends

Stable (artesian-type)

*A*rtesian-type conditions typically occur in areas where boreholes and/or wells are drilled into a confined section of an aquifer system. In these zones the groundwater is under greater hydrostatic pressure and therefore the water-table, when intersected, will rise to meet equilibrium. In the present study this was evidenced in some boreholes and an example of this is shown in Figure 25.

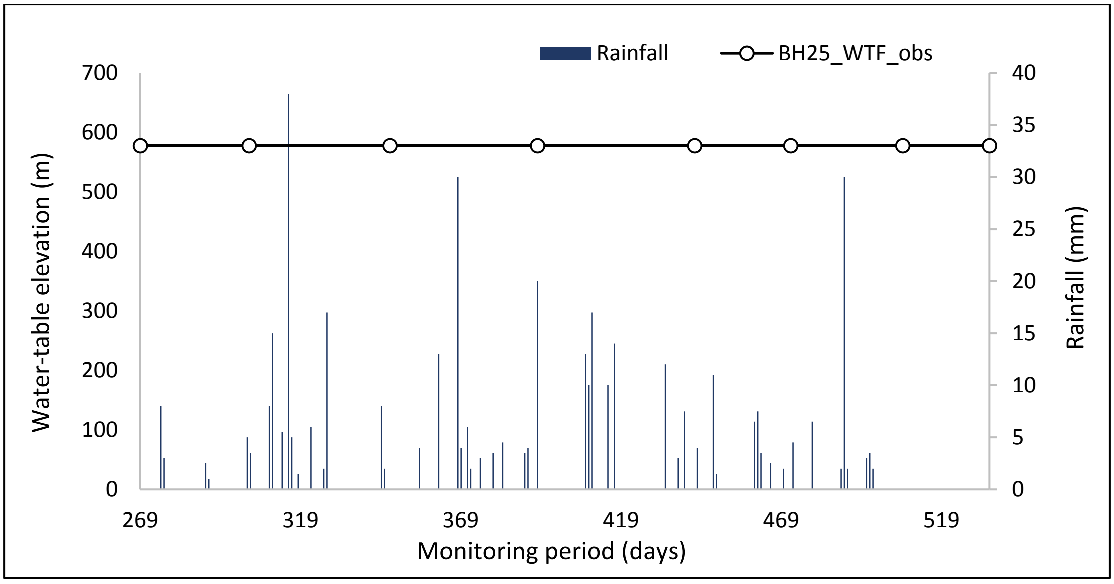


Figure 25 Stable water-table observed at BH25, suggesting artesian-type conditions.

Artesian-type conditions were suggested for BH22 and BH25 as they showed very stable conditions and their water levels remained either at or near to the land surface during the entire monitoring period. The positions of possible current and historical artesian wells were plotted onto a catchment map (Figure 26).

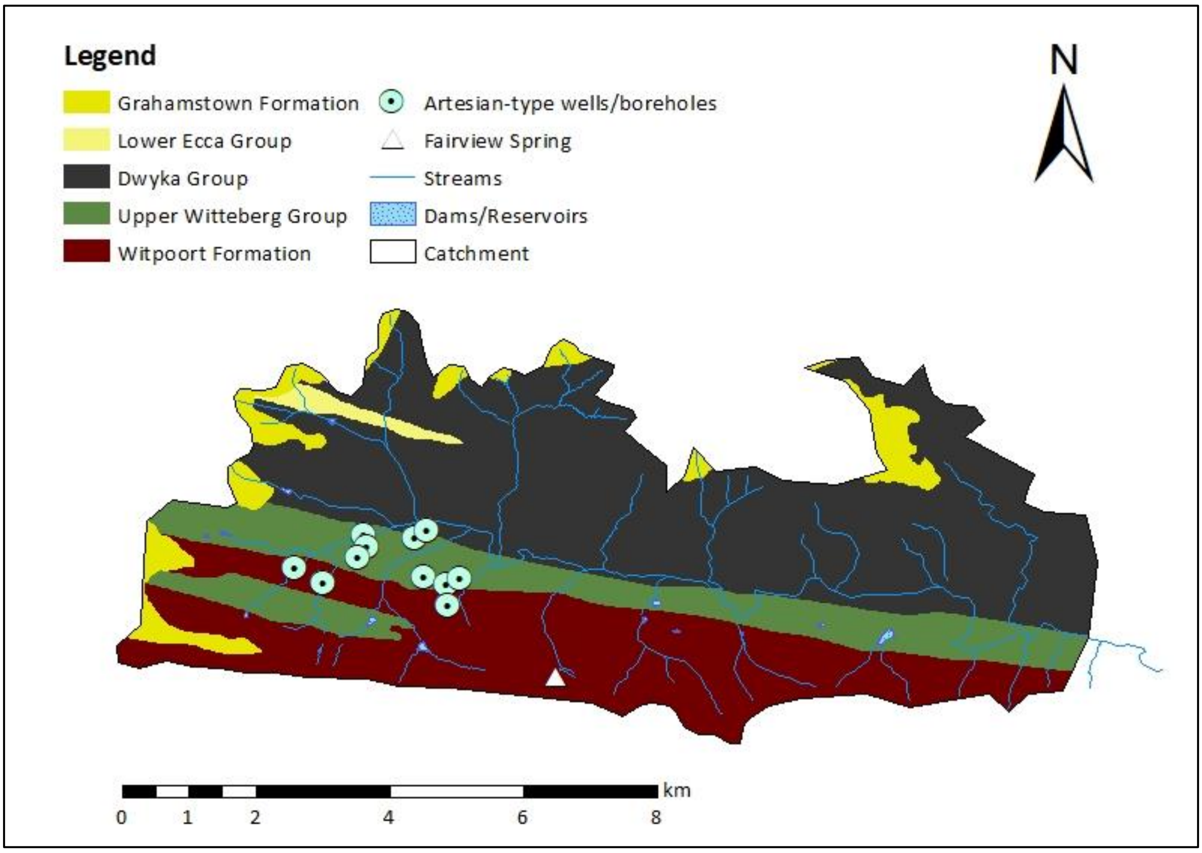
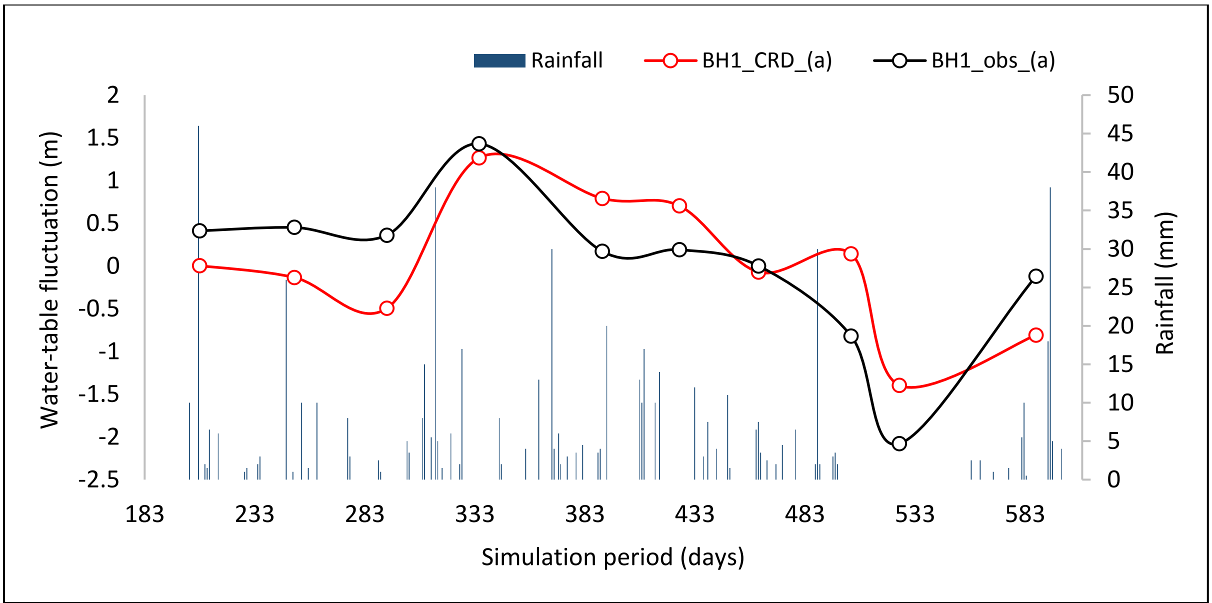


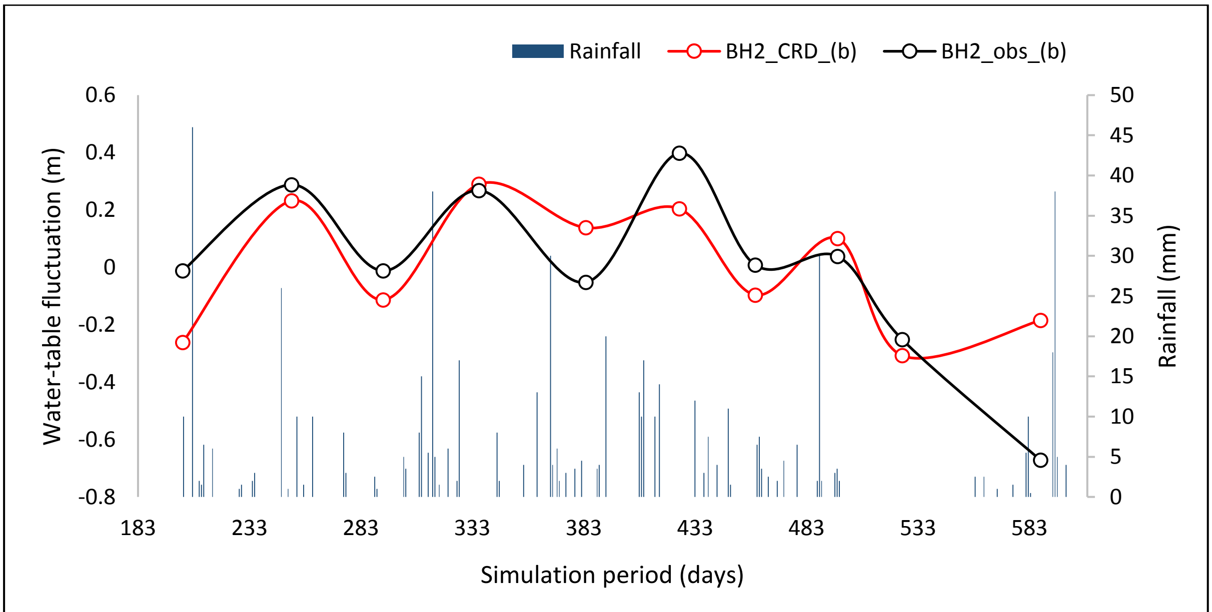
Figure 26 Map indicating the position of past and present artesian-type boreholes and wells.

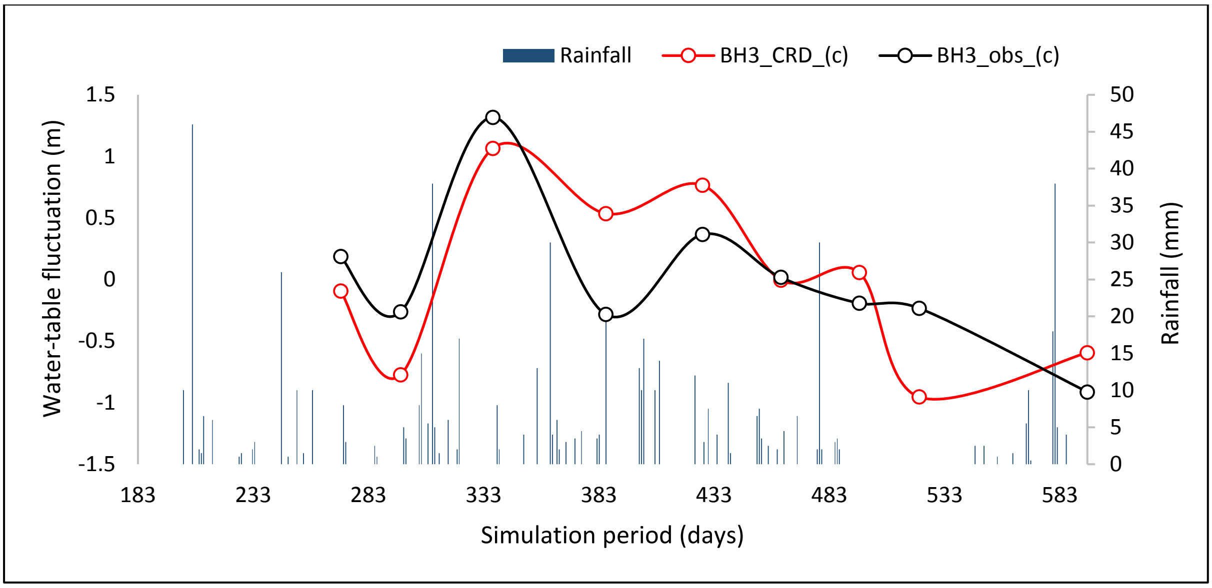
Although most of these boreholes/wells plot on the upper Witteberg Group shale (Figure 26), they were most likely drilled through this aquitard as this is the area where the Witpoort aquifer transitions from an unconfined to confined environment, favouring artesian-type conditions.

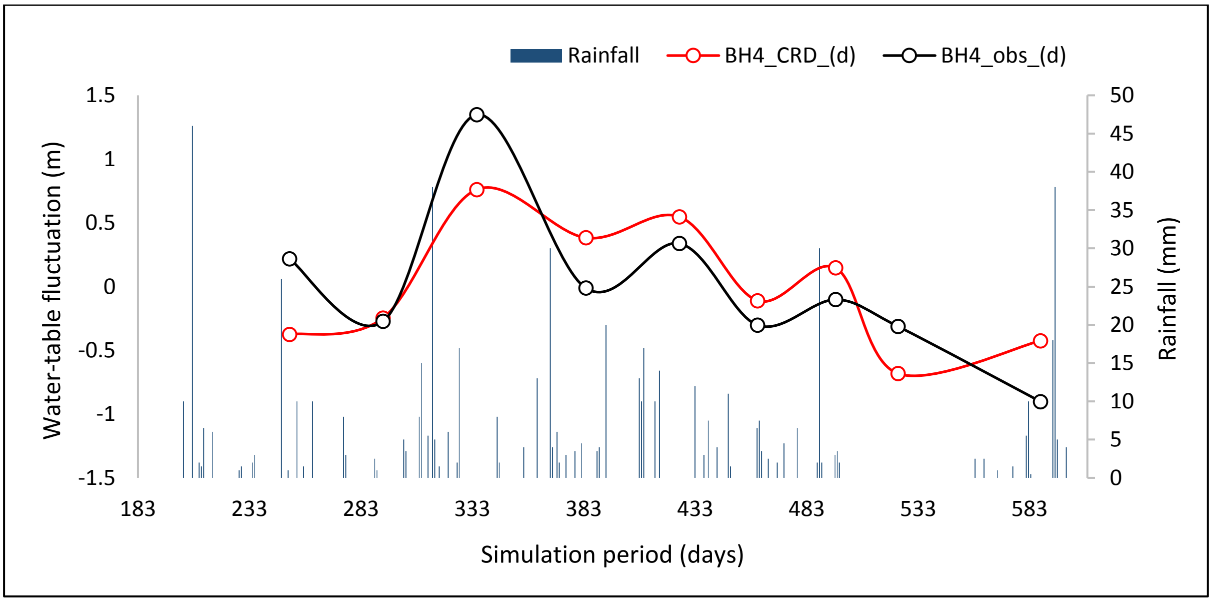
5.3.5. Cumulative rainfall departure (CRD) method

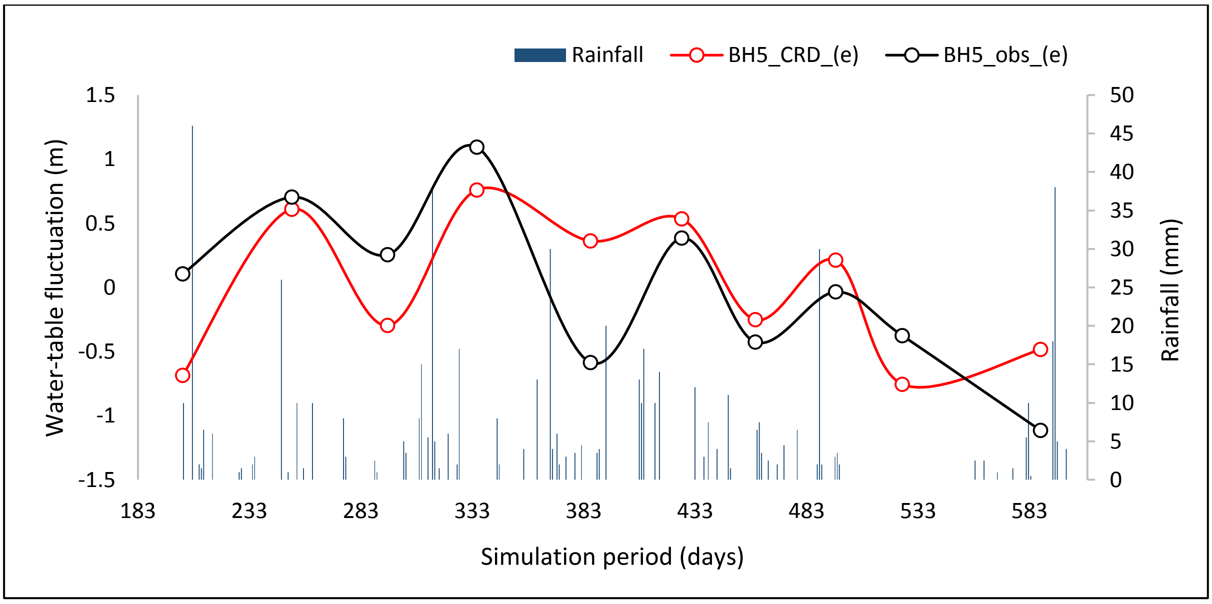
The CRD method was applied to monitored boreholes that showed positive fluctuations following any rainfall event and not necessarily a single response as in the WTF method (Figure 27a-q). The method simulates recharge and specific yield (*BHx_CRD*) in an effort to replicate water-table fluctuations observed in monitored boreholes (*BHx_obs*).

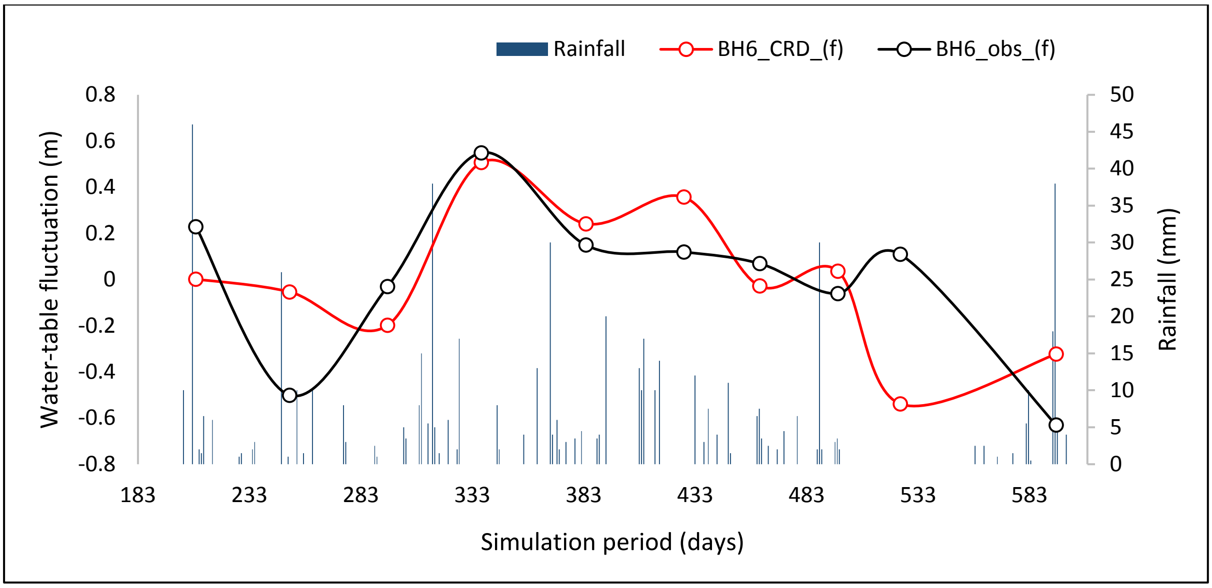


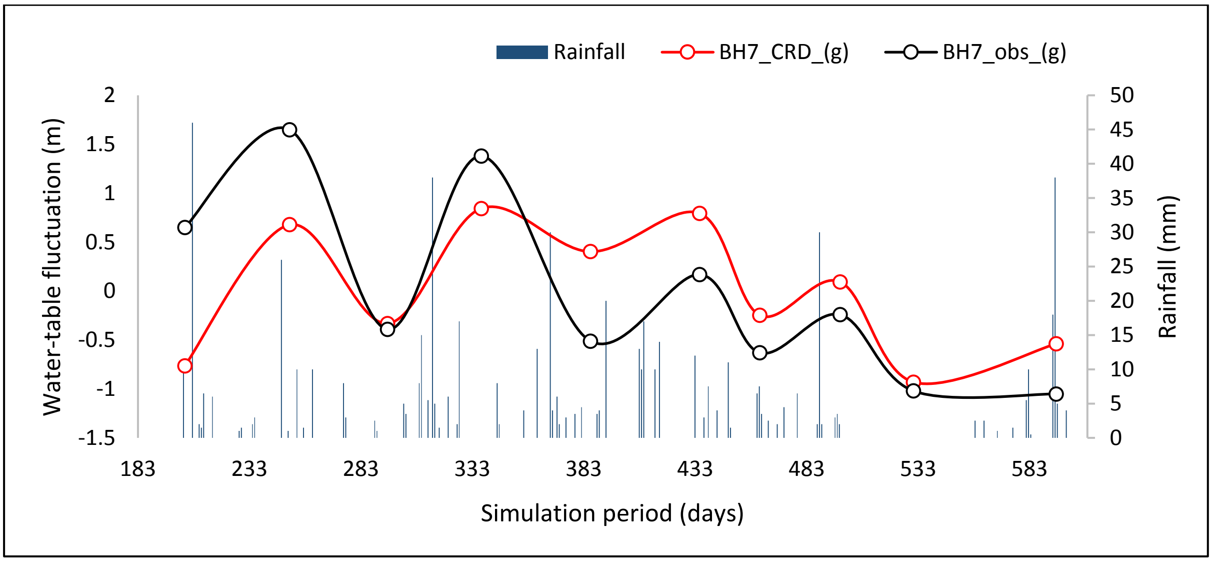


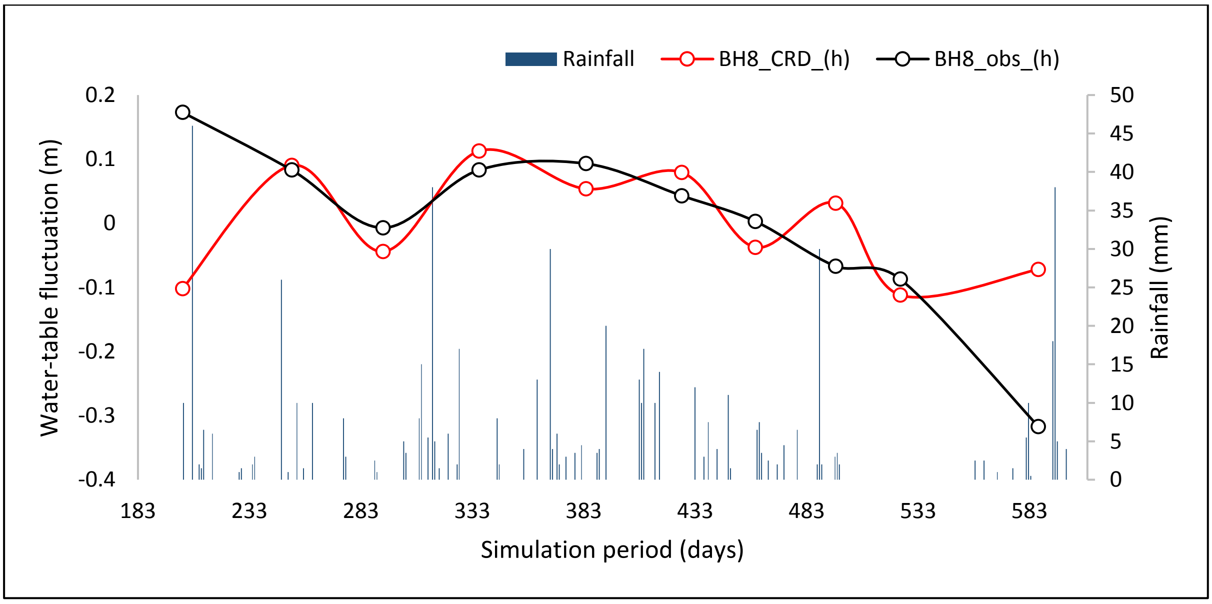

Rainfall
BH3_CRD_(c)
BH3_obs_(c)
Water-table fluctuation (m)
Rainfall (mm)
Simulation period (days)
1.5
1
0.5
0
-0.5
-1
-1.5
50
45
40
35
30
25
20
15
10
5
0
183
233
283
333
383
433
483
533
583

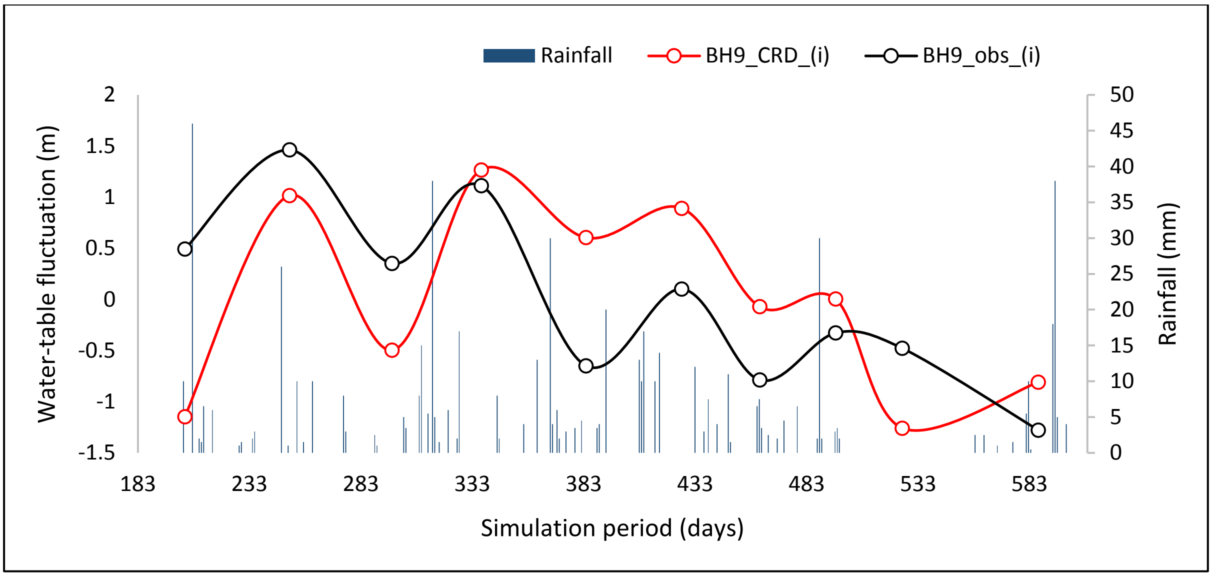

Rainfall
BH4_CRD_(d)
BH4_obs_(d)
Water-table fluctuation (m)
Rainfall (mm)
Simulation period (days)
1.5
1
0.5
0
-0.5
-1
-1.5
50
45
40
35
30
25
20
15
10
5
0
183
233
283
333
383
433
483
533
583


Rainfall
BH5_CRD_(e)
BH5_obs_(e)
Water-table fluctuation (m)
Rainfall (mm)
Simulation period (days)
1.5
1
0.5
0
-0.5
-1
-1.5
50
45
40
35
30
25
20
15
10
5
0
183
233
283
333
383
433
483
533
583

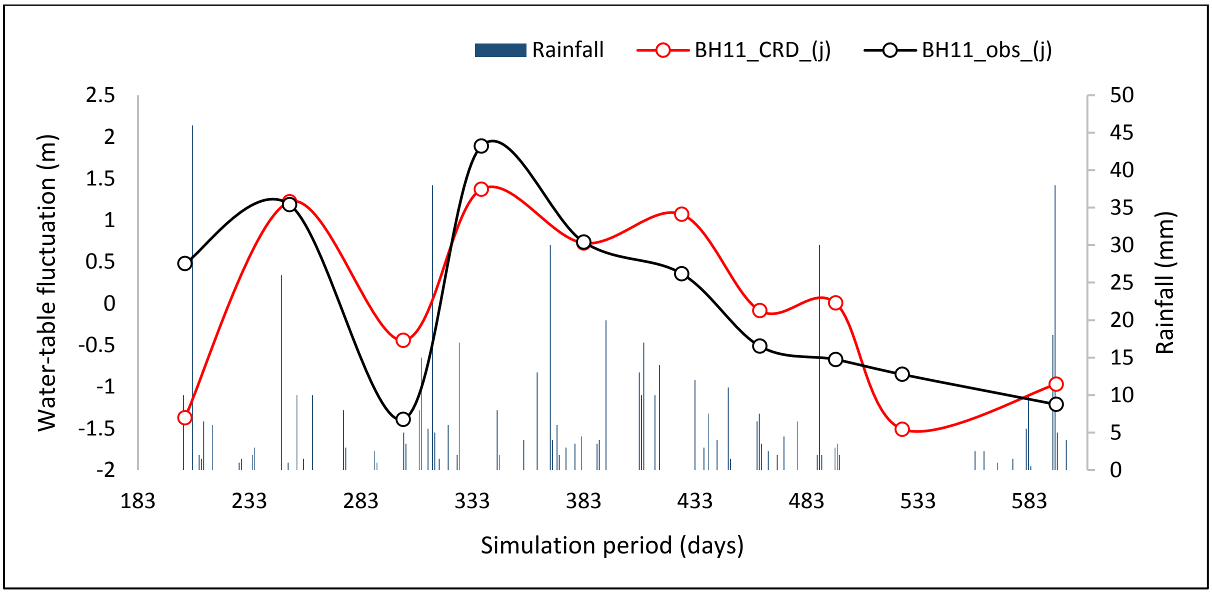

Rainfall
BH6_CRD_(f)
BH6_obs_(f)
Water-table fluctuation (m)
Rainfall (mm)
Simulation period (days)


Rainfall
BH7_CRD_(g)
BH7_obs_(g)
Water-table fluctuation (m)
Rainfall (mm)
Simulation period (days)

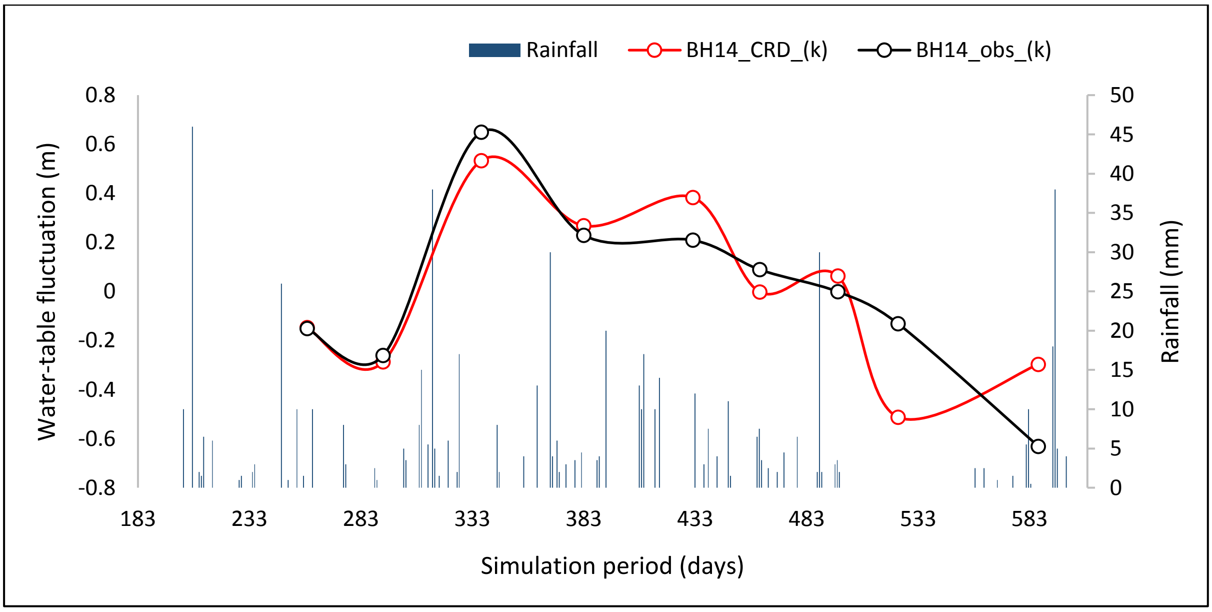

Rainfall
BH8_CRD_(h)
BH8_obs_(h)
Water-table fluctuation (m)
Rainfall (mm)
Simulation period (days)



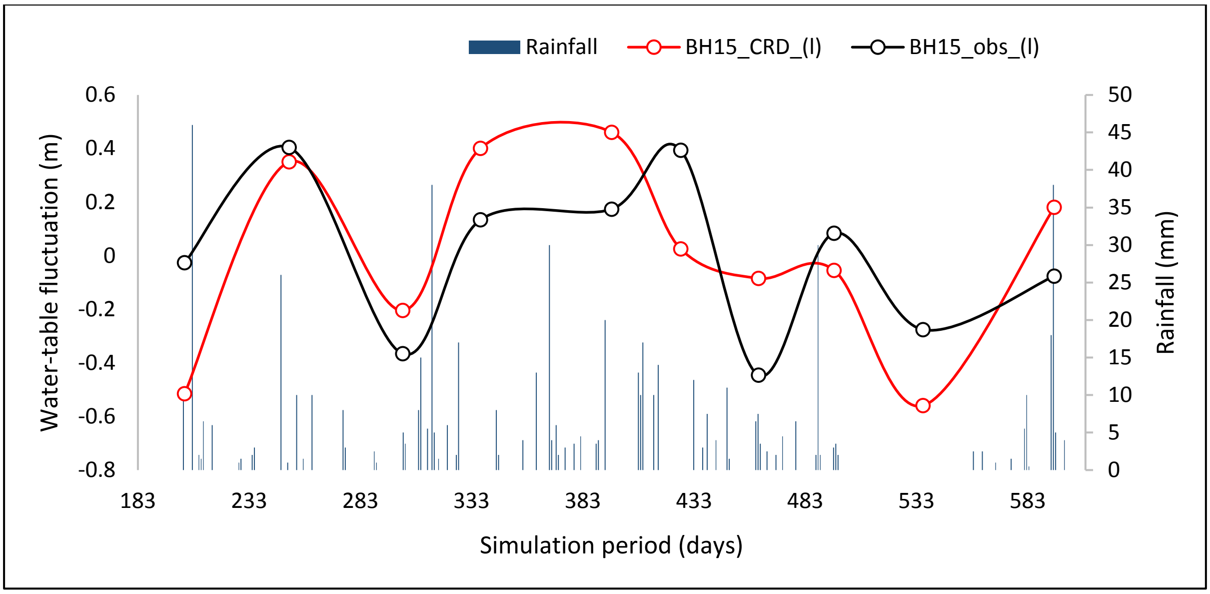
Rainfall
BH9_CRD_(i)
BH9_obs_(i)
Water-table fluctuation (m)
Rainfall (mm)
Simulation period (days)

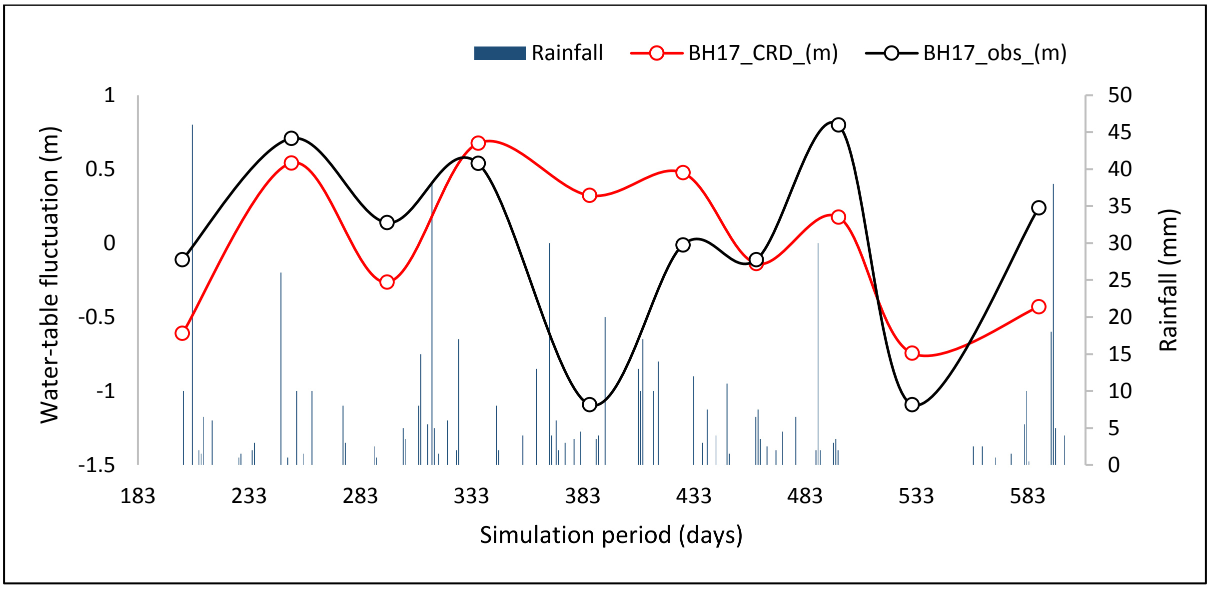


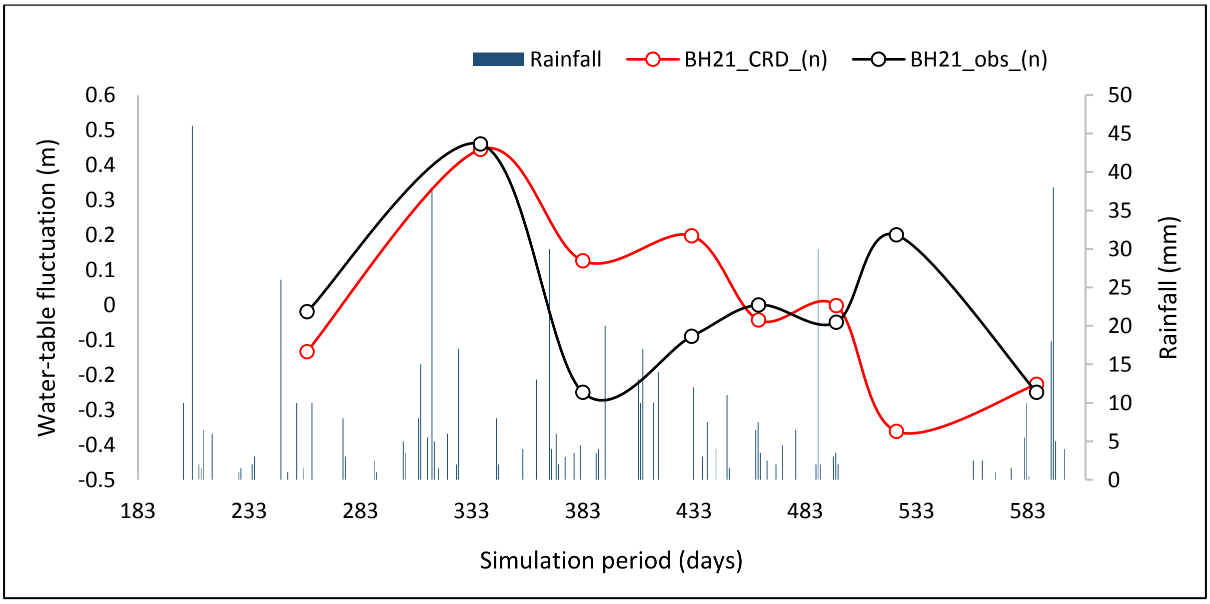
Rainfall
BH11_CRD_(j)
BH11_obs_(j)
Water-table fluctuation (m)
Rainfall (mm)
Simulation period (days)

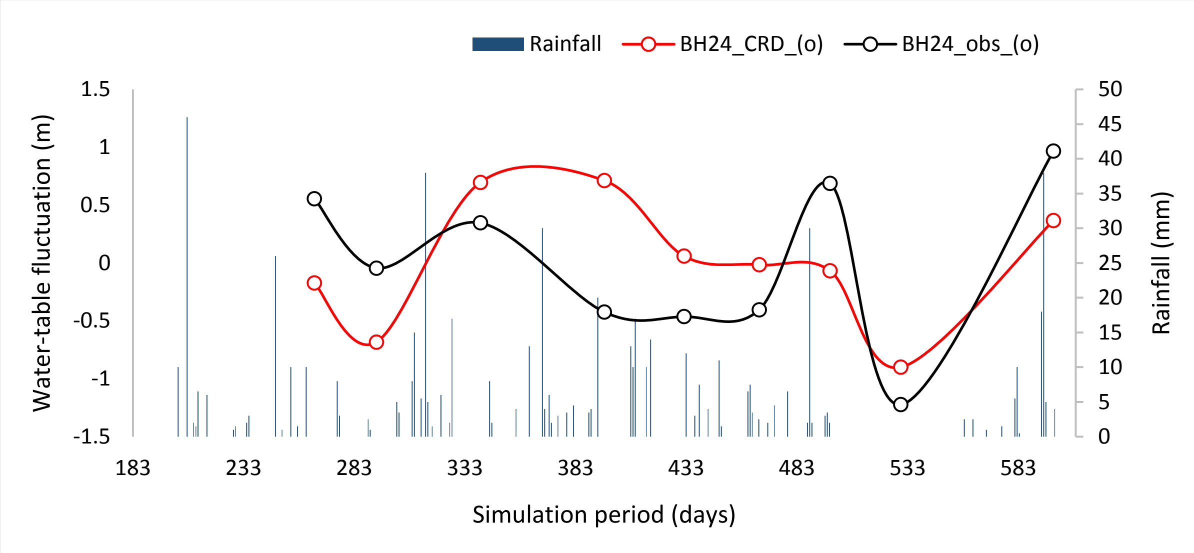


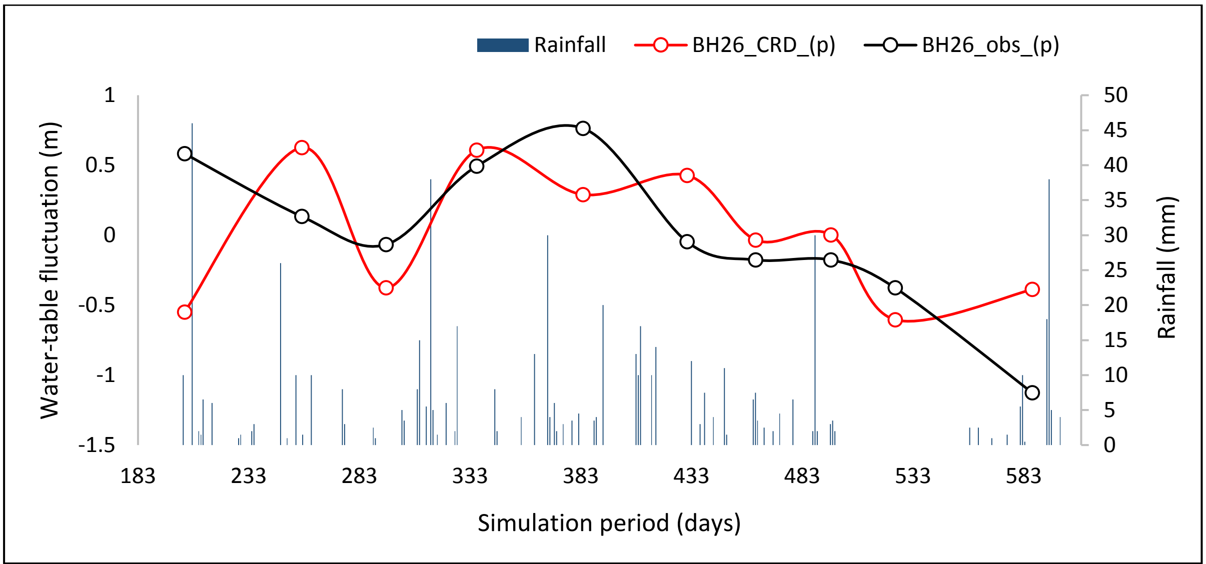
Rainfall
BH14_CRD_(k)
BH14_obs_(k)
Water-table fluctuation (m)
Rainfall (mm)
Simulation period (days)


Rainfall
BH15_CRD_(l)
BH15_obs_(l)
Water-table fluctuation (m)
Rainfall (mm)
Simulation period (days)
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
50
45
40
35
30
25
20
15
10
5
0
183
233
283
333
383
433
483
533
583


Rainfall
BH17_CRD_(m)
BH17_obs_(m)
Water-table fluctuation (m)
Rainfall (mm)
Simulation period (days)
1
0.5
0
-0.5
-1
-1.5
50
45
40
35
30
25
20
15
10
5
0
183
233
283
333
383
433
483
533
583


Rainfall
BH21_CRD_(n)
BH21_obs_(n)
Water-table fluctuation (m)
Rainfall (mm)
Simulation period (days)
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
50
45
40
35
30
25
20
15
10
5
0
183
233
283
333
383
433
483
533
583





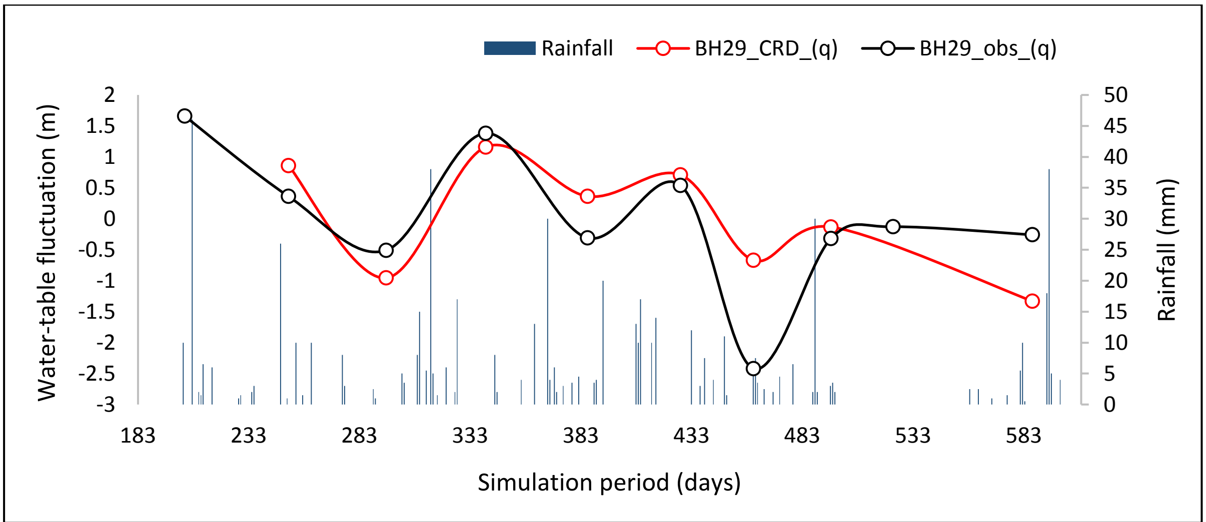


Figure 27a-q Comparison between CRD simulations (*BHx_CRD*) and the water-table fluctuations observed in the monitored boreholes (*BHx_obs*).

Numerous boreholes showed similarities in their water-table fluctuations compared to their respective CRD simulations. Each was run at a time scale that mirrored that of the observed data measurements. It should also be noted that 29 out of the 31 monitored boreholes are actively pumped which may have caused dissimilarities in places and appears to be the case for certain boreholes, namely BH29 where a drop in the observed data is evidenced on day 461, while the rest of the measurements seem to correlate well. On this occasion it is possible that the owner may have pumped less than 24 hours before and forgot to inform me when I took the measurement. This uncertainty relating to pumping events discouraged further analysis and the application of an efficiency coefficient, instead the simulations were simply used to provide additional estimations of specific yield and recharge, of which were comparable to the estimates determined through the WTF method. The results of the CRD method are summarised in Table 5 below:

Table 5 Recharge and specific yield estimates for individual boreholes simulated through the CRD method.

BOREHOLE	RECHARGE_%MAP_SIM	SPECIFIC YIELD_SIM
BH1	5	0.002
BH2	4	0.007
BH3	4	0.002
BH4	5	0.0035
BH5	3	0.002
BH6	5	0.005
BH7	5	0.003
BH8	2	0.009
BH9	5	0.002
BH11	6	0.002
BH14	4	0.004
BH15	5	0.005
BH17	4	0.003
BH21	5	0.008
BH24	6	0.004
BH26	6	0.005
BH29	4.5	0.0015

The CRD method estimated recharge at 2 - 6 % of MAP compared to 2 - 6.7 % for the WTF method. The baseline specific yield of 0.002 estimated during the WTF method was kept in mind during CRD simulation and this parameter was estimated at 0.0015 – 0.009. Therefore, both recharge and specific yield estimates from the two methods showed to be comparable results.

5.3.6. Pumping tests

During 1885/86 Andrew Stone conducted pumping tests for three separate boreholes located in different areas of the town, namely African Street, the old caravan park (presently Makana Resort) and York Street (Figure 28). During the current study, these boreholes will be named and referred to by these locations.

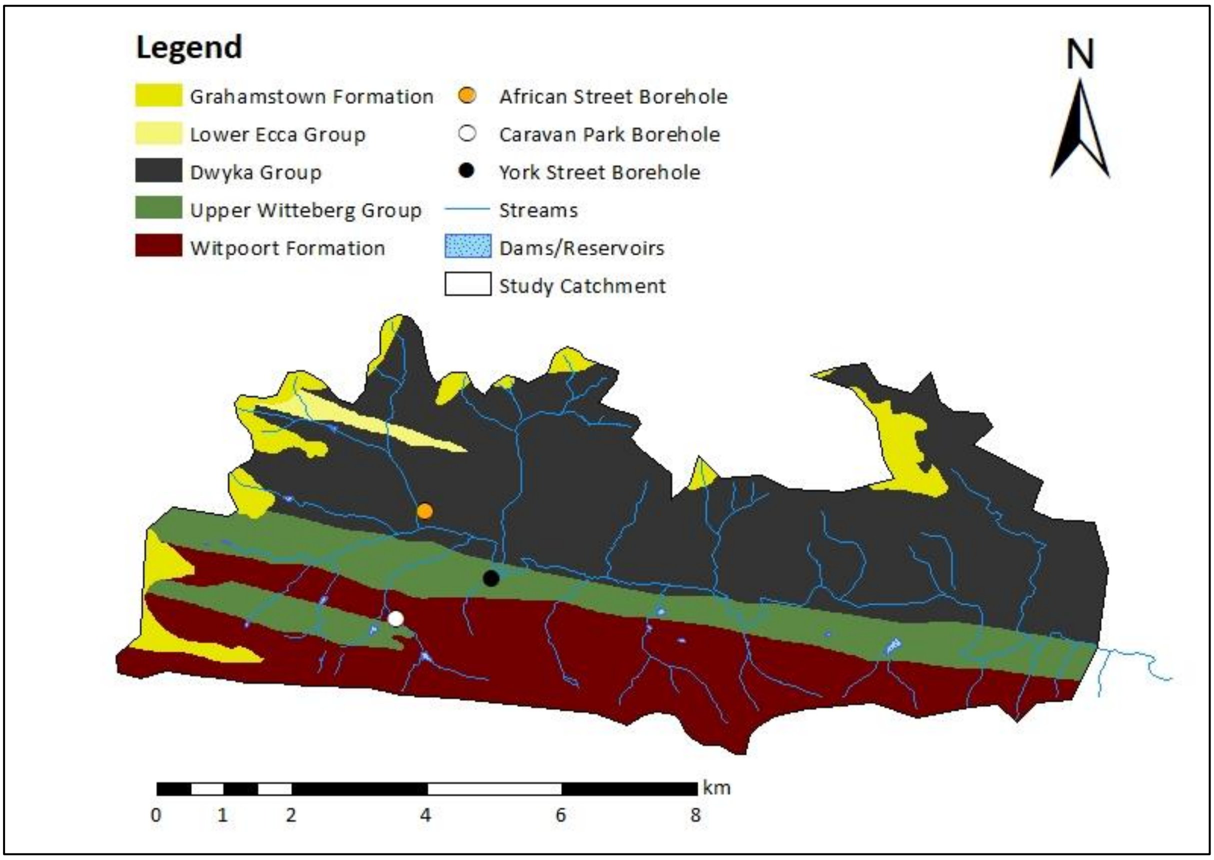


Figure 28 Study catchment including the positions of three boreholes involved in previous pumping tests and the rock lithologies into which they were drilled.

The positions of the African Street, Caravan Park and York Street boreholes in Figure 28 indicate the aquifer system into which they were drilled. The African Street and Caravan Park boreholes were drilled into the Dwyka and Witpoort aquifers respectively, while the York Street borehole most likely penetrated through the upper Witteberg Group shale aquitard and into the underlying quartzitic sandstone of the Witpoort aquifer. Pumping tests involve a period of drawdown, during which the borehole is pumped, followed by a period of recovery, which occurs after the pump has been switched off. The periods of drawdown and recovery helped Andrew Stone to estimate sustainable yield for each of the three boreholes (Figure 29, Figure 30 and Figure 31).

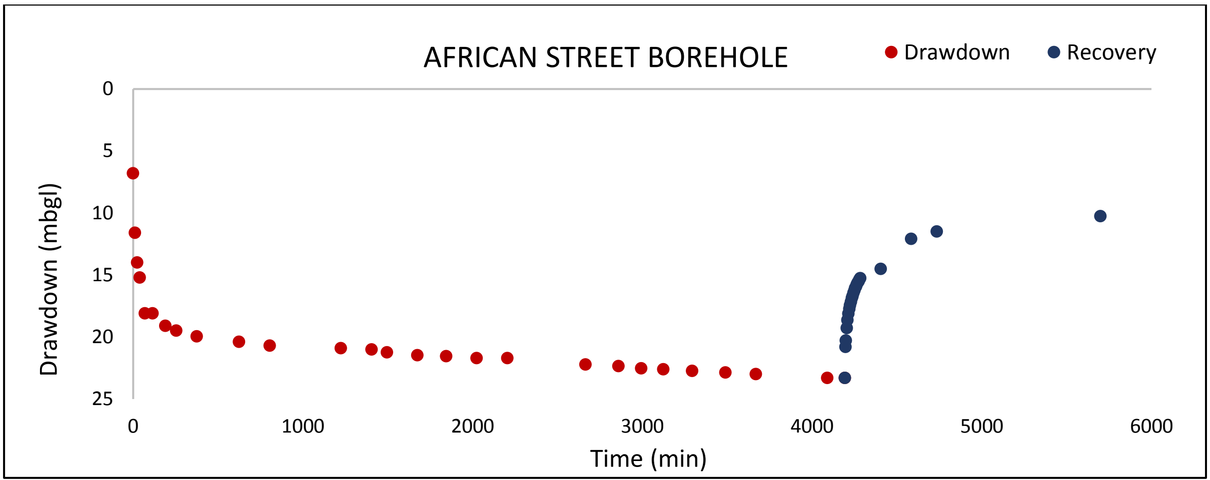


Figure 29 Drawdown and recovery data (Stone, 1986) from a pumping test conducted by Andrew Stone for a borehole drilled into the Dwyka Group.

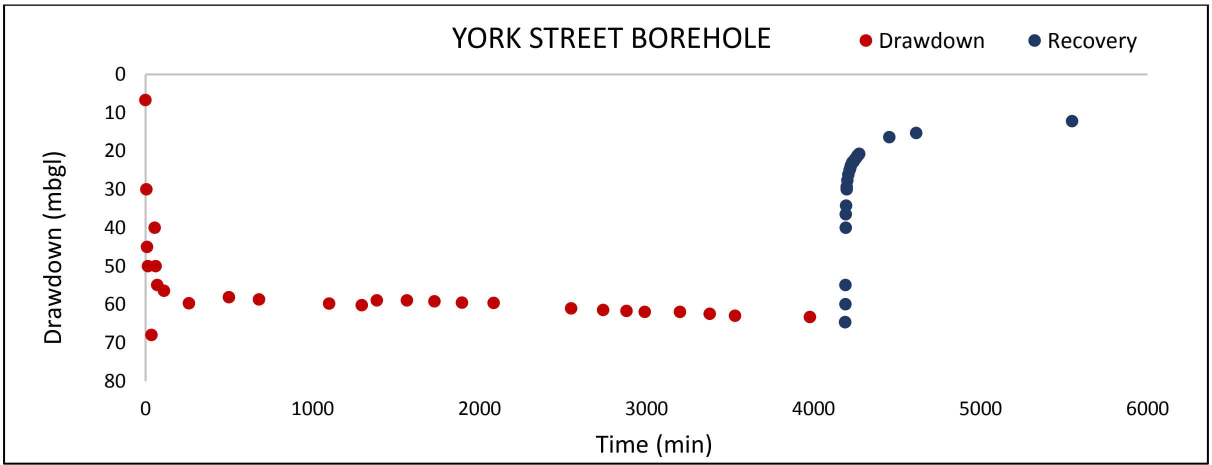


Figure 30 Drawdown and recovery data (Stone, 1986) from a pumping test conducted by Andrew Stone for a borehole drilled into the Witpoort Formation.

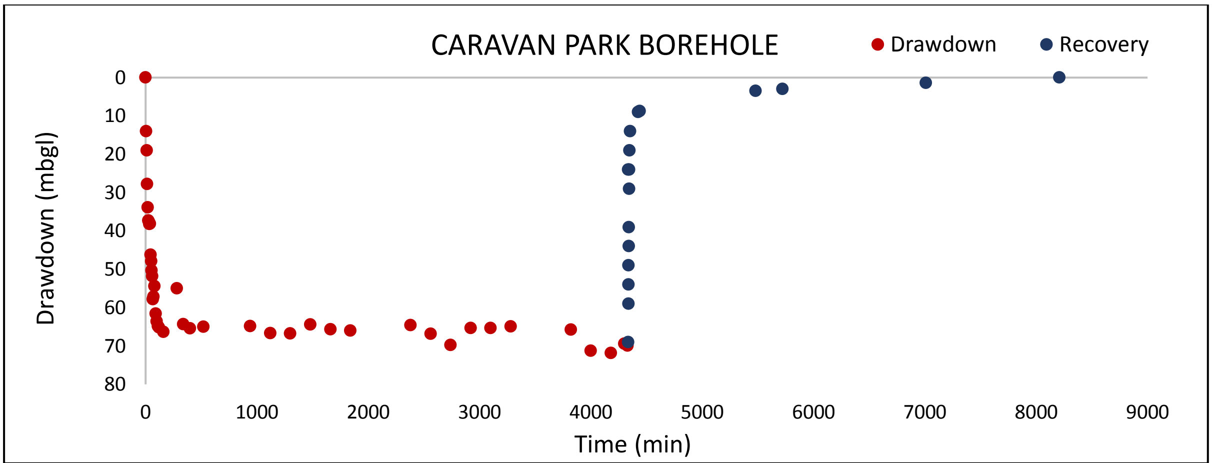


Figure 31 Drawdown and recovery data (Stone, 1986) from a pumping test conducted by Andrew Stone for a borehole assumedly drilled through the shale aquitard into the Witpoort Formation.

For these three pumping tests, evaluations of maximum recommended yield were estimated and are summarised in Table 6, along with some other features of the tested boreholes.

Table 6 Summary of properties from three boreholes evaluated in Andrews Stones report.

BH	Aquifer		BH Depth (m)	Pump depth (m)	Max recommended yield ($l\ s^{-1}$)
	Type	Conditions			
African Street	Dwyka	Unconfined	42	36	6.8
York Street	Witpoort	Semi-confined	82	76	3.2
Caravan Park	Witpoort	Confined	92.5	84	2.4

5.4. Hydrogeochemistry

5.4.1. Sample sites

A total of ten samples were tested for common chemical ions, nine from boreholes and one from the Fairview Spring. The locations of these sample sites are shown below (Figure 32).

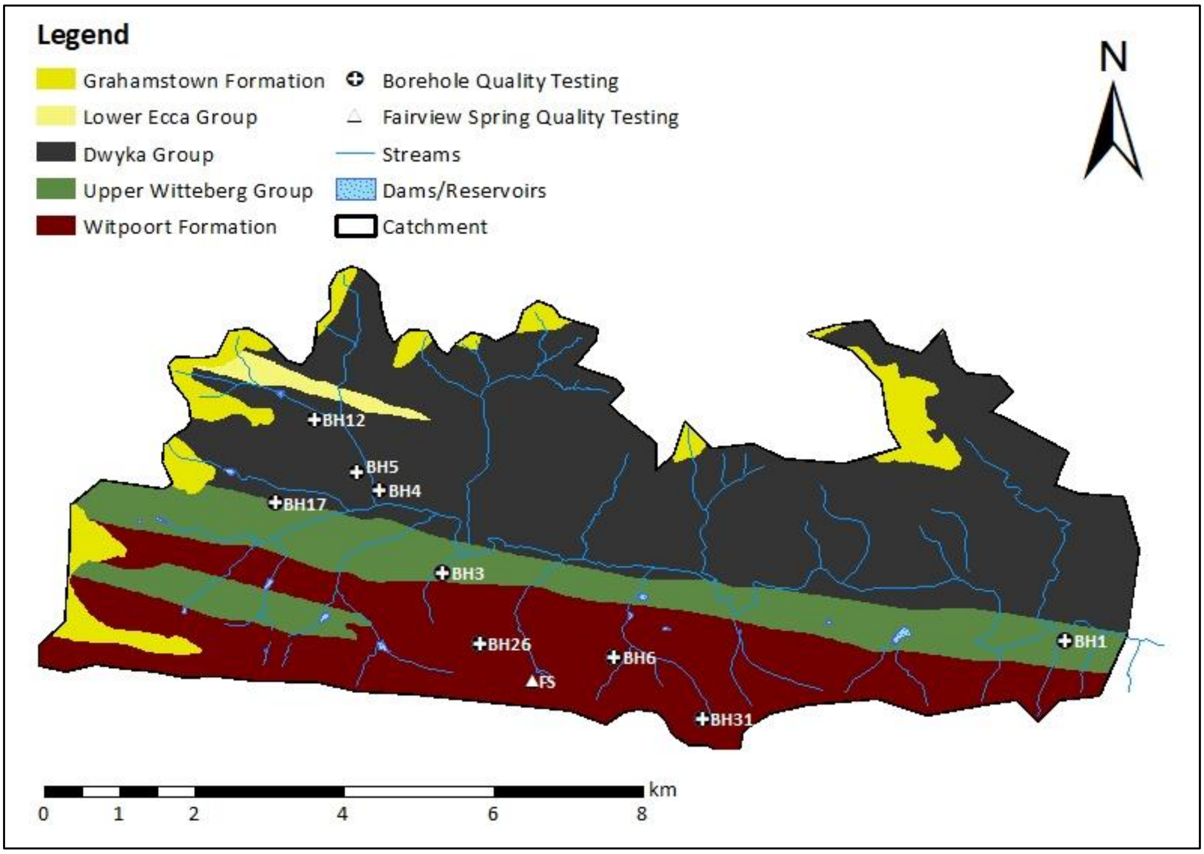


Figure 32 The localities of the nine boreholes and Fairview Spring that were sampled and sent for basic chemical analysis.

Groundwater chemistry is largely influenced by the geology through which it flows as well as residence time. From Figure 32 it is clear to see that samples from BH12, BH5 and BH4 were extracted from the Dwyka aquifer while samples from BH31, BH26, BH6 and the Fairview Spring relate to the Witpoort aquifer. Samples from BH17, BH3 and BH1 appear to be from the upper Witteberg Group aquitard, however these boreholes are most likely drilled through this shale aquitard and likewise extract groundwater from the underlying quartzitic sandstone of the Witpoort aquifer. A detailed table with all hydrogeochemical results from the relative samples is shown in Table 7 below.

Table 7 Summary of hydrogeochemical results from sampled boreholes and spring, along with WHO (2012) water quality guidelines.

Geologic drill location	Witpoort Formation				Upper Witteberg Group			Dwyka Formation			Human consumption (WHO, 2012)
Locality Code	SPR	FK	18SH	WF	BEL	7WEB	3DBN	GC	GBC	77C	
Borehole number	N/A	BH6	BH31	BH26	BH1	BH3	BH17	BH12	BH4	BH5	
Units	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}
Cl	39.6	84.8	90.1	9.6	241	368	865	824	922	1460	0 - 600
SO_4	2.21	5.97	1.74	6.71	45.9	101	124	125	555	281	0 - 250
Ca	2.45	4.26	7.73	8.02	20.8	32	121	73.8	148	210	0 - 200
Mg	3.21	5.27	9.67	11.3	24	36	107	77.4	129	206	0 - 150
Na	21.4	45.6	40.3	52.2	188	309	435	721	605	1027	0 - 200
K	0.415	0.464	0.862	0.561	0.886	0.962	5.45	3.4	4.93	8.85	0 - 12
HCO_3	3.65	0.01	0.757	13.5	173	216	122	336	270	231	0 - 500
Fe	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0 - 0.1
Mn	0.001	0.001	0.001	0.01	0.684	0.034	0.379	0.126	0.001	0.001	0 - 0.05
Cu	0.002	0.002	0.287	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0 - 1
pH	7.03	6.57	5.7	6.66	7.51	7.97	7.8	7.87	8.01	7.64	6.5 - 8.5
EC (mS m^{-1})	17.1	30.7	34.2	40.8	114	173	312	331	381	537	150
Alkalinity	3.66	1.99	1.99	13.5	173	218	123	338	273	232	N/A
Carbonate alkalinity	0.01	0.01	0.01	0.01	0.521	1.89	0.723	2.33	2.57	0.938	N/A

The hydrogeochemical results were compared to WHO (2012) water quality guidelines and any sample component that exceeded the recommended limit for human consumption was highlighted by a border (Table 7). All samples drilled into the Dwyka aquifer have at least three chemical components that exhibit concentrations that are unsafe for consumption, with BH5 being the worst, exceeding the recommended concentrations for Cl, SO_4, Ca, Mg, Na and well as the EC limit. Boreholes drilled into the upper Witteberg Group aquitard have at least one chemical component that exceeds the WHO (2012) guidelines. In comparison, the Witpoort aquifer shows no chemical concentrations above the recommended limits, although a low pH level of 5.7 is evident from BH31. Overall this provides good evidence that the Witpoort aquifer not only holds the better groundwater quality of the two systems, but also good quality groundwater that is safe for human consumption. If groundwater from the Dwyka aquifer and upper Witteberg Group is to be used for human consumption, then treatment would be required.

Electrical conductivity is directly proportional to total dissolved solids and can be a useful aid in differentiating aquifer systems as well as to provide important clues regarding recharge dynamics and groundwater residence time (Figure 33).

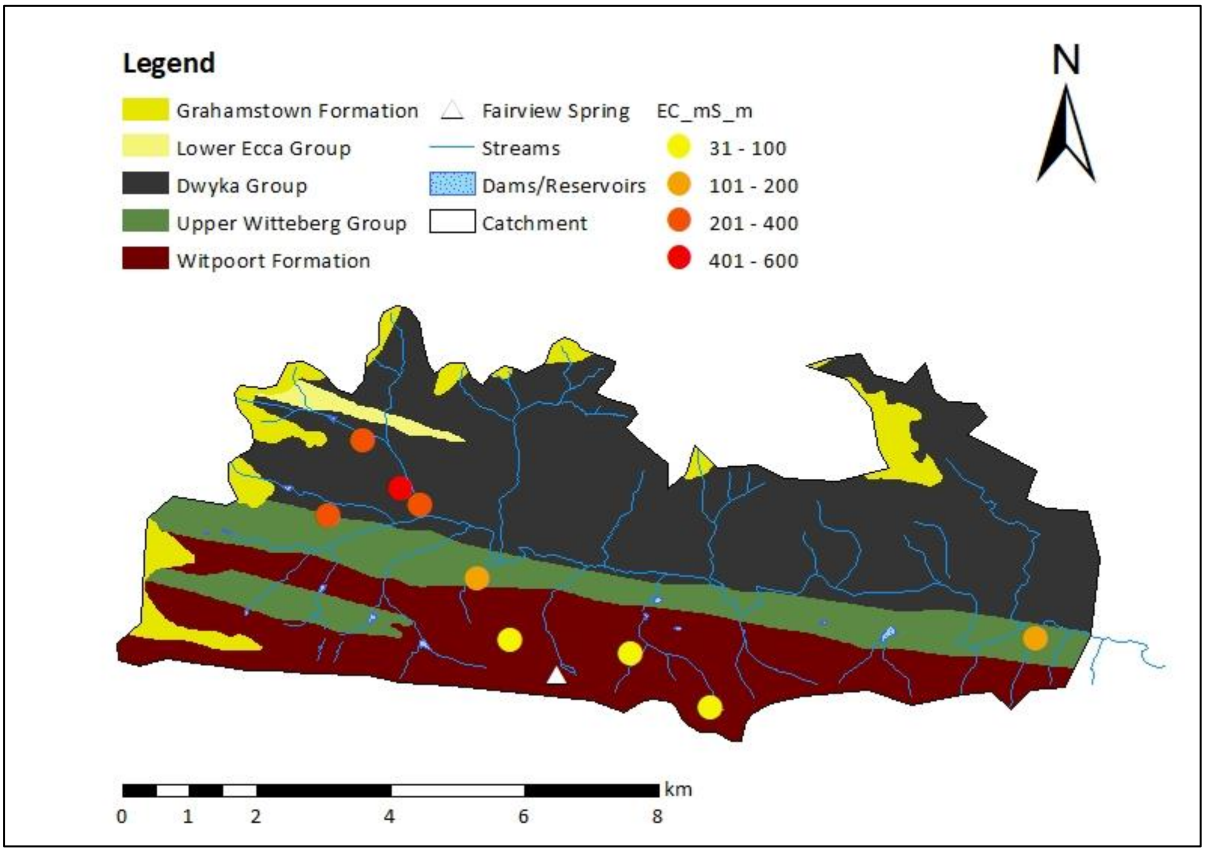


Figure 33 Illustrates the variations in electrical conductivity for sampled boreholes, expressed as milliSiemens per metre (mS m^{-1}).

From Figure 33 it is evident that electrical conductivity levels are lowest in the Witpoort aquifer, ranging from 31 – 200 mS m^{-1}, compared to the Dwyka aquifer which produced electrical conductivity levels ranging from 201 – 600 mS m^{-1}. The sample from the Fairview Spring, situated in the Witpoort aquifer (Figure 33), revealed an electrical conductivity of 17 mS m^{-1}, the lowest of all samples tested.

An interesting observation was made for BH1, BH3 and BH17. These three boreholes are all drilled into the upper Witteberg Group aquitard and all showed raised concentrations of Mn (Figure 34). This led to the assumption that the shale aquitard holds Mn-containing groundwater that is drawn into the boreholes drilled through this geologic unit. Only one other borehole showed to have concentrations of Mn, namely BH12, perhaps this borehole is drilled deep enough that it intersects the shale aquitard beneath the Dwyka aquifer? On the same topic, it is unusual that significant Fe concentrations were not evident in these boreholes, as it is commonly associated with Mn. This may be due to the environment under which the shale was deposited and lithified.

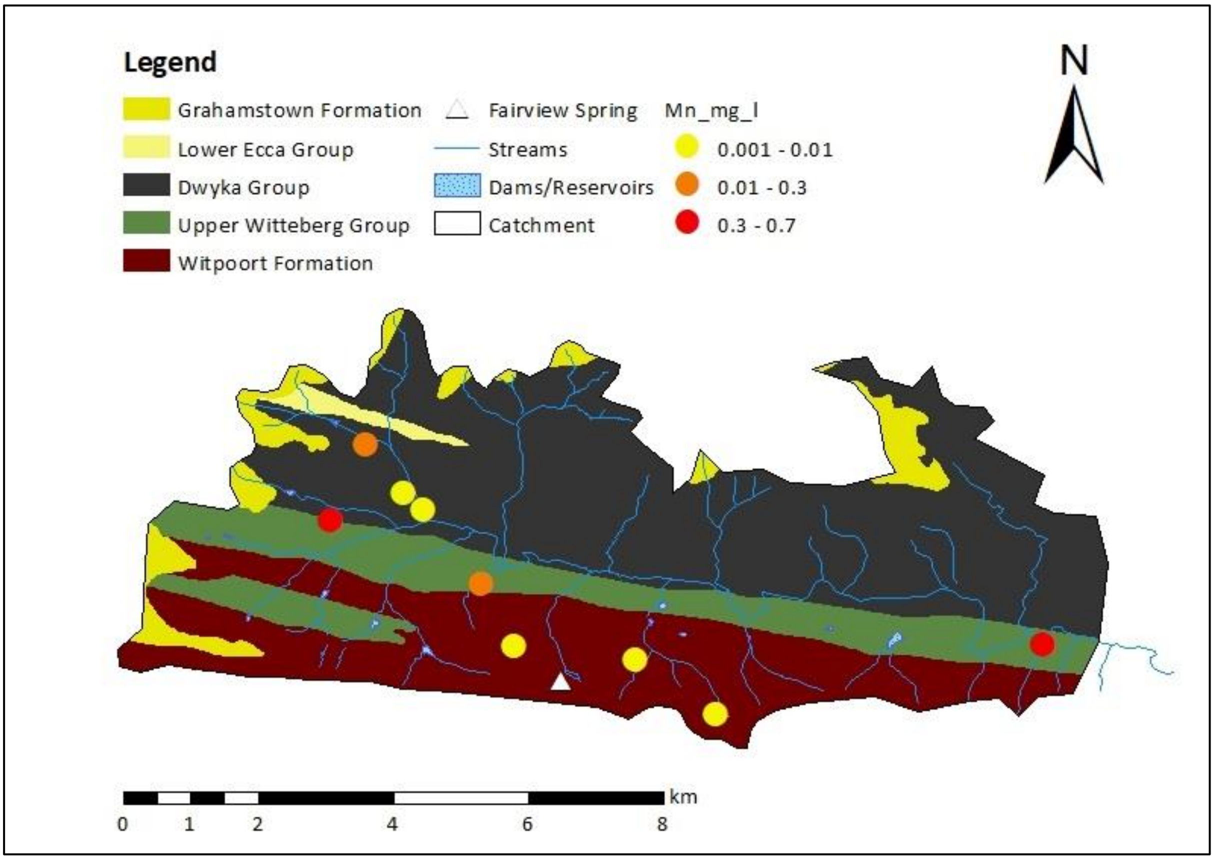


Figure 34 Illustrates the variations in manganese (Mn) concentrations for sampled boreholes within the study catchment, expressed as milligrams per litre (mg l^{-1}).

5.4.2. Schoeller plot

A Schoeller plot provides a good indication of variations in major anions and cations among the ten samples (Figure 35).

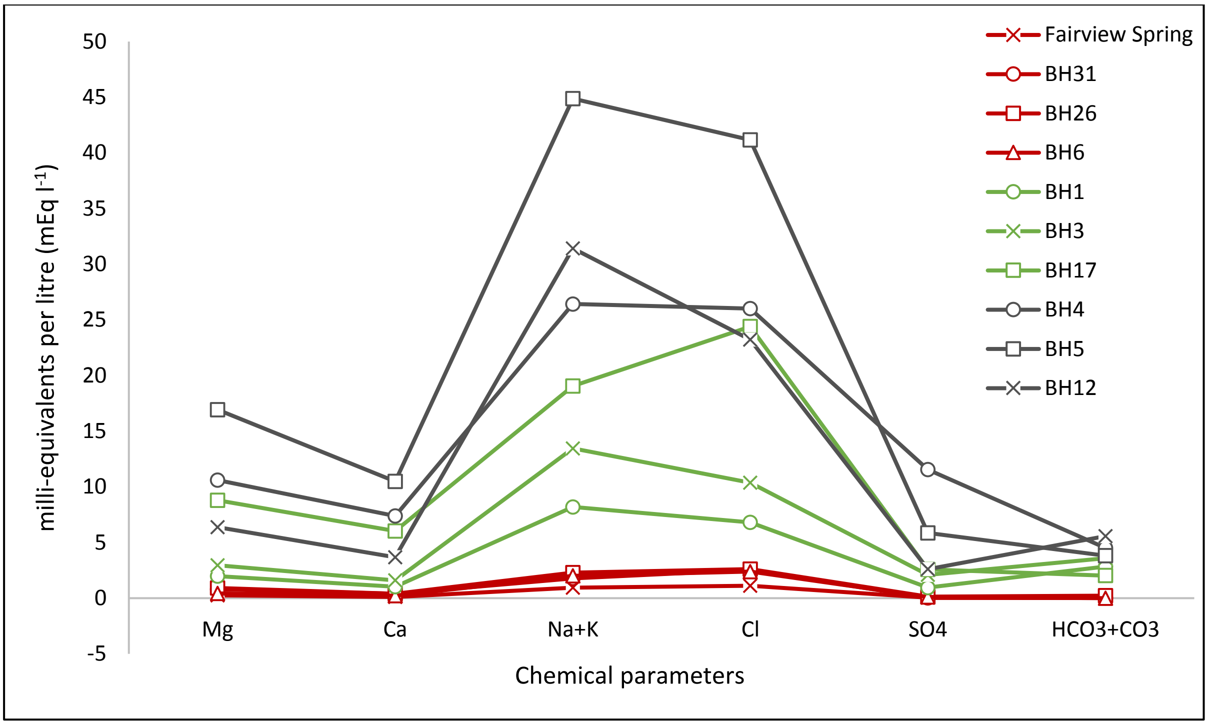


Figure 35 Schoeller plot highlighting the major anions and cations from each of the ten samples, expressed as milliequivalents per litre (mEq l^{-1}). Samples have been separated according to the geology into which they are drilled, namely red = Witpoort aquifer, green = upper Witteberg Group aquitard and dark grey = Dwyka aquifer.

Of all the chemical parameters plotted, Na + K and Cl appear to differ most significantly from sample to sample (Figure 35). Interestingly, there are clear similarities in samples drilled into the same rock type and in general, ion signatures are lowest in the Witpoort aquifer, intermediate for those drilled into the upper Witteberg Group aquitard and highest for those drilled into the Dwyka aquifer (Figure 35). As revealed in the Schoeller plot (Figure 35), all chemical components seemed to follow a similar trend to that observed in Figure 33 relating to EC levels.

5.4.3. Piper plot

The ten samples in the present study all plotted in the same zone on the Piper plot, defining the groundwater as 'sodium chloride waters' (Figure 36). The classification seems appropriate as Na + K and Cl concentrations were the dominant ions observed in the Schoeller plot.

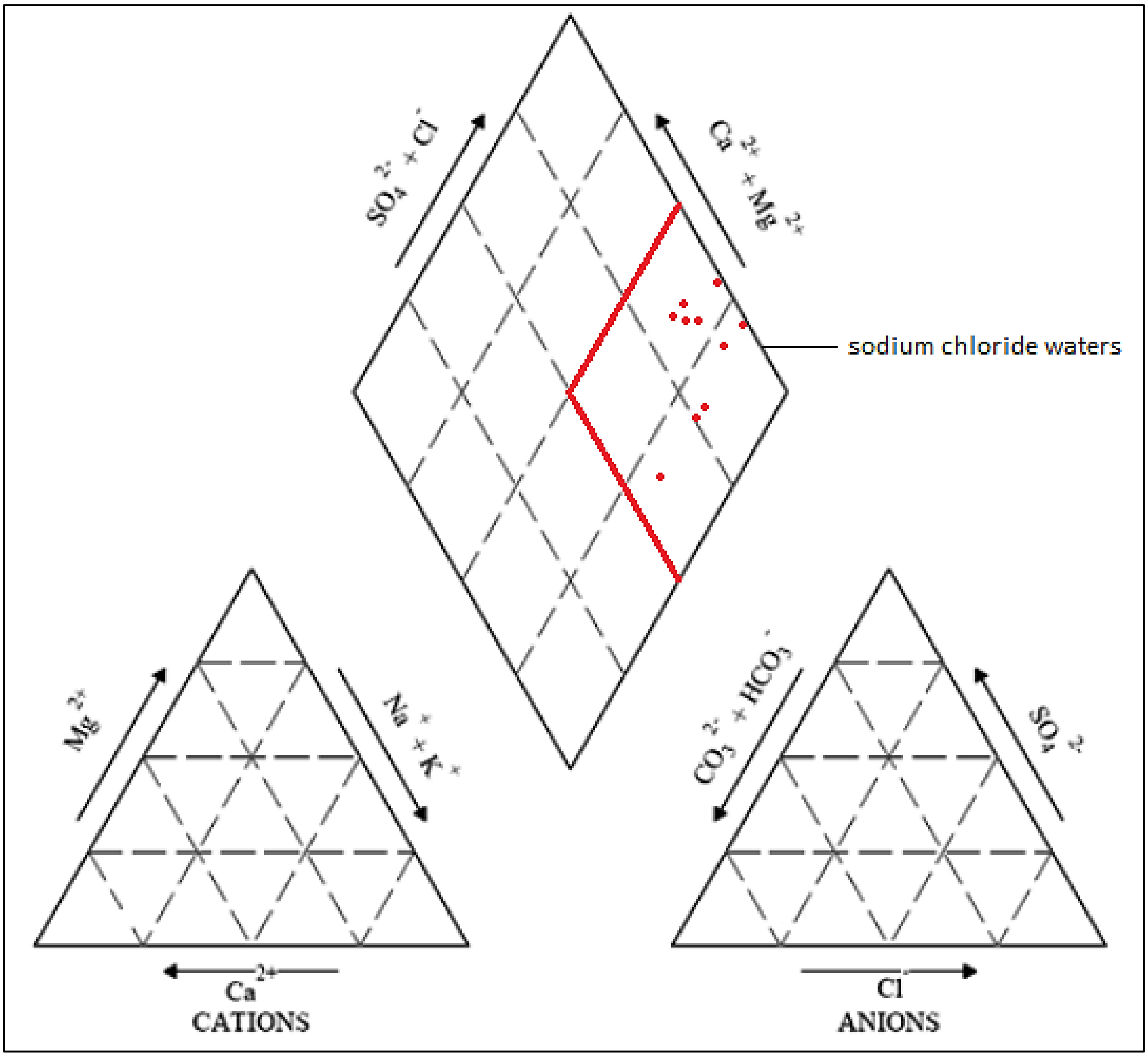


Figure 36 Piper Plot indicating primary water type of the nine boreholes and one spring sample. All samples plot in the zone classified as sodium chloride waters.

5.5. Fairview Spring

5.5.1. Spring monitoring

Monitoring discharge rates from the Fairview Spring started on the 13/03/2016 and continued until the 14/11/2017. Over this monitoring period a total of 93 discharge measurements were collected and are summarised in APPENDIX 3. In general, a negative trend in discharge rate was evidenced although a number of recharge events, ranging in scales, were also observed (Figure 37).

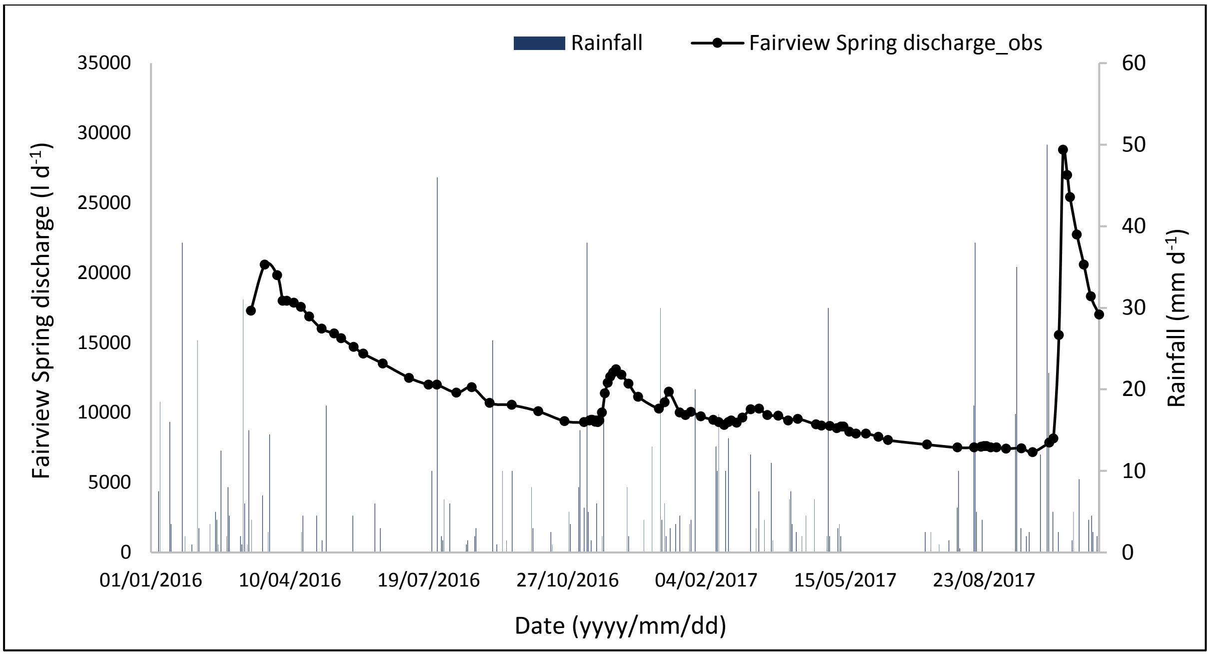


Figure 37 Spring discharge rate and rainfall over the monitoring period. Discharge rate expressed as litres per day (l d^{-1})

The observation period was generally drier than normal with both 2016 and 2017 being well below the average annual rainfall of ~740 mm y^{-1} observed since 1997, nevertheless it started with a recharge event. There was a further sequence of recharge events during the observation period and a major event at the end of the period. Some, but not all of the rainfall events, caused a relatively rapid, but small, increase in discharge and relatively minor changes to the longer-term recession. However, after the October/November 2017 rainfall events it is clear that the longer-term recession shape has been drastically adjusted.

The observations suggest that two quite distinct processes are contributing to the spring discharge; a relatively slowly changing contribution that is evidenced by the longer-term recession slope and a more rapidly responding, but apparently lower volume contribution that is more directly associated with individual rainfall events. This is analogous to the classical hydrological model of stream flow generation with rapid surface, or near surface, processes combined with slower 'baseflow' (often assumed to be groundwater) processes (Hughes, 2010b).

One of the notable conclusions that can be reached through close examination of the observation data is that similar amounts of rainfall do not lead to similar responses in spring flow. While it might be suggested that this result could be associated with the differential effects of surface runoff due to varying rainfall intensity and duration (removing water contributions to the sub-surface system), such processes have not been observed on the slopes of the catchment above the spring.

The initial conceptual model for the spring suggests a contribution of rapid interflow within the unsaturated zone, coupled with a slower responding groundwater drainage component. Hughes (2010) argued that some of the subsurface contribution to stream flow in steep topography could be generated through rapidly draining fracture zones that are above the water-table. Whether the rapid 'interflow' observed at the Fairview Spring is caused by a similar process, or whether it is related to a perched aquifer that is intermittently saturated is uncertain.

5.5.2. Conceptual model

Perched aquifer process

Development of a perched aquifer system relies on the presence of an underlying, low permeability lithologic unit that restricts the downward percolation of groundwater. The geological barrier directs groundwater laterally until it meets the land surface where it discharges as a spring. A similar process may be occurring at the Fairview Spring involving an impermeable carboniferous shale unit interbedded within the Witpoort Formation. An observation made at a road-cutting approximately 1.7 km from the Fairview Spring initiated this assumption (Figure 38).

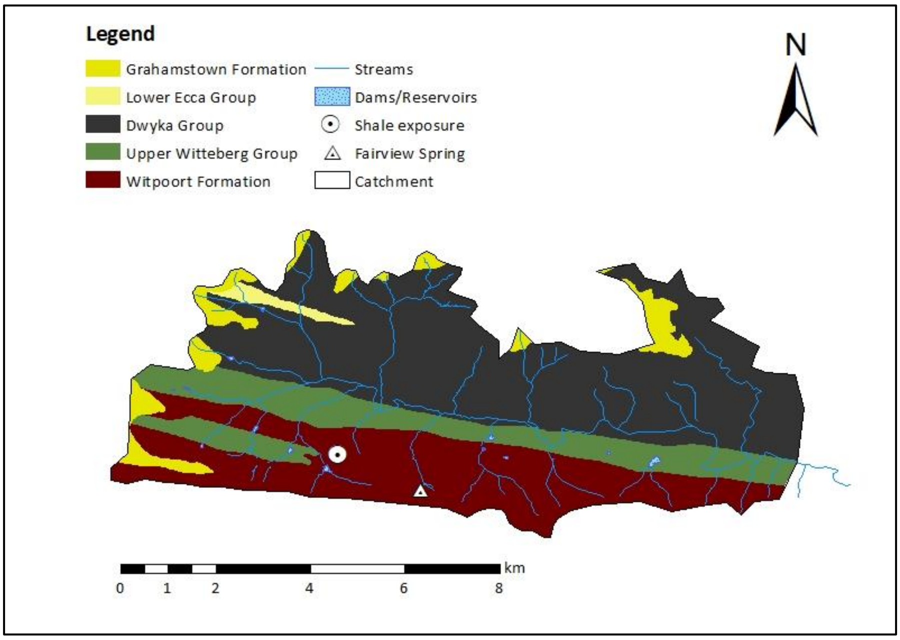


Figure 38 A perched aquifer type seepage (road-cutting) in relation to the Fairview Spring.

The observation was that of a seepage draining from a sharp contact between an overlying quartzitic sandstone and an underlying (but interbedded), impermeable carboniferous shale unit (Figure 39). This seepage appeared a few days after a rainfall event and resembled a process similar to that of a perched aquifer.

Figure 39 Seepage (darker shaded areas) from a sharp contact between quartzitic sandstone and an underlying, interbedded carboniferous shale unit. North and south indicated.

A simple geological cross-section sketch, assuming a perched aquifer situation, is shown in Figure 40. Although the proposed perched aquifer model is plausible, and the seepage evidenced at the road-cutting provides a visual example of the potential process, there are too many uncertainties. Principally these uncertainties stem from the absence of known dimensions and characteristics regarding the proposed shale unit, namely the width, length, thickness and gradient. There is essentially a lack of evidence that the shale unit extends beneath the Fairview Spring catchment. Furthermore, the short-term drainage from the overlying fractured rock at the road-cutting (Figure 39) was only observed as a temporary seepage, while discharge at the Fairview Spring is permanent. Drilling would confirm if a shale layer is in fact present, however that is not a viable option and a further model was envisioned that excluded a shale unit and instead included processes associated with fracture zones above the water-table.

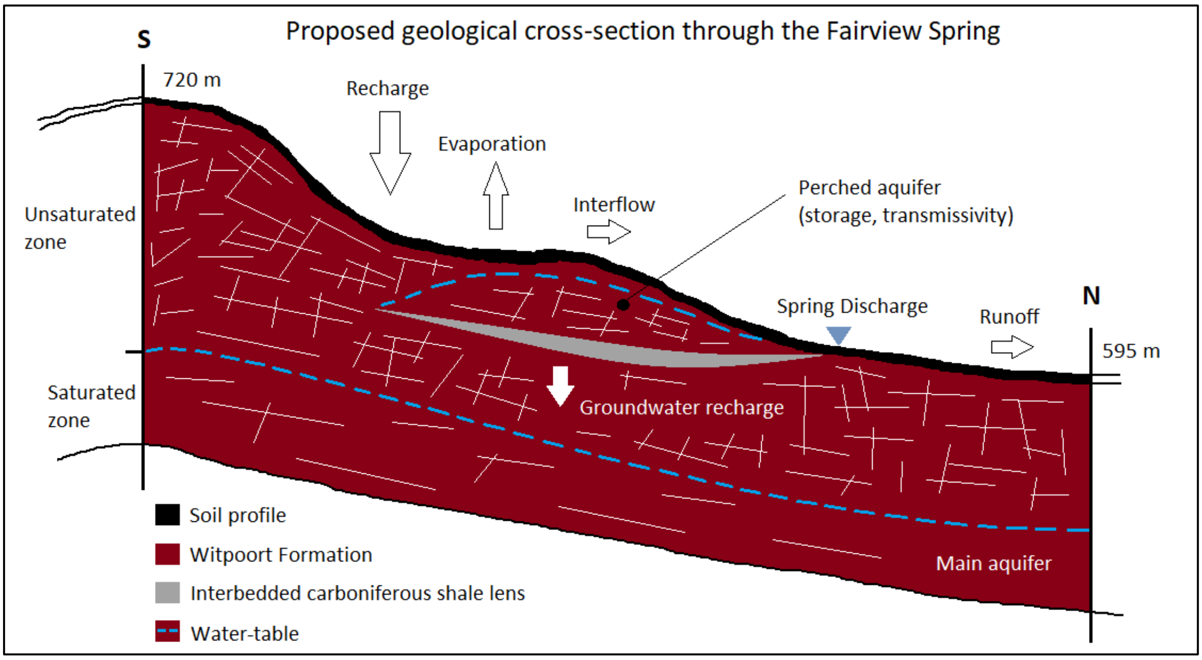


Figure 40 Cross-sectional sketch through the Fairview Spring, involving a proposed perched aquifer process.

Fault-related process

In some fractured terrains, natural springs may form in areas where a fault zone or fracture zone intersects the land surface (Hughes, 2010b). At a road-cutting approximately 2.5 km from the Fairview Spring, a fault zone (Figure 42) is evident and its relative position to the Fairview Spring is shown in Figure 41.

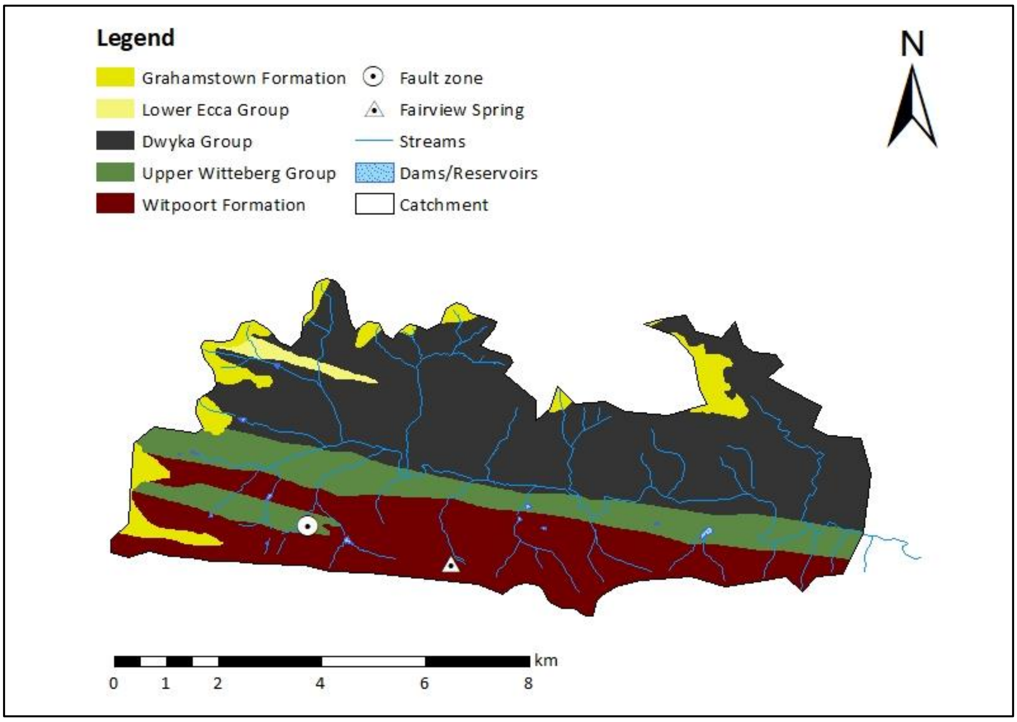


Figure 41 Position of the fault zone (road-cutting) in relation to the Fairview Spring.

Figure 42 Reverse fault (red) and thrust faults (blue) along with associated drag fold (orange) at a road-cutting in Grahamstown. Modified from Büttner *et al*. (2015).

Fault zones can act as good groundwater pathways and may influence the movement of water seeping downwards through the unsaturated zone above the water-table. The presence of two small trees along this fault zone highlights its role as a preferential pathway (Figure 42) and demonstrates its potential as a controlling process driving spring dynamics. However, the uncertainty and lack of direct evidence led to the suggestion of another, more probable explanation for the development and occurrence of the Fairview Spring.

Water-table intersection combined with directed interflow process

The alternative and current spring model excludes the presence of both an underlying shale unit and a fault zone but rather a spring process that involves a water-table intersection concept combined with interflow through fractures (Figure 43). The Fairview Spring is positioned on the upper section of a north-dipping synclinal limb which suggests that bedding planes act as primary flow paths directing groundwater to the spring orifice. As evidenced, structural elements such as fractures and joints increase connectivity between bedding planes as well as enhance the storage capabilities of the Fairview Spring system.

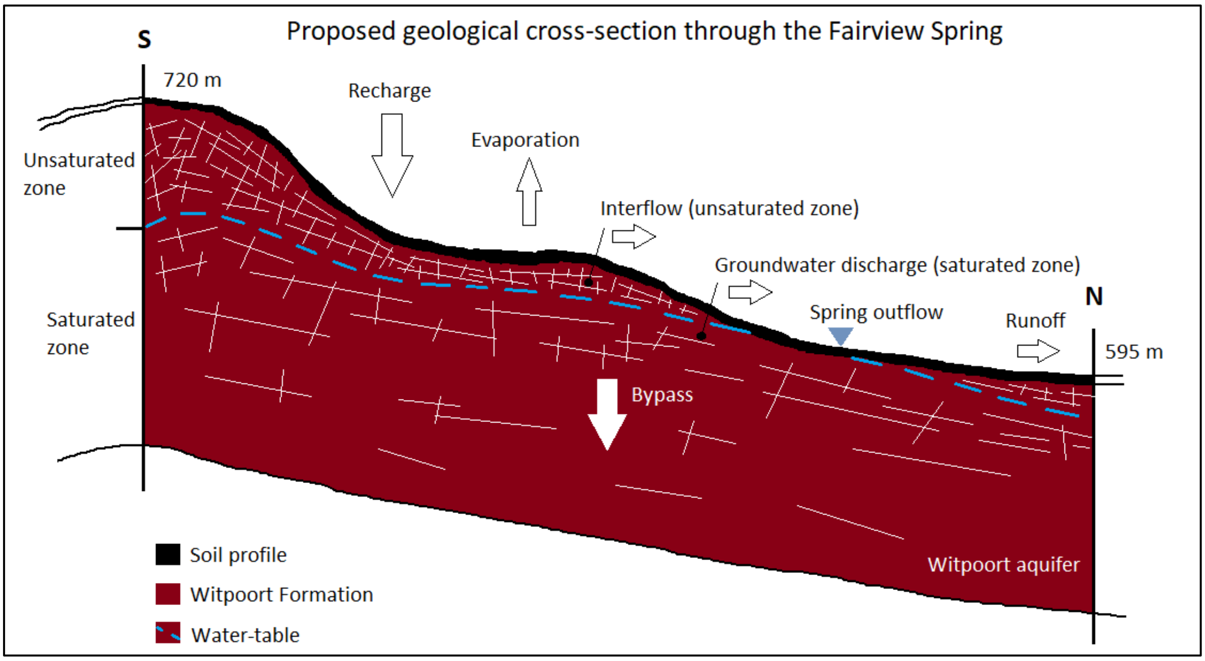


Figure 43 Cross-sectional sketch through the Fairview Spring, involving both groundwater and directed interflow components.

The current model, as depicted in Figure 43, may involve several processes when modelled. The primary input to the system is recharge (as precipitation), while evaporation is the main output variable. Other important components to consider are catchment area, storage and transmissivity, slope gradient and aspect, interflow discharge (to the spring), groundwater discharge (to the spring), groundwater bypass to the deeper aquifer and runoff. This combination of processes need to be simulated in such a way as to generate model outputs that can best replicate the variations in the observed discharge rate during the monitoring period. To reduce uncertainty, the model parameters that relate to groundwater recharge and storage can be partly calibrated by comparing the estimated values obtained during the borehole analysis.

5.5.3. Developing a Fairview Spring model

Before a spring model can be proposed it is necessary to make several assumptions, some of which can be evaluated by changing the parameterisation of the model, while others are difficult to test without further information. The initial basic model formulation is the same as that used by Hughes *et al*. (2013) to simulate the stream flow response of a small (0.02 km^2) catchment draining the same range of hills to the south of Grahamstown that are considered to be the main recharge zone of the Fairview Spring. The model is largely based on the same non-linear storage concepts (Figure 44) as the widely used monthly time-step Pitman model, but it is applied at a daily time scale.

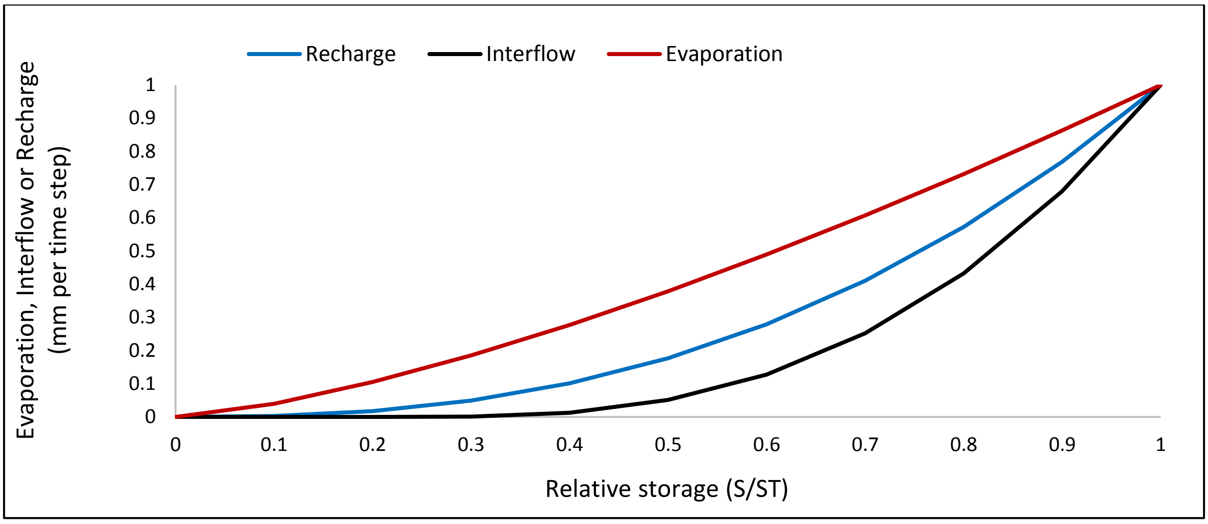


Figure 44 Graphs illustrating the relationships used to simulate evapotranspiration, interflow and recharge as functions of the relative storage in the unsaturated zone.

The first assumption is that the sub-surface catchment area is approximately the same as the surface catchment (Figure 45), which can be approximated by a triangle with a base of some 400 m along the top of the hills and a length of 500 m (from hilltop to spring outlet) (Figure 45 and Figure 46). This is difficult to test but given the topography it is hard to imagine that any additional area can contribute, although it is very possible that fault and fracture zones direct water from some additional areas lying outside of this proposed area.

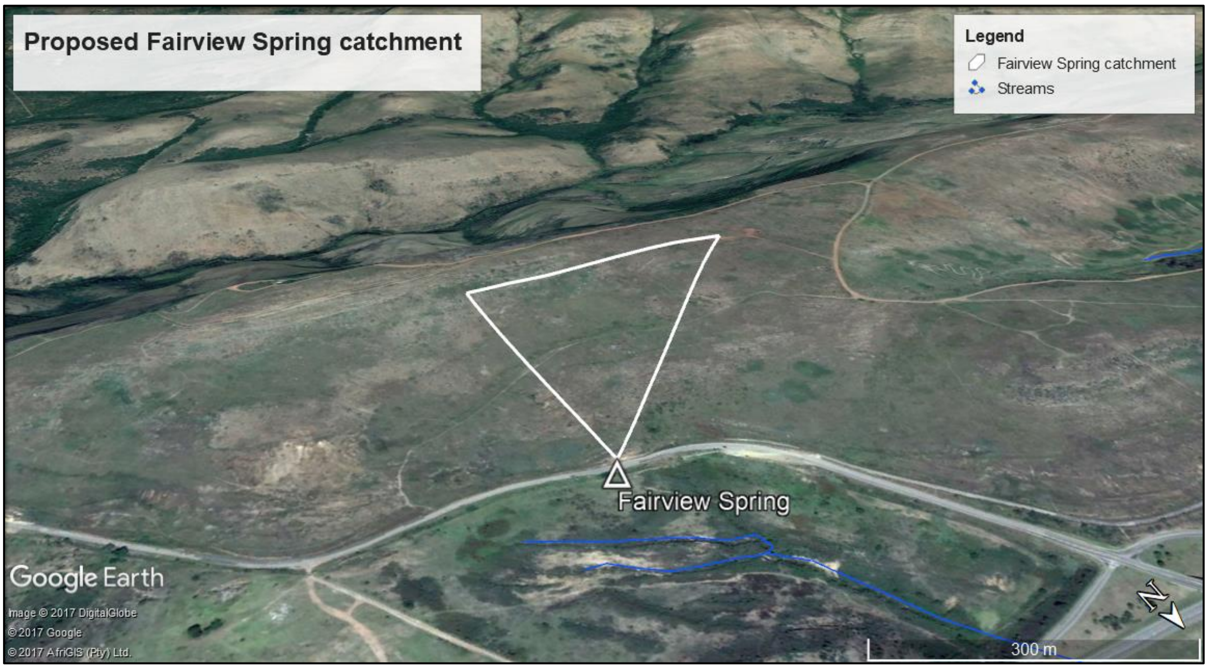


Figure 45 Google Earth^{PRO} image of proposed triangular surface catchment at the Fairview Spring.

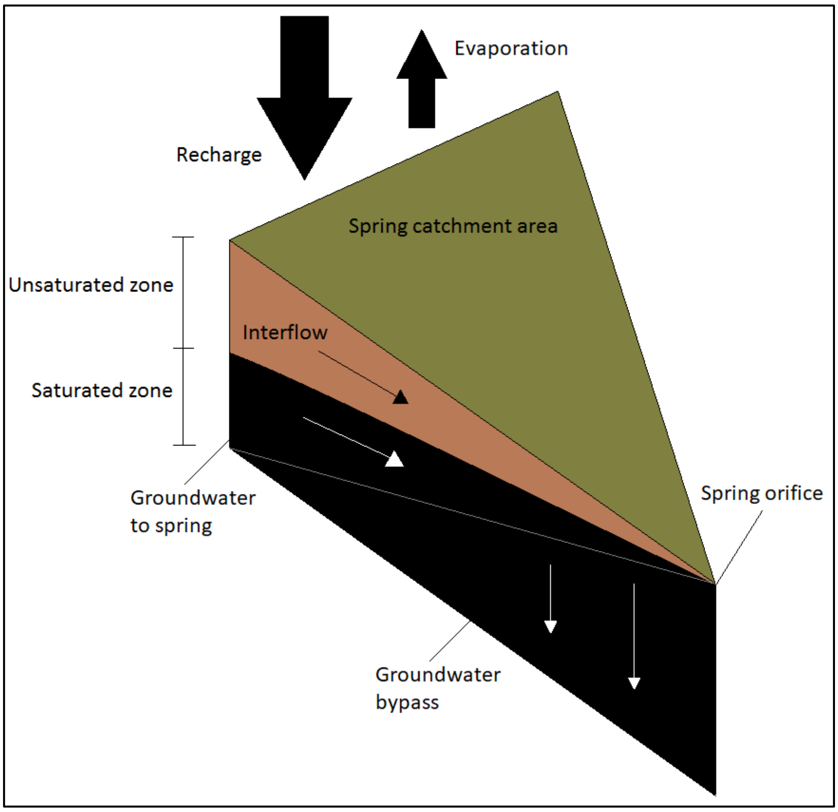


Figure 46 Conceptual 3D sketch of the sub-surface catchment above the Fairview Spring.

The second assumption is that the spring discharge is partly made up of lateral drainage within fracture zones above the water-table (referred to as interflow in Figure 46) and that this is controlled by a non-linear relationship with unsaturated zone storage, with a threshold storage below which interflow is zero. The evidence for this process is based on an analysis of the observed discharges relative to the rainfall data. An alternative assumption is that a temporary perched aquifer develops following relatively high rainfall events and that this aquifer is more directly connected to the spring discharge point through high fracture density material. The way in which this process is represented in the model is the same regardless of whether this process is considered to be fracture zone interflow or a perched aquifer. The key assumption is that it is more rapidly responding than the aquifer outflow (third assumption below) and not continuous and is therefore associated with some threshold of unsaturated zone storage.

The third assumption is that the remainder of the spring discharge is made up of outflow through the spring fractures from the aquifer upslope of the spring. This aquifer is represented by a triangular wedge (Figure 46) that increases (or decreases) in volume with recharge from the unsaturated zone (or discharge to the spring). A nearby borehole (BH31) is situated at Stones Hill, approximately two kilometres east from the Fairview Spring and 200 m south (in relative terms), along the high-lying ridge (Figure 47).

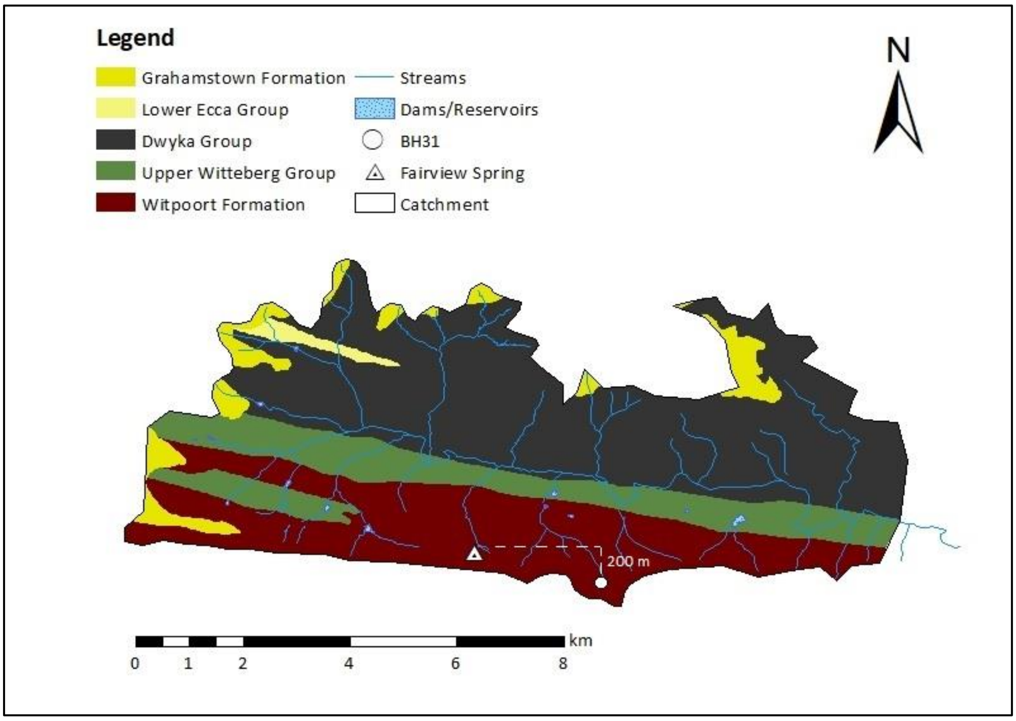


Figure 47 Position of BH31 in relation to the Fairview Spring.

The land and average groundwater elevations at BH31, relative to the Fairview Spring, are plotted in Figure 48 and provide evidence of an upslope groundwater gradient that would contribute to spring outflow. It is further assumed, due to the fractured nature of the lithology, that some of the groundwater flow bypasses the spring and continues to flow north-east within the Witpoort aquifer underlying Grahamstown.

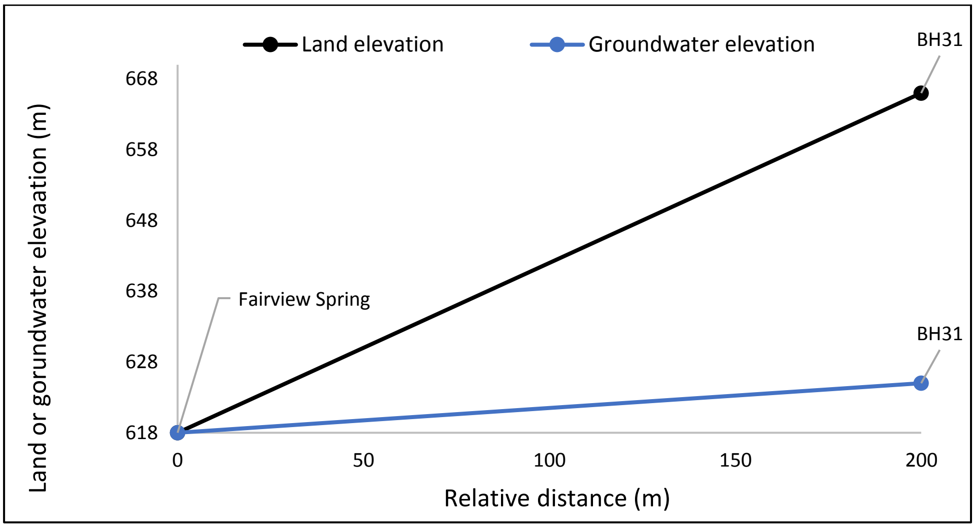


Figure 48 Land and groundwater elevation at BH31 relative to the Fairview Spring.

The fourth assumption is that the contributions to unsaturated zone storage from rainfall are partially delayed, first satisfying soil-moisture deficits, and attenuated through the effects of a near surface storage zone. This assumption is based on the observation that the quite rapid spring discharge responses to rainfall seen in Figure 37 are slightly delayed.

Groundwater and interflow (or a perched aquifer) are therefore both considered to contribute to spring outflow but occur in separate subterranean sectors, namely the saturated and unsaturated zones, respectively. Storativity is expected to differ between these zones and it is suggested that the unsaturated zone will have greater storage capabilities (and more rapid discharge) as fractures closer to the surface are likely to have greater aperture sizes and be more abundant due to stress release caused by erosional removal of overburden pressures (Cook, 2003). Initial storativity input values for the saturated zone compared well with estimates obtained through application of the WTF and CRD methods used during borehole analysis.

5.5.4. The model algorithms

The input daily rainfall data, P (mm), is partitioned into contributions to the unsaturated zone (P_1) and surface runoff using a simple threshold, P_{thres} (mm), such that:

If $\mathrm{P} \leq \mathrm{P_{thres}}$

$$\mathrm{P_1} = \mathrm{P} \tag{Eq. 4}$$

If $\mathrm{P} > \mathrm{P_{thres}}$

$$\mathrm{P_1} = \mathrm{P_{thres}} \tag{Eq. 5}$$

The actual rainfall contribution to unsaturated storage during a day (P_2 mm), is then partly delayed by routing it through a near surface storage (NSS):

$$\mathrm{P_2} = \mathrm{P_1} \times \mathrm{P_{direct}} + \left[0.03 + 0.47 \times \left(\frac{\mathrm{S_i}}{\mathrm{ST}}\right)^2\right] \mathrm{NSS_{i-1}} \tag{Eq. 6}$$

And

$$\mathrm{NSS_i} = \mathrm{NSS_{i-1}} + \mathrm{P_1} - \mathrm{P_2} \tag{Eq. 7}$$

Where i represents the current day, S represents the storage depth (mm) of the unsaturated zone, ST is the maximum storage (mm) and P_{direct} is the direct (non-delayed) rainfall contribution (a fraction set initially to 0.25). The 0.03 and 0.47 values in Eq. 6 can be modified if necessary. Equation 6 suggests that a relatively small proportion of the accumulated near surface storage will be added to the unsaturated zone during dry conditions, while 50 % of NSS will be added under wet conditions.

Interflow generation is limited to unsaturated storage levels (S mm) above a threshold value (SL mm) and estimated using a non-linear equation (see also Figure 44).

If $\mathrm{S} > \mathrm{SL}$

$$\mathrm{IQ} = \mathrm{I_{MAX}} \left(\frac{\mathrm{S} - \mathrm{SL}}{\mathrm{ST}}\right)^{\mathrm{I_{pow}}} \qquad \text{(Eq. 8)}$$

Where IQ is interflow discharge (mm), SL is minimum storage and I_{MAX} (mm) I_{pow} are the parameters of the power function.

The recharge to groundwater is calculated for a similar non-linear power equation, but without a threshold, based on parameters (R_{MAX} and R_{pow}):

$$\mathrm{GWR} = \mathrm{R_{MAX}} \left(\frac{\mathrm{S}}{\mathrm{ST}}\right)^{\mathrm{R_{pow}}} \qquad \text{(Eq. 9)}$$

Similarly, actual evapotranspiration (ET mm) is calculated from a non-linear power equation, with maximum values in any day being limited to the input potential evapotranspiration (PET):

$$\mathrm{ET} = \mathrm{PET} \left(\frac{\mathrm{S}}{\mathrm{ST}}\right)^{\mathrm{E_{pow}}} \qquad \text{(Eq. 10)}$$

The water balance of the unsaturated zone is therefore updated each day from:

$$\mathrm{S_i} = \mathrm{S_{i-1}} + \mathrm{P_2} - \mathrm{ET} - \mathrm{IQ} - \mathrm{GWR} \qquad \text{(Eq. 11)}$$

Where ET is actual evaporation, IQ is interflow discharge to the spring and GWR is recharge to the aquifer or 'groundwater bypass' (all in mm).

By treating the groundwater storage as a simple triangular wedge, and through simple geometry, the change in groundwater height at the assumed catchment boundary for each day is calculated from:

$$\Delta\mathrm{GWh} = 2\left[\frac{(\mathrm{GWR} - \mathrm{GWQ} - \mathrm{Bypass})}{\mathrm{s} \times 1000}\right] \qquad \text{(Eq. 12)}$$

Where ΔGWh is the change in groundwater height (m), GWR is groundwater recharge (mm), GWQ is groundwater discharge (mm), s is storativity and 1000 is used to correct the units. When calculating the groundwater height, the spring orifice is considered a fixed point and therefore only the height of the up-gradient point is considered to change (Figure 49).

A further loss to the groundwater storage is assumed to occur as bypass flow (Bypass mm) beneath the spring. This is estimated as a simple function of the relative groundwater storage level:

$$\mathrm{Bypass} = \mathrm{BPQ}\left(\frac{\mathrm{GWh_i}}{\mathrm{GWh_{MAX}}}\right) \qquad \text{(Eq. 13)}$$

Where GWh_i (m) is the groundwater level at a specific time period, GWh_{MAX} (m) is the maximum groundwater level and BPQ is the bypass parameter (mm day^{-1}).

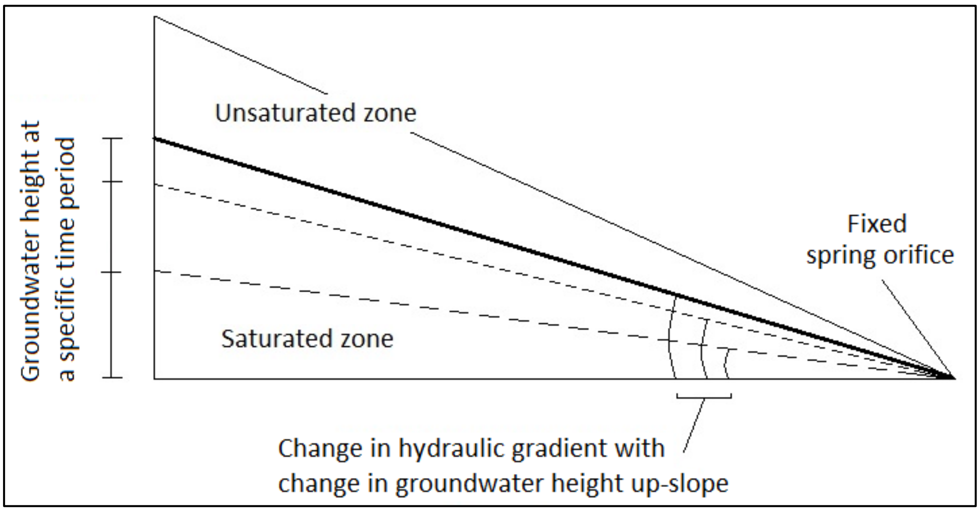


Figure 49 Sketch illustrating the influence that a change in hydraulic head will have on the hydraulic gradient, while the spring orifice remains fixed.

The groundwater discharge is calculated from:

$$\mathrm{GWQ} = \mathrm{gradient} \times \mathrm{T} \times \mathrm{w} \qquad \text{(Eq. 14)}$$

Where GWQ is the groundwater discharge, T is transmissivity and w is the effective flow width contributing to the spring. It will be clearly difficult to estimate T and w independently and the calibration of the model will be based on the product of these parameters. The gradient is calculated from the simple geometry as GWh/catchment length (assumed to be 300 m)

5.5.5. The model parameters and flow diagram

The Fairview Spring model incorporates numerous parameters which have been summarised in Table 8 below.

Table 8 Fairview Spring model parameters.

Model parameters	Units	Description of model parameters
P_{thres}	mm	Surface runoff rainfall threshold
R_{MAX}	mm	Maximum recharge
R_{pow}	-	Recharge
S	mm	Storage depth of unsaturated zone
T	$m^2\ day^{-1}$	Transmissivity
s	-	Storativity
w	m	Effective flow width
BPQ	mm	Bypass
I_{MAX}	$m^2\ d^{-1}$	Maximum interflow
I_{pow}	-	Interflow
SL	mm	Minimum storage threshold
P_{direct}	-	Direct rainfall contribution to unsaturated zone
E_{pow}	-	Evaporation
ST	mm	Maximum storage threshold

The parameters in Table 8 were quantified based on estimates and calibration. The rainfall threshold parameter was based on a lack of observed surface runoff at the spring catchment and therefore set very high (~100 mm). The recharge and groundwater discharge parameters, namely R_{MAX}, R_{pow}, S, T, w and BPQ, were all based on calibrating the long-term recession of the spring flow, although some of these parameters were initially quantified based on common sense and knowledge of the aquifer system. This includes S and w, which were estimated using the dimensions of the proposed wedge-shaped spring catchment, as well as R_{MAX}, which was based on values estimated during borehole analysis. The interflow parameters, namely I_{MAX}, I_{pow} and SL, were based on calibrating against the short-term interflow peaks in the observed data. The rain delay parameters, which include P_{direct} and NSS, were based on the delays in the short-term spring response relative to rainfall. The evaporation parameter, E_{pow}, influences the overall water balance. The storage parameter, ST, was based on assumptions regarding the volume of available storage and storativity of the unsaturated zone. Due to the increased weathering in the unsaturated zone, this storativity value was suggested to be higher than the storativity value determined through borehole analysis for the saturated zone.

Although caution was taken to make suitable, as well as reasonable, quantifications for all parameters it should be noted that there will be a great deal of equifinality in this model. In some cases, this meant different combinations of variables produced the same, sometimes favourable, results and therefore required interpretation.

A flow diagram describing the Fairview Spring model is shown in Figure 50 below:

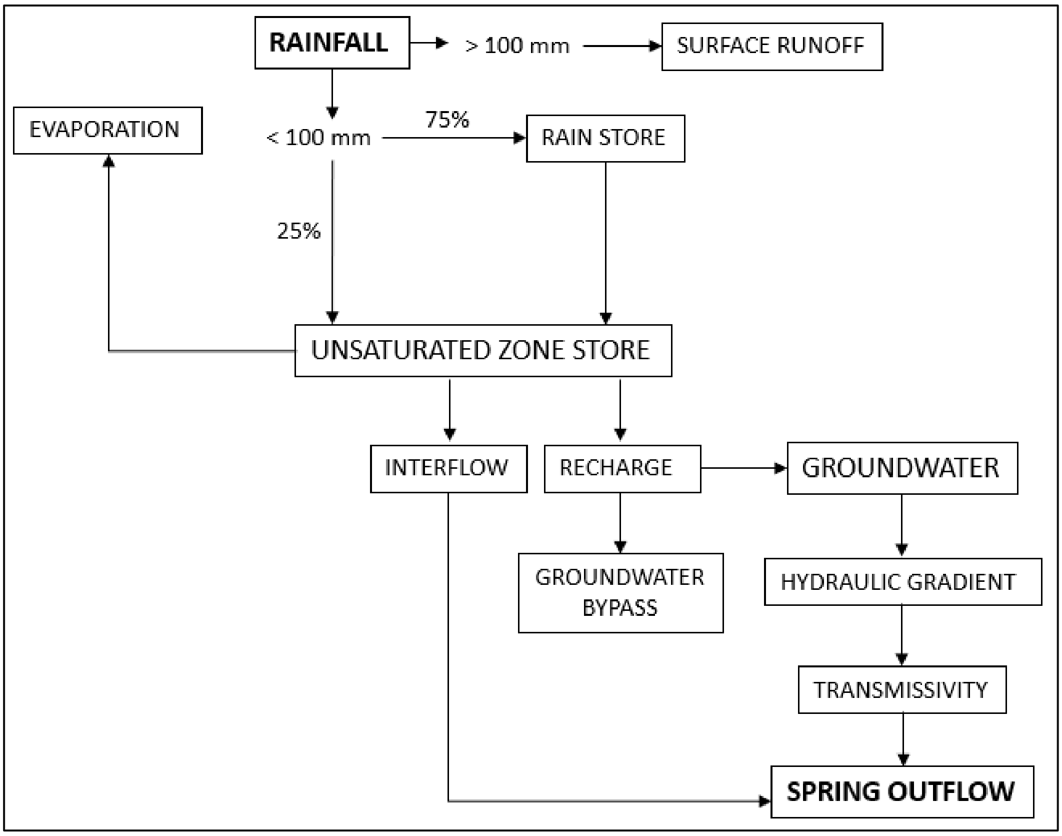


Figure 50 Flow diagram summarising current model functioning.

Essentially, the current model describes a spring system that operates as follows:

If a specific rainfall event is over 100 mm the excess will contribute to surface runoff. This threshold is quite high, however surface runoff was never observed at the site and therefore the surface runoff routines are based on fairly simplistic functions. This high value, however, will have very little effect on the outcome, unless it is set unrealistically low at around 40 mm. Any rainfall event less than 100 mm is either routed immediately into the 'unsaturated zone store' (25%) or otherwise directed into the 'rain store' (75%) as to generate a delay in spring outflow. The ratio of this routing function can be adjusted in the model. The water in the unsaturated zone is reduced by evaporation and the remaining water either recharges the groundwater reservoir or otherwise contributes to the interflow component of spring outflow. Some of the recharge to groundwater is suggested to continue beneath the spring orifice and does not contribute to spring outflow, this component is included as a 'groundwater bypass' parameter in the model. The groundwater component to spring outflow depends on a transmissivity parameter as well as changes in hydraulic gradient. The relative values for interflow and groundwater therefore make up the overall spring outflow.

5.5.6. Model calibration and sensitivity analysis

Overview of the initial model simulation

The initial model generated results that seemed to pose more questions than answers, yet the background recession curve correlated well with the observed data and was easy to replicate by manipulating recharge and interflow conditions (Figure 51). The initial model did not include all the components and processes represented in the current model and the additions and adjustments are discussed in this section.

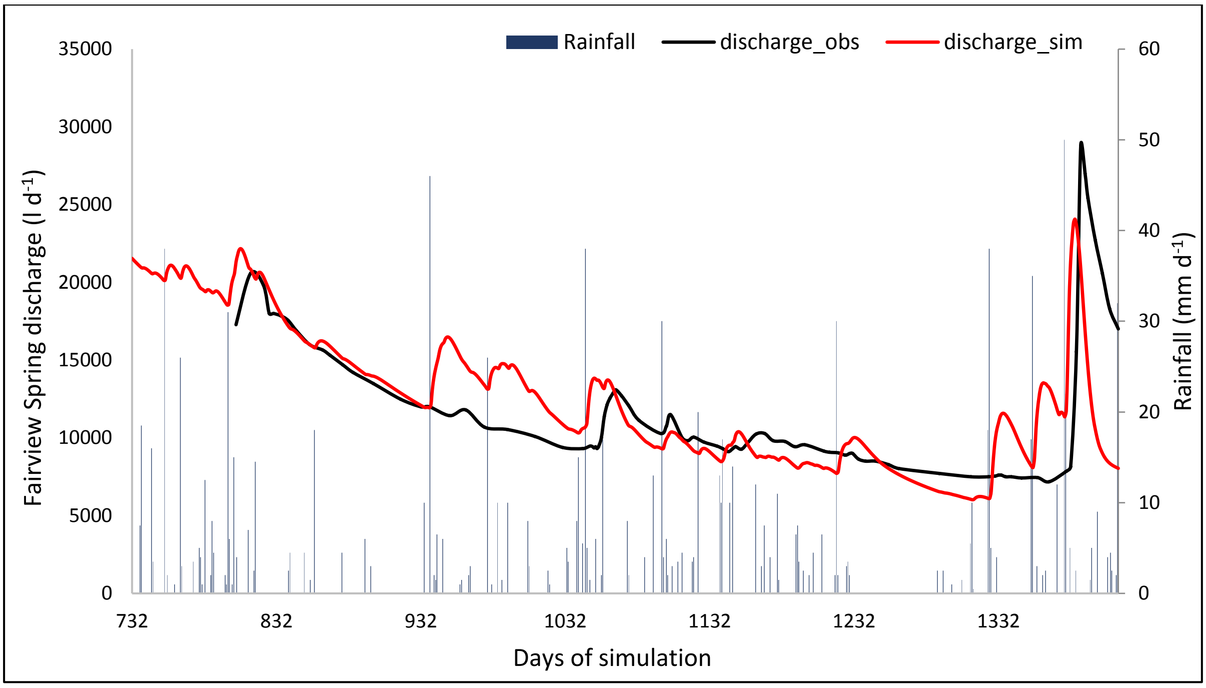


Figure 51 Initial model developed for the Fairview Spring.

The most obvious dissimilarity was observed on five separate occasions, following rainfall events, where the simulated outflow spiked while the corresponding observed data remained relatively unchanged (Figure 51). Initially this lack of response in the observed data was thought to relate to surface runoff and the unknown rainfall-runoff dynamics related to rainfall duration and intensity. However, closer inspection of the spring catchment area following rainfall revealed that surface runoff is fairly limited as the fractured nature of the rocks encourage infiltration. One of the key factors in these initial simulations was that the unsaturated zone storage levels were similar at times when the model generated interflow that was not observed, as well as times when the model generated interflow that was observed. This suggests that changing the threshold storage level used to initiate interflow would not improve the simulations. These observations suggested that there could be large uncertainties in the way in which evapotranspiration losses are being simulated. Furthermore, during recharge periods where the model responded adequately, the simulated response was generally earlier than the observed outflow, suggesting the need to account for a delay in the interflow response and rainfall. The initial model could not be calibrated to remove the above-mentioned problems and there was clearly a need for either structural changes, or changes to some of the input data, or both.

Current model

The errors reviewed in the initial model run proved that adjustments were necessary to improve the accuracy of the model. The current model included modifications to the input potential evaporation data and accounted for the delay in the rainfall data through the addition of a rain store. The details of the final model, including these two modifications are discussed below:

Potential evapotranspiration:

MODIS satellite data (Mu *et al*., 2012) were initially used to estimate the potential evaporation. However, these data are based on regional climate data and do not appear to be sensitive to slope aspect and gradient. A study by Jackson (1967) showed that potential evaporation can differ significantly depending on aspect and, for steep south facing slopes (in the southern hemisphere) may be as much as 60 % greater than average values in the winter months (Figure 52).

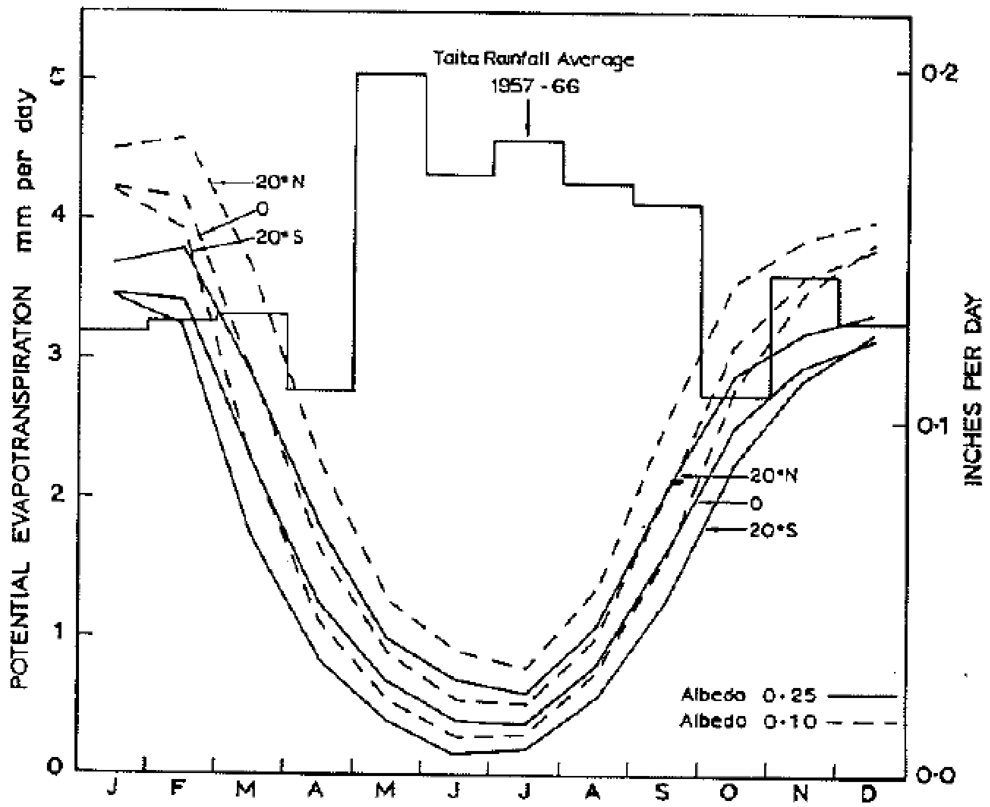


Figure 52 Estimates of potential evapotranspiration rates on horizontal surfaces and 20° north and south-facing slopes. Taken from Jackson (1967).

The results of the Jackson (1967) study were used to scale the MODIS data to better represent potential evapotranspiration values for the south facing slope in the study area. The monthly scaling factors, shown in Table 9, were roughly estimated from Figure 52 using the differences between the lines for the horizontal and 20° south facing slope.

Table 9 Monthly scaling factors that were used to adjust the MODIS evapotranspiration data.

Month	Monthly scaling factors
1	1,1
2	1,1
3	1,25
4	1,4
5	1,55
6	1,6
7	1,55
8	1,45
9	1,35
10	1,25
11	1,2
12	1,1

The revised evapotranspiration data improved the model significantly and generally resolved the issues surrounding the false peaks, however, the simulated data still produced an insufficient lag time compared to that of the observed data (Figure 53).

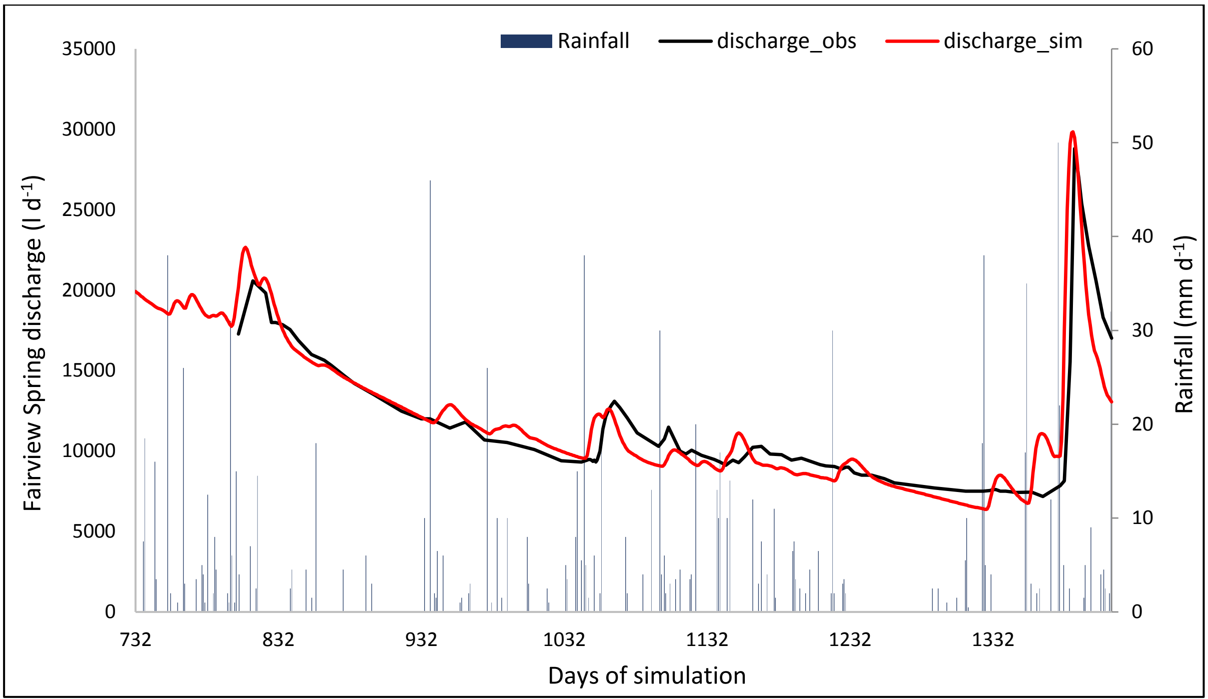


Figure 53 Model simulation using the scaled MODIS evapotranspiration data.

Incorporation of a rain store

The addition of a rain store compensated for the timing issue encountered during the initial simulations (Figure 54). Essentially, it is a storage routing function that operates by directing most of the immediate rainfall (75 %) into a rain store that slowly drains to the unsaturated zone storage, while the remainder is directed immediately to the unsaturated zone. The 75/25 ratio can be modified as part of the model calibration process. The rate at which the rain store drains to the unsaturated zone is dependent upon the level of storage in the unsaturated zone (Equation 6).

The adjustment of the potential evaporation and addition of the rain store proved to be important inclusions in the model, improving the performance and the agreement with the observed spring response (Figure 54).

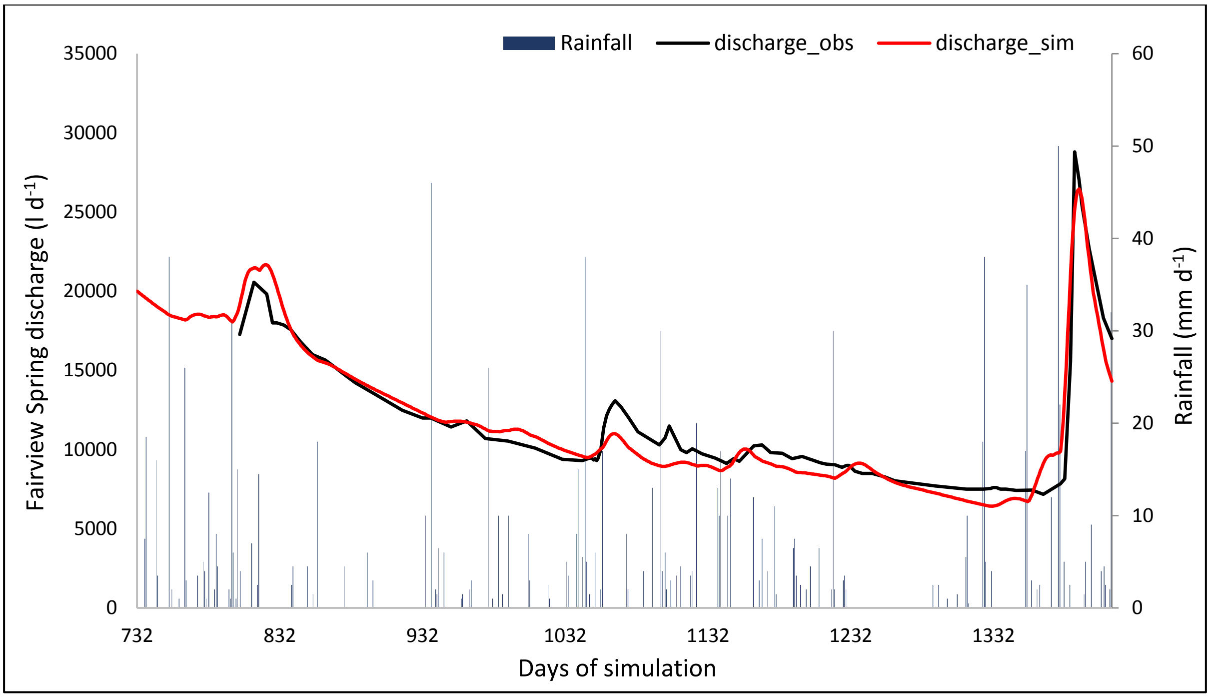


Figure 54 Current model simulation combining adjustments made to evapotranspiration and the addition of the rain store.

Unsaturated zone storage

Maximum storage (ST mm) from the unsaturated zone was initially estimated at 300 mm by using the average thickness for the unsaturated and multiplying that by the estimated storativity value. The saturated storativity value was set at 0.005 which compared well with storativity values calculated through application of the CRD method during borehole analysis, which ranged between 0.0015 – 0.009. Therefore, the storativity value for the unsaturated zone was estimated to be higher than this due to the influence of erosional stress release in fractures. Uncertainties were assessed through three model runs which included the initial storage estimate as well as an over- and under- estimation of this initial storage value (Nash-Sutcliffe coefficient

The Nash-Sutcliffe coefficient is a factor of efficiency used to measure the fit between the measured data and modelled values. Essentially it determines the degree of deviation and can range between 0-1, with 1 indicating a perfect fit (Nash and Sutcliffe, 1970). The technique was used in the current study to quantitatively assess the effectiveness of the Fairview Spring model.

Table *10*).

Nash-Sutcliffe coefficient

The Nash-Sutcliffe coefficient is a factor of efficiency used to measure the fit between the measured data and modelled values. Essentially it determines the degree of deviation and can range between 0-1, with 1 indicating a perfect fit (Nash and Sutcliffe, 1970). The technique was used in the current study to quantitatively assess the effectiveness of the Fairview Spring model.

Table 10 Testing the maximum unsaturated zone storage of the Fairview Spring by model simulation of three separate storage values, namely 150, 300 and 500 mm. During the runs, certain model inputs remained constant and are included in the bottom section of the table.

Model outputs	**Simulation runs**		
	ST = 150 mm	ST = 300 mm	ST = 500 mm
SL (mm)	60	78	150
Recharge (% of the total rainfall)	11.1	9	8
Interflow contribution to spring outflow (%)	14	31	43
Groundwater contribution to spring outflow (%)	86	69	57
Bypass (% of the total recharge)	24	24	25
Nash-Sutcliffe coefficient	0.774	0.907	0.886
Major water balance components			
Total rainfall (mm)	2700.5		
Total evapotranspiration (mm)	2340.6	2281.5	2183.7
Total recharge (mm)	299	242.5	217
Total Interflow (mm)	35.1	79	119.7

As expected, and shown by the model simulations, when the maximum sub-surface storage increases there would be more ‘space’ available in the system and therefore overall recharge can decrease to generate the same spring discharge. In contrast if storage is reduced then there is less ‘space’ and recharge must increase to account for this.

Other notable implications of adjusting the maximum storage were observed in the contributions of interflow and groundwater to spring discharge. As the storage was increased the model responded by increasing the contribution of interflow relative to groundwater, evidenced by a 14/86 ratio at ST = 150 mm, compared to a 43/57 ratio at ST = 500 mm. A proposed reason for this may be that if ST is increased, without increasing the storativity, then the general catchment surface, and sub-surface, area/volume would also need to increase. The increase in ST therefore makes interflow and groundwater recharge less sensitive to inputs of rainfall and more rainfall is needed to get an increase in relative storage. This will not only affect interflow but also groundwater recharge equally.

Of the three simulations shown in Table 10, run one (ST = 150) proved to be the most challenging and the relatively low Nash-Sutcliffe coefficient of 0.774 verified this, with seemingly no other combination of parameters able to better this correlation. The deduction was that a storage value of 150 mm did not allow a sufficient buffer to play with the other parameters. Run 3 (ST = 500) showed good correlation and by manipulating certain parameters a Nash-Sutcliffe coefficient of 0.886 was achieved. However, an excessive contribution of interflow to spring discharge (43%) dismissed this as a realistic simulation with the primary reason relating to the fact that discharge at the Fairview Spring has never stopped, even in extremely dry periods, indicating that a groundwater component must contribute significantly to spring outflow. The simulation of run 2 (ST = 300), with a 31/69 ratio of interflow and groundwater, therefore seemed to be a better, more robust option as the primary replication of observed conditions at the Fairview Spring (shown in Figure 54 above). Furthermore, run 2 produced the highest Nash-Sutcliffe coefficient of 0.907, highlighting its impressive correlation to the observed data. This simulation at ST = 300 mm was then used to test the bypass component of the model.

Groundwater bypass

As mentioned, a proportion of the water that enters the spring system is assumed to bypass beneath the spring orifice and continue northeast as groundwater within the Witpoort aquifer. It is suggested that relatively small changes in recharge can be offset by changes in the bypass flow parameter and therefore any significant increase in recharge would also increase the amount of bypass. An attempt was made to test this by model simulation, however when the overall recharge was increased to any value above ~12 % total rainfall it was impossible to adjust the other components in such a way to correlate the model with the observed spring discharge. A further simulation, shown in Table 11, involved setting the bypass to 0, even though this was not believed to be realistic.

Table 11 Results of model simulation run where the bypass was set to 0.

Model outputs	**Simulation run**
	Bypass = 0 mm
ST (mm)	300
SL (mm)	78
Recharge (% of the total rainfall)	6.2
Interflow contribution to spring outflow (%)	36
Groundwater contribution to spring outflow (%)	64
Nash-Sutcliffe coefficient	0.911
Major water balance components	
Total rainfall (mm)	2700.5
Total evapotranspiration (mm)	2342.8
Total recharge (mm)	166.9
Total Interflow (mm)	90.7

Interestingly, the model produced an impressive simulation, shown in Figure 55 below, with a Nash-Sutcliffe coefficient of 0.911, the highest of all model simulation runs. The adjustment of the recharge parameters was the only change necessarily to achieve this result and subsequently lowered the recharge from 9 to 6.2 % total rainfall. The contribution of interflow and groundwater recharge to spring outflow also changed, but only slightly, to 36 and 64 % respectively. These results seem logical, if there was no bypass then the system would require less recharge to achieve the same spring outflow. Furthermore, the decreased recharge would presumably reduce the groundwater contribution to spring flow, and this is also observed. Overall, it is unlikely that no bypass is occurring without the presence of some sort of impermeable geologic layer, however there is no direct evidence for a perched aquifer system at the Fairview Spring.

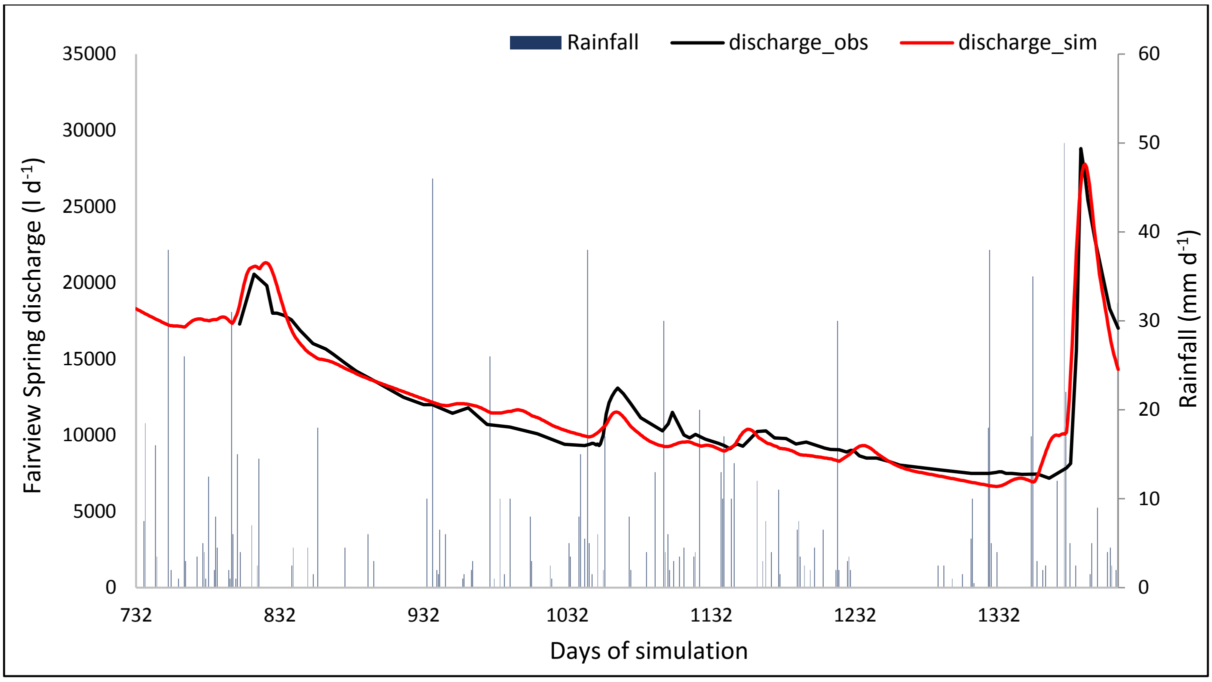


Figure 55 Model simulation at ST = 300 mm and bypass set to 0.

CHAPTER 6. DISCUSSION

6.1. Conceptual Model

6.1.1. Flow pattern

Generally, as water infiltrates through the soil layer and into the saturated zone within the study catchment it will flow downslope towards the low-lying areas of Grahamstown and ultimately eastwards towards the Bloukrans River valley bottom. The mapping of water-table elevations from various boreholes confirms this flow path from high to low hydraulic head, ultimately drained by the river elevations. The upper Witteberg Group shale acts as an aquitard separating the two aquifer systems and therefore any baseflow to the main stream channel, which eventually feeds into the Bloukrans River, is suggested to originate primarily from the Dwyka aquifer. The build-up of hydrostatic pressure in the confined section of the Witpoort aquifer may act as an important mechanism where groundwater is forced up, through the shale aquitard, and into the Dwyka aquifer. However, it is rather believed that most of the groundwater in the Witpoort aquifer flows under the surface catchment until it meets the regional groundwater reservoir and continues east. Additionally, groundwater quality differs quite significantly between the local aquifers and further suggests low interaction between the two systems.

6.1.2. Abstraction and use

Accurate estimation of groundwater abstraction is a complicated process, which is made more difficult by government policy that only requires citizens to register individual private boreholes if their usage is over 10 000 litres per day. Furthermore, this regulation is seldom supervised, and it is inevitable that over-extraction occurs without any management interventions or regulations. Having said this, most of the boreholes included in this study do not exceed this daily extraction limit and are primarily used for small-scale irrigation purposes of lawns and garden plants. The abstraction volume is limited due to quality reasons, as many private boreholes are drilled into the Dwyka aquifer, restricting its use for consumption without treatment systems. Along with influences surrounding government policy and groundwater quality, groundwater abstraction also differs from owner to owner and of the 31 boreholes included in the study, each is utilised differently. Additionally, this use varies according to the current or seasonal weather patterns, making it very difficult to estimate. A basic feasibility study which includes an estimated groundwater abstraction value will be revisited when recommending strategies in section 6.5 below.

6.1.3. Preferential flow paths

Structural elements in the rocks within the study catchment are fundamental to groundwater movement providing conduits that can store and transmit groundwater. Observational evidence from the Witpoort Formation suggests that bedding planes act as preferential flow paths for groundwater, with the addition of interconnecting joints that increase overall fracture connectivity and therefore enhance storativity and permeability within this aquifer system. Therefore, according to the classification of fractured reservoirs developed by Kuchuk *et al*. (2014), the Witpoort aquifer is suggested to be a reservoir both continuously and discretely fractured, with much of the connectivity represented by fractures that both cross-cut and share a common edge with other fractures (Cook, 2003). Classification of the Dwyka aquifer was more challenging as there are only minor outcrops in the study catchment. Nevertheless, a common trend was evident during the observation of drilling projects where water strikes were often accompanied by the appearance of quartz veining. The presence of quartz as veins relates to fracturing in the rock and suggests that groundwater flow is similarly controlled by secondary porosity within the Dwyka aquifer. According to Meyer (1998), tillite traditionally has a poor permeability and acts as an aquitard in some cases, however in the study site, numerous boreholes extract adequate yields from this aquifer. Furthermore, following a pumping test performed by Andrew Stone on a borehole drilled into the Dwyka aquifer, a recommended yield of 6.8 l s^{-1} was estimated. Therefore, following the same classification produced by Kuchuk *et al*. 2014, this aquifer is also suggested to be both discretely and continuously fractured.

6.2. Recharge to the system

Beekman and Xu (2003) define four main types of recharge that may occur independently or together in a natural system. For simplicity and to apply certain recharge methods the present study defined the recharge process as downward percolation of water through the unsaturated zone and into the groundwater reservoir. Furthermore, this type of recharge is commonly applied in semi-arid climatic zones and accounts for sources such as rainfall and surface water bodies. Other recharge mechanisms that relate to lateral and/or vertical flow within the aquifer and/or influx from existing water bodies due to nearby extraction are probably also at play.

Drought conditions during the study period limited significant recharge to the system although minor recharge events were evidenced through water-table fluctuations in certain boreholes as well as positive discharge responses at the Fairview Spring. A rainfall series from the 28/10/2016 to the 22/11/2016, amounting to a total of 106.5 mm, was a focus as it produced a clear water-table rise in several of the monitored boreholes and interestingly a sudden rise in discharge also occurred at the Fairview Spring. The event indicated a possible link between deeper aquifer and spring dynamics, which suggested the contribution of a groundwater component to Fairview Spring discharge and subsequent inclusion into the Fairview Spring model. Most of the boreholes that showed this water-table fluctuation were drilled into the fractured quartzitic sandstone of the Witpoort Formation, highlighting its role as the primary recharge zone and furthermore, the importance of the Fairview Spring as a small-scale recharge model for the study catchment.

Water-table fluctuations in boreholes drilled into the Dwyka aquifer are suggested to have occurred due to stream channel recharge and this is proposed as the main recharge mechanism to this aquifer system. This was evidenced by the observation of shallow water-tables in a few monitored boreholes that were drilled near to stream channels. Furthermore, a substantial portion of the Dwyka aquifer in the study site is covered by urban Grahamstown which most likely decreases direct rainfall infiltration and increases street runoff into storm water drains and eventually stream channels. Aging infrastructure and leaking pipes may also contribute to recharging the Dwyka aquifer. Consistent recharge to the Witpoort aquifer is most likely due to its numerous fractured networks that act as groundwater pathways into which water can easily infiltrate and move. The clear relation between rainfall and water-table rise together with known specific yield values are pre-requisites for the application of the water-table fluctuation (WTF) method, which proved to be a valuable tool in determining initial estimates.

6.2.1. Specific yield and the water-table fluctuation (WTF) method

Specific yield is a parameter that relates to the amount of water released from storage per unit aquifer drained by gravity, but due to the fractured characteristic of the aquifers in the study catchment it is virtually impossible to determine with absolute certainty and may differ significantly even within the same aquifer system. Due to this heterogeneity a continuum approach, described by Fitts (2013), was applied in the present study, where each aquifer system was considered to be a homogenous medium with relatively equal specific yield values. The high abundance and connectivity of fractures in the Witpoort aquifer favours this continuum approach. Having discovered that the high-lying rocks of the Witpoort Formation form the primary recharge zone in the study catchment, all recharge estimates became focused on this specific aquifer system. Initial estimates of specific yield were needed to apply the WTF method and a study, conducted by Sun *et al.* (2013) which included TMG sediments, provided them. The reasons for the initial use of these estimates were due to similarities surrounding rock type and structural characteristics, with both being primarily fractured quartzitic sandstone units of the Cape Supergroup. Applying these trial estimates for specific yield (0.2, 0.02 and 0.002) in the WTF method produced a range of recharge estimates. By comparing the various WTF recharge outputs to recharge estimates published on hydrogeological maps as well as recharge estimates simulated at the Fairview Spring model, an appropriate estimate of specific yield was selected (0.002) and used as a basis for the CRD method which followed.

6.2.2. Cumulative rainfall departure (CRD) method

Unlike the WTF method which focused on a single recharge event, the CRD method was applied to any monitored boreholes that appeared to show regular water-table responses to rainfall. Initially the CRD method was applied using a daily time scale for the simulated data, while the time scale for the observed data remained as is. At this point the simulated water-table fluctuations did correlate to a certain extent but it was decided to rather mirror the time scales. However, extrapolating the observed data to develop a daily time scale would increase uncertainty and instead the simulated data was generated at the exact time scale as the observed data measurements. While this approach did improve the overall correlation, there were clear uncertainties in the scaling that caused contrasting scenarios between simulated and observed water levels at times. An example of this is shown below (Figure 56).

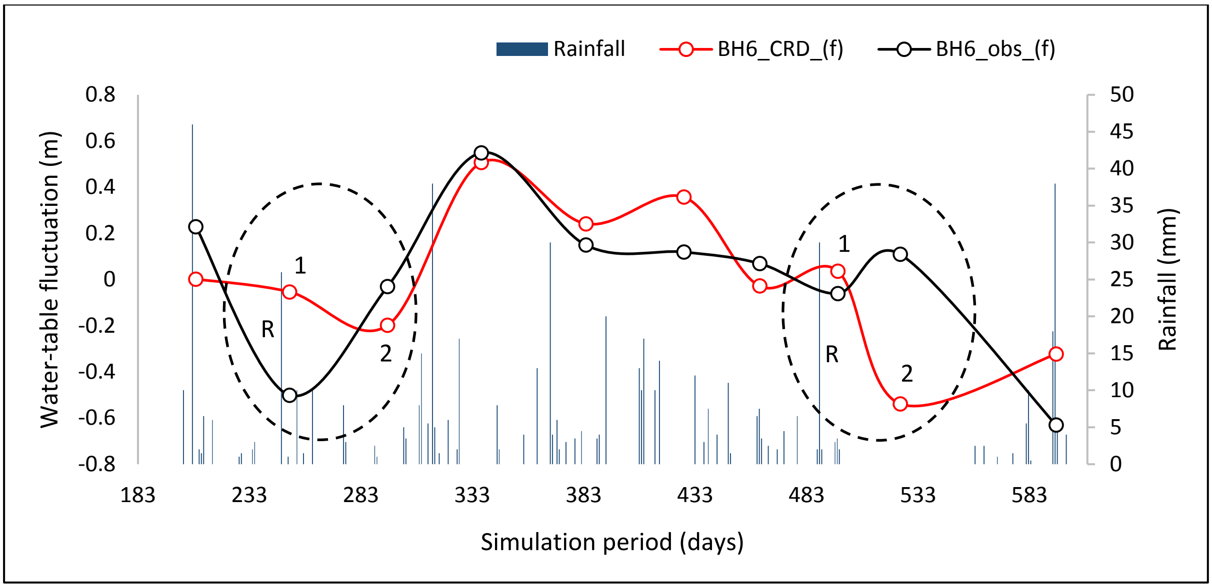


Figure 56 Example of time scale issues with applied CRD method for BH6.

The primary concern arose at scenarios where the time scale either included or excluded certain rainfall events and thereby caused over- or under-estimation of the following water level point. Two similar examples from BH6 are shown in Figure 56, where simulated water level '1' includes rainfall event 'R' which then causes water level '2' to be under-estimated compared to the observed measurement. Essentially, the time scale could not account for the lag time in water-table response and water level '1' should have rather been scaled slightly earlier so that rainfall event 'R' is included in water level '2'. This would increase the rainfall amount for that time step and reduce the difference from the average, causing water level '2' to increase.

Perhaps a more appropriate approach would be to use a daily time scale for both the observed and simulated data, although of course, this would require daily water-table measurements. The installation of data loggers into monitoring boreholes could increase the frequency of measurements and aid in gathering this daily water-table data.

Overall the cumulative rainfall departure (CRD) method proved to be a viable method for simulating water-table fluctuations and therefore determining recharge and specific yield estimates in the study site. In most boreholes, water levels simulated through the CRD method correlated with the observed data with enough conviction to suggest that the method should be developed and extended further. It must be stressed that these methods can only improve with more data and therefore long-term strategic monitoring is essential.

6.2.3. Primary recharge zone

The Witpoort Formation is considered the primary recharge zone in the study catchment and is highlighted in Figure 57 below.

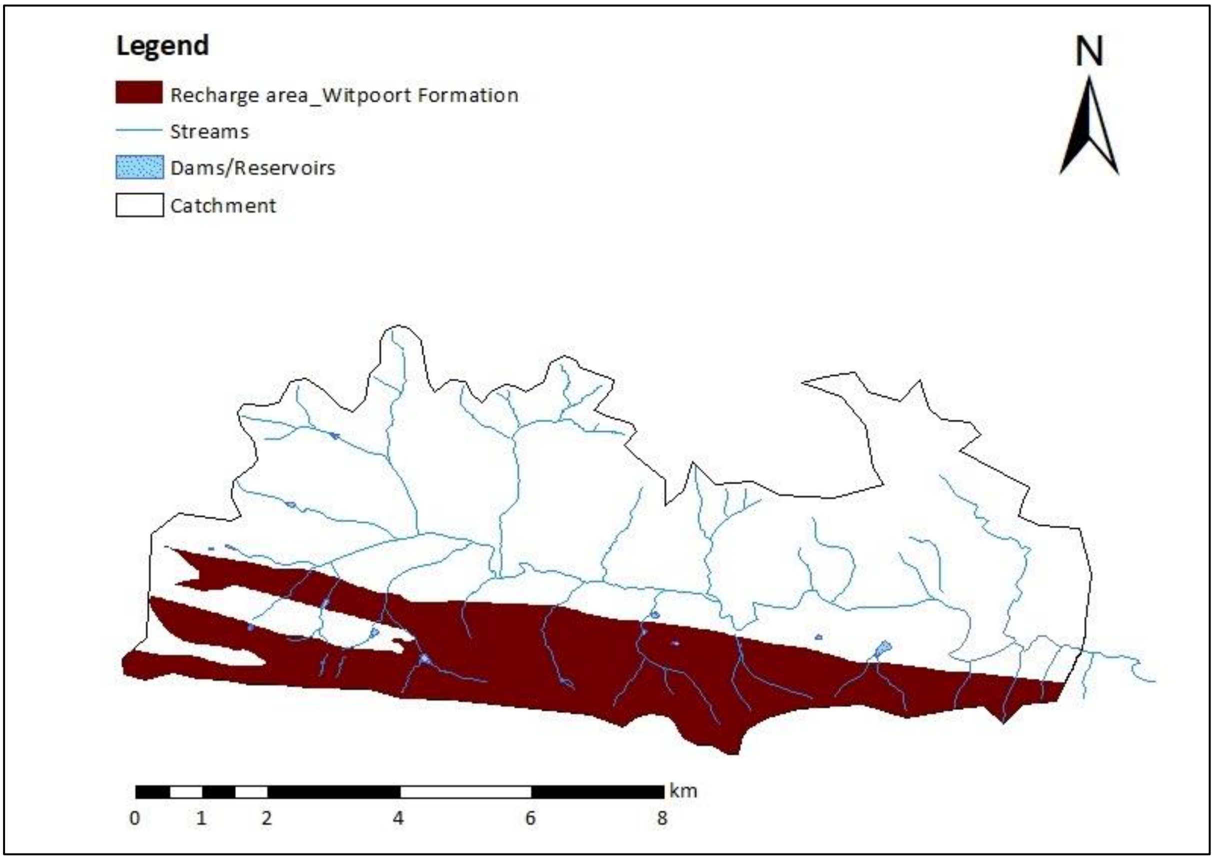


Figure 57 Primary recharge zone (Witpoort Formation) in the study catchment.

The groundwater recharge component (excluding recharge to interflow) for the Fairview Spring model was best simulated at 6.2 % MAP which compares well to ranges of 2 - 6.7 % (specific rainfall series) and 2 - 6 % MAP estimated by the WTF and CRD methods, respectively. Furthermore, these estimates correlate well with the recharge estimate of 3 - 5 % MAP given for Grahamstown on the hydrogeological map (DWS, 2012). The primary recharge zone (Witpoort Formation) covers a total land area of approximately 13 km^2 (Figure 57) and when applying the overall recharge estimate range of 2 - 6.2 % MAP, this amounts to a water volume range of 192 400 - 596 440 m^3 y^{-1} that is proposedly available for utilisation from this aquifer system. This volume estimate was determined using an average annual rainfall of 740 mm y^{-1} which may differ quite significantly from year to year. It should be noted that the recharge estimate range of 2 - 6.7 % determined by the WTF method was not included in this evaluation as it does not relate to MAP.

6.3. Groundwater quality

The ten samples (nine from boreholes and one from the Fairview Spring) that were analysed provided some interesting insights into groundwater chemistry and aquifer dynamics. It was interesting that through simple analysis of major anions and cations a clear difference in groundwater chemistry was evident between the two aquifer systems. Nevertheless, all the samples were classified as 'sodium-chloride waters' when plotted on a Piper diagram.

Dwyka aquifer

The chemical weathering of rocks is considered to be the main geological factor that influences groundwater quality. During these chemical reactions, certain elements within the rock-forming minerals are released into solution and change the composition of the groundwater. According to Tordiffe (1978), the highly saline groundwater found within the Dwyka tillite is due to a combination of main factors that can be summarised as follows:

- An influence of saline connate water that is marine in origin. The Dwyka Group which forms the start of the Karoo Supergroup developed when southern Africa drifted over the poles, freezing the Karoo Sea and initialising glacial action. During this process sea salt may have been trapped within the rock formation with which current day groundwater is able to interact and mix with.
- Tillite generally has low porosity and permeability which limits drainage and increases the residence time of the groundwater.
- The Dwyka Group contains more primary rock material than any other rock unit within the Karoo Supergroup and is therefore extremely susceptible to weathering and release of mineral elements (Figure 58ab) (Tordiffe, 1978).

Figure 58ab Difference between fresh (left) and weathered tillite (right). Hand for scale.

All these factors are relevant and most likely apply in some way to the groundwaters within the Dwyka aquifer in the study site. Overall the Dwyka aquifer is considered to hold poor quality groundwater that is not safe for human consumption (WHO, 2012), unless properly treated.

Witpoort aquifer

A Schoeller plot showed clearly that ion concentrations of all groundwater samples from the Witpoort aquifer are lower compared to those from the Dwyka aquifer, proving that this aquifer system holds better quality groundwater. Furthermore, the levels suggest that it is safe for human consumption (WHO, 2012), although additional sampling and analysis should be undertaken. The primary reason for the lower ion levels is due to the rock type and its extensive secondary porosity. The high silica content of quartzite makes this rock relatively insoluble when water interacts with mineral surfaces and highly resistant to chemical weathering, evidenced by the preservation of the high-lying ridges which border the southern margin of Grahamstown. Furthermore, the abundant and extensively connected fractured networks suggest that lower mineral-water interaction will occur as opposed to an aquifer in which groundwater passes through pore spaces and interacts frequently with individual mineral surfaces.

Upper Witteberg Group aquitard

The three sampled boreholes drilled into the shale aquitard, namely BH1, BH3 and BH17, all showed at least one component above the WHO (2012) recommended limit for human consumption. This included unsafe levels of the components Cl, Na and/or Mn. The elevated levels of Cl and Na are most likely due to similar natural mechanisms discussed for the Dwyka aquifer, but principally those related to the chemical weathering of rocks. However, the raised concentrations of Mn in these three samples are of particular interest. It is not uncommon for Mn to be drawn from shales into nearby groundwaters, although it is usually accompanied by Fe and therefore it is quite odd that no significant concentrations of Fe were also detected. Both Mn and Fe in groundwater are commonly concentrated in systems that are depleted in oxygen. The Kweekvlei and Waaipoort Formations (termed the upper Witteberg Group in the present study) mainly comprise of dark grey shale units, suggesting a carboniferous component. The organic material has the ability to use up oxygen, creating a reducing environment in which Fe and Mn will dissolve more readily. As the groundwater is pumped to the surface it encounters oxygen from the atmosphere and causes any dissolved Fe and Mn to oxidise. Perhaps, during this pumping phase, the Fe oxidised at a faster rate compared to that of the Mn, however this is an assumption and it remains unknown as to why no Fe traces above 0.004 mg l^{-1} were detected. Overall, any groundwater that is drawn from this shale aquitard unit should be treated prior to human consumption.

6.4. Fairview Spring model

The Fairview Spring has become an increasingly important water source for many Grahamstown residents, especially during current drought conditions. Therefore, the need to better understand and model the system has become very relevant. Frequent monitoring of spring discharge provided observed data with which to validate the model. A modelling approach was used which attempted to realistically represent the observed data through the simulation of processes such as interflow and recharge dynamics. Conceptualising spring functioning was necessary to input realistic initial parameters and variables that could then be simulated.

6.4.1. Conceptual model

Conceptual understanding of spring dynamics and the process by which water is able to discharge is important when setting up a model. The structural geology in the spring area suggests that directed fractured flow plays a key part in spring operations (Hughes, 2010b). Be that as it may, the continuous discharge throughout the monitoring period, even during extended times of little to no rain, justified that a certain storage capacity must be present. This led to the assumption that the Fairview Spring may be functioning as a perched aquifer system creating its own unique aquifer system above the regional aquifer. An observation of a seepage above a carboniferous shale unit at a nearby road-cutting offers some support regarding this hypothesis, however, the existence of such a unit below the spring could not be proved in the absence of geophysical evidence. Instead, the spring was conceptualised as a system where the total spring discharge is considered to be a combination of an intersection of the water-table with the land surface, which accounted for the continuous discharge, as well as lateral flow from fractures and weathered material above the water-table level, namely interflow.

6.4.2. Current model

Establishing an accurate model to represent conditions at the Fairview Spring was a process that involved extensive trial and error to effectively balance accuracy with realism. Uncertainty is inevitable in natural systems and this is no different for the Fairview Spring, where three plausible spring process conceptualisations were developed, of which all had some sort of supporting evidence. A process that combined water-table intersection with a directed interflow component was preferred and thereafter appropriate parameters were applied to generate the current model.

The current model was based on modified Pitman Model (Hughes, 2004) components and algorithms. Based on certain assumptions, this initial model included several parameters and variables namely recharge, storage, interflow, groundwater discharge/outflow, groundwater recharge/bypass, hydraulic gradient, transmissivity and storativity. The model inputs of daily precipitation were available through past and recent rainfall records (collected by D. A. Hughes), while the initial potential evaporation inputs were based on the MODIS potential evaporation data. The initial model produced some false peaks (Figure 51) which suggested the introduction of a storage threshold to limit the interflow estimates. However, this didn't help as the soil moisture content in the unsaturated zone store was very similar at the start of all the periods when the false peaks occurred. It was then decided to modify the potential evaporation inputs to account for different slope aspects (Jackson, 1967) and the problem of false peaks was resolved, yet still there was a slight premature response in the peaks. The addition of a rain store which delays and slightly smooths the interflow response solved this issue and was the final component which formed the current model.

6.5. Potential management strategies

6.5.1. Supplementary supply

Ideally, if groundwater is to be used as a supplementary and/or emergency drinking water resource, then supply boreholes should be drilled and groundwater extracted from the Witpoort aquifer system. These potential supply boreholes should be drilled in strategic areas and a suggested site is shown in Figure 59.

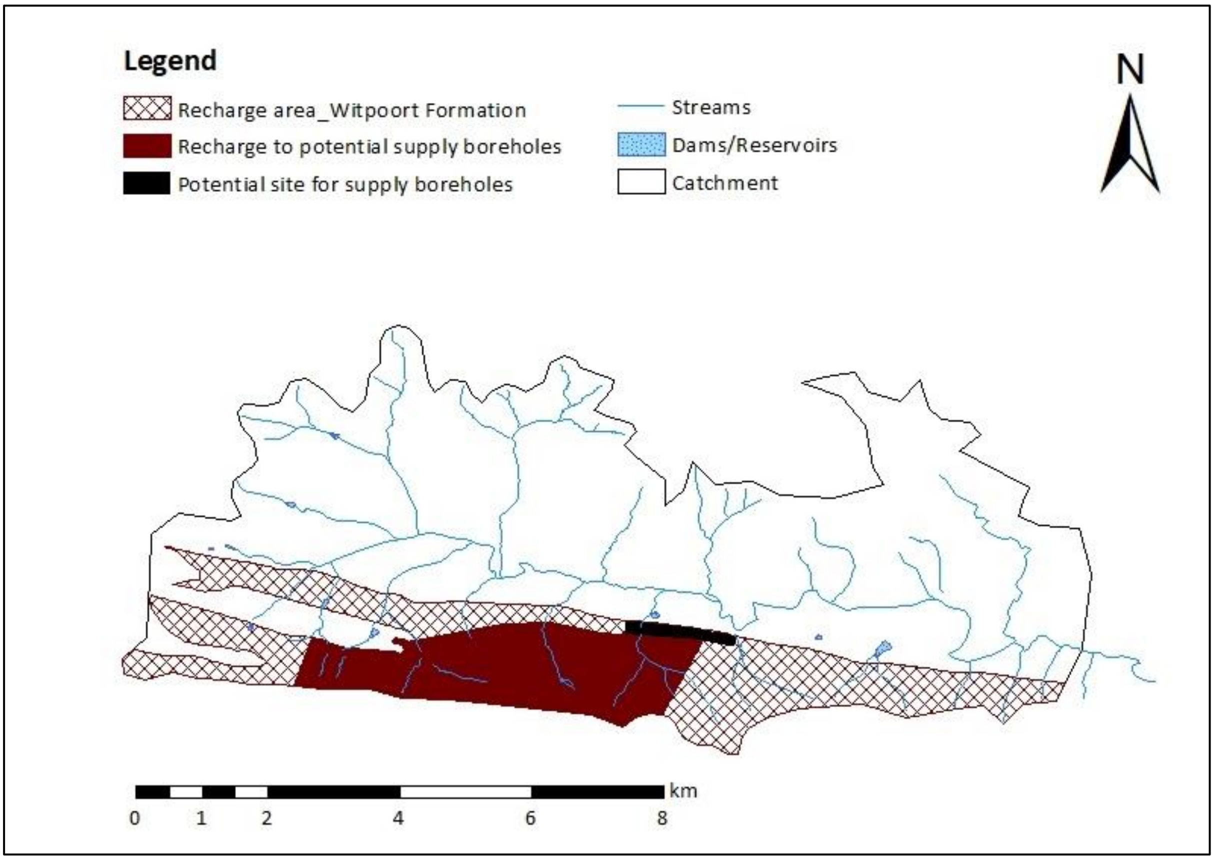


Figure 59 A proposed site where potential supply boreholes could be drilled.

The reasons for developing this site include:

- The folded nature of local geological units means that the Witpoort Formation is characterised as a semi-confined aquifer and makes it possible to drill artesian-type supply boreholes. The position of past and present artesian-type boreholes and wells provides evidence that these conditions can be achieved if boreholes are drilled in suitable sites. Although the drill site, shown in Figure 59, is situated just on the edge of the unconfined section of the Witpoort aquifer, the high lying ridges to the south should maintain the water-table at a stable and relatively elevated level. Furthermore, certain water samples drilled through the adjacent shale aquitard contained traces of Mn (0.034 mg l^{-1} – 0.684 mg l^{-1}), therefore although artesian conditions may be more favourable north of this proposed drilling site the Mn contamination could be problematic and increase treatment expenses.

- Recharge to the Witpoort aquifer is frequent and adequate as evidenced by correlation between rainfall events and water-table fluctuations.
- Samples from the Witpoort aquifer exhibited a chemical quality acceptable for human consumption (EC ranging between 17.1 mS m^{-1} - 40.8 mS m^{-1}), therefore saving costs on treatment.
- The position of the shale aquitard suggests that much of the recharge to the Witpoort aquifer flows underneath the catchment to the east and could therefore be utilised.
- Past pumping tests have shown borehole yields of 2.4 l s^{-1} and 3.2 l s^{-1} (Stone, 1986) for the Witpoort aquifer, which are sufficient for development.

On evidence relating to geology, recharge, quality and quantity it seems practical that 5 - 10 supply boreholes be drilled in the mentioned strategic site where all favourable conditions most likely occur. The projected recharge area to this site is approximately 5 km^2 and by reviewing the recharge estimations from the WTF, CRD and spring model, which ranged from 2 - 6.2 % MAP, together with an average annual rainfall of 740 mm y^{-1}, it allows for a basic groundwater supply approximation. Therefore, the average overall groundwater volume that could potentially be extracted from these supply boreholes ranges between 74 000 – 229 400 m^3 y^{-1}. If this groundwater supply is exclusively used for drinking purposes it could significantly reduce pressures on surface water supply and treatment. For example, the population of Grahamstown is approximately 70 000 and if the average person drinks 2 l d^{-1}, this amounts to a total of 51 100 m^3 y^{-1} – well below the estimated extractable groundwater volume. However, the site is approximately 4 km from the main residential area of Grahamstown with an elevational difference of around 160 m, therefore costs involved in developing the necessary infrastructure as well as pumping would most likely be high. To reduce some of these costs the extracted groundwater could be integrated into an existing treatment and reticulation system. Of the two treatment works that supply Grahamstown, Waainek is the most proximal to this proposed well field and would therefore be the most appropriate

(Figure 60). However, the Waainek treatment works is approximately 8 km away (Figure 60) and at a much greater elevation (~200 m), thus pumping costs from this proposed well field would still be very high. Having said that, once the groundwater reaches this treatment works it could be distributed via existing pipelines using gravity feed means, saving costs on both piping infrastructure and pumping.

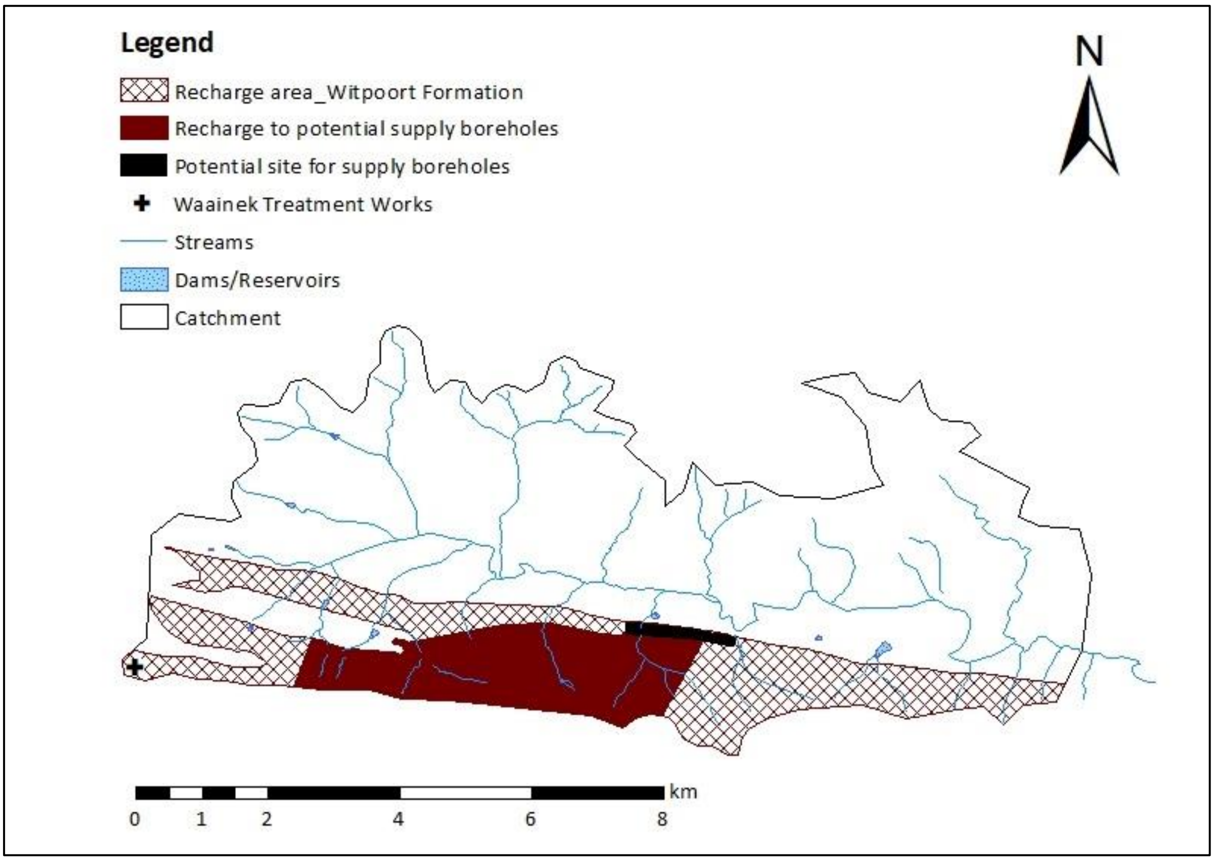


Figure 60 Proposed well field site in relation to the Waainek treatment works.

Another option could be to develop a well field adjacent to the Waainek treatment works as to significantly reduce pumping costs (Figure 61). Observations from a drilling project in this area proved that groundwater is available and accessible, although the borehole had to be drilled to a depth of 114 m and the first water strike was only reached at a depth of 80 m. There is steep topographic slope south west of this treatment works which may also reduce storage potential. Furthermore, in this case, the borehole collapsed due to instability caused by intersection of a ~50 m thick, soft shale unit, assumedly the upper Witteberg Group shale, and had to be re-drilled.

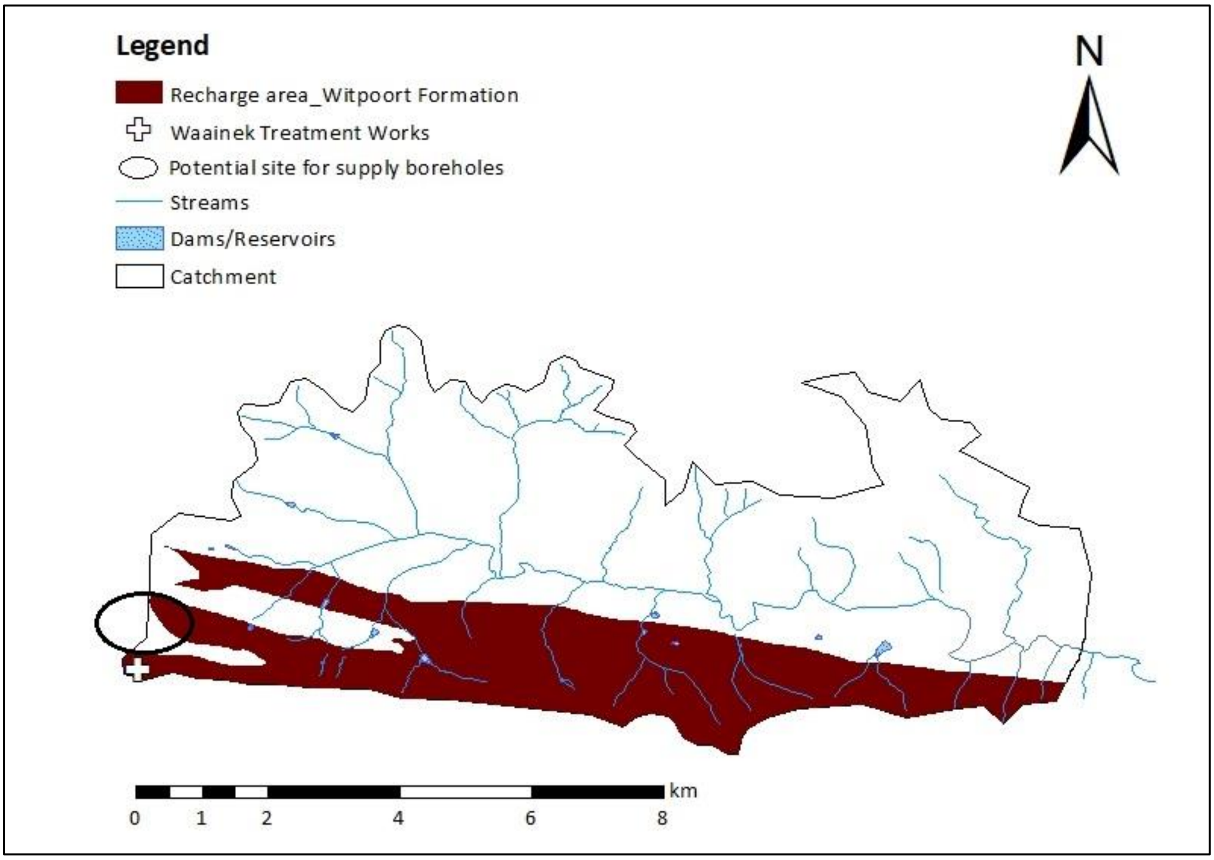


Figure 61 Proposed small-scale well field site in relation to the Waainek treatment works.

In general, boreholes drilled close to or on this high-lying ridge, such as those at Stone's Hill and the one just mentioned, intersect the water-table at deeper levels compared to other monitored and observed boreholes. However, their relative water-table elevations are the highest, again highlighting the high-lying ridge as a recharge zone. Having said this, it is important to note that any water which percolates down and meets the water-table in these uppermost recharge zones will almost certainly move away due to the high hydraulic gradient. This motion may impact the sustainable yield of these boreholes as the amount of horizontal recharge is limited to that specific area rather than a combination of horizontal and lateral recharge build-up over a larger area within the aquifer (Beekman and Xu, 2003). Ideally, boreholes should be drilled in areas not necessarily where recharge is occurring but rather where recharge is being directed. Overall, the development of a small-scale well field adjacent to the Waainek treatment works (Figure 61) would incur high drilling costs along with a potential risk of borehole collapse and possibly a lack of supply, particularly following drought years. Furthermore, installation and incorporation of such a project would still be very expensive.

Consequently, a compromise must be made if a supplementary groundwater supply is to be developed in one of the two proposed sites. Either pumping costs to Waainek will be very high but drilling cost should be reasonable and supply should be consistently good, or alternatively, pumping costs to Waainek will be low but drilling costs will be high and overall supply may be a concern.

By exploring both these options it becomes clear that neither is possible without excessive costs being placed on the municipality. As a result, the way forward could be through individual and individual company borehole development, where policies or municipal management encourages private users and companies to develop groundwater for personal or business use. The goal of this development would be to take pressure off the main water system while sustainably utilising the local aquifer systems. A basic feasibility analysis of this was done to investigate its practicality.

Annual groundwater abstraction estimate:

- 1000 borehole users in Grahamstown
- 25 m^3 per borehole per month (average household use)

= **300 000 m^3 y^{-1}**

Conservative annual groundwater recharge estimate:

- 3% MAP recharge (conservative estimate from current study)
- 600 mm MAP (considered a dry year)
- 13 km^2 recharge area (Witpoort Formation)

= **234 000 m^3 y^{-1}**

The above analysis only includes the Witpoort Formation as this is considered the primary recharge zone in the study site. By isolating this recharge area, it is evident that the development of 1000 boreholes abstracting 25 m^3 per month could have damaging effects on the longevity and sustainability on this aquifer system. However, it must be remembered that these recharge estimates were based on conservative values of recharge and MAP, therefore in slightly wetter years where recharge is greater, this utilisation may be sustainable. The estimate excludes any abstraction from the Dwyka aquifer and this is primarily due to its poor quality, however if groundwater is to be developed on a more private basis and owners are prepared to cover the expense of installing treatment systems then groundwater from this aquifer system should also be added to this feasibility analysis. Furthermore, a large portion of the residential area in Grahamstown is situated on the Dwyka Group and therefore inclusion of groundwater abstraction from this aquifer system seems appropriate.

A shale aquitard separates the Witpoort from the Dwyka aquifer and significant differences in hydrogeochemistry between the systems suggests limited interaction. This evidence is important as it indicates differing recharge zones between the two systems and therefore the additional recharge zone for the Dwyka aquifer should also be considered into the feasibility analysis. Recharge to the Dwyka aquifer is suggested to be primarily through stream channels and their immediate surrounding areas. A basic evaluation of this proposed recharge zone was done, and the recharge area was estimated to be approximately 12 km^2. This additional area was included into the recharge estimate calculated for the initial feasibility analysis and is shown below.

Conservative annual groundwater recharge estimate:

- 3% recharge (conservative)
- 600 mm MAP (considered a dry year)
- 25 km^2 recharge area (13 km^2 Witpoort aquifer and 12 km^2 Dwyka aquifer)

= **450 000 m^3 y^{-1}**

The addition of groundwater from the Dwyka aquifer has elevated the recharge estimate well above the water volume required for the projected 1000 borehole users. This revised recharge estimate would be able to sustainably supply 1500 boreholes abstracting an average of 25 m^3 per borehole per month. However, it is vital that one aquifer system doesn't become over developed while the other remains under used, and in Grahamstown this may be a concern as most of the residents have their properties situated on the Dwyka Group. Perhaps going forward some of the boreholes in this area should be drilled deep enough that they intersect the underlying Witpoort aquifer. Such projects will incur higher drilling costs and possibly require additional casing due to possible contamination and collapse associated with the underlying shale unit, however the overall supply and better quality of the groundwater should be beneficial in the long-term.

Currently the Waainek and James Kleynhans treatment works supply Grahamstown with approximately 8 000 m^3 d^{-1} and 12 000 m^3 d^{-1} of treated water, respectively. That amounts to a total supply of 7 300 000 m^3 y^{-1}. Therefore, although the addition of 450 000 m^3 y^{-1} of groundwater may relieve certain stress from the municipal supply, it would only reflect about 6 % of this total. Nevertheless, in dry years this could be the difference. Furthermore, as mentioned, this projected supplementary groundwater supply is a conservative estimate and will most likely increase quite significantly in wetter years and when additional recharge occurs. Though in wetter years there will likely be less water demand and more surface supply.

6.5.2. Alternative short-term options

Establishing the infrastructure for a supplementary groundwater resource may be a long-term solution and perhaps short-term alternatives could be more practical. One such alternative could involve the distribution of so-called 'mobile water treatment systems' (MWTS). These are portable units that include reverse osmosis (RO) treatment systems and could be used in specific areas during emergency times. Implementation of MWTS strives for an approach that involves the sharing of groundwater in an area. As an incentive, private owners that connect their borehole to the MWTS could receive some sort of compensation for their groundwater supply.

Currently the water at James Kleynhans treatment works does not have the capacity to process and store the full supply of water that makes its way to Grahamstown through the Orange-Fish River transfer scheme. The post-treatment storage capacity at this treatment plant is supposedly being upgraded although this may take a few years. In the meanwhile, any excess water could be diverted to a section of the Dwyka and/or Witpoort aquifer/s as a means of artificial recharge. The process, either via wells or surface spreading, requires sufficient storage capacity and high transmissivity for the aquifer too accept water. The idea of artificial recharge has been adopted for the Atlantis aquifer in the Western Cape and could potentially improve groundwater yields, quality and supply as well as lower the demand for the resource.

6.6. Recommendations for further research

Extensive groundwater quality analysis

The current study included a basic chemical analysis of nine borehole samples and one spring sample. The results proved to be very helpful, however a more comprehensive study could be undertaken in future studies. The analysis could improve by including more boreholes and/or incorporating other quality related variables, namely bacterial-type. Furthermore, quality monitoring could be done at the spring and/or boreholes to aid in better understanding the movement and residence time of the groundwater in the different geological compartments.

Application of additional recharge methods

Accurate estimation of recharge is difficult, but through application of numerous methods the uncertainty can be reduced. In the current study three methods were used, namely the WTF, CRD and a spring model, however, multiple other methods exist which can be applied if sufficient data is collected. Table 2 summarises these methods and can be used to select appropriate methods going forward.

Perform strategic pumping tests

Strategic boreholes should undergo pumping tests to comprehensively evaluate the sustainable yields of the local aquifer systems. The positions of these boreholes could be in areas similar to those mentioned for the proposed monitoring boreholes. It is recommended that the tests include one or more observational boreholes that will aid in applying methods. During any testing, care should be taken not to cause the water-table to drop below the main water strike as this may compromise the performance and life of the borehole. It is this reason, as well as a lack of equipment and cost, that pumping tests were not performed during the current study. Additionally, it is recommended that a trained professional provides advice on this aspect. If several tests are done, then an accurate yield map could be generated that will be highly beneficial to overall groundwater management and utilisation in the town.

CHAPTER 7. CONCLUSIONS

Water resources in many parts of South Africa are being pressured to a critical point. Grahamstown is a town that relies heavily on surface water supplies, however, high demand, low supply, insufficient treatment capacity as well as aging infrastructure has recently enhanced residents' perspectives of the importance of saving water and the possible use of alternative sources. Groundwater is one such resource, although following a report by Andrew Stone in 1986 little has been done to monitor, manage and effectively utilise the resource. The present research aimed to initiate an up-to-date understanding of the hidden resource.

The Witpoort Formation and Dwyka Group are two fractured aquifers beneath Grahamstown and are separated by an upper Witteberg Group shale aquitard. Generally, groundwater flow is downslope and eastwards, similar to the natural topography, although variations in groundwater quality suggests limited interaction between the aquifers. The Witpoort aquifer generally contains good quality water with EC levels ranging between 17 – 200 mS m^{-1}, while the Dwyka aquifer is very saline, with EC levels ranging between 331 – 537 mS m^{-1}, therefore unsuitable for human consumption.

Year-long, approximately monthly monitoring of 31 boreholes provided an opportunity to evaluate water-table fluctuations over time and specifically how the water-table responds to rainfall events. During the monitoring period a sudden rise in water-table was observed in many of the boreholes following a rainfall series amounting to 106.5 mm. This clear response allowed for the application of the WTF method through which initial estimations of both recharge and specific yield were determined. Most of the boreholes that showed this water-table fluctuation were drilled into the fractured quartzitic sandstone of the Witpoort Formation, highlighting its key role as a recharge zone. Recharge was estimated at 2 – 6.7 % for that specific rainfall series and importantly a realistic estimate of specific yield was determined. Using this specific yield estimate as a baseline, the CRD method was applied to estimate recharge which ranged from 2 – 6 % MAP. The borehole monitoring took place over a very dry period and recharge events were few and far between. Nevertheless, throughout this entire dry period, the Fairview Spring continued to flow indicating a possible link between deeper aquifer and spring dynamics and suggesting the contribution of a groundwater component to Fairview Spring discharge. Numerous conceptualisations were made regarding spring functioning, but it was decided that discharge resulted as a combination of water-table intersection and interflow processes.

The discharge from the Fairview Spring was monitored from March 2016 to November 2017 and a variation of the Pitman Model was applied in an effort to simulate the discharge processes and replicate the observed discharge. Through the development of assumptions and adjustment of parameters (calibration) to meet these assumptions a robust model was formed that aided in understanding sub-surface dynamics in the Witpoort Formation. Interestingly the groundwater recharge output at the Fairview Spring was simulated at 6.2 % MAP, a similar estimate to that determined by the WTF and CRD methods using the borehole water level data and further highlighting the importance of the Fairview Spring as a small-scale recharge model for the study catchment.

The hydrogeochemical analysis of ten samples (nine from boreholes and one from the Fairview Spring) clearly indicated the major difference in groundwater quality between the two local aquifers. This difference is primarily attributed to the differing rock type of each aquifer system and specifically the increased dissolution rate and weathering of minerals that make up the Dwyka Group compared to the more resistant quartzitic sandstone of the Witpoort Formation. The analysis also proved to be a valuable tool in showing groundwater movement and residence time in both aquifer systems and in general high-lying areas showed lower concentrations, increasing as the groundwater flows through the aquifers to lower elevations.

On evidence relating to geology, recharge, quality and quantity a strategic area was identified as a potential site to drill supply boreholes that could be utilised to supplement the current water supply to Grahamstown with groundwater from the Witpoort aquifer. The estimated extractable volume from this proposed well field may not be sufficient to support the entire town with all their water needs, however, if utilised as a supplementary and/or emergency supply exclusively for drinking purposes then the resource would be more than adequate. However, the development of necessary distribution infrastructure and associated pumping for such a project would most likely be very expensive. To reduce these costs, it was proposed that the abstracted groundwater be pumped to the Waainek treatment works and incorporated into the existing reticulation system, however the distance and elevational gradient that the water would need to be pumped to reach this treatment plant would increase costs quite significantly. Therefore, a site adjacent to the Waainek treatment plant was investigated as a potential well field to save costs on pumping, however high drilling costs and the idea that recharge will be moving away rather than towards this site were proposed issues. There are certain expenses associated with all these options and therefore perhaps government policy should try to better encourage private groundwater development by both individuals and businesses in Grahamstown. A feasibility analysis based on conservative recharge estimates across both local aquifers concluded that 1500 boreholes using 25 m^3 per borehole per month could be used sustainably, although care would need to be taken as not to over use one aquifer system over the other.

Based on careful consideration of conceptual models, some basic monitoring and a simple model the dynamics of the overall groundwater system were able to be simulated fairly well. This is a support for the capabilities and application of simple models, that do not necessarily require large amounts of data, to be used as a management tool. The lack of past monitoring data meant that the current two-year study was not sufficient to fully explore the modelling possibilities. If historical data was available to perform long-term simulations then it would be possible to investigate past patterns, such as the frequency and variations in recharge. This would not only improve recharge estimates but also aid in performing accurate yield and vulnerability studies. These are the possibilities and benefits involved in gathering data as part of a long-term monitoring plan.

Long-term monitoring enhances the understanding of aquifer systems and certain aspects should be considered to increase the benefit of establishing such a program. One being the drilling of monitoring boreholes in strategic areas across both aquifers. To increase reliability of data the boreholes should not be utilised for groundwater abstraction but exclusively for monitoring purposes and most should be drilled into the Witpoort aquifer due to its importance as a possible drinking water supply. It is suggested that 5 - 10 evenly spaced, west-east trending, monitoring boreholes be drilled just south of the contact between the Witpoort Formation and upper Witteberg Group, as to properly monitor recharge entering the system. A further 5 - 10 monitoring boreholes should be drilled into the Dwyka aquifer at varying elevations as to monitor the potential overuse of groundwater from this aquifer system.

The current research has shown that in many areas, the water-table is continuously responding to rainfall events and ideally data loggers should be installed in all or some of the proposed monitoring boreholes to constantly track these changes. Along with water-table fluctuations, the monitoring plan could be expanded to include an up-to-date record of groundwater use, however this may require identification of all known groundwater users in the study site, together with their pump capacity and frequency of use. Perhaps the implementation of an online system where borehole users could input details about their groundwater abstraction could be useful in this regard. Through this approach a comprehensive local groundwater database could be developed that will aid in firstly, refining the understanding of system dynamics and secondly, ensuring that the resource is not being misused in areas. The present study has demonstrated the effectiveness and practicality when using ArcGIS software as a groundwater research tool and this could be used to generate a local groundwater database moving forward. This potential database could form part of an overall Makana water management plan and help to better manage the resource.

The current research is hopefully just the first step to many groundwater studies in Grahamstown and extensive investigation of groundwater quality, recharge and/or sustainable groundwater yields are just some aspects that could be explored further. Equipment relating to geophysics, data logging and advanced chemical analysis should be improved and/or introduced to better achieve these goals. Overall there is a fundamental need for long-term monitoring of water-tables in Grahamstown, and it is only through the continuous development of this database that sustainable management and use of the resource can be achieved.

REFERENCES

Ahmadi, T., Ziaei, A. N., Rasoulzadeh, A., Davary, K., Esmaili, K. and Izady, A. (2015). Mapping groundwater recharge areas using CRD and RIB methods in the semi-arid Neishaboor Plain, Iran. *Arab Journal of Geoscience*. Vol. 8: pp 2921-2935.

Akoachere, R. A. II and van Tonder, G. (2009). Two methods for the determination of hydraulic fracture apertures in fractured-rock aquifers. *Water SA*. Vol. 35: No. 3.

Beekman, H.E., Gieske, A. and Selaolo, E.T. (1996). GRES: Groundwater Recharge Studies in Botswana 1987-1996. *Botswana J. of Earth Sci*. Vol. III, 1-17.

Beekman, H. E. and Xu. Y. (2003). Review of groundwater recharge estimation in arid and semi-arid Southern Africa. In Xu, Y and Beekman, H. E (Eds). *Groundwater recharge estimation in Southern Africa* (pp 3-18). France: UNESCO Paris.

Bertram, E. (2016). To register or not to register…? Permitted water use explained in terms of the National Water Act. *Borehole Water Association of Southern Africa*. Vol. 102.

Bond, G.W. (1946). Geochemical survey of the underground water supplies of the Union of South Africa. Mem. 41, geol. Surv. S. Africa.

Booth, P. W. K. and Goedhart. M. L. (2014). Thrust faulting in the northernmost foreland zone of the Cape Fold Belt, Fort Beaufort, Eastern Cape, South Africa. South Africa. *Journal of Geology*. Vol. 120: No. 1.

Brassington, R. (2007). *Field Hydrogeology*. Third Edition. John Wiley & Sons, Ltd, the Atrium, Southern Gate, Chichester, West Sussex PO19 8SQ, England.

Braune, E., Adams, S. and Fourie, F. (2014). *20 Years of Groundwater Research, Development and Implementation in South Africa 1994-2014*. Department of Water and Sanitation, University of the Western Cape, Water Research Commission. Republic of South Africa.

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*. WRC Report TT 73/95. Pretoria, South Africa, pp. 407.

Büttner, S. H., Prevec, S. A. and Gess, R. (2015). *Field guide to geological sights in the Grahamstown area*. Department of Geology, Rhodes University.

Cai, Z. and Ofterdinger, U. (2016). Analysis of groundwater-level response to rainfall and estimation of annual recharge in fractured hard rock aquifers, NW Ireland. *Journal of Hydrology*. Vol. 535: pp 71-84.

Catuneanu, O. (2004). Retroarc foreland systems – evolution through time. *Journal of African Earth Sciences*. Vol. 38: Issue 3: pp 225-242.

Compton, J. S. (2004). *The Rocks and Mountains of Cape Town*. Juta & Co. Ltd, Cape Town.

Cook, P. G. (2003). *A guide to regional fracture flow in fractured rock aquifers*. Australia: CSIRO Land and Water.

David, K., Liu, T. and David, V. (2014). Use of several different methods for characterising a fractured rock aquifer, case study Kempfield, New South Wales, Australia. In Sharp, J. M. (Ed). *Fractured Rock Hydrogeology* (pp 307-327). London: Taylor & Francis Group.

Department of Water and Sanitation (DWS). (2012). National Groundwater Maps. Hydrological Services. Groundwater Information.

Dondo, C., Chevallier, L., Woodford, A. C., Murray, R., Nhleko, L. O., Nomnganga, A. and Gqiba, D. (2010). *Flow conceptualisation, recharge and storativity determination in Karoo aquifers, with special emphasis on Mzimvubu – Keiskamma and Mvoti - Umzimkulu water management areas in the 151 Eastern Cape and KwaZulu-Natal provinces of South Africa*. Water Research Commission, Pretoria, WRC Report No. 1565/1/10, 250 pp.

Fitts, C. R. (2013). *Groundwater Science*. Second Edition. Oxford. Elsevier.

Gieske, A. (1992). *Dynamics of groundwater recharge: A case study in semi-arid Eastern Botswana*. Doctor of Philosophy. Vrije Universiteit, Amsterdam.

Gleeson, T., Novakowski, K. and Kyser, T. K. (2009). Extremely rapid and localised recharge to a fractured rock aquifer. *Journal of Hydrology*. Vol 376: pp 496-509.

Healy R. W. and Cook. P. G. (2002). Using groundwater levels to estimate recharge. *Hydrogeology Journal*. Vol 10: pp 91-109.

Hiller, N. and Taylor, F. F. (1992). Late Devonian shoreline changes: an analysis of Witteberg Group stratigraphy in the Grahamstown area. *South African Journal of Geology*. Vol 95: pp 23-212.

Hughes, D. A. (2004). Incorporating groundwater recharge and discharge functions into an existing monthly rainfall-runoff model. *Hydrological Sciences Journal*. Vol 49 (2): pp 297-311.

Hughes, D. A. (2010b). Unsaturated zone fracture flow contributions to stream flow: evidence for the process in South Africa and its importance. *Hydrological Processes*. Vol 24: pp 767–774.

Hughes, D. A., Gush, M., Tanner, J. and Dye, P. (2013). Using targeted short-term field investigations to calibrate and evaluate the structure of a hydrological model. *Hydrological Processes*.

Jackson, R. J. (1967). The effect of slope, aspect and albedo on potential evapotranspiration from hillslopes and catchments. In Hitchmough, R. A., and Sutherland, G. P. *New Zealand Journal of Agricultural Research*. Vol. 24: No. 1: pp 61-69.

Jacob, R. E., Mitha, V. R. and MacPherson, D. (2004). The kaolinic clay deposits on Beaconsfield, north of Grahamstown. *South African Journal of Science*. Vol: 100.

King, G. M. (1995). *The development potential of Kwa Zulu-Natal aquifers for rural water supply*. National Research Foundation (NRF). Master of Science.

Kresic, N. (2010). *Types and classification of springs*. In Kresic, N and Stevanovic, Z (Eds). Groundwater Hydrology of Springs. Engineering, Theory, Management, and Sustainability. Oxford. Elvsevier.

Kuchuk, F., Biryukov, D. and Schlumberger, T. F. (2014). *Fractured Reservoir Modeling and Interpretation*. International Petroleum Technology Conference (IPTC), Kuala Lumpur, Malaysia.

Lerner, D. N., Issar, A. and Simmers, I. (1990). A guide to understanding and estimating natural recharge. *Int. contribution to hydrogeology, I.A.H*. Publ. Vol. 8, Verlag Heinz Heisse, pp. 345.

Lin, L. (2007). *Hydraulic properties of the Table Mountain Group (TMG) aquifers*. Doctor of Philosophy. University of the Western Cape. Cape Town, South Africa.

Lin, L., Lin, H. and Xu, Y. (2014). Characterisation of fracture network and groundwater preferential flow path in the Table Mountain Group (TMG) sandstone, South Africa. *Water SA*. Vol. 40: No. 2.

Meyer, P. S. (1998). *An Explanation of the 1:50 000 General Hydrogeological Map Port Elizabeth 3324*. Department of Water Affairs and Forestry. Pretoria

McCarthy, T. and Rubidge, B. (2005). *The Story Of Earth & Life: A southern African perspective on a 4.6-billion-year journey*. Struik Publishers, Cape Town.

Mouton, E. (2004). *Albany Coast situation assessment study*. Department of Water Affairs and Forestry (DWAF).

Mu, Q., Zhao, M. and Running, S. W. (2012). *Brief Introduction to MODIS Evapotranspiration Data Set (MOD16)*. Numeric Terradynamic Simulation Group, available from: http://www.ntsg.umt.edu/project/mod16#data-product

Nash, J. E. and Sutcliffe, J. V. (1970). River Flow Forecasting through Conceptual Models Part I-A Discussion of Principles. *Journal of Hydrogeology*. Vol. 10: pp 282-290.

Nel, M. (2013). *The History of South African hydrogeology: maybe short, but surely swee*t. In Howden, N., and Mather, J (Eds). History of Hydrogeology (pp 275-290). Taylor & Francis Group, London, UK.

O'Keeffe, J. (2011). *Water Supply and Sanitation in Grahamstown: A Historical Perspective.* Green Hill, Blue Cities.

Parsons, R. (2002). Recharge of Table Mountain Group Aquifer Systems. In: Pietersen, K., Parsons, R. (Editors), (2002). *A synthesis of the hydrogeology of the Table Mountain Group – formation of a research strategy*. WRC report no. TT 158/01, 97-102.

Parsons, R. and Conrad, J. (1998) *Explanatory Notes for the Aquifer Classification Map of South Africa.* Water Research Commission. Department of Water Affairs and Forestry. SA Oil Industry Environment Committee.

Pietersen, K., Beekman, H. E. and Holland, M. (2011). *South African Groundwater Governance Case Study*. World Research Commission (WRC). WRC Report No. KV 273/11.

Rivard, C., Lefebvre, R. and Paradis, D. (2013). Regional recharge estimation using multiple methods: an application in the Annapolis Valley, Nova Scotia (Canada). *Environmental Earth Sciences*. Vol. 71: pp 1389-1408.

Rosewarne, P. (2002). Hydrogeological characteristics of the Table Mountain Group aquifers. In: Pietersen, K., Parsons, R. (eds.) *A synthesis of the hydrogeology of the Table Mountain Group – formation of a research strategy*. WRC report no. TT 158/01, 33-44.

Sami, K. and Hughes, D.A. (1996). A comparison of recharge estimates to a fractured sedimentary aquifer in South Africa from a chloride mass balance and an integrated surface-subsurface model. *Journal of Hydrology*. Vol. 179: No. 1-4: pp 111-136.

Selaolo, E.T. (1998). *Tracer studies and groundwater recharge assessment in the eastern fringe of the Botswana Kalahari – The Lethlakeng – Botlhapatlou area*. Ph.D Thesis. Free University- Amsterdam, pp. 224

Sherman, H. M. (1998). *The assessment of groundwater quality in rural communities: two case studies from Kwa-Zulu Natal*. National Research Foundation (NRF). Master of Science. Department of Geology and Applied Geology. University of Natal (Durban).

Smart, M.C. and Tredoux, G. (2002). Groundwater quality and fitness for use. In: Pietersen, K., Parsons, R. (Eds). *A synthesis of the hydrogeology of the Table Mountain Group – formation of a research strategy*. WRC Report No. TT 158/01, 118-123.

Smith, R. H. M., Eriksson, P. G. and Botha, W. J. (1993). A review of the stratigraphy and sedimentary environments of the Karoo-aged basins of Southern Africa. *Journal of African Earth Science*. Vol. 15: pp 143-169.

Stewart, Sviridov and Oliver Consulting Engineers. (1985). *Report on underground water supply*. City of Grahamstown. Water Scheme.

Stone, A. W. (1986). *Assessment of groundwater resources in the Grahamstown municipal area*. Report. Rhodes University.

Sun, X., Xu, Y., Jovanovic, N. Z., Kapangaziwiri, E., Brendonck, L. and Bugan, R. D. H. (2013). Application of the rainfall infiltration breakthrough (RIB) model for groundwater recharge estimation in west coastal South Africa. *Water SA*. Vol. 39: No. 2.

Tordiffe, E. A. W. (1978). *'Aspects of the Hydrogeochemistry of the Karoo sequence in the Great Fish River basin, Eastern Cape Province, with special reference to the groundwater quality'*. Doctor of Philosophy. University of the Free State. Bloemfontein.

Truswell, J. F. (1977). *The Geological Evolution of South Africa*. Purnell, Cape Town.

Van der Lee, J. and Gehrels, J.C. (1997). Modelling of groundwater recharge for a fractured dolomite aquifer under semi-arid conditions. In IAH-Recharge of Phreatic Aquifers in (Semi-) Arid Areas (ed. I. Simmers). A.A. Balkema/Rotterdam: 129-144.

Van Veelen, M., Baker, T., Mulale, K., Bron, A., Fanta, A., Jonker, V., Mullins, W. and Schoeman, H. (2009). Feasibility study of the potential for sustainable water resources development in the Molopo Nossob watercourse, Orange Senqu River Commission, Report No. 007/209, 106 pp.

Van Wyk, E., van Tonder, G. J. and Vermeulen, D. (2011). Characteristics of local groundwater recharge cycles in South Africa semi-arid hard rock terrains – rainfall input. *Water SA.* Vol. 37: No. 2.

Wang, X., Jardani, A., Jourde, H., Lonergan, L., Cosgrove, J., Gosselin, O. and Massonnat, G. (2016). Characterization of the transmissivity field of a fractured and karstic aquifer, Southern France. *Advances in Water Resources*. Vol. 87: pp 106-121.

Weaver, J.M.C. and Talma, A.S. (1999). *Field studies of Chlorofluorocarbons (CFC's) as a Groundwater Dating Tool in Fractured Rock Aquifers*. Pretoria, WRC Report 731/1/99.

Weaver, J.M.C., Talma, A.S. and Cavé, L. (1999). Geochemistry and isotopes for resource evaluation in the fractured rock aquifers of the Table Mountain Group. WRC Report No. 481/1/99.

Weaver, M. J. T., O, Keefe, J., Hamer, N. and Palmer, CG. (2017). Water service delivery challenges in a small South African municipality: Identifying and exploring key elements and relationships in a complex social-ecological system. *Water SA*. Vol. 43: No. 3.

World Health Organisation (WHO). (2012). *Guidelines for Drinking Water Quality*. Recommendations, Geneva. 4th Edition: pp 1-6.

Xu, Y., Titus, R., Holness, S.D., Zhang, J. and van Tonder, G.J. (2002). A hydrogeomorphological approach to quantification of groundwater discharge to streams in South Africa. *Water SA*. Vol. 28: No. 4: pp 375-380.

Xu, Y. and van Tonder, G. J. (2001). Estimation of recharge using a revised CRD method. *Water SA*. Vol. 27: No. 3.

Zha, Y., Yeh, T. J., Illman, W. A., Tanaka, T., Bruines, P., Onoe, H. and Saegusa, H. (2015). What does hydraulic tomography tell us about fractured geological media? A field study and synthetic experiments. *Journal of Hydrology*. Vol. 531: pp 17-30.

Zhang, L. and Guilbert, E. (2012). A study of variables characterizing drainage patterns in river networks. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*. Vol. XXXIX-B2.

APPENDIX 1: INFORMATION SHEET FOR MONITORED BOREHOLES

Borehole	*Latitude	*Longitude	Date drilled	Estimated depth (m)	Pump depth (m)	Use	Quality
BH1	-33,32405	26,61006	over 3 yrs	Unknown	Unknown	Domestic	Clear (soapy/sulphur/brown)
BH2	-33,31649	26,53916	Over 35 yrs	Unknown	±20 m	Irrigate garden	Good
BH3	-33,31577	26,5352	Unknown	39	Unknown	Irrigation/Domestic	Good/clear
BH4	-33,306	26,52759	Over 15 yrs	Unknown	± 30/40	Irrigation (bowl lawns)	Very brackish
BH5	-33,3038	26,52486	± mid 1980's	± 40	Unknown	Pool, Irrigate garden	Clear
BH6	-33,32604	26,55587	over 40 yrs	Unknown	± 30	Kennels (clean/drink)	Very good (drinkable)
BH7	-33,30052	26,5237	± 1970's	± 40	± 25/30	Irrigation/domestic	Brackish, clear
BH8	-33,31725	26,53545	Over 8 yrs	± 200	No pump	No use	Unknown
BH9	-33,30187	26,52643	Unknown	Unknown	Unknown	Irrigation	slightly brackish
BH10	-33,31094	26,51656	over 13 yrs	50	48	Irrigation/gardens	High Fe content (brown/red)
BH11	-33,30161	26,53106	2014	130	80	Irrigation	slightly brackish
BH12	-33,29739	26,51988	Unknown	43	Unknown	Irrigation/top up pool	Sometimes brown
BH13	-33,31108	26,52052	over 13 yrs	58	56	Irrigation/gardens	High Fe content (brown/red)
BH14	-33,31287	26,51408	over 13 yrs	40	38	Irrigation/gardens	High Fe content (brown/red)
BH15	-33,302	26,53241	Unknown	100/110	70/80	Swimming pool	slightly brackish
BH16	-33,30742	26,51541	Over 2 yrs	Unknown	Unknown	Irrigate garden	Brown (Fe?), brackish
BH17	-33,30748	26,5151	Early 2016	70	45	Irrigation	Brown (Fe?), brackish
BH18	-33,29879	26,52907	Over 27 yrs	± 60	± 50/55	Irrigation/domestic	Brackish, clear
BH19	-33,32645	26,55433	over 20 yrs	Unknown	± 80	Main drinking supply	Very good (drinkable)
BH20	-33,29795	26,51885	Over 11 yrs	Unknown	Unknown	Irrigation	Possible Fe
BH21	-33,31197	26,50834	over 13 yrs	86	84	Irrigation/gardens	High Fe content (brown/red)
BH22	-33,31436	26,51046	over 13 yrs	44	42	Irrigation/gardens	High Fe content (brown/red)
BH23	-33,2949	26,51858	1985	80	40	Domestic/drinking/irrigation	Good quality
BH24	-33,307212	26,513408	50+ years	±100	±50/60	Domestic/drinking (RO system)	Brackish
BH25	-33,31589	26,51449	over 13 yrs	Unknown	Unknown	Irrigation/gardens	High Fe content (brown/red)
BH26	-33,32431	26,53965	Unknown	±40	Unknown	N/A	N/A
BH27	-33,30677	26,50849	Unknown	Unknown	Unknown	Irrigation garden	N/A
BH28	-33,33715	26,56952	±15 yrs	Unknown	Unknown	Domestic/drinking	Very good (drinkable)
BH29	-33,33489	26,56324	Over 10 yrs	Unknown	Unknown	Domestic. 90% rainwater	Very good (drinkable)
BH30	-33,33442	26,56377	Over 10 yrs	Unknown	Unknown	Domestic. With rainwater	Very good (drinkable)
BH31	-33,33343	26,5664	Unknown	Unknown	Unknown	Domestic/irrigate garden	Very good (drinkable)

* latitude and longitude in decimal degrees

APPENDIX 2: TIME-SERIES WATER-TABLE DATA FOR MONITORED BOREHOLES

Borehole	Land elevation (masl)	Collar height (m)	Water depth (m)									
			2016				2017					
			July	Sep	Oct	Nov	Jan	Mar	Apr	May	June	July
BH1	456	-0.5	20.79	20.75	20.84	20.77	21.03	21.01	21.2	22.02	23.28	21.32
BH2	514	0.22	4.98	4.68	4.98	4.7	5.02	4.57	4.96	4.93	5.22	5.64
BH3	530	-0.54	N/A	10.2	10.65	10.15	10.67	10.02	10.37	10.58	10.62	11.3
BH4	532	-0.55	N/A	2.13	2.62	2.1	2.36	2.01	2.65	2.45	2.66	3.25
BH5	542	-0.38	7.42	6.82	7.27	7.19	8.11	7.14	7.95	7.56	7.9	8.64
BH6	544	0	19.25	19.98	19.51	18.93	19.33	19.36	19.41	19.54	19.37	20.11
BH7	546	0.27	12.96	11.96	14	12.23	14.12	13.44	14.24	13.85	14.63	14.66
BH8	546	0.25	16.51	16.6	16.69	16.6	16.59	16.64	16.68	16.75	16.77	17
BH9	548	0.88	10.26	9.29	10.4	9.64	11.4	10.65	11.54	11.08	11.23	12.03
BH10	548	-0.57	N/A	6.91	7.38	7.43	8.66	4.58	4	4.55	4.5	5.62
BH11	556	-0.53	28.63	27.92	30.5	28.28	28.37	28.75	29.62	29.78	29.96	30.32
BH12	560	0.92	25.74	24.26	25.1	26.13	27.84	28.23	28.71	27.85	27.58	27.92
BH13	561	-0.34	N/A	N/A	N/A	1.49	1.61	1.04	1.08	0.91	0.99	1.54
BH14	562	-0.32	N/A	1.24	1.35	1.08	0.86	0.88	1	1.09	1.22	1.72
BH15	563	0.31	29.44	29.01	29.78	29.28	29.24	29.02	29.86	29.33	29.69	29.49
BH16	563	-0.53	29.52	33.94	20.98	29.86	24.18	23.58	24.48	24.23	26	25.07
BH17	568	0.21	29.95	29.13	29.7	29.3	30.93	29.85	29.95	29.04	30.93	29.6
BH18	569	0.14	N/A	23.22	22.7	23.39	23.75	23.14	23.32	23.21	23.43	23.32
BH19	569	0.06	22,25	21.11	21.71	21.9	22.76	22.26	22.09	22.34	22.11	22.54
BH20	571	0	38.16	36.19	37.15	N/A	40.04	40.3	40.8	39.66	41.05	39.88
BH21	571	-0.4	N/A	1.84	N/A	2.16	2.07	1.91	1.82	1.87	1.62	2.07
BH22	573	-0.4	N/A	0	0	0	0.11	0.11	0.12	0.12	0.34	0.1
BH23	575	0.1	N/A	N/A	8.42	8.31	N/A	7.91	7.8	7.92	7.9	8.72
BH24	576	0.2	N/A	37.34	37.94	37.55	38.32	38.36	38.3	37.21	39.12	36.93
BH25	578	0	N/A	0	0	0	0	0	0	0	0	0
BH26	602	0.36	7.68	8.13	8.33	7.77	7.5	8.31	8.44	8.44	8.64	9.39
BH27	610	-0.45	N/A	38.65	38.69	38.72	37.37	36.92	42.54	43.21	44.75	40.44
BH28	622	0.05	78.26	78.18	78.76	78.98	79.03	79.13	79.48	80.25	81.5	81
BH29	652	0.32	58.58	59.88	60.75	58.86	60.55	59.7	62.66	60.56	60.37	60.5
BH30	656	0.19	40.09	39.15	39.84	39.21	39.63	39.45	42.6	42.67	42.14	43.82
BH31	666	0.29	41.76	43.32	44.45	45.53	46.28	46.73	47.15	47.62	48.28	49.76

APPENDIX 3: TIME-SERIES DISCHARGE RATE DATA FOR THE FAIRVIEW SPRING

Date	Discharge rate ($l\ d^{-1}$)	Date	Discharge rate ($l\ d^{-1}$)	Date	Discharge rate ($l\ d^{-1}$)
13/03/2016	17280	19/11/2016	9432	28/04/2017	9076
23/03/2016	20571	21/11/2016	10000	04/05/2017	9038
01/04/2016	19817	23/11/2016	11368	09/05/2017	8889
05/04/2016	18000	25/11/2016	12135	12/05/2017	9000
08/04/2016	18000	27/11/2016	12558	14/05/2017	9000
13/04/2016	17851	29/11/2016	12857	18/05/2017	8640
18/04/2016	17561	01/12/2016	13091	23/05/2017	8504
24/04/2016	16875	05/12/2016	12706	30/05/2017	8504
03/05/2016	16000	10/12/2016	12067	08/06/2017	8276
12/05/2016	15652	17/12/2016	11134	15/06/2017	8030
17/05/2016	15319	01/01/2017	10286	13/07/2017	7714
26/05/2016	14694	05/01/2017	10746	04/08/2017	7500
02/06/2016	14211	08/01/2017	11489	16/08/2017	7500
16/06/2016	13500	16/01/2017	10000	21/08/2017	7552
05/07/2016	12486	20/01/2017	9818	23/08/2017	7606
19/07/2016	12000	24/01/2017	10047	25/08/2017	7606
25/07/2016	12000	31/01/2017	9730	28/08/2017	7500
08/08/2016	11429	09/02/2017	9474	01/09/2017	7500
19/08/2016	11803	13/02/2017	9310	08/09/2017	7423
01/09/2016	10693	17/02/2017	9114	19/09/2017	7448
17/09/2016	10537	20/02/2017	9310	27/09/2017	7176
06/10/2016	10093	22/02/2017	9432	09/10/2017	7855
25/10/2016	9391	26/02/2017	9270	12/10/2017	8151
08/11/2016	9310	02/03/2017	9643	16/10/2017	15540
12/11/2016	9432	08/03/2017	10237	19/10/2017	28800
13/11/2016	9474	14/03/2017	10286	22/10/2017	27000
14/11/2016	9474	20/03/2017	9818	24/10/2017	25412
15/11/2016	9432	28/03/2017	9774	29/10/2017	22737
16/11/2016	9351	04/04/2017	9432	03/11/2017	20571
17/11/2016	9432	11/04/2017	9558	08/11/2017	18305
18/11/2016	9310	24/04/2017	9153	14/11/2017	17008