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An assessment of the contribution of surface and subsurface flows to river flows of the Sandspruit in the Berg River Catchment, South Africa.

A thesis submitted in fulfilment of the requirements for the degree of Magister Scientiae in
Environmental and Water Science

By

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Abstract

An assessment of the contribution of surface and subsurface flows to river flows of the Sandspruit in the Berg River Catchment, South Africa.

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Studies have shown that the primary origin of salinity in river flows of the Sandspruit in the Berg Catchment located in the Western Cape Province of South Africa was mainly a result of atmospheric deposition of salts. The salts are transported to rivers through surface runoff and subsurface flow (i.e. through flow and groundwater flow). The purpose of this study was to determine the contributions of subsurface and surface flows to the total flows in the Sandspruit, Berg Catchment. Three rain events were studied. Water samples for two rain events were analysed for environmental tracers $\delta^{18}O$, Silica or Silicon dioxide (SiO2), Calcium ($Ca2^{+}$) and Magnesium ($Mg2^{+}$). Tracers used for two component hydrograph separation were $\delta^{18}O$ and SiO2. The tracers, $Ca2^{+}$ and $Mg2^{+}$, revealed inconsistent contributions of both subsurface flow and surface flow. Two component hydrograph separations indicated is that groundwater is the dominant contributor to flow, while surface runoff mainly contributes during the onset of the storm event. Groundwater response to precipitation input indicated that boreholes near the river have a quicker response than boreholes further away from the river. Boreholes nearer to the river also indicate higher water levels in response to precipitation, in comparison to boreholes further from the river.

February 2018

Declaration

I declare that '***An assessment of the contribution of surface and subsurface flows to river flows of the Sandspruit in the Berg River Catchment, South Africa.***' is my own work, that it has not been submitted for any degree or examination in any other University, and that all the sources I have used or quoted have been indicated and acknowledged by complete references.

Full name: Matthew Damons   Date: 09 February

Signed....MDamons.............

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Chapter 1 : Introduction

Increasing salinity of freshwater in both rivers and groundwater is a global problem and affects over 100 countries (Rengasamy, 2006). A common problem is the effect of salinity on crop growth, pastures and forestry. The effects of high salinity concentrations on plant growth, are low occurrence of seedling emergence and in extreme cases even plant death (Shiati, 1989; Rengasamy *et al.*, 2003; Dong, 2012). Low seedling germination results in reduced crop yield. Low seedling germination and plant death are a consequence of salts reducing the osmotic potential of soil water thereby reducing water available to plants. Salinity also affects water resources and has an impact on aquatic and riparian biodiversity (Montague and Ley, 1993; Lymbery *et al.*, 2003). Periods of low flows increase river salinity. In rivers and the riparian zone, life cycles of organisms are affected by an increase in salinity. During periods of increased salinity, there low egg hatching of aquatic fauna in the riparian zone. In order to survive, organisms have to lower or stop reproduction until periods of high flow when salinity concentrations are reduced (Nielsen *et al.*, 2003). These periods of reduced biodiversity lead to a reduction of production by riparian and aquatic systems, and consequently a loss in ecosystem services (Hart *et al.*, 2003). Ecosystem functions are dependent on one another; for example, organic matter production, which is the primary energy source is, dependent on organic matter breakdown and delivery of this energy downstream by the river. Any reduction in either the production of energy or the delivery of energy causes losses in biodiversity (Sekercioglu, 2010). These losses of biodiversity ultimately affect the functioning of the ecosystem. Losses in vegetation mean a loss in energy production as well as soil in which new vegetation may grow as soil may become unstable and erode. The changes in ecosystem functioning affect water purification processes, flood control, storage of water, erosion rate, nutrient absorption and export (Sekercioglu, 2010).

Salinity affects South Africa and other countries globally. A drop in crop production results in an increase in food prices especially in countries that rely on imports of fruits and grain products. In South Africa salinity poses both societal and environmental problems especially since the country is ‘water stressed’ (Otieno and Ochieng, 2004). Societal problems include loss of crops and arable land, whereas environmental problems include loss of riparian vegetation which can exacerbate soil erosion. Salinization of freshwater has been identified as one of the major threats to water resources in South Africa (Du Plessis and Van Veelen, 1991; Williams, 2001; Lerotholi *et al.*, 2004). This occurs predominantly in semi-arid and arid environments and is a result of both natural and anthropogenic causes (Lerotholi *et al.*, 2004). The natural causes of salinization include weathering of shale and atmospheric deposition of salts, while anthropogenic causes are poor irrigation drainage and replacement of deep rooted vegetation by shallow rooted crops or urbanization. Strydom and King (2009) report that 10% of South Africa’s soils are affected by irrigation salinity, and 40000 hectares of soil are out of production and are permanently salinized. In the Vaal region, salinization of water resources occurs as a result of the presence of sodium ions and limestone in the geological environment (Dikio, 2010). In the province of KwaZulu-Natal increases in chlorine from sewage effluent was shown to kill up to 100% of mayflys when chlorine ranged between 8-16 µg/L (Williams *et al.,* 2003).

According to Van Rensburg et al (2011) only 6% of agricultural land is irrigated in the Berg River. Clearing of natural vegetation by the early European settlers resulted in an increase in salinity of groundwater, as a result of increased groundwater recharge, a reduction in the uptake of water by plants, and the weathering of minerals. Increased weathering resulted in the increase in concentrations of salt in the Sandspruit Catchment (Vermeulen, 2010). Salt from the Atlantic Ocean enters the Sandspruit Catchment by deposition of salt from the atmosphere during the winter months (Flugel, 1991; Vermeulen, 2010). The dominant land use in the Sandspruit Catchment is dryland farming (Bugan, 2008). A factor increasing the concentrations of salinity in the Berg River is the diversion of water to urban areas (Haas *et al.,* 2010). Diverting water to urban areas decreases the amount of water available to dilute salts. Even though environmental flows are provided for, the diversion of water for urban use has effects downstream of the dam.

Flugel (1991) indicated that salt leached from soil and groundwater is transported to the Sandspruit during flood events. The increase in salinity during flood events is strongly linked to high flows in the Sandspruit Catchment. Various runoff components such as interflow, groundwater flow and surface runoff contribute to river flows during storm events, and their contributions vary. Understanding these processes is important for water resource management (Partington *et al.,* 2009). The information on the aforementioned processes assists water resource managers in determining the amount of water available for use, and to identify potential threats to water resources by identifying the flow paths of contaminants. Understanding runoff processes and their flow paths yields information on surface and subsurface sources of contamination.

Runoff processes are well documented in the literature (Wels *et al.,* 1990; Ogunkoya and Jenkins, 1993; Hoeg and Uhlenbrook, 2000; Ladouche *et al.,* 2001). Understanding the sources of river flows during storms is important because this gives an understanding of whether storm flow is predominantly composed of ‘new’ or ‘old’ water. The especially useful when determining which component is more important in water resource development. Another reason is to determine the amount of that water remaining in the catchment as storage and the amount of water that leaves the catchment. Flood prediction is possible if flow processes are understood. We can use the knowledge of the various flow components to understand the quality of water during storms and explain the flux of pollutants during storms (Kollongei and Lorentz, 2014).

The increase in salt in the Sandspruit could result in an increase in the salinity of the Berg River, as the Sandspruit is a tributary of the Berg River. Over the long term an increase in salinity is detrimental to water users, therefore methods to reduce salt transport should be investigated. An understanding of runoff processes and their relative contributions to total flow is therefore necessary for water resource managers to implement methods to reduce salt transport and reduce river salinization. Flugel (1991) and Bugan (2008) suggested that salts are transported during periods of runoff in the Sandspruit catchment.

The increase in salt in the Sandspruit may not have an immediate effect due to dilution, however during the dry season as a result of evaporation, salinity poses a threat to water resources and vegetation alike. A reduction in discharge is therefore important especially since the Berg River is one of the major water supply sources to the city of Cape Town.

1.1 Problem statement

In the Sandspruit Catchment there is an increase in salinity in soil and the Sandspruit as pre-existing salts move from storage during rainfall events as established by Flugel (1991) and Bugan (2008). An understanding of the relative importance of the contribution of surface and subsurface runoff to storm flow is unknown in the Sandspruit Catchment. Within the Sandspruit Catchment knowledge of runoff components and flow paths is crucial for evaluating the vulnerability of surface and groundwater systems to salinity. This study therefore aims to investigate the relative contributions of surface and subsurface runoff to total channel flow.

1.2 Research questions

- What are the relative contributions of surface and subsurface runoff to total flows in the Sandspruit?
- How do these attributes vary?
- What is the impact/influence of catchment characteristics on contributions?

1.3 Aims and objectives

The aim of this study is to improve the understanding of the contributions of surface and subsurface flow to river flows in a sub-catchment of the Berg River.

Specific objectives are:

1) To determine the contribution of surface and subsurface runoff to river flows.

2) To establish how the surface and subsurface components of river runoff vary between rainfall events and seasonally

3) To establish the influence of catchment characteristics on the relative contributions of surface and subsurface flow components.

1.4 Thesis outline

Chapter 1 introduces the topic of study and the motivation for the study, its aim and objectives and the thesis outline. **Chapter 2** presents a review of the relevant literature. **Chapter 3** describes the study area, the methods and materials as well as the experimental set-up used. Results and discussion are presented in **Chapter 4**. Conclusions and recommendations that were made are presented in **Chapter 5**.

1.5 Conclusion

The adverse effects of salinity on water resources are of major concern. The degree of salinization of river flows can be influenced by the relative importance of surface and subsurface runoff in a catchment. Thus, this study seeks to evaluate the relative importance of surface and subsurface runoff in contributing to river flows. Flugel (1991) and Bugan (2008) said that an increase in salinity is associated with periods of high flows. Increases in salinity are detrimental to plant and animal life in terms of energy production, survival, growth and this affects ecosystem services. The research done is important as it is imperative that flow components as well as flow paths be understood. assist water resource managers in implementing methods to reduce the movement of salts as well as develop controls that prevent the movement of salts from storage.

Chapter 2 : Literature Review

2.1 Introduction

The mitigation of salinity in a catchment is dependent on the knowledge of the sources and the rate of transport of salts throughout the catchment. However, these cannot be determined if major flow pathways are unknown (McCarthy and Zachara, 1989). It is therefore important that sources and active mechanisms of salt accumulation are understood within a catchment.

Salinity is defined as the presence of major dissolved inorganic solutes in either soil or water (Alison *et al.*, 1990; Schofield, 1992; Mcfarlane and Williamson, 2002, Welfare *et al.*, 2002 and Bugan, 2008). Salinization of water resources is a result of many geochemical facies with the dominant facies being Sodium-Chloride (Na-Cl) and Calcium-Sulfate (Ca-SO4). This is due to the high solubility of chloride and sulphate minerals (Clark and Fritz,1997; Bennetts *et al.*, 2006). Salinity is related to electrical conductivity (EC) which is expressed in Siemens, alternatively salinity can be related to total dissolved salts (TDS) and expressed in mg/L or in parts per million (ppm).

2.2 Types and causes of salinization

There are two main types of salinity. These are primary salinity and secondary. Primary salinity is defined as salinity which occurs naturally within an area (Bugan, 2008). Salt is introduced into an area by atmospheric deposition, mineral weathering or transport by wind or water. Salt accumulates in soils when saline groundwater reaches the soil zone and is subjected to evaporation. The effects of primary salinity are not immediately apparent, as this takes years for large quantities of salt to be deposited to the extent that affects plants and animals.

Secondary salinity or dryland salinity is the process of land salinization caused by the rise in saline groundwater table (Yeo, 1999; Bradd et. al, 1997). Rain, irrigation return flows or snowmelt infiltrate the soil and reach the water table thereby recharging the aquifer allowing the water table to rise (Timms, 2005). The increase in the rate of movement of water to the water table mobilises previously stored salt. This results in the water table rising especially when deep rooted vegetation is cleared, or replaced by shallow rooted vegetation in areas of high recharge and at regional scales (Bradd et. al, 1997). When the water table of saline groundwater reaches the earth's surface, this is subject to evaporation, resulting in soil salinity (Bradd et. al, 1997; Timms, 2005).

Industrial salinity is the salinization of water resources by industrial processes. One of the largest contributors to salinity is effluent from waste water treatment plants released into rivers or into boreholes (Jaar, 2009). Other industrial processes include food processing, industrial laundry, metal finishing industries and health industries (Central Arizona salinity study, 2006).

Urban salinity arises from land clearing for human occupation. Deep rooted vegetation is removed and usually gets replaced by shallow rooted vegetation or paved areas. The salinization process is caused by the rising of the water table due to result of increased infiltration which moves salts to the surface. Sources of salts in urban areas are pools, salt applied to roads for de-icing, food products, fertilisers, soap and detergents, industry and building materials introduce salts from the various sources (Miyamoto *et al.,* 2005; Ryan and McGhie, 2006; Novotny *et al.,* 2008).

2.3 The problem of salinity at a global level

In Australia, Central Asia and India salinity occurs in semi-arid and arid environments (Ritzema *et al.,* 2008; Tweed *et al.,* 2011; Létolle and Chesterikoff, 1999). Many of these environments require additional irrigation to produce crops. During dry months, when evaporation rates are highest, water is evaporated and salt remains in the root zone. The build-up of salts in the root zone affects plant growth and reduces crop production (Greiner, 1997).

In the Netherlands, increases in salinity as a result of mining of potash and brown coal affected two of the major water resources, the Rhine River and Lake Ijsselmeer. In north-east Spain potash mining and agricultural activities increased salinity of groundwater near the mines (Bonte and Zwolsman, 2010; Otero and Soler, 2002). Measures to reduce emissions from mining activities, in the Netherlands, were put into place which showed a reduction in chloride from 400 mg/L to 100 mg/L. Although these measures were put in place, another cause of salinity was identified to be climate change (Matthijs and Zwolsman, 2010). Changes in climate would cause more frequent low flow periods to occur. River salinization will increase as a result of low dilution of salts.

Salinity affects the Ethiopian highlands, the Rift Valley and the lowlands. As a result of the occurrence of droughts every 3-5 years in the highlands, several dams have been constructed to ensure food security (Kebede, 2008). In the Rift Valley, as a result of a decrease in flows because of water storage, several areas have been affected by at least 30% salinity and the subsequent abandonment of a banana farm (Asfaw and Danno, 2010). The cause of increases of salinity is the increase in irrigation to increase crop productivity (Kebede, 2008; Asfaw and Danno, 2010). Salinity reduces crop growth in its early stages, and at the advanced stages of growth results in the death of crops (Kebede, 2008). Bekele et al (2012) found irrigation water may contain high levels of mineral salts and that elements such as chloride, sodium and boron accumulate in the soil.

Land use changes in Argentina that do not account for the lag effects of the salinization processes and the risk of increased groundwater recharge have contributed to an increase in salinization (Amdan *et al.,* 2013). The changes in land use increase the amount of precipitation infiltrating to the water table and salt leaching (Jayawickreme *et al.,* 2011). As a result of an increase in the amount of precipitation infiltrating to the water table, water tables rise and displace salts from the groundwater zone to the surface of soil.

2.4 *Effects of salinity on ecosystems*

Salinity affects aquatic ecosystem functions and the services provided by the ecosystems. An increase in salinity affects the physical and chemical environment by increasing the ability of light to penetrate water as well as changes in the mixing properties of water (Nielsen *et al.*, 2003). The increases in light penetration are caused by salt induced aggregation and flocculation of suspended matter and its removal from the water column (Nielsen *et al.*, 2003). The increase in light penetration may cause an increase in photosynthesis and could result in algal blooms. An increase in salt in an aquatic ecosystem changes the "relative proportions of cations and anions in water that can change chemical equilibria and solubility of some minerals" (Nielsen *et al.*, 2003). As a result, the cycling of nutrients and energy is reduced. The reduction in energy and nutrient cycling affects growth of animals and plants. If there is a reduction in egg hatchings and seed germination there will be reduction in biomass and biodiversity (Hart *et al.,* 1990). A study by Sanzo and Hecnar (2006) showed that larval wood frogs (*Rana sylvatica)* had growth defects as well as a decreased survivorship. The effect of salinity on reduced biomass and biodiversity has implications on ecosystem function.

The main type of salinity affecting the terrestrial ecosystems is soil salinity. Soil salinity can be caused by anthropogenic factors such as clearing of land and over abstraction of water, and overgrazing and uprooting of plants by animals during periods of drought. Salinization of soil in terrestrial landscapes decreases the amount of vegetation and micro-organsims by decreasing the available water in the soil (Ghollarata and Raiesi, 2007; D'odorico *et al.*, 2010). A loss of available water in terrestrial landscapes reduces the amount of vegetation. The loss of vegetation affects the hydrological cycle because vegetation modulates the water cycle by sustaining evapotranspiration and precipitation. The loss of vegetation changes the hydrological cycle as a result of smaller evaporative losses and lower precipitation (D'odorico *et al.*, 2010). A loss in vegetation destabilizes soil and results in a loss of nutrients. A loss in plant biomass within an ecosystem could result in an increase in erosion as a result of the lack of plant roots stabilizing the soil. Nutrient loss as a result of increased erosion not only affects food production but also habitat and breeding ground loss.

2.5 *Salinization in South Africa*

There is an increase in the need to understand the risk and extent to which freshwater is salinized in South Africa, because the country has scarce water resources as a result of low rainfall with a mean annual precipitation of 480 mm/yr (van Rensburg *et al.,* 2011). Increases in salinity poses a threat to water supply and will result in the need to implement water restrictions to reduce water usage by agriculture, industry and human consumption. An example of a water resource in South Africa that is under threat of salinity as a result of irrigation is the Cape Flats aquifer in the Philippi farming area, Cape Town (Aza-Gnandji *et al.*, 2013). Aza-Gnandji et al. (2013) used major and minor ions to determine the nature, source and extent of irrigation water. Their findings indicated that groundwater and pond water are mostly brackish with electrical conductivities exceeding South African Water Quality Guidelines on irrigation (DWAF, 1996b) The only fresh water is found in the central parts of the Philippi area. The accumulation of salts was found to be a result of farming practices, evaporation in ponds which traps salt in the root zone and movement of groundwater through the geological formation in the Cape Flats region.

In the Vaal region, le Roux et al (2007) investigated the redistribution and accumulation of salts in sandy soils. Soil samples were analysed for properties that change under irrigation with particular focus on electrical conductivity of the saturated soil samples. Le Roux et al. (2007) concluded that salinity was caused by limited leaching of salts as a result of irrigation practices, soil texture and drainage.

The accumulation of salts in soils of arid and semi-arid areas can be caused by poor irrigation practices. Poor irrigation practices, such as over irrigation of crops or the use of saline groundwater, degrade soil and water quality (van Rensburg *et al.,* 2008). Van Rensburg et al (2008) indicated that irrigation water was the primary contributor of salt in the Vaal region. Using models, 6 soils were irrigated for 17 to 53 years. These soils gained 0.6 to 9.8 tons of salt per hectare, and had a significant loss of osmotic potential which would affect wheat and maize growth. To maintain good soil quality, sufficient leaching and drainage of salts is necessary. The processes of leaching and drainage, though important to maintain soil quality, are the same processes that contribute to the salinization of rivers and groundwater (de Clercq, 2009). The use of saline water for irrigation also affects drinking water quality and fisheries can be affected by high saline water.

Domestic practices contribute to the salt loading by wastewater effluent. An increase in salts from domestic wastewater can affect the reuse of wastewater by municipalities and industry. This is because wastewater treatment processes are not always equipped to remove certain types of salts, such as sodium chloride and potassium sulphate which pass through the treatment works (Morrison *et al.,* 2001). The Keiskammahoek sewage treatment plant in the Eastern Cape Province, is an example of a treatment works that cannot adequately treat wastewater. Because these salts move through the treatment works unaffected, the receiving water can be become brackish and cannot be used for water supply downstream. The consumption of saline or brackish water leads to diseases and influence life expectancy (Igbinosa and Okoh, 2009). Fatoki et al (2003) reported that electrical conductivity as well as other physicochemical properties of the Keiskamma River were above South African Water Quality Guidelines for domestic uses (DWAF, 1996a). Lake Rietvlei which is used as a drinking water source for Pretoria in the Rietvlei Nature Reserve is affected by salinization from irrigation return flows and industry (Oberholster *et al.,* 2008). The high rate of evapotranspiration worsens the problem of salinity in Lake Rietvlei. The consumption of saline or brackish water can lead to intestinal and renal diseases and influence life expectancy (Igbinosa and Okoh, 2009).

In arid and semi-arid regions salinity in groundwater, stream water and soils is controlled by the soil chemistry and weathering rates of bedrock. Salts produced by weathering are to a larger extent not directly transported to the sea. The salts that are not transported to the sea can develop into salt pans as is the case in Darling in the Western Cape (Smith and Compton, 2003). Pans are important for water supply and therefore salinity adversely affects the quality of the available water resources (Smith and Compton, 2003). In the case of salt pans as soil gets more saline, vegetation cannot thrive which causes the water table to rise higher than normal during the winter months. This brings salts from weathered bedrock to the surface when the water table rises, which is similar to dryland salinity. Soluble salts in soils such as clayey alluvial and colluvial soils are leached when the soils are flooded during the rainy season (de Villiers *et al.,* 2003). In some arid areas of South Africa with irrigation schemes, there is an increase of sodium ions in the soil due to irrigation. In areas such as these where canals are constructed on porous geological material, and water seeping through the rock causes salts to accumulate in the soils and water (Van der Merwe, 1967).

Salts that are deposited by atmospheric processes originate from the ocean. According to de Clercq (2009), this is a dominant source of salts upstream of non-irrigated areas in the Berg River Catchment. Salts deposited by atmospheric processes are continually added to the catchment and stored in regolith. In the Sandspruit Catchment, a tributary of the Berg River, atmospheric deposition of salts accounted for a third of the total salt output into the catchment (Flugel, 1991). The remaining two thirds was reported to be from weathered shale and soils that leached out during groundwater flow.

Changes in land use and vegetation affect the ability of soil and vegetation to store and release water back into the atmosphere, respectively. The change in land use, especially the shift from indigenous vegetation to agricultural crops, can increase water infiltrating to the water table as well as increase runoff (de Clercq *et al.,* 2010). An increase in water infiltrating to groundwater causes a rise in the water table. This rise in the water table deposits salts at the surface. During storm events these salts are leached from the soil and may enter rivers. Leaching affects crop growth and aquatic life. Land use changes also increase water demand especially in coastal areas where groundwater is used for domestic supply. The exploitation of water from coastal aquifers, which are in contact with saline water, speeds up the process of salt water intrusion (Sarukkalige *et al.,* 2006).

The salinization of soil and water in the Sandspruit Catchment has been reported as far back as 1991. Flugel (1991) reported that dryland salinity was the main cause of river salinization. Flugel's results showed that variations in salt concentration occur from summer to winter. As a result of the presence of an alluvium layer (Bugan *et al.,* 2012) the first rains fill up the shallow soils on the slopes. As the rainy season progresses soil moisture increases. This results in surface runoff resulting from interflow which increases salinity in the river. Salts from weathered shale are transported by groundwater to the valley bottom where baseflow results in salt entering the river. River flows cease during November

(Bugan *et al.*, 2012) and no flows occur during the summer months. This results in salt being transported to upper soil layers and the surface by capillary action in the valley bottom. Flugel (1991) concluded that soil in the valley bottom is more concentrated in salt as a result of two processes. These processes are capillary rise of salts and the downward movement of salts because infiltration which results in a solonet type soil. Along hill slopes soils are leached during winter which results in a less saline soil.

Jovanovic et al (2013) investigated the characterization and quantity of the salts stored in the regolith of a small catchment which is representative of the saline environment of the Berg River Basin. Measurements were taken over a three-year period, from 2005-2007. Jovanovic et al (2013) found vast salt storage within the Goedetrou catchment. Borehole logs revealed the presence of a salt bulge in the unsaturated vadose zone. It is within this zone that soluble salt concentrations peak, at a depth of 5-10 m. Electromagnetic induction and resistivity tomography identified flow pathways for salt transport. It has been noted that salinity in the Goedetrou catchment is controlled by landscape features and the anti-erosion contours acting as barriers to water and salt fluxes. Areas within the Goedetrou catchment lacked a B-horizon, which had been replaced by saline scalds, and had very thin A-horizons that formed on shale. Resistivity tomography revealed areas with shallow soils to have low resistivity, which corresponds to the saline soils with low clay content. Electromagnetic induction indicated lower soil salinity at the end of the rainy season compared to the dry season. This is because of dilution of salts during high flow events. The marked increases in salinity as noted by Jovanovic et al (2013) could be a result of evaporation in the Berg River basin during the dry season, from both the river and storage dams. Increases in water demand and salt seepage into the lower reaches during periods of low flow increase salt concentration during the dry season.

2.6 Solute transport

Geochemical facies that comprise salts have to be mobile in order for salts to be transported as solutes. Salts in the subsurface enter rivers through processes of leaching and move as solutes. Salts found at the soil surface enter rivers through washoff, in rills or gullies (McLaughlin *et al.,* 1998; Bugan, 2008). Salts at the surface may move as solutes or when adsorbed to sediments as part of the particle during processes of erosion (Baldwin *et al.,* 2002). Solute transport occurs during periods of runoff and their response during storm events are linked to antecedent moisture conditions in the catchment and event size (Kollongei and Lorentz, 2014). If an event is large enough to induce runoff, salts will move as solutes to the discharge point. Abbasi et al (2003) found that chemicals applied with irrigation water leached rapidly, as well as solutes applied before irrigation events followed preferential pathways. Mulholland et al (1990) and Boufadel (2000) also indicate that solutes follow preferential flow paths and move with the water during periods of runoff. Other evidence that solutes move with the water and follow preferential pathways is derived from tracer studies. The fact that solutes follow preferential pathways indicates that the same mechanisms that induce runoff induce solute transport. The exchange of water and solutes between the subsurface and surface occurs in the hyporheic zone which is situated between a surface water body and aquifer. This is a zone of increased geochemical activity, and bi-directional movement of oxygen and solutes (Triska *et al.*, 1993, Sophocleous, 2002 and Parsons 2004).

2.7 Runoff processes

Runoff is generated when there is an input of water into a catchment, such as rain or snow. Catchments may respond to the input of water by a single mechanism or by several mechanisms (Hoeg and Uhlenbrook, 2000; Ladouche *et al.*, 2001; Laudon and Slaymaker, 1997; Partington *et al.*, 2009)**.** This is dependent on the magnitude of the storm event, the antecedent soil moisture conditions and the heterogeneity of the soil hydraulic properties (Hoeg *et al.*, 2000). Water in storage is displaced by new water and moves to a lower gradient under the influence of gravity generally towards a river, but not all water that contributes to runoff is displaced from storage. Several studies indicate that storm flow is composed of at least two sources of water, either new water from precipitation or old water that existed in the catchment such as groundwater or snowmelt (Sklash and Farvolden, 1979; Wenninger *et al.*, 2008). Different mechanisms occur at the surface and in the subsurface to induce runoff and subsequently solute transport (Buttle, 1994). These mechanisms are briefly discussed below.

2.7.1 Groundwater ridging

Groundwater ridging is a mechanism linked to a rise in the water table during storm events. As the water table rises the capillary fringe, the zone where water rises due to capillary action, becomes completely water filled and moves into a saturated zone near the stream surface (Buttle, 1994). This transition results in a change in direction of the hydraulic gradient toward the stream and groundwater discharge is increased in the direction of the stream (Cloke *et al.*, 2006). The rapid response of a stream to a precipitation event is assumed to be due to groundwater ridging (Sklash and Farvolden, 1979; Peters *et al.*, 1995; Uhlenbrook and Leibundgut, 1999). The groundwater ridging theory as stated by Sklash and Farvolden (1979) is: "Along the perimeter of transient and perennial discharge are the water table and its associated capillary fringe lie very close to the surface. Soon after a rain or snowmelt event begins, infiltrating water readily converts the near-surface tension-saturated capillary fringe into a pressure-saturated zone or groundwater zone." The groundwater ridge provides the early onset of groundwater displacement, the rapid increase in storm flow at the start of an event, as well as the increase in size of the groundwater discharge area (Wilson, 1981). An increase in groundwater discharge rates results in larger groundwater contributions to streamflow. Groundwater flow during ridging may be directly through the stream bed or as overland flow (Wilson, 1981). During groundwater ridging, dissolved salts from bedrock can be brought to the surface and deposited into soils, or move directly to the stream when groundwater is discharged directly into the stream or as overland flow. Salts deposited in the soil increase soil salinity, and salts that move directly into the stream during groundwater discharge or overland flow increase stream salinity.

2.7.2 Overland flow

The Hortonian overland flow is a process of runoff generation whereby runoff is caused by rainfall intensity exceeding the infiltration capacity (Kollet and Maxwell, 2006). Under these runoff conditions water flows on the surface before the subsurface is saturated. This process varies spatially and temporally and is largely dependent on scale and spatial redistribution of water fluxes (Darboux *et al.*, 2001). Another process whereby water flows on the surface during a storm event is termed saturation excess overland flow. Saturation excess overland flow occurs when soil has reached its maximum storage capacity and the water table rises to the surface (Kollet and Maxwell, 2006). During processes of saturation excess overland flow, water enters the soil either vertically by infiltration or by lateral subsurface flow (Gaevert *et al.,* 2014). Gaevert et al (2014) indicate that runoff during saturation excess overland flow conditions is generated around the stream bed and expands upslope, and is based on the variable source area concept. During processes of overland flow salts at the soil surface are mobilized and transported to the stream as solutes increasing stream salinity. Salt contained in the soil may also move closer the surface increasing soil salinity.

2.7.3 Pipe flow

Rapid movement of pre-event water in shallow soils move through interconnected macropores which form pipes (Uchida *et al.*, 2002). During periods of runoff, water moves laterally in the surface before entering the stream. For pipe flow to occur water supply to the pipe has to exceed flow of water out of the pipe and the pipe walls (Buttle, 1994; Weiler and Naef, 2002). Other factors that influence pipe flow are antecedent moisture, rainfall intensity, hydraulic conductivity of the soil and the contributing soil surface area (Weiler and Naef, 2002). The presence of pipes in soils influences infiltration, runoff and solute transport (Weiler and Naef, 2002).

2.8 Flow components contributing to storm flow

Flow mechanisms occur at different points either on or within a soil and are depth-dependent. Runoff generation at various depths of the soil profile are dependent on antecedent soil moisture being above the threshold, hydraulic conductivity, rainfall intensity and amount, and vary spatially and temporally (Penna *et al.,* 2011). According to Penna et al (2011) runoff generation is controlled by soil moisture reaching threshold conditions, which varies depending on soil type, texture and depth. For threshold conditions to be reached an adequate amount of precipitation is required over a period of time and space. Soil moisture is dependent on time between rainfall, if rainfall has not occurred for several weeks or month’s soil moisture may be below threshold conditions and minimal runoff may occur. Sidle et al (1995) reported that catchments that produce little to no runoff during the dry season contribute

significantly to total runoff once soil moisture threshold conditions were reached during the wet season. Other factors influencing soil moisture over space and time are soil texture which determines water-holding capacity, slope of the land surface which influences infiltration and runoff, as well as vegetation and landcover which affects evapotranspiration and deep percolation (Mohanty and Skaggs, 2001).
Four components have been identified that contribute to storm flow (Parsons, 2004). These components are direct channel precipitation, surface runoff, and baseflow which consist of soil water and groundwater. Channel precipitation can be considered insignificant as channel width is not wide enough to catch large amounts of water. Therefore, it may be too complicated or unnecessary to quantify the direct channel precipitation component. In tracer studies, tracer composition of precipitation is assumed to be the same or similar to surface runoff (Uhlenbrook and Hoeg, 2003). Using the same tracer values for channel precipitation and surface runoff, the channel precipitation can be indirectly calculated as surface runoff.

Several studies have documented the groundwater component being the dominant contributor to storm flow (Midgley and Scott, 1994; Buttle, 1994; Laudon and Slaymaker, 1997). Many of these studies (Wenninger *et al.*, 2004; Covino and McGlynn, 2007; Uhlenbrook *et al.*, 2008; Wenninger *et al.*, 2008) have been conducted in temperate regions (Laudon and Slaymaker, 1997). In arid environments, such as the Sandspruit catchment, runoff processes may vary due to low soil moisture content after long periods without rain and catchment geology. In the Sandspruit catchment due to the 'argillaceous nature' of soil material, groundwater water may not be the dominant contributor to storm flow (Bugan *et al.*, 2012).

2.9 Hydrograph separation

Hydrograph separation is a technique used to separate the components of storm flow. The separation of the hydrograph using tracers is a common technique used to determine the contributions of pre-event and event water to total flow (Richey *et al.*, 1998; Huth *et al.*, 2004; Uhlenbrook and Hoeg, 2003; Mul *et al.*, 2008). Pre-event water is water such as groundwater, soil water and water stored in reservoirs before the onset of rainfall. Event water or new water is water added to a catchment from precipitation and includes surface runoff and direct channel precipitation. Tracers are used as markers to distinguish different sources of water. Changes in the contributions of surface and subsurface flows to river flows for storm events can be determined using tracers. Hydrograph separation studies use tracers to differentiate between different water sources, surface runoff, interflow and groundwater flow (Brown *et al.*, 1999; Weiler *et al.*, 1999; Uhlenbrook and Hoeg, 2003). Understanding runoff generation processes that contribute to flow in semi-arid and arid environments, is important to properly manage the available water resources, in terms of quality and quantity (Bohté *et al.*, 2010). Hydrograph separation could also reveal how flow components affect each other especially when coupled with geochemistry.

2.9.1 *Two component hydrograph separation*

The two component hydrograph separation technique uses a mass balance approach to determine the contribution of pre-event and event water. Tracers from end-members with distinct differences in their chemical concentrations or isotopic signatures can be used to separate the storm hydrograph using a mass balance approach (Hoeg and Uhlenbrook, 2000; Uhlenbrook and Hoeg, 2003):

$$Q_t = Q_p + Q_e \tag{2.1}$$

$$Q_t C_t = Q_p C_p + Q_e C_e \tag{2.2}$$

$$Q_p = \mathrm{Q_t} \frac{Q_t C_t - Q_e C_e}{Q_p C_p - Q_e C_e} \tag{2.3}$$

$$Q_e = \mathrm{Q_t} - \mathrm{Q_p} \tag{2.4}$$

$$Q_{p\%} = \frac{Q_t}{Q_p} \times \frac{100}{1} \tag{2.5}$$

$$Q_{e\%} = Q_{t\%} - Q_{p\%} \tag{2.6}$$

where Q_t is total streamflow, Q_p is the pre-event (old water) contribution to total flow, Q_e is the event water (new water) contribution to total flow, $C_{t,}$ C_p, C_e are the tracer concentrations of each end member (Klaus and McDonnell, 2013; Uhlenbrook and Hoeg, 2003; Huth *et al.*, 2004). The Subscripts for Equations 2.5 and 2.6 $Q_{t\%}$, $Q_{p\%}$ and $Q_{e\%}$ are the percentage of total flow, pre-event water and event water. Event water end-member chemical concentrations before the rise of the hydrograph are negligible. Therefore, it is important to assign a pre-event concentration for the end-members (Hoeg and Uhlenbrook, 2000).

2.10 *Tracers*

Tracers are natural or human induced substances that flow with the water and are used for understanding processes within the hydrological system from the tracer signal (Flury and Wai, 2003). Tracers provide insight into the movement of water and nutrient leaching in a catchment (Amin and Campana, 1996;

Heijden *et al.*, 2013). Natural tracers are those that occur in the environment, and are therefore non-invasive as a result of rock water interactions or the chemical property of the water molecules. Human induced tracers are added to the system either intentionally or unintentionally.

Tracers have been used in hydrograph separation studies. These include human induced tracers such as dyes and natural tracers such as water chemistry. Below is a list of basic tracer requirements:

- Tracers should be conservative in nature, which means that they do not react with material such as soil and rocks and should not suffer degradation during the period of observation;
- A tracer should move in a similar manner as water;
- A tracer should be easily distinguishable from the background of the system;
- A tracer should not be subject to change when pH, alkalinity, iconic strength of the solution change;
- A tracer should be detected either by visualization or through chemical analysis;
- A tracer should not be toxic and should not have an impact on the environment or the system which it flows through (Davis *et al.*, 1980; Flury and Wai, 2003).

Tracers are invaluable for characterising and understanding a hydrological system. The problem is finding a tracer that meets most/all the above requirements. An ideal tracer does not exist. The tracers that meets the above requirements are stable isotopes of the water molecule itself Deuterium (^{2}H) and Oxygen 18 (^{18}O). The properties of stable isotopes ^{2}H and ^{18}O are:

- Precipitation processes allow for the application of the tracer across the entire drainage basin (Buttle, 1994).
- They are not altered chemically during contact with mineral matter at the temperatures at the earths surface (Buttle, 1994).
- The stable isotopic composition of water is modified by meteoric processes. This results in recharged water having a different isotopic composition than meteoric water. This process is called isotopic fractionation. Isotopic fractionation is a geochemical tool that can be used to determine the origin of groundwater, the age and residence time and how water is influenced by the geohydrologic and meteorological factors. It can also be used to determine the source of contaminants from agricultural areas and other point sources (Flury and Wai, 2003).

- As water moves through the unsaturated zone to the water table, variations in isotopic composition are reduced, and uniformity in the isotopic composition is reached in groundwater over time and space. The isotopic composition of groundwater is only changed with the mixing of other water, such as snowmelt or rainfall. This temporal variability in the isotopic composition (δ) of precipitation and groundwater means that pre-event water and water input into the system at the basin surface results in a difference in the δ values (Buttle, 1994).

2.10.1 Isotopes of water (^{18}O and ^{2}H)

Isotopes are atoms with the same electrical charge, but have different atomic masses (Domenico and Schwartz, 1998). The mass differences are due to the presence of extra neutrons in some atoms. The presence of the extra neutron/s could result in unstable atoms that 'decompose' at rates proportional to the number of atoms remaining in an element (Faure and Mensing, 2005). Conversely, atoms with equal number of protons and neutrons are more stable (Mook, 2000).

Oxygen and Hydrogen isotopes are subject to fractionation (Faure and Mensing, 2005). There exist tiny differences in both chemical and physical behaviour of isotopes, termed 'isotope fractionation' (Mook, 2000). These differences in chemical and physical behaviour are a result of the isotope mass differences. The mass differences allow isotopes to be partitioned by fractionation processes, which can be either physical or chemical processes (Clark and Fritz, 1997). The greater mass differences of 18O results in lower mobility (Mook, 2000). As a consequence, 18O has a lower diffusion velocity and a reduced collision frequency with other molecules (Mook, 2000). Therefore, 18O has a low reaction rate relative to 16O. The heavier isotopic species also have higher binding energies than lighter isotopes. Therefore, more energy is required for bonds with heavier isotopes to be broken.

The properties described above make isotopes of water an ideal tracer. Fractionation processes result in different isotopic composition of waters. The determination of the isotopic composition of water sources of interest allows for the differentiation of various waters contributing to storm flows as well as their relative quantities.

2.10.2 Hydrochemical tracers

Hydrochemical tracers are natural tracers which include pH, electrical conductivity (EC), different concentrations of anions and cations can be used to determine flow paths (Hoeg *et al.,* 2000). Anion and cation concentrations are dependent on groundwater residence times, (Hoeg *et al.,* 2000). Longer residence times would result in high anion and cation concentrations and are indicative of groundwater contributions to storm flow. Conversely, low anion and cation concentrations indicate that interflow could be the dominant process contributing to storm flow due to short residence times. Anion and cation contributions to flow have to be characterised, this requires sampling prior to the onset of a storm event (Laudon and Slaymaker, 1997).

Rapid dissolution of the tracer is necessary for chemical hydrograph separation (Wels *et al.,* 1991). Rapid dissolution and equilibration of a tracer with the mineral matrix enables the determination of the dominant flow path. Wels et al (1991) and Laudon and Slaymaker (1997) report that silica dissolves rapidly and is more of a flow path tracer. Rapid dissolution of silica is supported by Wels et al (1991).

Rain water silica concentrations is zero and therefore low silica concentrations are indicative of short residence time, which could be event water contributing to flow.

Due to the uptake of silica by diatoms an alternative geochemical tracer/s should be coupled with silica. Magnesium is a suitable substitute for silica as it dissolves rapidly and concentrations are independent of residence times (Wels *et al.,* 1991; Fritz *et al.*, 1979).

2.11 Isotope sample and statistical analysis

2.11.1 Laser spectroscopy

Laser spectroscopy does not require water to be equilibrated and water samples can be analysed in its raw state. The laser spectroscopy system measures water vapor for isotopes ^{2}H and ^{18}O is model DLT-100 water vapour isotope analyser WVIA, LGR Inc. (Model 908-0008) (Kurita *et al.,* 2012).This analyser is based on an Off-Axis integrated cavity output spectroscopy (ICOS) system using a high-finesse optical cavity as an absorption cell (Liquid-Water Isotope Analyzer: Automated Injection, 2008) . This is due to the limitations of multi-pass arrangements which only allow path lengths of less than 200m to pass through the cell (Liquid-Water Isotope Analyzer: Automated Injection, 2008). The Off-Axis ICOS allows thousands of passes before leaving the absorption cell. This results in the effective optical path length, which may be several thousands of meters using high reflectivity mirrors and therefore the measured light absorption after it passes through the optical cavity is significantly enhanced (Liquid-Water Isotope Analyzer: Automated Injection, 2008).

2.11.2 Boxplots

Boxplots are used to display and summarise data and provide a variation of distribution and indicates the presence of unusual values among several data sets. boxplot has a centre line which indicates the median value, and whiskers which display the last observation within a step. A single step within the plot is 1.5 times the height of the box. If any outliers are present within one to two steps of the plots, they are marked with an asterisk. Outliers greater than three steps above the plot are marked by a circle.

2.12 Conclusion

This Chapter has summarized the effects salinity has on the environment, and established links between salinity and flow processes as well as the need to understand these flow processes. Due to the lack of knowledge of flow paths and the relative importance of these flow paths on salinity is also not understood. This chapter also highlights the movement of salts as solutes which indicates that solutes follow the same as the pathways as water. Since solutes follow the same pathways as water tracers can be used to determine the dominant flow paths as well as assist in determining the relative contributions of these pathways.

Chapter 3 : Methodology

3.1 Site selection

The Sandspruit Catchment with an area of 152 km^2 was selected as there are already both shallow and deep boreholes for groundwater monitoring. Shallow boreholes penetrate the perched aquifer and have been drilled to depths of 12 m with the exception to one borehole drilled to 15 m (Table 3.1.). Deep boreholes were drilled to depths varying from 18 to 151 m and penetrate the fractured aquifer. Access to the shallow and deep boreholes allowed for the quantifying of any differences in isotopes or chemicals of water within the perched aquifer and the deep aquifer.

Table 3.1: Location, depth and altitude of the monitoring boreholes. Borehole numbers with letter "A" indicate shallow boreholes adjacent to the deep boreholes with the same number.

Catchment zone	Borehole No.	Borehole Depth (m)	Altitude (m)	Latitude S (°)	Latitude E (°)
Upper Catchment	ZB002	18	278	33.34896	18.81472
	ZB003	120	272	33.34921	18.81642
	ZB003A	12	272	33.34921	18.81642
	ZB004	115	361	33.35187	18.82455
	ZB005	15	361	33.35187	18.82455
	ZB006	151	303	33.35279	18.81962
	ZB006A	12	303	33.35284	18.81973
	ZB007	85	303	33.34745	18.81996
Middle Catchment	OKR1	85	219	33.34023	18.80592
	OKR1A	12	219	33.34023	18.80592
	DM2	78	144	33.28504	18.77325
	DM2A	12	144	33.28504	18.77325
	OK001	103	107	33.25959	18.80986
	OK002	30	118	33.25757	18.80806
Lower Catchment	UV001	72	70	33.19636	18.86041
	UV002	30	62	33.19873	18.86535
	UV003	42	64	33.20017	18.86819
	UV004	48	81	33.20425	18.87108

3.2 Study Area

3.2.1 Location

The Sandspruit catchment is part of quaternary catchment G10J, and is approximately 80 km north of Cape Town (Figure 3.1). The major towns located near to the Sandspruit Catchment are Riebeeck West, Riebeeck Kasteel, Mooreesburg and Malmesbury (Figure, 3.1).

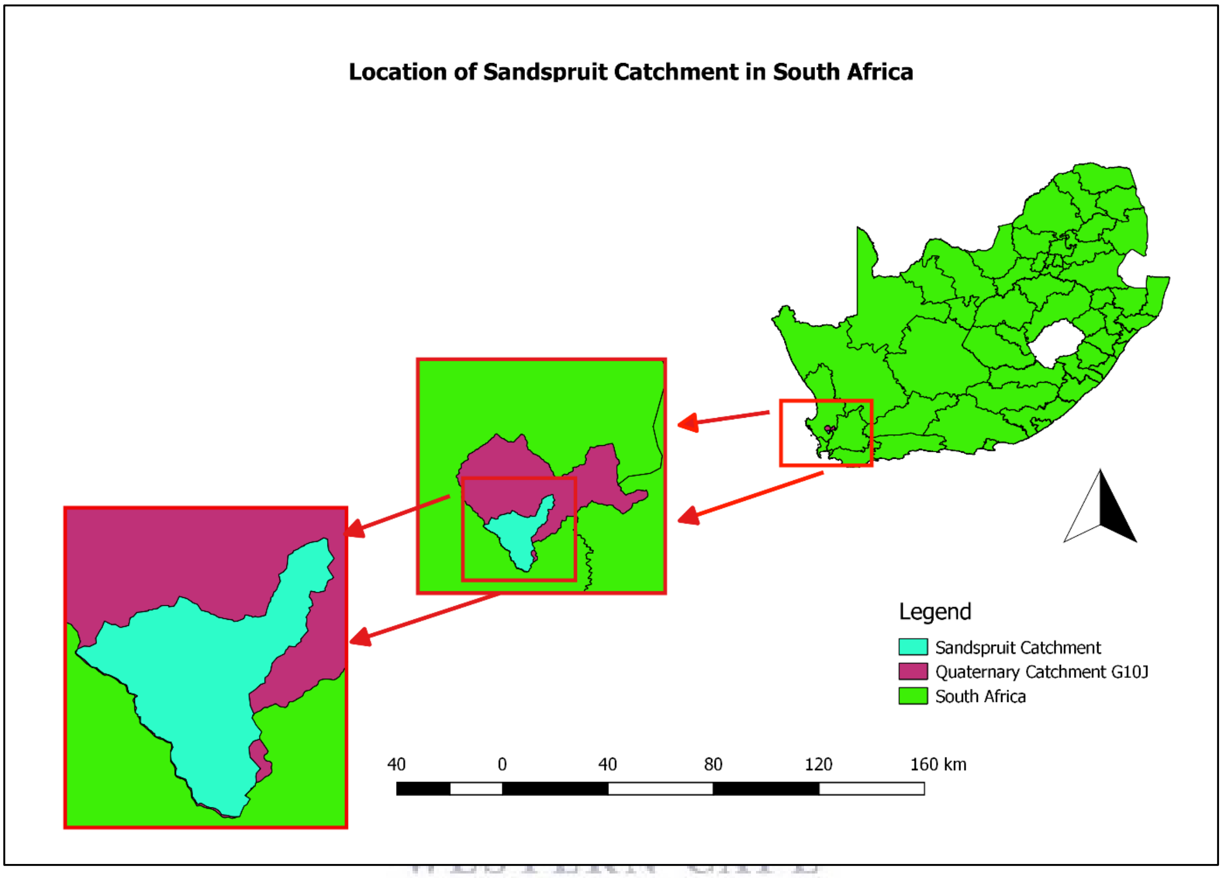


Figure 3.1: Location of the Sandspruit Catchment, Western Cape, South Africa

3.2.2 Topography and land use

The topography of the Sandspruit Catchment is generally flat with elevations between 320 m above mean sea level in the upper parts and 80 m above mean sea level in the lower parts of the catchment (Figure 3.2) (Bugan, 2009). The average slope is 0.013 (Jovanovic *et al.*, 2011). Agriculture is the dominant land use within the catchment, with wheat and livestock farmlands covering 90% of the catchment area (Figure3.3) (Naicker and Demlie, 2014).

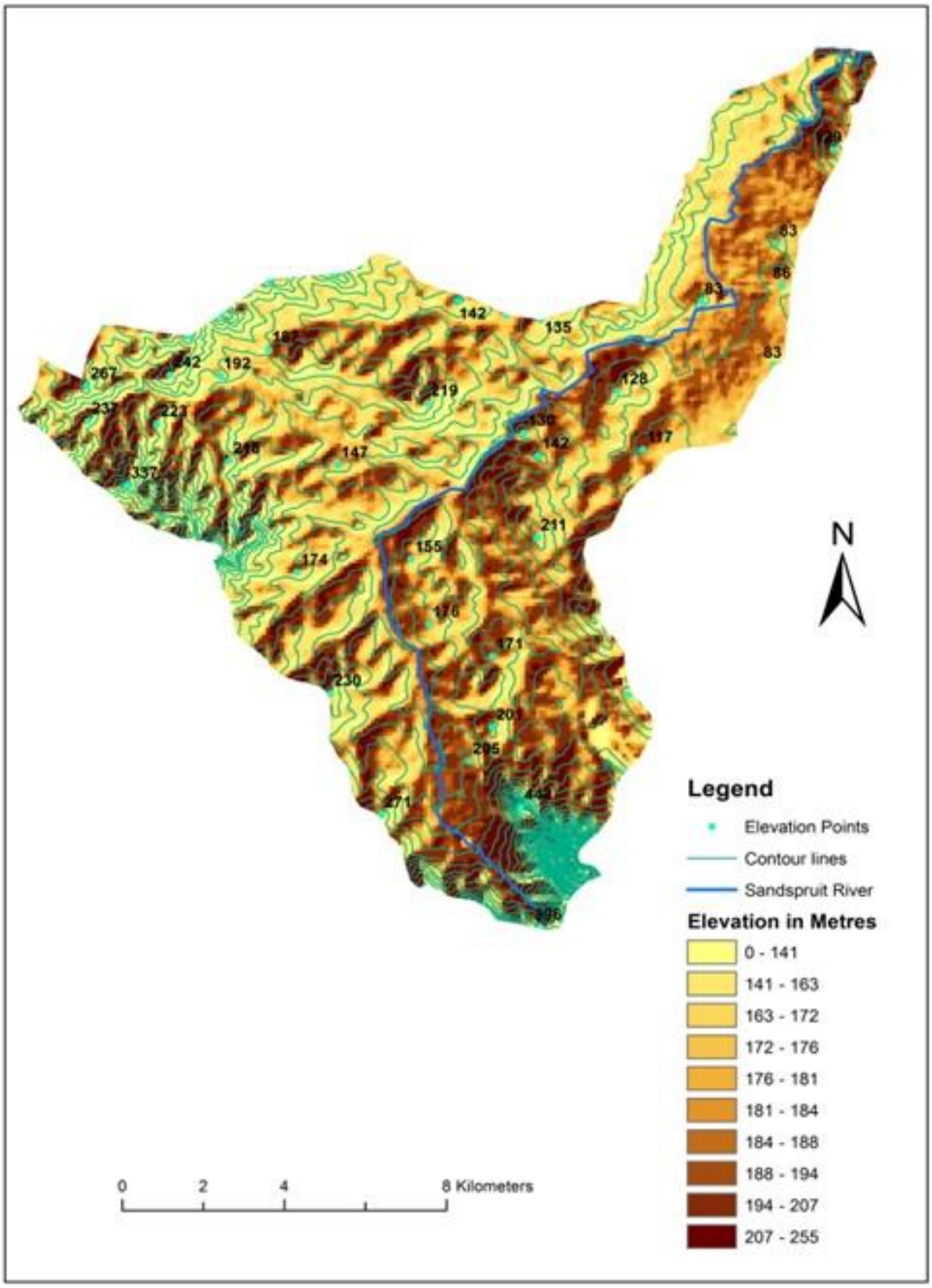


Figure 3.2: Variation of altitude in the Sandspruit Catchment

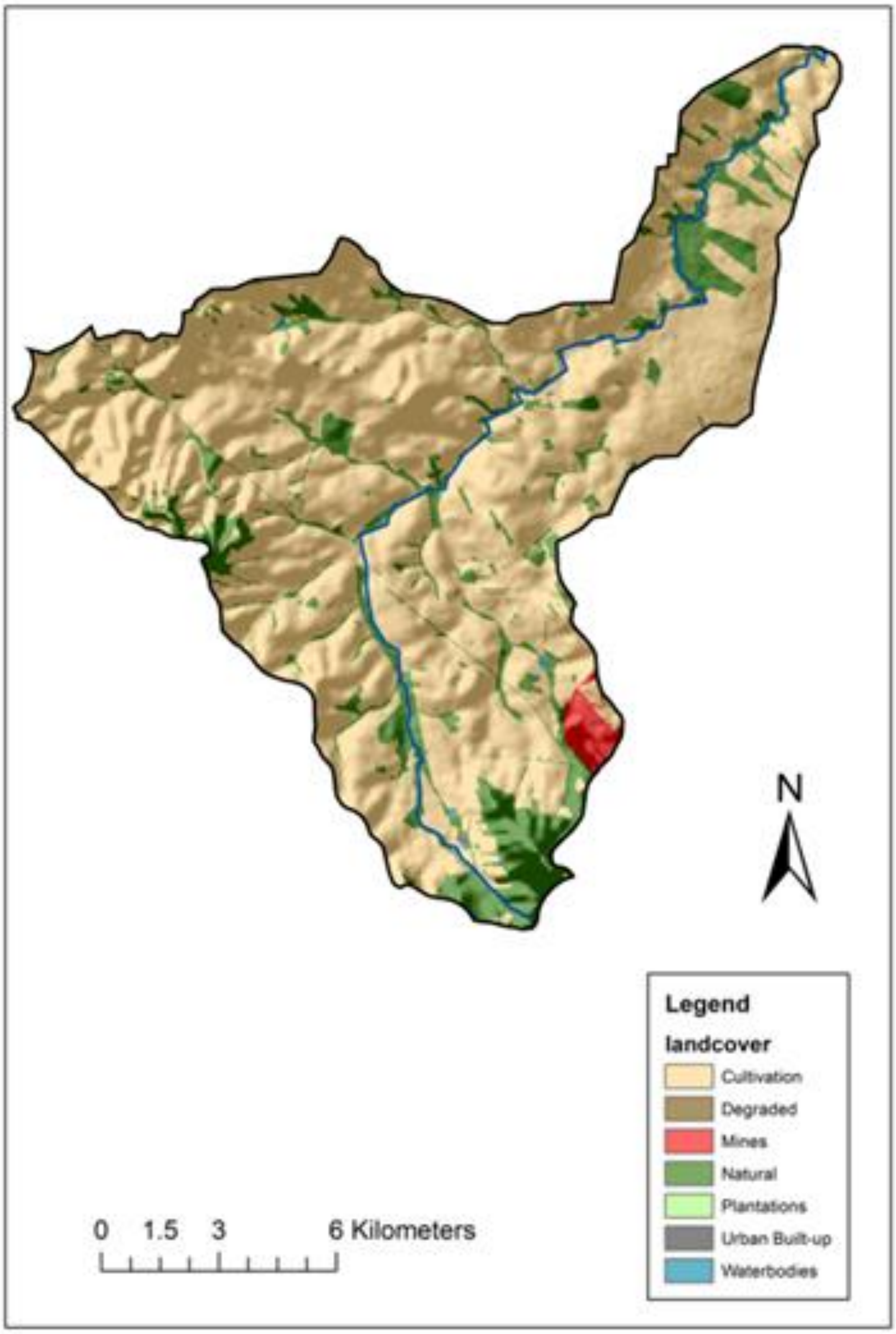


Figure 3.3: Land cover and land uses in the Sandspruit catchment.

3.2.3 Geology and soils

The geology of the Sandspruit Catchment is predominantly Precambrian Malmesbury Shales (Figure 3.4) with smaller sequences of fine sediment such as silcrete-ferricrete, greenstone, quartzite, marine sandstone and granite (Mashimbye *et al.*, 2014; Naicker and Demlie, 2014). Soils are considered poor, low in nutrients, and very thin on hard or weathered rock (Bugan *et al.*, 2009). Soil types are brownish sandy loams, which are prone to caking after heavy rains (Mashimbye *et al.*, 2014). Topsoil ranges from 0.5 to 1 m in thickness. Soil water holding capacity can be up to 80 mm in the upper and lower reaches of the catchment, and only 20-40 mm in the middle reaches of the catchment (Bugan *et al.*, 2012; Flügel, 1991). The Malmesbury shales cover 90% of the catchment area, the Cape Granite suite covers 1% of the catchment area, Table Mountain Group (TMG) covers 3.5% and cenozoic deposits of the Springfontyn formation covers 5.5%. The Sandspruit catchment is bound by the Colenso and Piketberg-Wellington fault systems (Naicker, 2012).

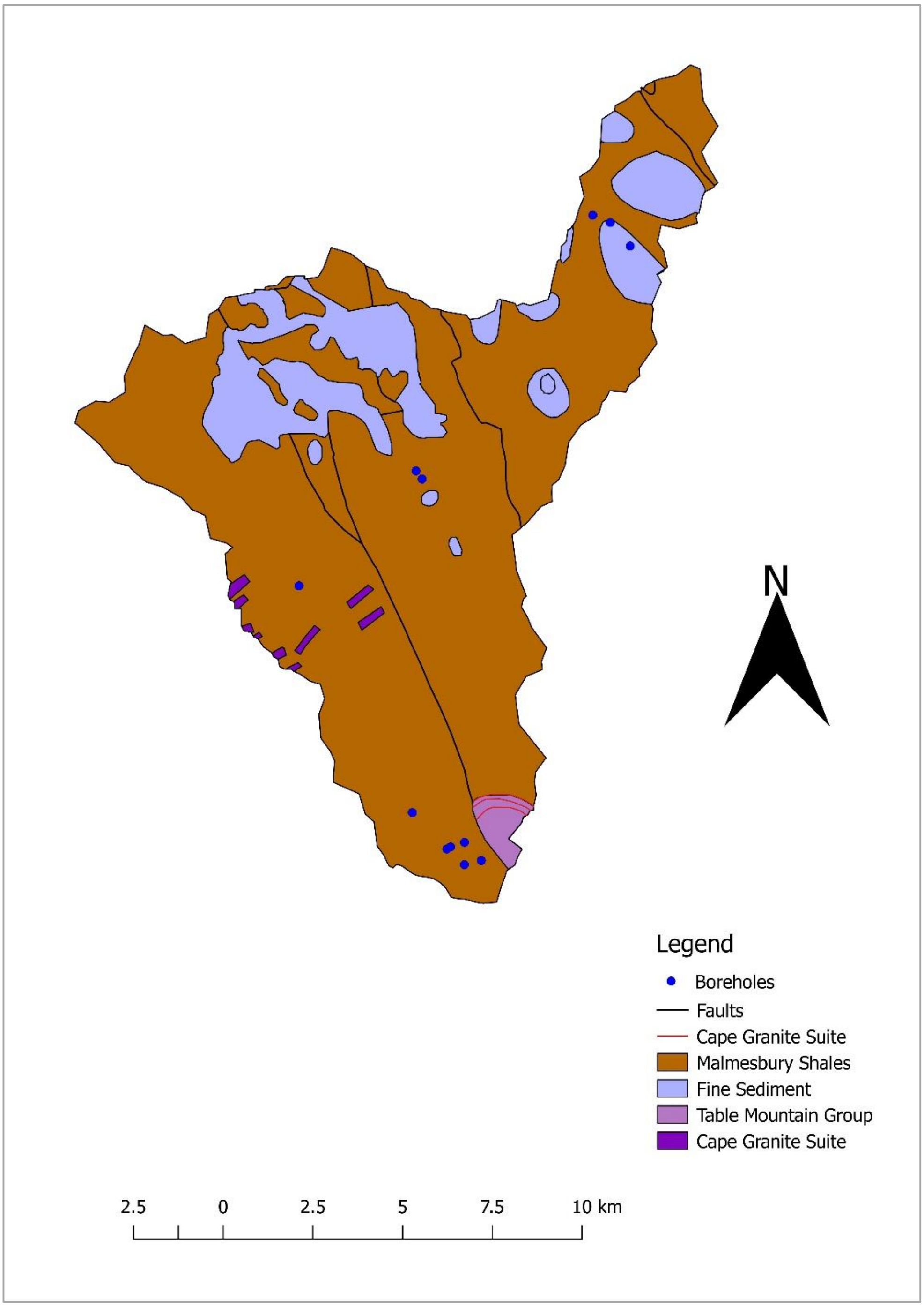


Figure 3.4: Geology of the Sandspruit Catchment

3.2.4 Climate and vegetation

The climate of the Sandspruit Catchment is mediterranean, with dry summers and wet winters (Mashimbye *et al.*, 2014). Mean annual maximum temperatures range from 24 to 31°C during the summer months, while mean annual minimum temperatures range from 8 to 11°C during the winter months (Figure 3.5) (Naicker and Demlie, 2014). Summer is from October to April, with winter starting during May and ending in September. Rainfall occurs during winter, with a mean annual rainfall depth of 460mm/yr (Bugan *et al.*, 2012). Rainfall direction is from the northwest along the West Coast and is in the form of frontal rain (Jovanovic *et al.*,2011). Most of the natural vegetation in the catchment area is a shrub known as *renosterveld* and is 'typified by the widespread occurrence of *Elytropappus rinnocerotis'* (Figure 3.6) (Meadows, 2003).

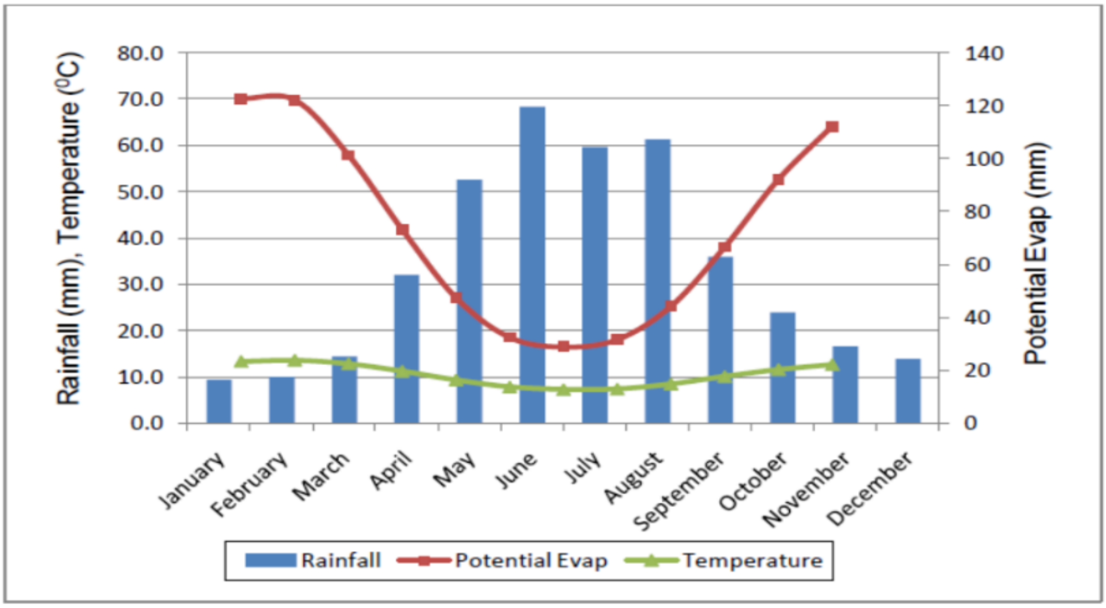


Figure 3.5: The graph indicates how climatic variables change with season. (Naicker, 2012)

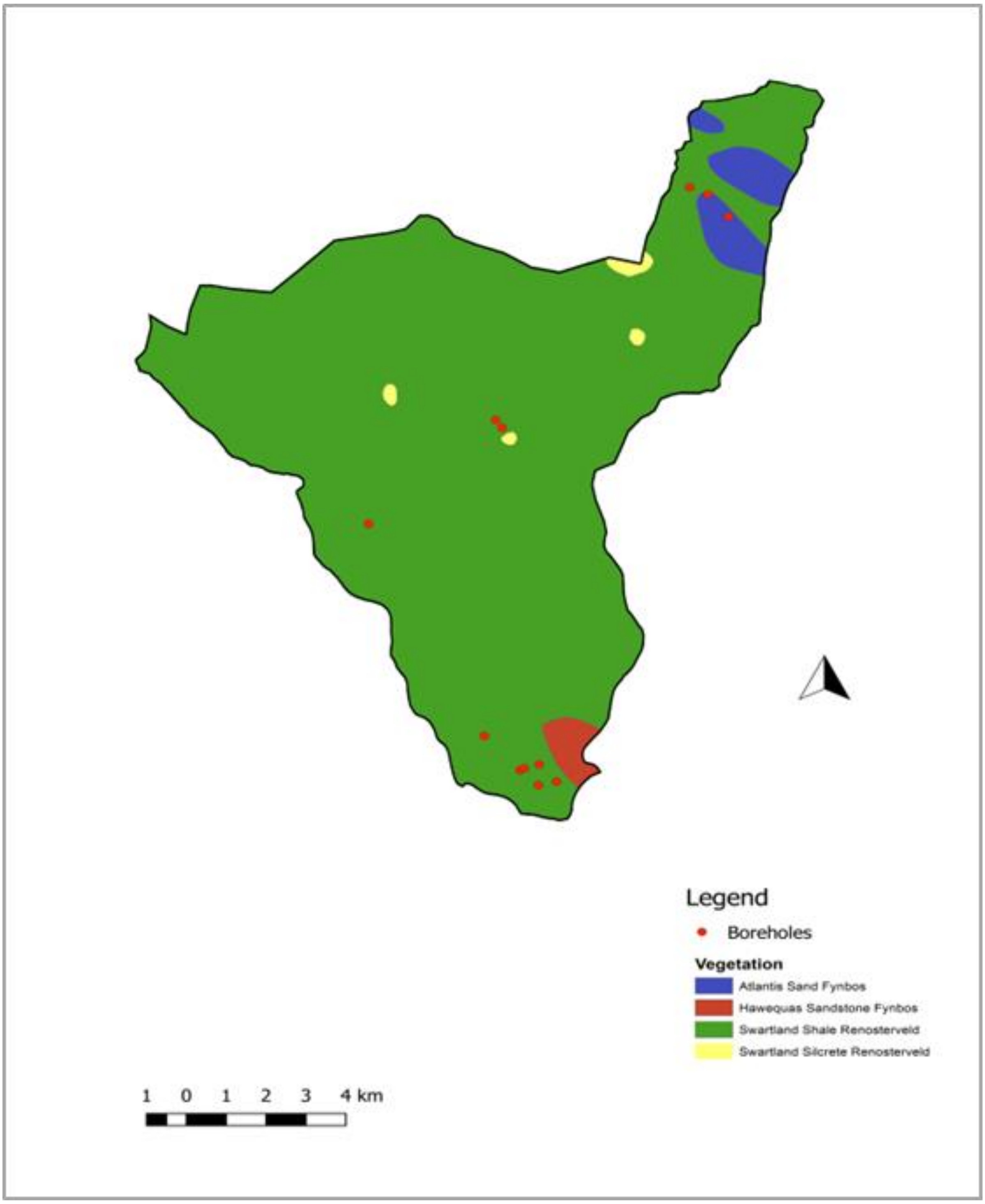


Figure 3.6: Vegetation type and distribution in the Sandspruit Catchment.

3.3 Data collection

To complete the objectives as outlined in chapter one, suitable data were required. These data included:

a) Historical daily and monthly rainfall collected for the period 2009 to 2014

b) Historical hourly and daily flows at the catchment outlet

c) Hourly rainfall for events

d) Hourly and daily flows at the catchment outlet for events
e) Groundwater levels
f) Tracer data for the events from groundwater and surface runoff

Historical daily and monthly rainfall data from 2009 to 2014 was used to characterize the Sandspruit Catchment. This indicated when typically, rainfall occurred and how long storm events would last. Historical hourly and daily flow data was used to determine the flow regimes of the Sandspruit i.e. when did flow occur and how long flow lasted. The rainfall and flow datasets were correlated to determine how long after rainfall did it take for the Sandspruit to respond.

Hourly rainfall and hourly flow data was used for the hydrograph separation as the hydrograph was separated at an hourly scale. Groundwater levels were used to determine if groundwater had a response to the rainfall, and to see which boreholes indicated hydrologic connectivity. Tracer data was used as part of the hydrograph separation, and was used to characterize surface and subsurface runoff components.

Rainfall data were collected in two ways. Rainfall amounts were measured using a tipping bucket rain gauge and rain water was collected in a collecting rain gauge for isotope analysis. Historical daily and monthly rainfall was used to determine when the most rainfall occurs during the year. Historical hourly and daily flows were used in order to determine when flow occurs and whether or not rainfall that occurs throughout the year induces flow. The locations of the monitoring sites are displayed in Figure (4.7)

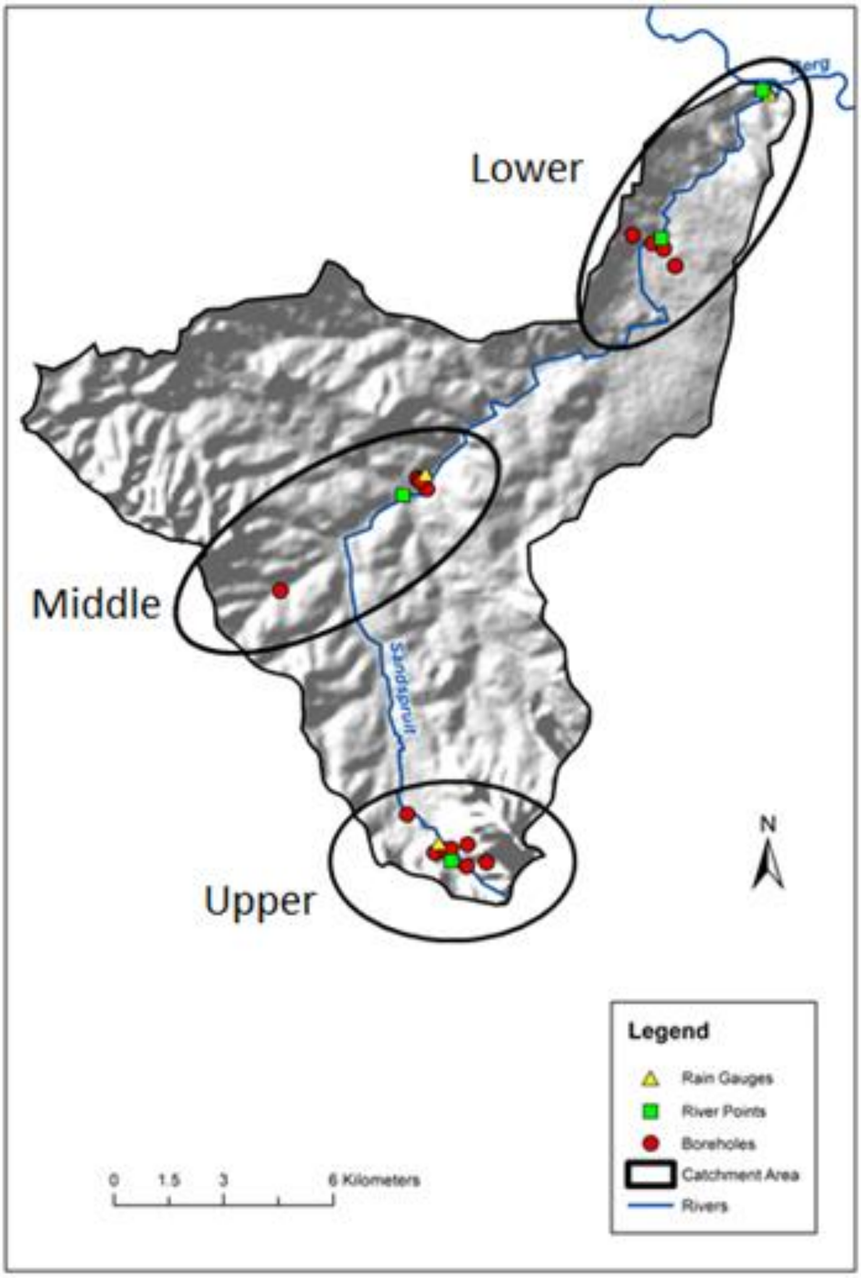


Figure 3.7: Locations of monitoring boreholes, river sampling sites and rain gauges used in the study area.

The Sandspruit (Figure 3.8), is an ephemeral tributary to the Berg River that flows from May to October (Flügel, 1991). Streamflows start at the onset of the rainfall events. Streamflow is measured at the catchment outlet using a crump weir. The Department of Water and Sanitation (DWS) station No. G1H043 has data from 1980 to the present (Jovanovic *et al.*, 2011). Due to salinization of stream water abstraction from the river is minimal (Flügel, 1991; Bugan *et al.*, 2012).

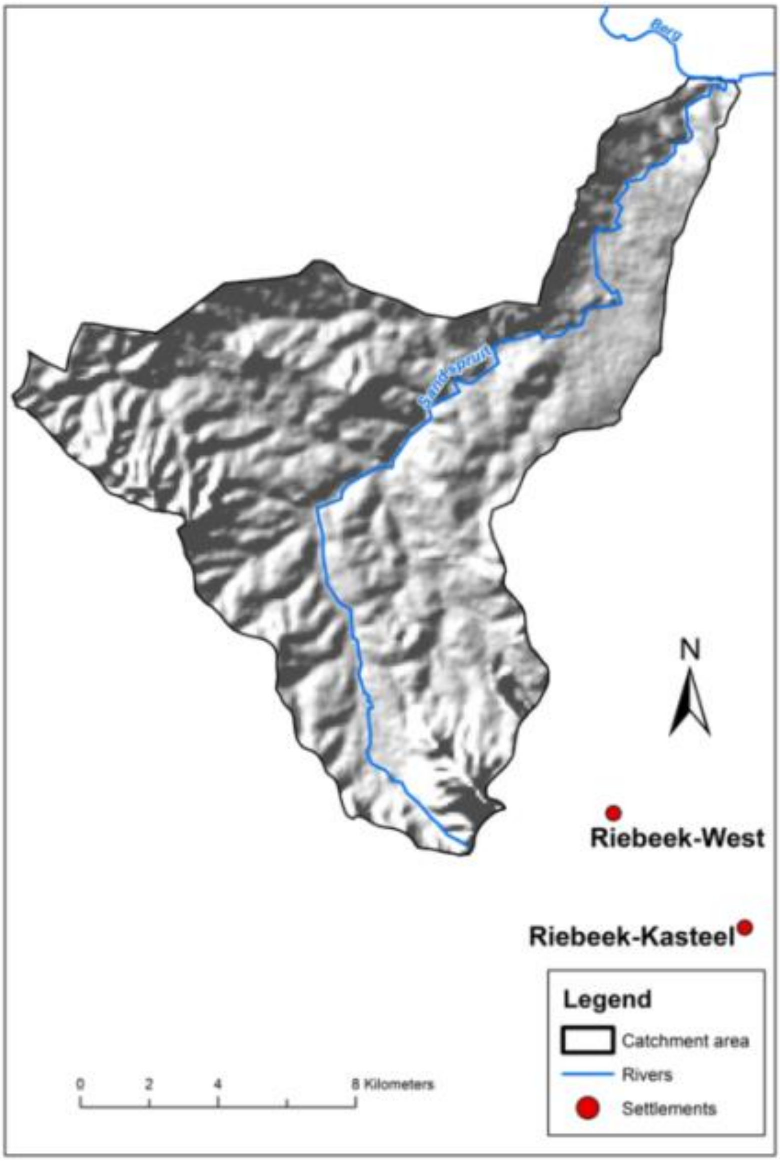


Figure 3.8: The Sandspruit and its flow direction. Flow is towards the Berg River.

The Malmesbury aquifer, the main aquifer system in the Sandspruit Catchment, is classified as a minor aquifer system. Minor aquifer systems are classified as those with low primary permeability (Parsons, 1995). According to Parsons (1995) aquifer classification, the groundwater quality of the minor aquifer system is variable and an important source for baseflow and local water supplies. Naicker and Demlie (2014) indicated that groundwater within the catchment is ‘brine type water’ and is unusable, with the exception to water associated with chert layers which are fresh water. The Table Mountain Group (TMG) aquifer in the Sandspruit Catchment comprises mainly of arenaceous anisotropic material. Average borehole yields are 2.8 L/s in the sandstone, though borehole yields of 4l/s have been observed at major discontinuities (Jovanovic *et al.,* 2011; Naicker and Demlie, 2014). Groundwater recharge occurs at the onset of major storm events, with annual recharge of 71mm/yr in the Sandspruit catchment (Bugan *et al.,* 2012). Groundwater quality is controlled by geology and rock-water interactions. Groundwater is generally a Na-Cl type with electrical conductivities ranging from 33 mS/m and 2060 mS/m (Jovanovic *et al.,* 2009; Bugan *et al.,* 2012; Naicker and Demlie, 2014). Jovanovic et al (2009) drilled 26 boreholes of which only 25 are monitored (Figure 3.7). Seven shallow boreholes were drilled that serve as piezometers. These were drilled as two water strikes were found at these locations. The 19 boreholes were drilled and penetrate the fractured aquifer. The catchment was separated into three zones based on elevation (Figure 3.7). Boreholes in the upper zone are located in areas with elevations exceeding 200 m, boreholes in the middle catchment are located in areas with elevations between 170 m to 199 m, and boreholes in the lower catchment are located in areas with elevations of less than 100 m. Land uses in each of these zones are primarily livestock and wheat farming. The topography in each zone is generally hilly with gradual slopes.

Prior to the onset of the storm events water levels of 13 deep boreholes with depths in excess of 18 m, and 5 shallow boreholes with depths of 15 m or less were measured. Deep boreholes were purged for 15 minutes, and shallow boreholes were purged for 15 minutes or until dry. If the shallow borehole dried up it was allowed to recover until 80% of the pre-purged volume. Water samples were collected for $\delta^{18}O$, SiO_2, Magnesium (Mg^{2+}), Calcium Carbonate ($CaCO_3$) analysis from the Sandspruit and boreholes, and put on ice until storage and analysis. Water samples were stored in airtight polyethylene bottles. During the storm event, grab samples were collected from the Sandspruit outlet. Boreholes were sampled for isotopes and water chemistry and water levels were monitored. Flow records were collected from the DWS website, for the period of study. Rainfall and temperature data were recorded using a tipping bucket rain gauge with an automated temperature logger respectively. Three rain gauges were setup. The rain gauges were located in the upper, middle and lower reaches of the catchment. This was so rain water could be sampled during and after storm events. Rain water used to characterise the surface runoff component. The Sandspruit flowed during storm events, and flow ceased about a week after each storm event.

3.4 Data analysis

3.4.1 Laboratory Analysis

Water samples that were collected for isotope analysis were analyzed at the University of the Western Cape hydrology laboratory using a DLT-100 Liquid Water Isotope analyzer (LWIA). Water samples were sorted by date of collection before analysis. Using disposable pipettes 1.5 ml of water was put into a 2 ml vial and sealed with cap equipped with a silicon septum. The silicon septum prevents evaporation during analysis. The vials were placed into the sample tray and the slot number containing the sample was marked on the laboratory sheet. The LWIA was setup to analyze each sample 6 times, the septum was changed and the syringe cleaned and placed back into position. After the setup was completed, the analysis was initiated and samples were analyzed for 15 hours. After the analysis the data was copied from the LWIA and a new tray was setup and the analyzer prepared again for the next sample.

The method used for isotope analysis was laser spectroscopy. Isotope concentrations are reported in units of δ and defined by:

$$\delta^{18}O = \frac{R_{Sample-}\, R_{Standard}}{R_{Standard}} 1000 \qquad (3.1)$$

where R_{sample} and $R_{standard}$ are the abundance ratios of the isotopic species $^{18}O/^{16}O$ of the sample and standard, respectively. ^{18}O is the isotopic species and δ is the relative deviation from the adopted standard. Water samples for Calcium, Silicon and Magnesium chemical analysis were analysed at Bemlab, following ISO/IEC 17025 Second Edition 2005-05-15. Method 3132 was used according to the Bemlab work instructions for the analysis of Calcium, Silicon and Magnesium.

3.4.2 Hydrograph separation

In order to establish the amount of runoff originating from surface and subsurface flow, the two component hydrograph separation method was used. This method has been found in previous studies to be suitable for this purpose (Hooper, 1986; Harris *et al.*, 1995; Liu *et al.*, 2008; Mul *et al.*, 2008). To determine when to monitor storm events, the potential of such storms occurring was obtained from weather forecasts produced by the South African Weather Services. Storm events which were predicted to have high rainfall depths were targeted. Three storm events met the criteria and were targeted during the rainy season of 2014. The tracers used for the separations were $\delta^{18}O$ and SiO2. The two component hydrograph was separated using the mass balance equations given in Equation (2.1) - (2.3). The flow volume on the receding limb that was selected for baseflow was the point where flow returned to pre-storm conditions. To determine whether the event and pre-event contributions vary and if the dominant process changes between storm events, correlation analysis will be used.

Baseflow separation was used to determine the percentage of pre-event water, soil water and groundwater, contributing to storm flow. Baseflow is the rate at which water is released naturally from storage (Brutsaert, 2012; Eckhardt, 2008; Hughes, 2002; Arnold *et al.*, 1994). These sources of storage are snowmelt, riparian aquifers, springs etc. (Brusaert, 2012). Knowledge of the contribution of pre-event water, especially groundwater, to storm flows is important for determining stream health, allocation of water, waste dissolution, ecosystem water requirements, impacts of contamination or determining peak stream salinities (Brodie and Hostetler, 2005). It is therefore important to understand this process and the techniques used to determine the contribution of pre-event water to storm flow.

Baseflow separation for the Sandspruit Catchment was done using a one parameter filter on historical data. The one parameter filter is as follows:

$$q_{b(i)} = \frac{k}{2-k} q_{b(i-1)} + \frac{1-k}{2-k} q_{(i)} \tag{3.1}$$

Where $q_{b(i)}$ is the filtered baseflow response for the i^{th} sampling instant, k is the filter parameter given by the recession constant, q_i is the original streamflow for the i^{th} sampling instant and $q_{b(i-1)}$ is the filtered baseflow response for the previous sampling instant to i (Brodie and Hostetler, 2005).

Baseflow index is a measure of the annual ratio of baseflow to total flow and is determined by the following equation:

$$BFI = \frac{q_b}{Q_t} \tag{3.2}$$

Where q_b is the annual baseflow and Q_t is the annual total flow. The mean annual BFI is an average of the BFI from 1980-2014.

3.5 The influence of catchment characteristics on surface and subsurface components.

To determine the influence of catchment characteristics on surface and subsurface components a connectivity between the catchment landscape and stream approach was used. This approach was used as it deals with the transfer of water, solutes and sediment from one part of the landscape to another (Lexartza-Artza and Wainwright, 2009). The raster DEM USGS SRTM DEM 1 arcsec for South Africa with a pixel resolution of 30m was used for analysis of catchment characteristics in Whitebox Geospatial Analysis Tool (GAT). The DEM was preprocessed by removing all topographic depressions and flat areas. After the DEM was hydrologically corrected the D8 flow pointer map was calculated using the D8 flow pointer tool. The D8 flow pointer is generated using the D8 algorithm as defined by O'Callaghan and Mark (1984). This generates a grid that is used to determine the flow accumulation map and the upslope area map. After the D8 flow pointer was generated, it was inserted into the D8 flow accumulation tool and log-transformed flow accumulation values were selected in order to better visually display smaller digital streams. After the flow accumulation map was generated the catchment outlet was selected on the map. This was done by placing a point shape at the catchment outlet. The catchment outlet was selected as the point where the flow gauging station is located. This was done to determine the upslope catchment area map. The upslope area map indicates which parts of the catchment direct water towards the catchment outlet. This method assumes that surface runoff follows slope and moves from high to low slope areas. When the point was selected the watershed tool was used to determine the upslope area.

3.6 Conclusion

The Sandspruit Catchment was sampled for three storm events. Three types of water samples were collected and these included groundwater samples, river samples and precipitation samples. Water samples were collected for $\delta^{18}O$ isotopes, SiO_2, Mg^{2+} and $CaCO_3$. The tracers selected for hydrograph separation were $\delta^{18}O$ and SiO_2. Rainfall amounts were measured using automated rain gauges and flow measurements were obtained from the Department of Water and Sanitation (DWS). A two component hydrograph separation was done to determine the components of flow. In order to determine the influence of catchment characteristics on surface and subsurface components a connectivity approach was used. This method required the use of GIS and field measurements to determine of there was a connection between the landscape and streamflow generation.

Chapter 4 : Results and Discussion

4.1 Introduction

This chapter presents historical data and discusses the results obtained during the study period. The historical data was used to determine and describe trends in rainfall and river flows. The historical rainfall data for the Sandspruit Catchment only exists from February 2009. Though relatively limited the historical data are still enough to determine the possible existence of trends as well as to establish if rainfall for the 2014 was above or below the average. The first set of information obtained during the study period displays boxplots for δ18O and silica and their variation from the upper to the lower zones of the catchment. The second set of information displays rainfall and flow data as well as the variation of tracer concentrations with flow. The third set of information displays the separated hydrographs. The storm events studied during 2014 are described as Event 1 and Event 2. Event 1 took place from the 16th to 19th of July, Event 2 took place from the 23rd to 26th of July.

4.2 Historical flow and rainfall data

Historical streamflow data for the Sandspruit Catchment exists from 1980. River flows from 1980 to 2014 shows that the dominant period of flow starts in May and peak in July (Figure 4.1). From August the flow decreases, and significant flow ends in September. Little to no flow occurs throughout the rest of the year.

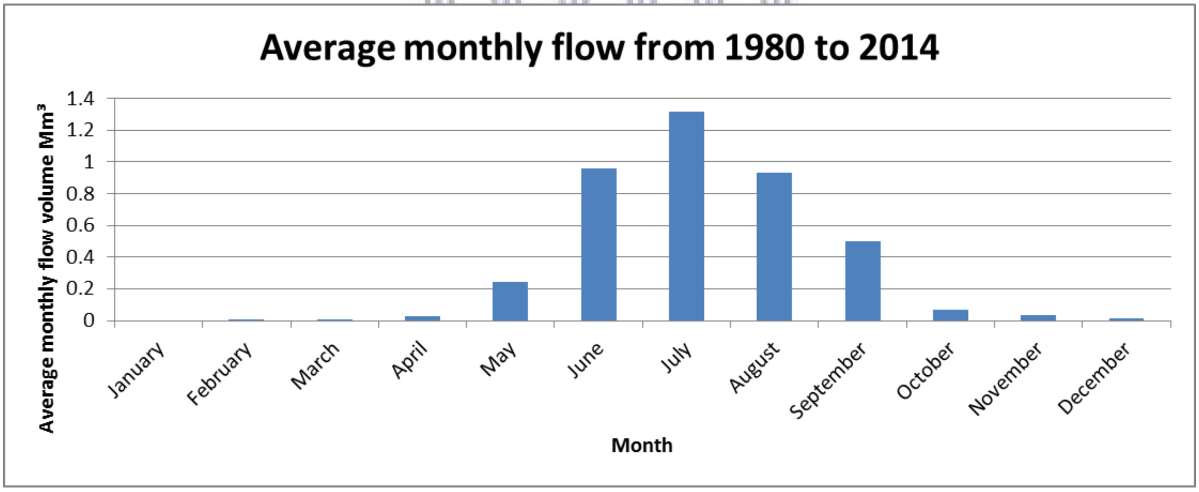


Figure 4.1: Historical monthly average flow for the Sandspruit Catchment from 1980 to 2014. Flow is dominant from May to September (DWS, 2014)

Historical rainfall data for the Sandspruit Catchment reveals that rainfall occurs throughout the year with most of the rainfall occurring from May to September (Figure 4.2). Rainfall during the rest of the year is minor and not enough to induce flow (Figure 4.2). Rainfall during the 2009 to 2012 period varied from 402.8 mm/yr to 529 mm/yr, with 2010 being the year with the lowest rainfall 402.8 mm/yr and 2011 being the year with the highest rainfall. The average rainfall during this period was 469.2 mm/yr. During 2012 rainfall was 467.2 mm/yr. The number of rainy days for each year is 110 days for 2009, 95 days for 2010, 107 days for 2011 and 118 days for 2012.

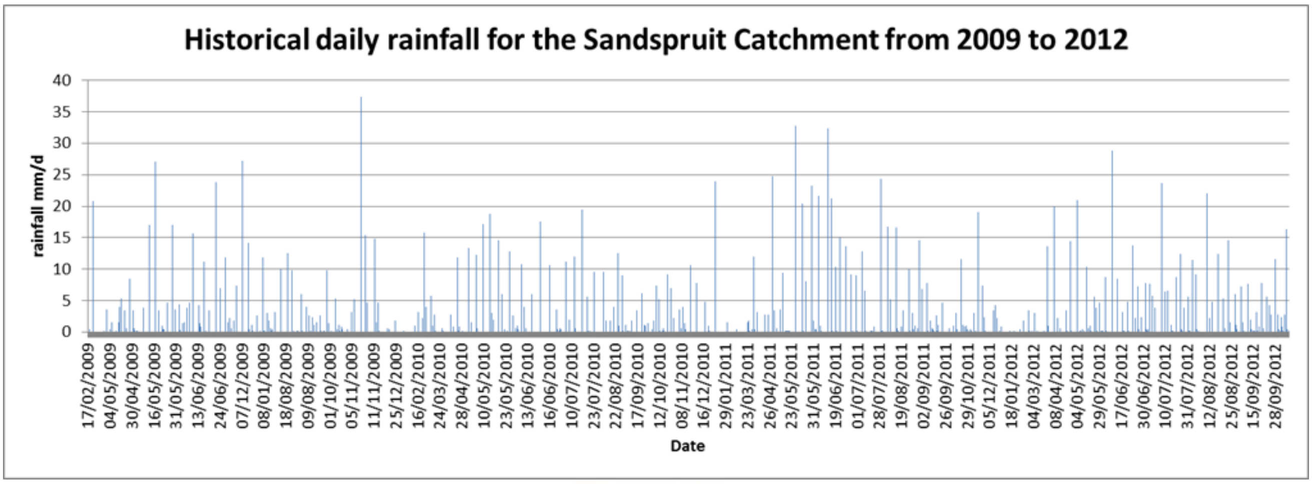


Figure 4.2: Historical rainfall for the Sandspruit Catchment from 2009 to 2012 (DWS, 2014).

Daily average data shows that flow only occurs during the winter months when there is sufficient rainfall to induce it. Flow increases rapidly during periods of high rainfall, and decreases rapidly as rainfall decreases (Figure 4.3). The 2009 rainfall period which received 477.6 mm/yr, had the highest flow with the highest peaks in average daily flow rates exceeding 8 m^3/s. In subsequent years a different trend was observed. Though flow increased after the onset of rainfall, this was significantly lower than that of 2009. 201 had the highest rainfall with total rainfall for the rainy season being 529 mm/yr, but had the lowest flow rate. High flows are only observed during the rainy season for a few days after a storm event. Low flows are observed for about one week after a storm event or until the next storm event when flow peaked. Flow ceases during October (Figure 4.3).

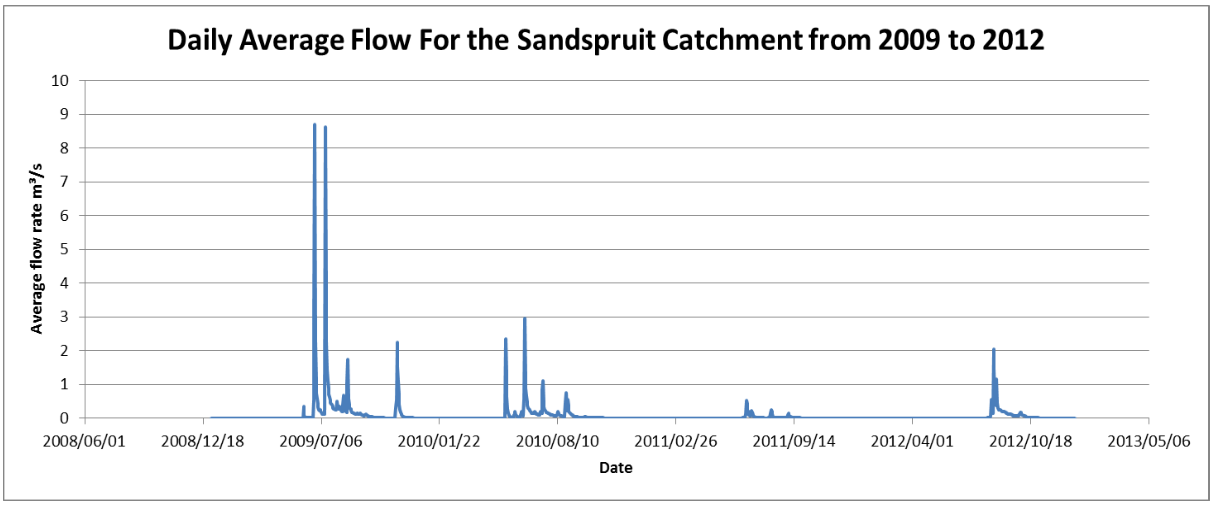


Figure 4.3: Daily average flow for the Sandspruit Catchment. Flow only occurs during periods of high rainfall (DWS, 2014).

4.3 Runoff coefficients

The calculated runoff coefficients for the Sandspruit Catchment indicate variations from one year to the next (Table 4.1). The 2009 rainy season had the highest total flow and incidentally the highest runoff coefficients. The 2011 rainy season though it had the highest rainfall it had the lowest total flow and as a result had the lowest runoff coefficient (Table 4.1). The Mean Annual Potential Evaporation (MAPE) for the catchment is 1651 mm (Bugan *et al.*, 2009). According to Bugan et al (2009) differences between evaporation losses during summer is 250 mm per month, with winter experiencing losses of 50 mm per month. The MAPE is significantly greater than the mean annual rainfall of 460 mm/yr. The Sandspruit Catchment is constrained due to the losses by evapotranspiration as most rainfall is returned to the atmosphere. Due to these losses of rainfall by evapotranspiration production of runoff is limited within the catchment as the runoff coefficients indicate. The implications of low runoff coefficients mean less water available for abstraction by humans. Low runoff coefficients are also indicative of the Sandspruit being an ephemeral river, with less than 10% of rainfall becoming runoff. This could be problematic in terms of water resources management as a) the diversion of water will have an impact on the quality of water within the river, and b) water within the river is not available for use during periods of drought.

Table 4.1:Annual rainfall and runoff for the 2009 to 2014 period.

Year	Rainfall (mm/yr)	Total flow (mm/yr)	Runoff Coefficient as %
2009	477.6	37.05	7.8
2010	402.8	15.98	4
2011	529	2.52	0.5
2012	467.2	8.46	1.8
2014	405.4	8.01	2

The runoff coefficients for the Sandspruit indicated a small percentage of the rainfall that became surface runoff. In comparison to the rest of South Africa, the Sandspruit Catchment's runoff coefficient is similar to northern and north-eastern parts of the country (Figure 4.4). These areas typically receive low annual rainfall, which results in low runoff.

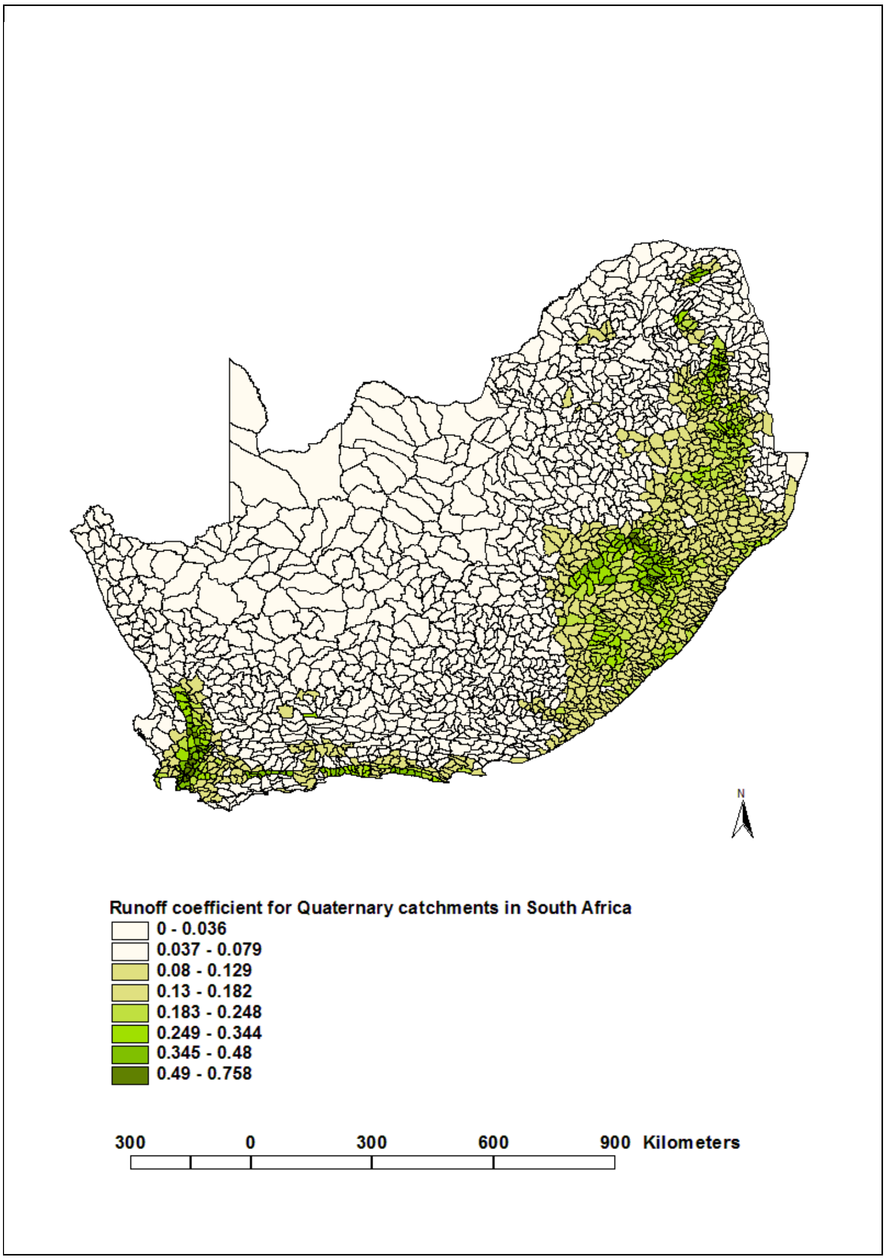


Figure 4.4: Average runoff coefficients for South Africa based on WR2005 data.

4.4 Baseflow separation

Baseflow separation for the Sandspruit Catchment indicates that at the start of the rainy season and at the onset of flow, streamflow is predominantly composed of surface runoff with significant contributions from subsurface runoff (Figure 4.5). Surface runoff is usually dominant during the first rain event as antecedent soil moisture is too low, and soil water has to be replaced before it can move to the water table. As the rainy season progresses and flow continues, a change can be observed and baseflow becomes the dominant contributor to flow. This usually occurs after a few rainfall events have occurred within the catchment. This is very common as soil moisture has been replenished and rain events usually occur within a few days to a week of each other during the rainy season. In some instances, though not common, baseflow is the dominant contributor to streamflow from the first flow inducing rains of the season. This could be a result of high rainfall that occurred at the time. High rainfall allows water to exceed the soil water threshold and infiltrated water can move down to water table and groundwater levels may rise enough for it to contribute to streamflow.

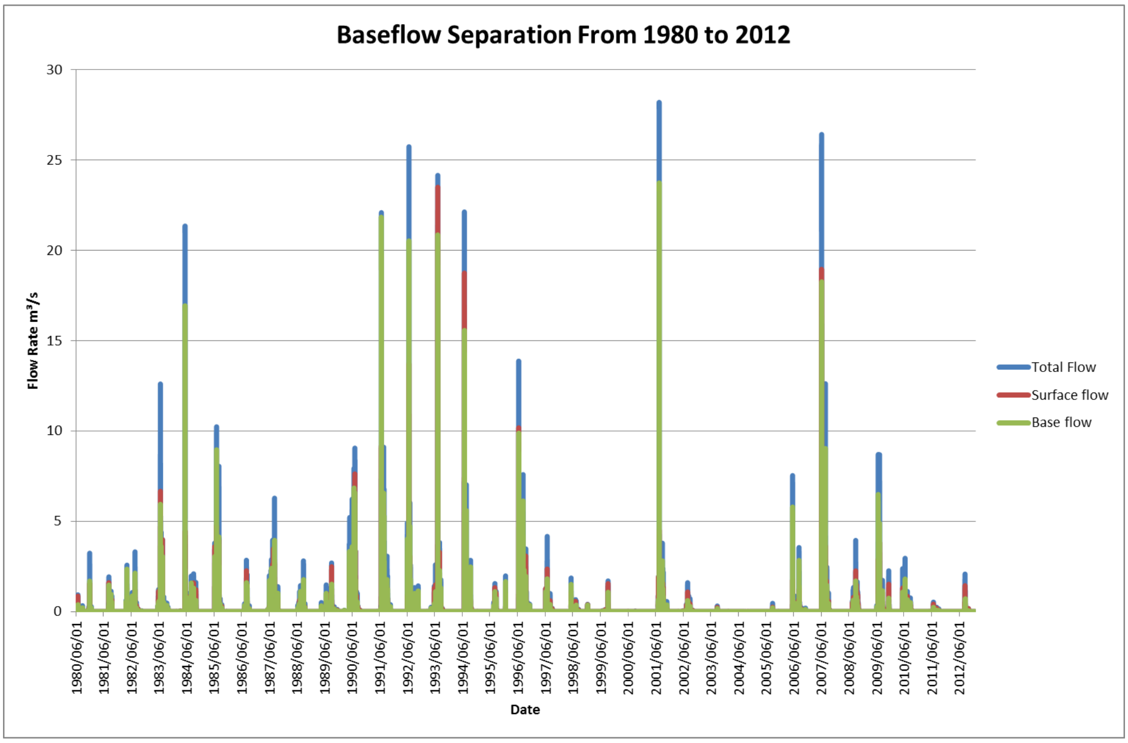


Figure 4.5: Baseflow separation for the Sandspruit using a one parameter algorithm (DWS, 2014).

Average monthly and yearly baseflow index (BFI) for the Sandspruit Catchment can be seen in table 4.2. Table 4.2 indicates that at the end of the rainy season flow is mainly composed of baseflow as BFI is usually 1 at the end of the rainy season. The contributions of baseflow starts from as early as April and continues until October. Baseflow decreases from November until flow eventually ceases usually in December. The average annual BFI is 0.26. The minimum average BFI for the catchment is 0.16 and the maximum BFI is 0.39. The estimated annual and average annual BFI indicate that baseflow contributions to flow is limited to periods of rainfall that infiltrate and reach the water table. The average annual BFI of 0.26 (Table 4.2) indicates that total flow is on average only composed of 26% subsurface runoff whereas surface runoff makes up the deficit of up to 74% of total flow on average. Low subsurface runoff is expected within the aquifer system in the Sandspruit Catchment as the aquifer is classified as a minor aquifer system (Parson, 1995). Minor Aquifers have generally low permeability, and do not produce large quantities of water but can vary within different formations. The Sandspruit catchment is underlain mainly by hard rock which makes up 93.5% of the catchment geology. The TMG is found on the upper catchment while the Malmesbury Shale covers most of the catchment. Shale which is a consolidated rock made up of fine sediment is associated with low permeability (Neuzil, 1986). Low quantities of subsurface runoff in the Sandspruit Catchment are understandably apparent as a result of the low permeability associated with the rock type and that there is minimal fracturing within the aquifer. The BFI map (Figure: 4.6) indicates that average baseflow for the Sandspruit Catchment is in the range of 0.299- 0.349 based on the WR2005.

Table 4.2: Average monthly and yearly BFI for the Sandspruit catchment form 1980-2014 (DWS, 2014).

Month	January	February	March	April	May	June	July	August	September	October	November	December	Average Yearly BFI
1980						0.96	0	0.8	1	0	0.4	1	0.59
1981	0	0	0	0	0	0	0	0	0.99	1	0	0	0.59
1982	0	0	0	0.99	0	0	0.61	0.83	0.85	1	0	0	0.17
1983	0	0	0	0	0	0.26	0.83	0.62	0.71	1	0	0	0.36
1984	0	0	1	0	0.95	0	0.13	0	0.39	1	0	0	0.28
1985	0	0	0	0	0	0	0.09	0.91	0.91	1	0	0	0.29
1986	0	0	0	0	0	0	0	0.88	0.99	1	0	0	0.24
1987	0	0	0	0	0	0	0.09	0.66	0.92	1	0	0	0.24
1988	0	0	0	0	0	0	0	0.49	0.96	0.94	1	0	0.22
1989	0	0	0	0.96	0	0	0	0	0.92	0.76	1	0	0.28
1990	0	1	0	0	0	0	0.83	0.84	0.96	1	0	0	0.3
1991	0	0	0	0	0	0	0.54	0.33	0.87	0.95	1	0	0.39
1992	0	0	0	0	0	0.55	0.82	0.13	0.41	0.93	1	0	0.31
1993	0	0	0	0	0	0.7	0.92	0.99	1	0	0	0	0.32
1994	0	0	0	0	0	0.65	0.83	0	0.97	1	0	0	0.3
1995	0	0	0	0	0	0	0	0.92	1	0	0	0	0.29
1996	0	0	0	0	0	0	0.12	0.31	0.79	0.84	1	0	0.16
1997	0	0	0	0	0	0.61	0.01	0.75	1	0	0	0	0.26
1998	0	0	0	0	0.31	0	0.7	0.94	1	0	0	1	0.2
1999	0	0	0	0	0	0	0	0	0.98	1	0	0	0.33
2000	0	0	0	0	0	0	0	0	0.86	1	0	0	0.17
2001	0	0	0	0	0	0	0.78	0	0.92	0.91	1	0	0.16
2002	0	0	0	0	0	0	0	0.77	0.81	1	0	0	0.3
2003	0	0	0	0	0	0	0	0.88	1	0	0	0	0.22
2004	0	0	0	0	0	0	0	1	0	1	0	0	0.16
2005	0	0	0	0	0	0	0	0.92	1	0	0	0	0.17
2006	0	0	0	0	0.72	0	0	0.93	0.87	0	1	0	0.16
2007	0	0	0	0	0	0.5	0.16	0.76	0.97	1	0	0	0.29
2008	0	0	0	0	0	0	0	0	0.86	1	1	0	0.28
2009	0	0	0	0	0	0	0.56	0.77	0.93	0	1	1	0.24
2010	0	0	0	0	0	0.34	0.27	0.77	0.95	1	0	0	0.35
2011	0	0	0	0	0	0.45	0	0.44	1	0	0	0	0.28
2012	0	0	0	0	0	0	0	0.66	0.73	1	0	0	0.16
2013	0	0	0	0	0	0	0	0.29	0.92	0.81	0.93	1	0.2
2014	0	0	0	0	0	0	0	0.6	0.96	1	0	0	0.33
Average Monthly BFI	**0**	**0.03**	**0.03**	**0.06**	**0.06**	**0.14**	**0.24**	**0.55**	**0.87**	**0.69**	**0.3**	**0.11**	**0.27**

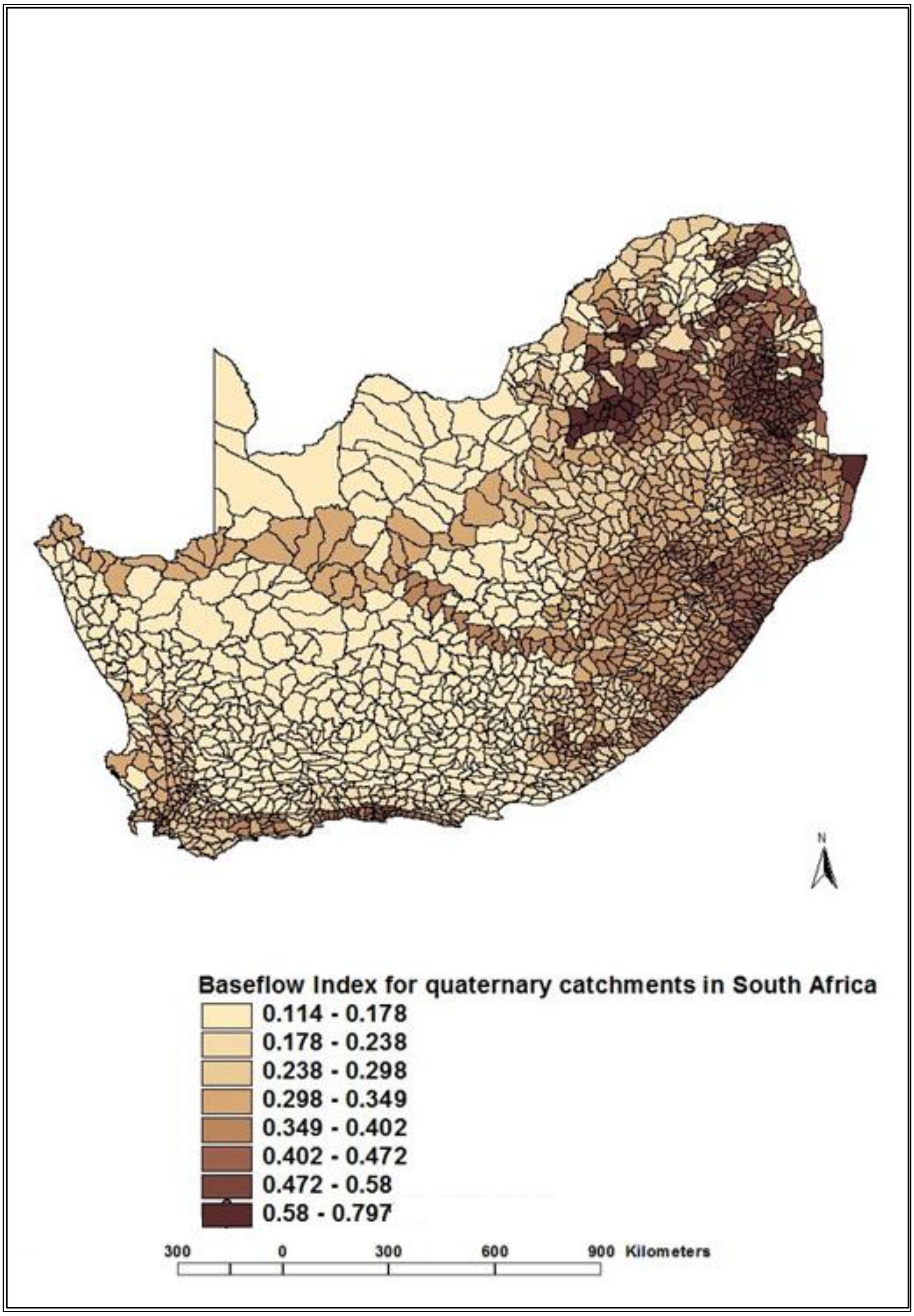


Figure 4.6: Average Baseflow for quarternary catchments in South Africa based on WR2005 data.

4.5 Rainfall runoff response

During 2014 from January to September total rainfall for the catchment was 405.4 mm (Figure 4.7). Rainfall occurred sporadically throughout the year, with the dominant rainfall period occurring during the winter months. During the rainy season, rainfall generally occurs for three to four days unlike during the dry season when rainfall occurs for one to two days. As with previous years, rainfall during the dry season was not enough to induce flow during the dry season and flow only occurred during the rainy season from July to October. Even though rainfall occurs throughout the year there is very little impact on river flows during the dry season. This could be a result of a combination of high evaporation rates experienced during the dry season, low rainfall and less frequent. Therefore, there is very little water that goes to storage in aquifers and very little soil moisture replenishment. During the rainy season evaporation rates are lower, rainfall is higher and more frequent. Therefore, excess water can infiltrate and be stored in aquifers and there is high soil moisture replenishment. As a result, rainfall during the rainy season is more significant.

The arid nature of the catchment has a major influence on runoff generation, especially if a storm event is minor and the time between storm events is a week or more. An ‘event’ is defined as periods of major rainfall separated by at least 24 hours of rainfall intensities averaging less than 0.1 mm/h (Wenninger *et al.*, 2008; Kollongei and Lorentz, 2014). Therefore, events average more than 2.4 mm of rainfall a day and minor events average less than 2.4 mm of rainfall a day. Before the targeted events a small storm event occurred from the 12th to14th of July 2014. Rainfall intensities during this time were less than 0.5 mm/h and total rainfall depth during that time was 1.4 mm. The event had very little impact as flow was not induced during the event. However, it contributed significantly to the soil moisture of the Sandspruit Catchment. Other evidence of the influence of aridity on runoff generation is that river flow only started during the time period of the first event 16th to 19th of July 2014, even though other events had occurred before this (Figure 4.7). Peak rainfall often occurs within a few hours after the onset of an event, thereafter it generally starts to decrease until it stops.

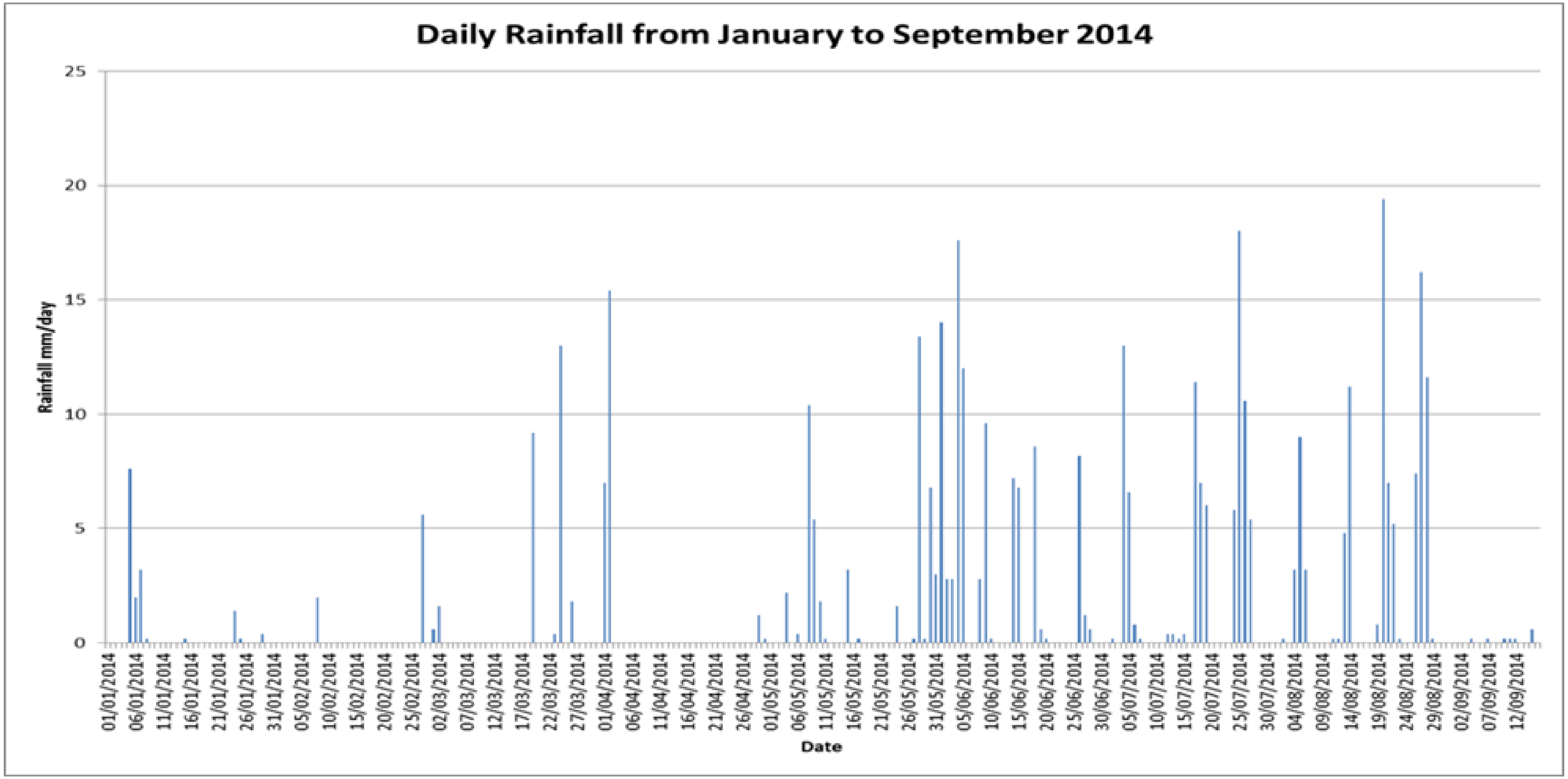


Figure 4.7: Daily rainfall amounts for the Sandspruit Catchment during 2014 from January to September.

Weather forecasts were monitored for the occurrence of high rainfall. When occurrence of high rainfall was forecasted by South African Weather Services (SAWS), the required sampling equipment was mobilized and setup at the monitoring sites in the Sandspruit Catchment (Figure 4.8). Due to weather forecasts not always being reliable there were instances when storm events were either missed or did not occur. Thus the number of events sampled depended on a) the weather forecast accuracy, and b) our timely presence at sampling sites. During the investigation period three storm events were studied. These occurred on the 16th-19th (event 1) and the 23rd-26th (event 2) of July 2014. The third storm event occurred during August of 2014 from the 12th-14th (event 3).

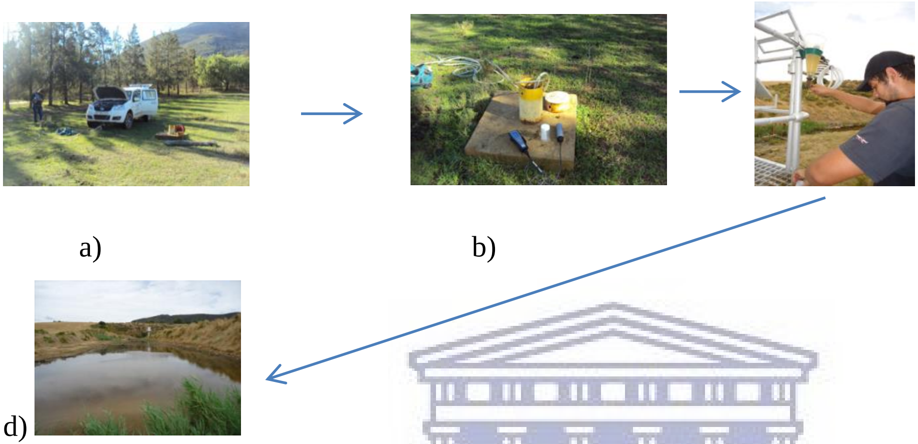


Figure 4.8: The procedure when arriving at sampling points. a) Water levels are measured in the borehole; b) the borehole is purged, physical parameters are measured and water samples are collected; c) rain gauges are sampled and refilled with liquid paraffin oil; d) The Sandspruit is sampled.

Event 1 is characterised by the onset of a storm event (Figure 4.9). Rainfall increased at the beginning of the event and continued to fluctuate during the course of the event. Flow in the Sandspruit only responded after 2 days after the onset of event 2. When rainfall was sufficient to induce flow there was an increase in flow in the Sandspruit (Figure. 4.9). At the onset of flow during July 2014 during rain Event 1 which commenced on the 16th and ended on the 19th of July 2014 there was an increase in flow for the river. During this time flow peaked rapidly, when peak flow was reached the flow rate remained constant for two days. After two days the flow rate decreased rapidly, until the flow rate became constant. At the onset of the second rain event, which commenced on the 23rd and ended on the 26th of July 2014, flow increased again to 0.051 m^3/s for 10 hours and decreased to 0.050 m^3/s. After the events were sampled, water samples were taken to the lab for analysis (Figure, 4.10).

Minor differences in flow were observed, these may not be significant as there may have been some measurement errors. Before the onset of storm Event 1, total flow was measured to be 0.050 m^3/s. From the onset of rainfall during Event 1 to the end of rainfall a total of 24.4 mm of rain had fallen over a 52-hour period. The Lag time between the onset of rain and the increase in streamflow was 50-hours. This could be due to low soil wetness in the Sandspruit Catchment during the period of study. When flow increased it peaked at 0.051 m³/s and remained constant for 35-hours until it decreased to 0.050 m³/s for one hour. After 1-hour flow increased again to 0.051m³/s for another hour, thereafter flow decreased back to 0.050 m³/s and remained constant for 11-hours. Flow decreased to 0.049 m³/s for one-hour, and increased to 0.050 m³/s for 2-hours. After these fluctuations, flow decreased gradually to 0.031m³/s where it remained constant until the onset of Event 2. Event 2 is marked by the onset of rainfall. From the onset of rainfall to the offset of rainfall a total of 34.4 mm of rain had fallen over a 60-hour period. The lag time between the onset of rain and flow was 41-hours. After this 41-hour period flow increased from 0.031 m³/s to 0.032 m³/s. Flow remained at 0.032 m³/s for 2 hours until it increased to 0.051 m³/s. flow remained at 0.051m³/s for 11 hours after which it decreased to 0.050 m³/s. There is an apparent difference in the response time of the River to the input of rainfall between Events 1 and 2. Event 1 only responded to the input of rainfall after 50-hours, whereas Event 2 responded after 41 hours. There is a 9-hour time difference between the response of between Event 1 and Event 2. This could be due to antecedent soil moisture from the previous storm event, as the amount of rainfall that occurred before flow increased during event 2 was only 25.6 mm (Figure 4.9). Peaks in flow were dependant on cumulative precipitation as flow only responded to the input of precipitation which varied each hour. Variations in flow were not always observed as there were times when flow was constant. This could be due to the slow release of water from groundwater from storage in the catchment. The duration of the events studied lasted from 52-hours for Event1 to 58-hours for Event 2.

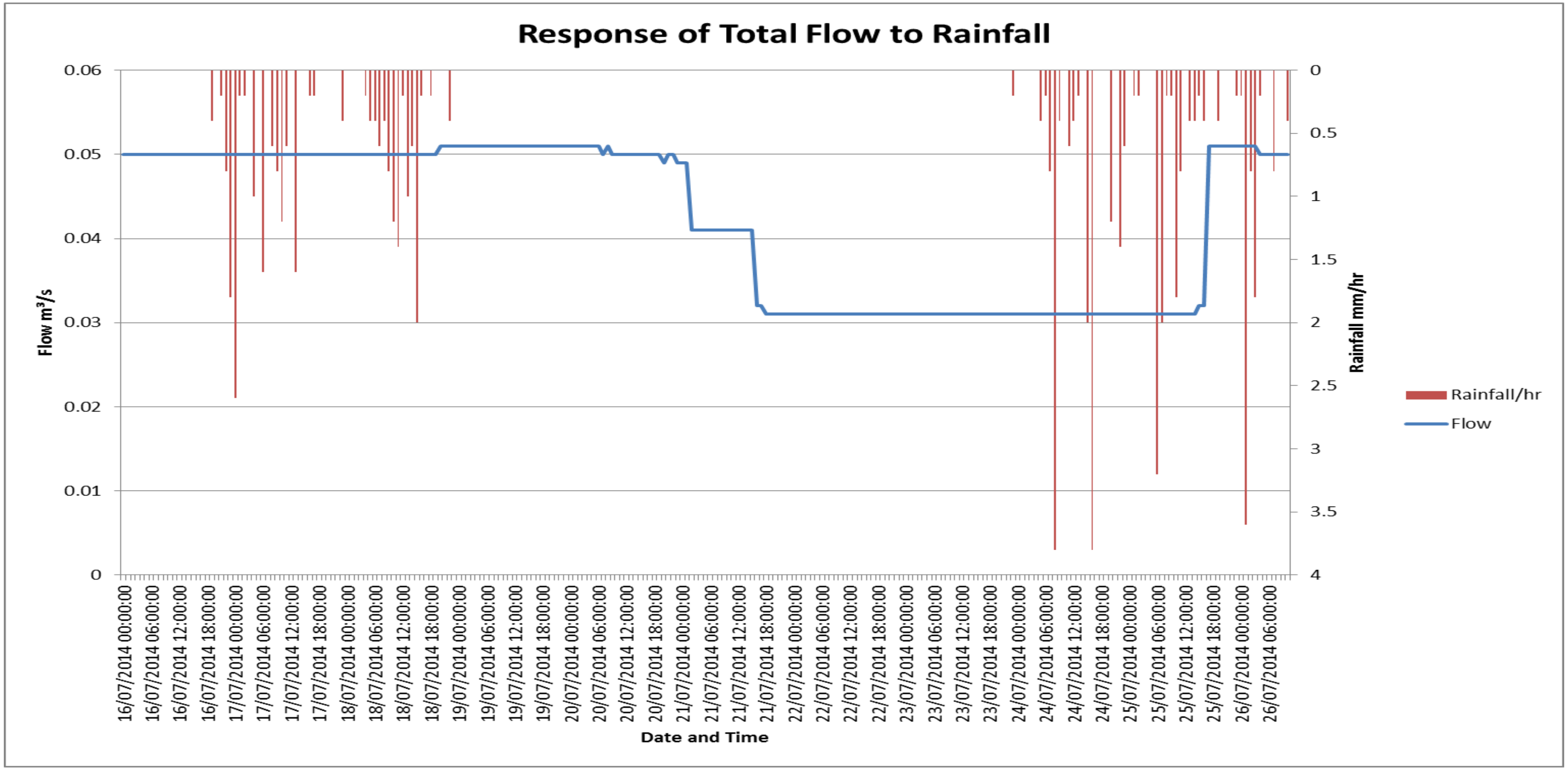


Figure 4.9: Response of runoff to the input of rainfall. Lag time for event 1 was 50 hours after the onset of rainfall for event 1. Lag time for event 2 was 41 hours after the onset of rainfall for event 2.

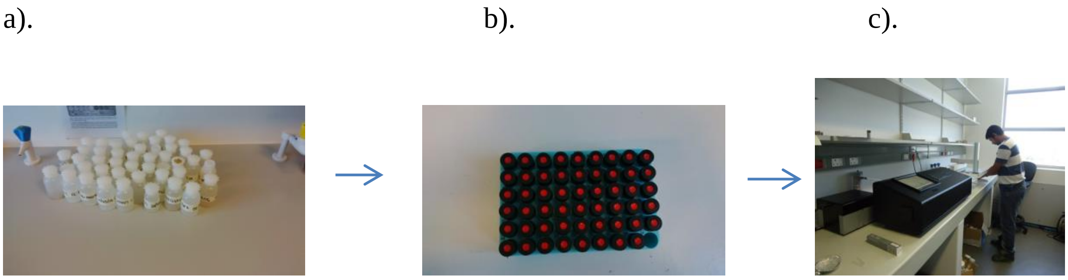


Figure 4.10: Isotope sample preparation for laboratory analysis. a) Samples are prepared and sorted; b) samples are placed into sampling tray; c) the isotope analyser is programmed.

4.6 Groundwater levels

An extensive groundwater level monitoring program was done during the rainy season of 2013. Changes in water levels were gradual (Figure 4.11 and Figure 4.12). The water levels in shallow boreholes in the upper part of the catchment increased more than the boreholes in the middle of the catchment (Figure 4.11). A similar trend was observed with deep boreholes whereby boreholes in the upper catchment indicated larger changes in water levels than those in the lower catchment. This could be due higher rainfall concentrations in the upper catchment.

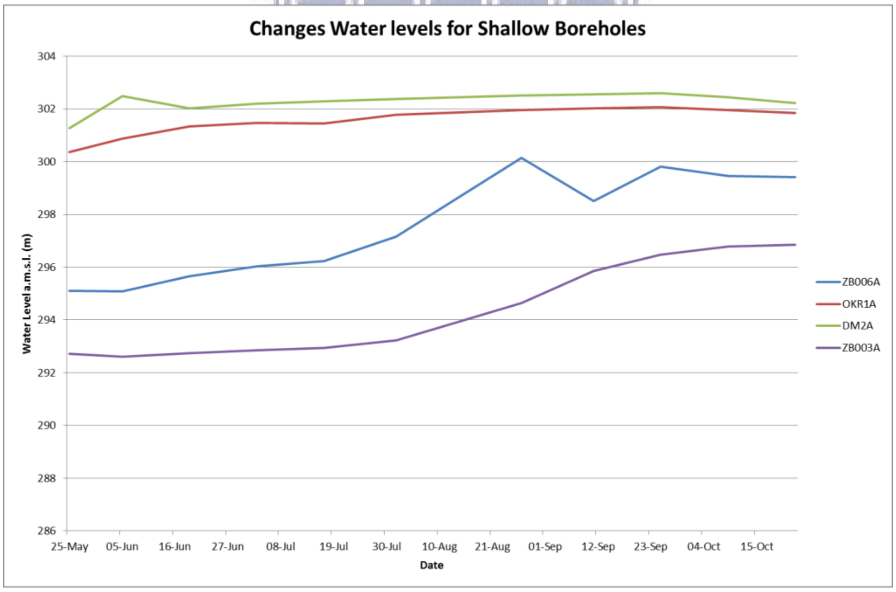


Figure 4.11: Observed water levels for shallow borehole during 2013.

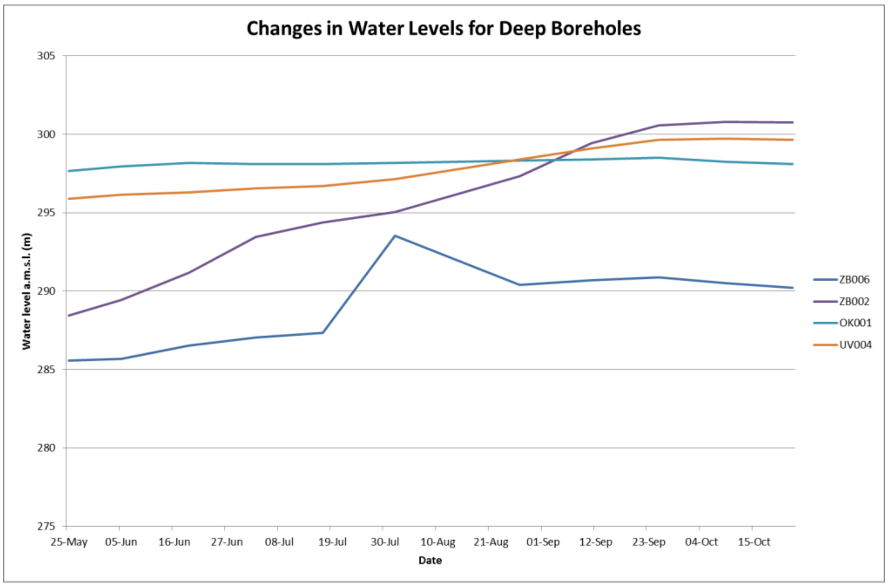


Figure 4.12: Observed water levels for deep boreholes during 2013.

4.7 Identification of flow paths using tracers

To determine the flow paths, the tracer concentrations of each source water had to be ascertained. This was done by collecting water samples for groundwater and rain water and analysing them for isotopes and silica. The results of the samples were used to identify the source of waters. Each source of water was assigned a signature concentration for δO^{18} and silica. The signature assigned to surface runoff was the rain water averages for δO^{18} and silica, and the signature for subsurface water was the average δO^{18} and silica of groundwater collected from the 18 boreholes. The values assigned for surface runoff for δO^{18} and silica for Event 1 were -2.39‰ and O mg/L, and Event 2 were -2.61‰ and 0 mg/L (Table 4.3), respectively. Mean Si concentrations for rain were assumed to be 0 mg/L across the catchment as described by Wels et al (1990), for both events. The values assigned for groundwater for δO^{18} and silica for Event 1 were -3.71‰ and 6.64 mg/L, and Event 2 were -3.62‰ and 7.05 mg/ L (Table 4.4), respectively.

The variation of tracer concentrations was observed in 18 boreholes across the catchment. The range and standard deviation of flow and tracer concentrations are displayed below (Table 4.3) and (Table 4.4). The proportion of surface runoff and groundwater flow contributions to total flow were calculated using Equations (2.2) and (2.3), respectively. Changes in tracer concentrations occurred during the events as well between events. During event 1 (Table 4.3) the input of rainfall increased the concentrations of Si in total flow from 0 mg/L to 0.184 mg/L as the storm progressed. Changes in flow have an influence on tracer concentrations, an increase in flow during Event 2 indicates changes in silica concentrations of total flow. During Event 2 the Si concentrations in total flow were 0.42 mg/L to 11.18 mg/L (Table 4.4), whereas with Event 1 these concentrations were from 0 mg/L to 0.184 mg/L (Table

4.3). The groundwater Silica concentrations indicated small changes between events. Variations in the δ^{18}O occurred with the input of rainfall and the increase in flow. The δ^{18}O concentrations of total flow, surface runoff and groundwater indicate changes between events (Table 4.3) and (Table 4.4).

Table 4.3: Definition, range and basis for measuring, calculating or estimating all equation variables for Event 1 – 16th-19th July 2014.

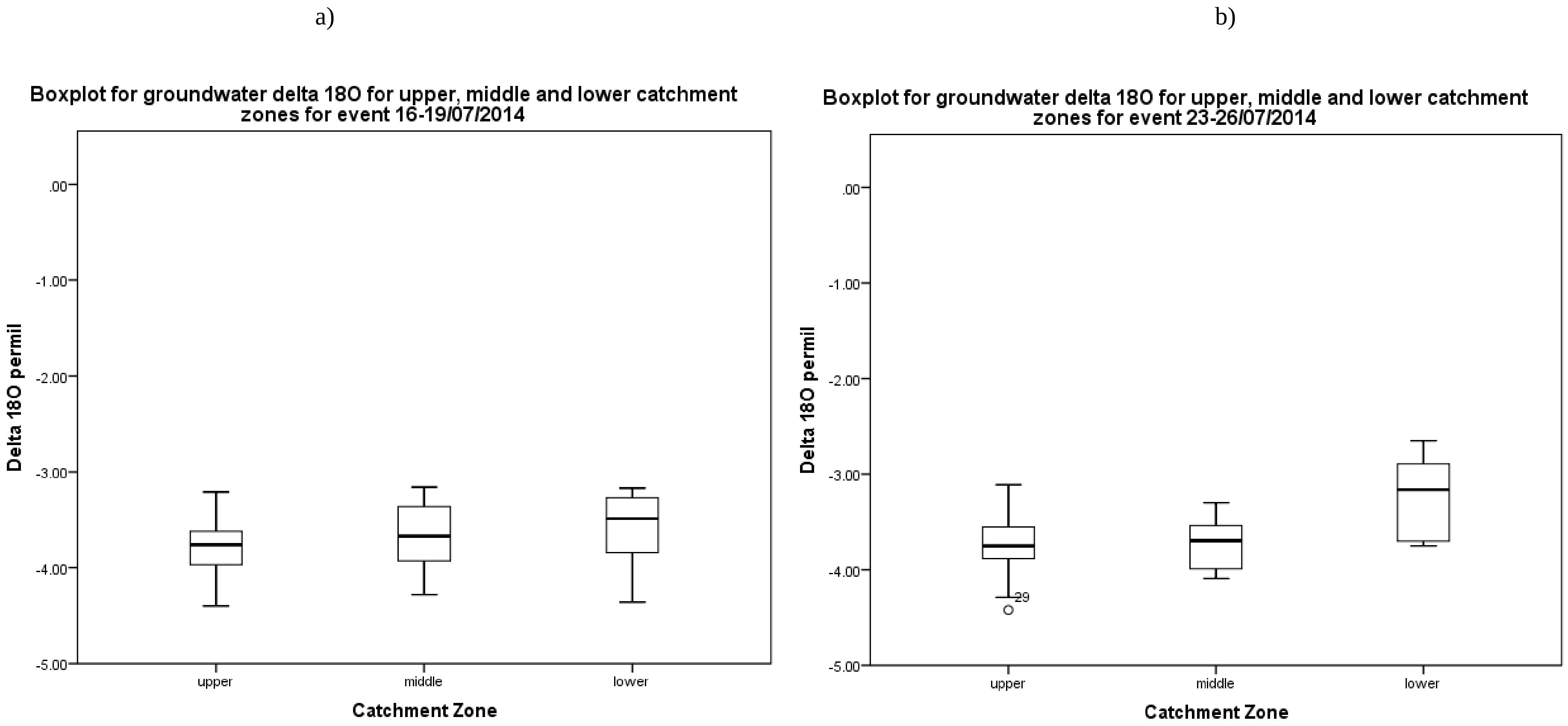
Variable	Definition	Range	Standard Deviation	Measuring, calculation, or estimation
Qt	Total flow	0.031-0.046 m^3/s	0	Measured at catchment outlet
Qe	Surface runoff/ event water	_a		Calculated using equation 2.2
Qp	Groundwater/ pre-event water	_b	0	Calculated using equation 2.3
Ct18O	18O concentration in total flow	-3.37 to -1.82 ‰	0.5	Measured from 8 samples taken at outlet
Ce18O	18O concentration in surface runoff	-3.45 to -1.36	0.97	Measured from 4 rainfall samples
Ce18O	18O concentration in surface runoff	-2.61‰		Average of 4 rainfall samples
Cp18O	18O concentration in groundwater	-4.42 to -2.65 ‰	0.4	Measured from 18 boreholes average of 37 samples
Cp18O	18O concentration in groundwater	-3.62‰		Measured from 18 boreholes average of 37 samples
CtSi	Silica concentration in total flow	0.47 to 11.18 mg/L	3.33	Measured from 6 samples taken at outlet
CeSi	Silica concentration in surface runoff	0	0	Measured from rainfall
CpSi	Silica concentration in groundwater	0.60 to 10.45 mg/L	2.54	Measured from 18 boreholes average of 34 samples
CpSi	Silica concentration in groundwater	7.05 mg/ L		Measured from 18 boreholes average of 34 samples
_a calculated using equation 2.2, _b calculated using equation 2.3				

Table 4.4: Definition, range and basis for measuring, calculating or estimating all equation variables for Event 2 - 23rd to 26th July 2014.

Variable	Definition	Range	Standard Deviation	Measuring, calculation, or estimation
Q_t	Total flow	0 to 0.022 m^3/s	0	Measured at catchment outlet
Q_e	Surface runoff/ event water	_a	0	Calculated using equation 2.2
Q_p	Groundwater/ pre-event water	_b	0	Calculated using equation 2.3
$C_t{}^{18}O$	^{18}O concentration in total flow	-2.8 to -2.29 ‰	0.19	Measured from 5 samples taken at outlet
$C_e{}^{18}O$	Average ^{18}O concentration in surface runoff	-3.94 to -1.10 ‰	0.90	Measured from 8 rainfall samples
$C_e{}^{18}O$	^{18}O concentration in surface runoff	-2.93‰		Average of 8 rainfall samples
$C_p{}^{18}O$	^{18}O concentration in groundwater	-4.40 to -3.16 ‰	0.34	Measured from 18 boreholes average of 54 samples
$C_p{}^{18}O$	^{18}O concentration in groundwater	-3.71‰		Measured from 18 boreholes average of 54 samples
C_tSi	Silica concentration in total flow	0 to 0.184 mg/L	0.06	Measured from 5 samples taken at outlet
C_eSi	Silica concentration in surface runoff	0	0	Measured from rainfall
C_pSi	Silica concentration in groundwater	0.654 to 10.42 mg/L	2.61	Measured from 18 boreholes average of 54 samples
C_pSi	Silica concentration in groundwater	6.64 mg/L		Measured from 18 boreholes average of 54 samples
_a calculated using equation 2.2, _b calculated using equation 2.3				

Groundwater $\delta^{18}O$ concentrations sampled from boreholes during Event 1 indicated little variation across the catchment, 16th to 19th July 2014 (Figure 4.13). Concentrations for groundwater $\delta^{18}O$ are comparable with respect to median, minimum and maximum concentrations. This could be indicative of the conservative nature of the isotope tracer across the catchment. During event two, 23rd to 26th July 2014, there is a change in the median, minimum and maximum concentrations. This is especially evident in Figure (4.13 b). The change could be due to delayed infiltration of rain water, which is more enriched in $\delta^{18}O$ than groundwater. In Figure (4.14) there is a similar trend with respect to median, 25th and 75th percentiles, as Figure (4.13 a). Groundwater Si concentrations vary between the upper, middle and lower catchment as well as between events one and two (figure 4.15). The most notable differences are apparent in the lower catchment with the minimum value of Event 1 being significantly less than that of event two. Silica concentrations for the upper and middle catchment are similar when compared between events one and two (Figure 4.15 a) and (Figure 4.15 b). Three outliers were found in Figure (4.16).

Rain water was sampled in the upper, middle and lower catchment indicate an increase in rain $\delta^{18}O$ concentrations from the lower catchment to the upper catchment. This could be due to altitudinal effects which result in areas with a high altitude having lower $\delta^{18}O$ concentration and also in more depleted water. Whereas areas with lower altitudes having high $\delta^{18}O$ concentrations, resulting in more enriched water. Another reason for this could be due to Rayleigh rainout processes. Rayleigh rainout processes cause water molecules that are composed of $\delta^{2}H$ and $\delta^{18}O$ to fall first. The decreasing trend of $\delta^{18}O$ was observed for groundwater, though changes in $\delta^{18}O$ for groundwater are minor.


a)

Boxplot for groundwater delta 18O for upper, middle and lower catchment zones for event 16-19/07/2014

b)

Boxplot for groundwater delta 18O for upper, middle and lower catchment zones for event 23-26/07/2014

Figure 4.13: Average observed δ18O contents ‰ in boreholes in the upper, middle and lower catchment zone of the Sandspruit Catchment. Boxplots (a) and (b) indicate δ18O ‰ for events 16-19/07/2014 and 23-26/07/2014, respectively.

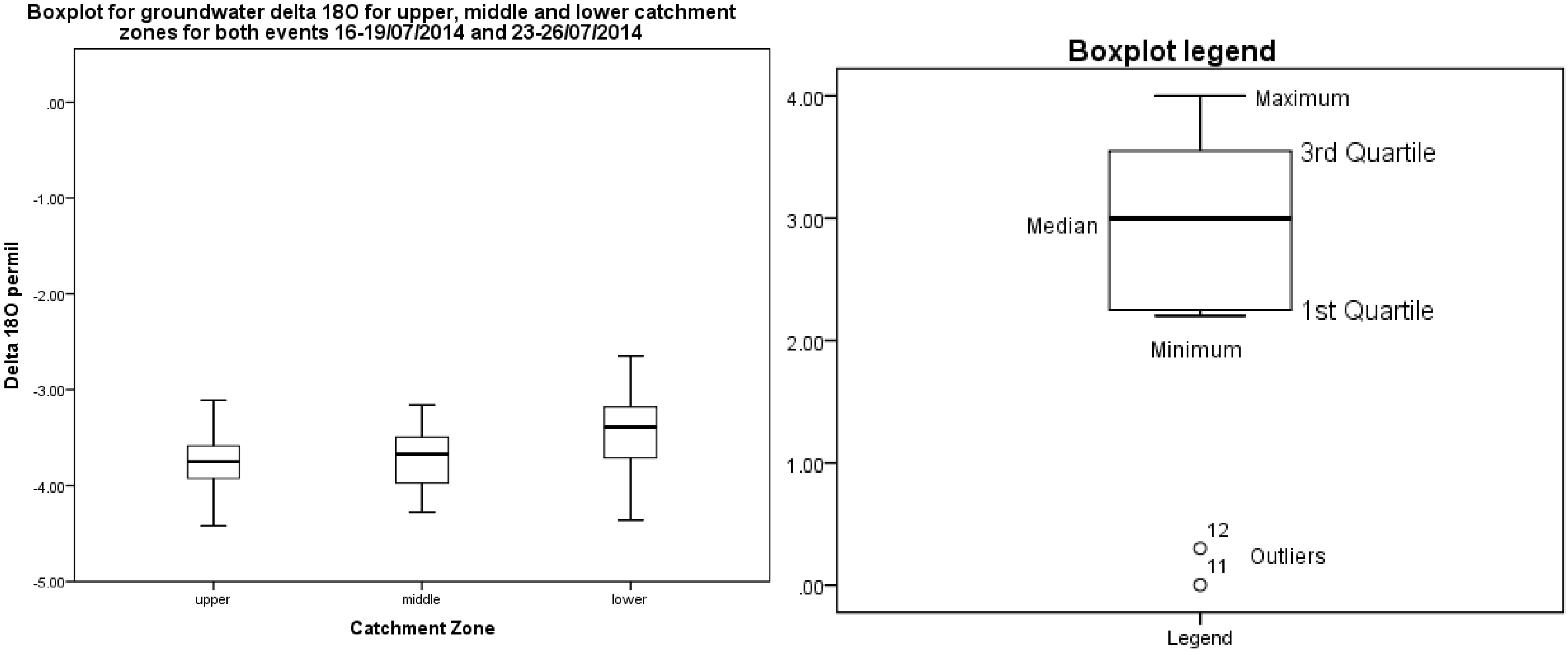
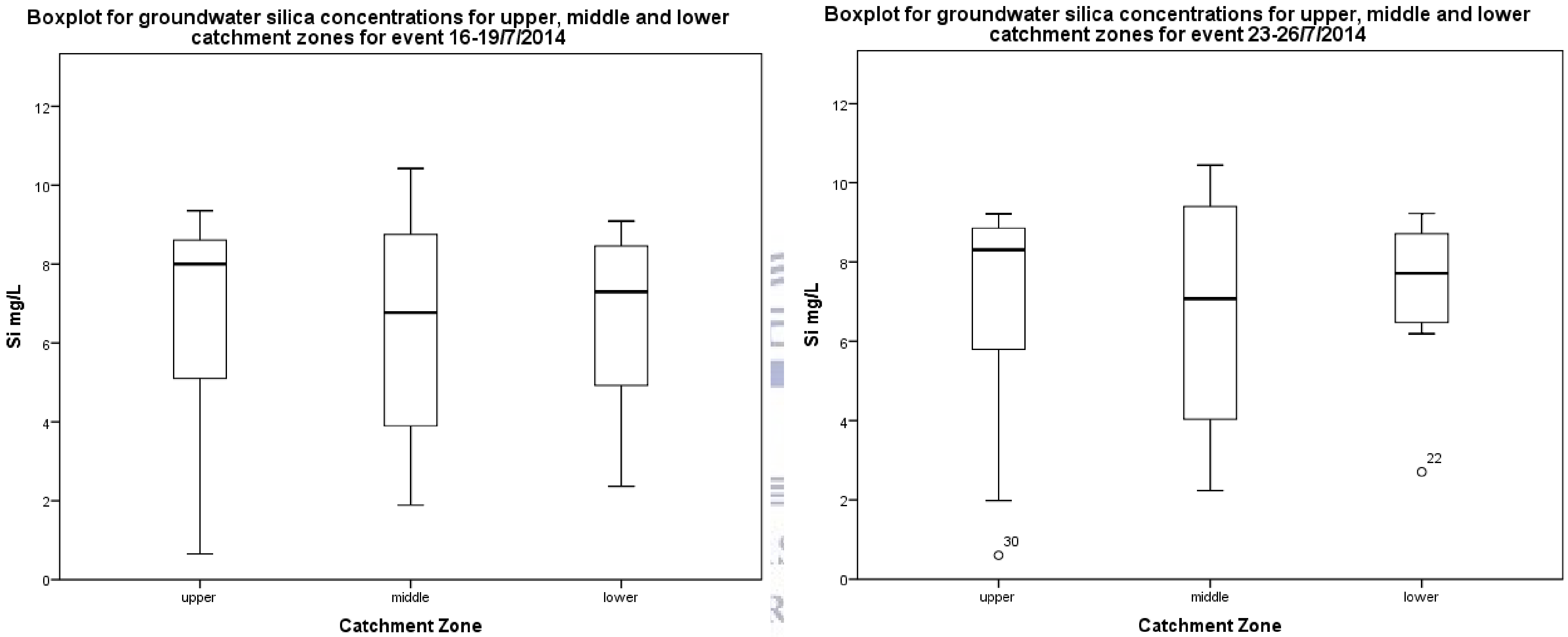


Figure 4.14: Boxplot is the average δ18O ‰ for the entire investigation period.



a)

b)

Figure 4.15: Average observed Si mg/L concentrations in boreholes in the upper, middle and lower catchment zone of the Sandspruit Catchment. Boxplots (a) and (b) indicate Si mg/L for events 16-19/07/2014 and 23-26/07/2014, respectively.

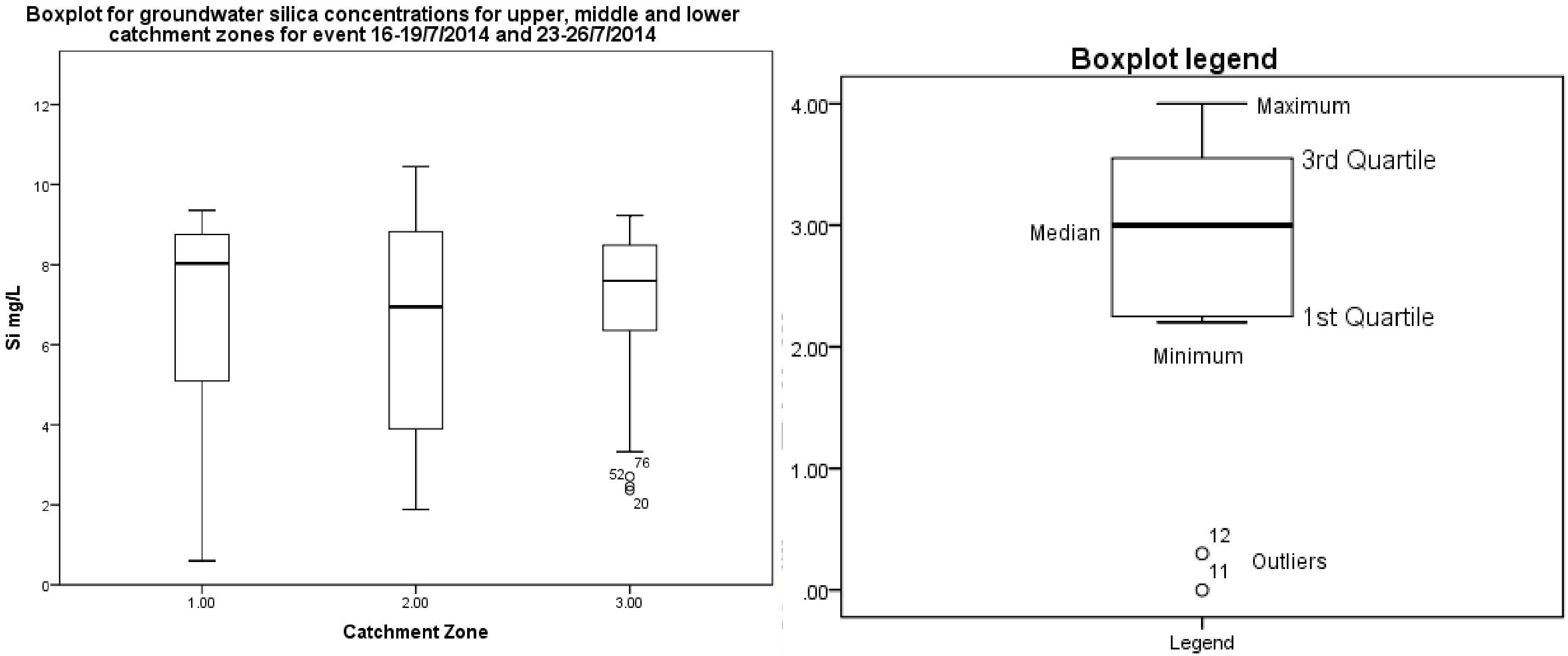


Figure 4.16 Boxplot is the average Si mg/l for the investigation period

4.8 Rainfall-runoff observations and tracer response

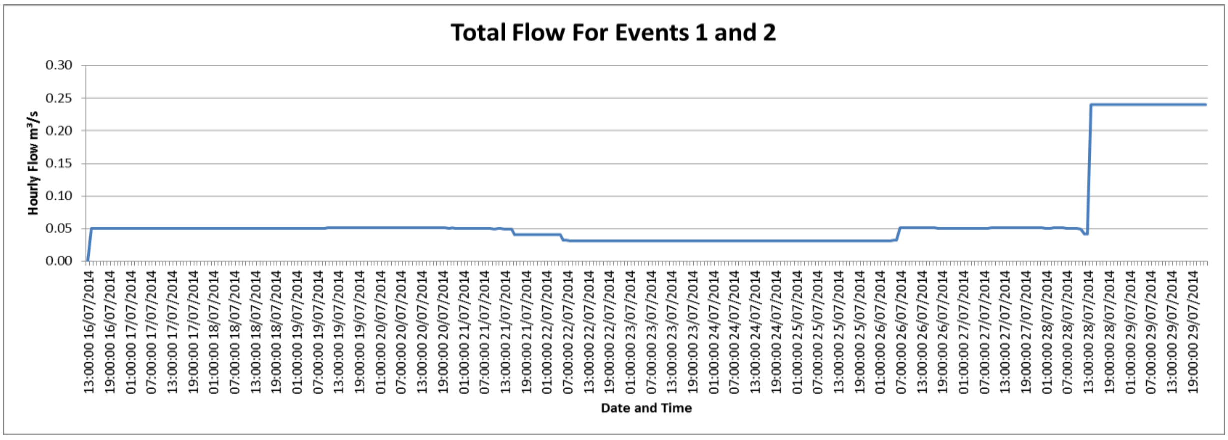


Figure 4.17: Variation of flow over time for event 1 and 2.

Water sampled for silica was collected at the catchment outlet. There were observable changes in the concentrations of δ^{18}O and Si (Figure 4.18 and figure 4.19). Due to the nature of isotopes of water when streamflow increases as a result of an input of water by rainfall, δ^{18}O concentrations decrease. Conversely, when streamflow decreases δ^{18}O increases (Figure 4.18). Silica however increased when streamflow increased, and decreased when streamflow decreased. At the onset of Event 1, δ^{18}O decreased and continued until rainfall decreased towards the end of the Event 1. At the end of the Event it decreased and until it stabilised two days before Event 2. Before Event 2, δ^{18}O continued to increase. At the onset of Event 2, δ^{18}O concentrations fluctuated, showing a sharp increase before decreasing slightly. When flow stabilised, δ^{18}O concentrations increased until it stabilsed.

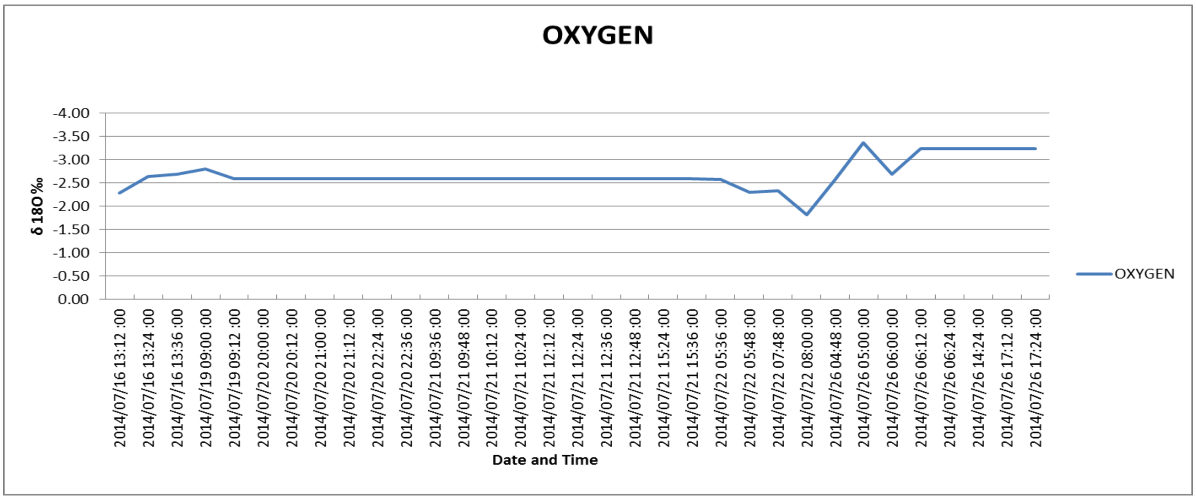


Figure 4.18: Variation of δ^{18}O over time for both Events. During Event 1 there is a minor increase in the δ^{18}O concentration. During Event 2 δ^{18}O concentrations fluctuates.

Silica concentrations at the onset of Event 1 had a minor increase from 0 mg/L to 0.102 mg/L (Figure 4.19). When flow decreased, silica concentrations decreased to 0 mg/L. Silica concentrations increased only two days before Event 2 (Figure 4.19). This could indicate a delayed response of runoff to the stream. Towards the end of Event 2 there was a major increase in silica concentrations which was followed by a smaller decrease in concentration. At the end of Event 2, silica increased rapidly to a concentration of 11.18 mg/l.

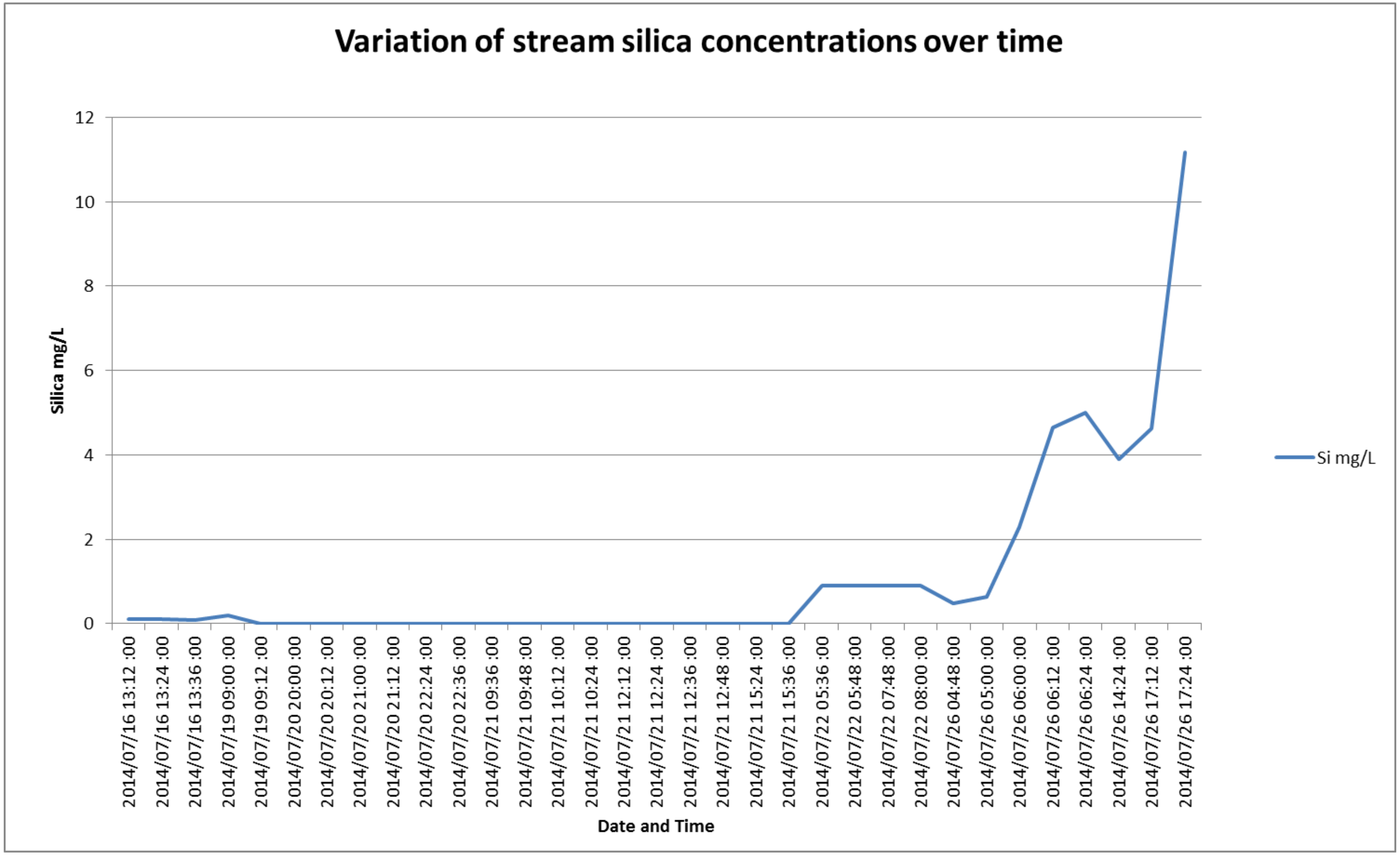


Figure 4.19: Indicates the changes of silica concentrations for both Events. There is a small increase in silica concentration that occurs briefly during Event 1 before decreasing back to zero. During Event 2 silica concentrations fluctuate.

4.9 Assessment of surface and subsurface flows by hydrograph separation

To determine the contributions of surface and subsurface flows to streamflow two types of hydrograph separations were used. The first hydrograph separation was an automated baseflow separation technique. The automated baseflow separation uses a one parameter algorithm to separate the stormflow hydrograph into the total flow component and the baseflow component (Equation 3.1), the storm flow component is calculated as the difference between total flow and baseflow.

The second type of hydrograph separation was a tracer-based hydrograph separation using $\delta^{18}O$ and silica as tracers using Equations (2.2 and 2.3). The tracer-based hydrograph separation provides different estimates for surface runoff and subsurface runoff contributions than the automated baseflow separation method. This is due to the fact that the tracer-based separation does not use a fixed parameter to determine streamflow, but uses a 'changing' parameter as streamflow increases and decreases. A comparison between these two methods was done to indicate the difference in the estimates provided by each method. The results for these separations are discussed below.

4.9.1 Baseflow separation for events 1 and 2

Baseflow separation was done for 2014 using the one parameter algorithm as defined in equation (3.1). Baseflow separation indicates that periods of flow during 2014 were predominantly composed of surface runoff component and minimally by the subsurface flow component (Figure 4.20). During the observed flow period subsurface water only contributes minimally to stream flow. This is indicative that as the flow decreases, baseflow conditions become more prevalent especially when surface runoff contributions start to decrease. When there is an increase in flow so do the contributions of the surface runoff component. There is a gap in the flow record during September from the 5th to the 8th and as a result baseflow could not be determined for that period (Figure 4.20). This was possibly due to maintenance during that period.

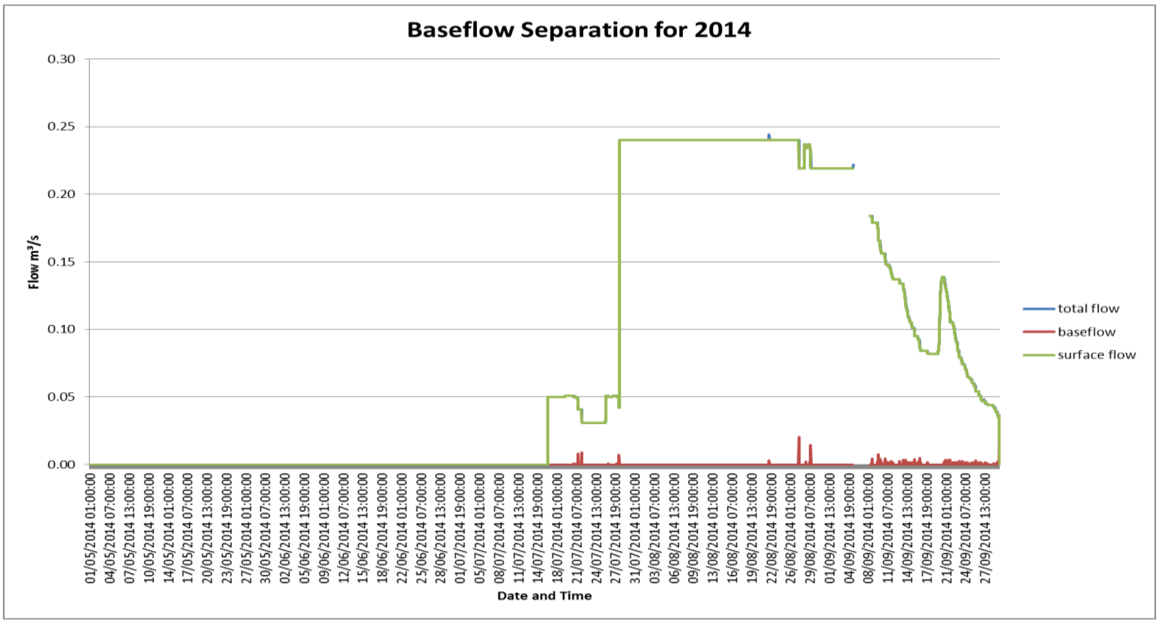


Figure 4.20: Baseflow separation using a one parameter algorithm.

4.9.2 *Tracer separations*

Hydrograph separations were done using the Equations (2.2 and 2.3). The tracer-based hydrograph separation indicated that at the onset of streamflow the increase in streamflow during Event 1 was due to surface runoff entering the stream (Figure 4.21). At the onset of flow surface runoff was the only contributor to storm flow for a brief period. As flow continued surface runoff contributions decreased, and groundwater released from storage entered the stream. The groundwater released from storage was enough to maintain a constant streamflow until flow increases again and surface runoff becomes the dominant contributor to flow. In order to calculate the percentage of each runoff component equations (2.5) and (2.6) were used. For Event 1, surface runoff is the dominant contributor to flow based on Isotope separations. Isotopic tracer separations for Event 1 indicated that total flow was composed of up to 77.8% surface runoff, and only 22.2% subsurface runoff. During baseflow conditions, total flow indicates minor fluctuations. During these fluctuation periods runoff components also varied. When flow decreases below 0.04 m³/s $\delta^{18}O$ hydrograph separations become unreliable for Event 2.

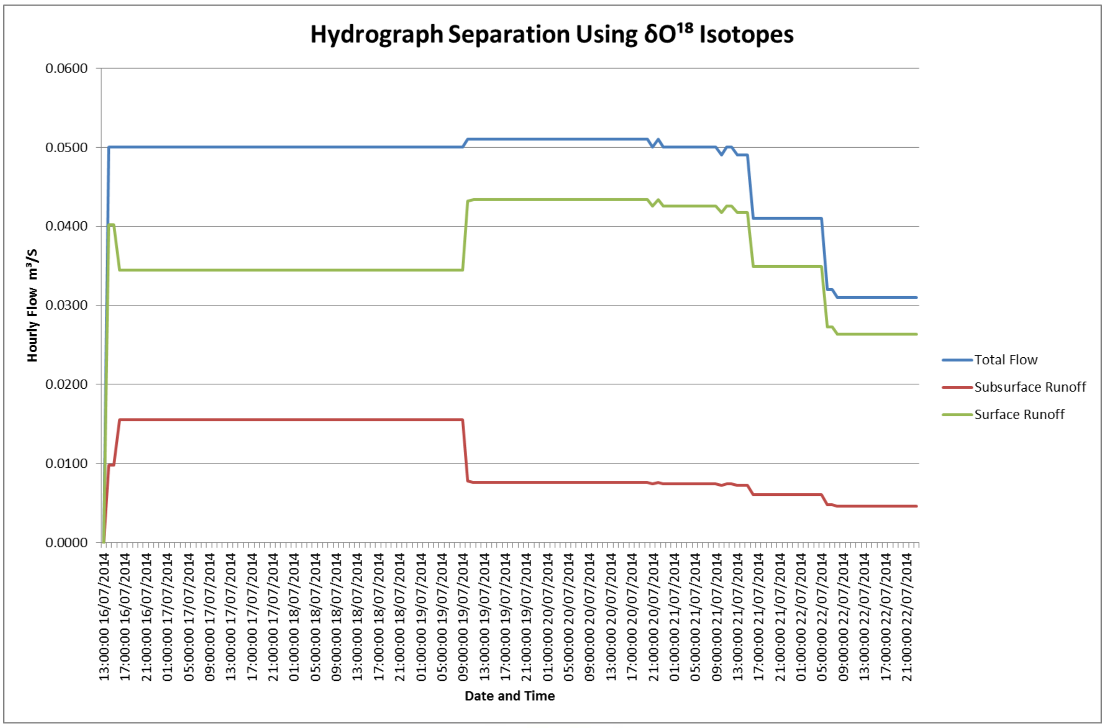


Figure 4.21: Hydrograph separation for the first event 16-19 July. The Graph indicates a greater contribution of surface runoff to storm flow than groundwater. The use of isotopes was only applicable for one storm event.

At the onset of Event 1, Si indicated surface runoff contributes predominantly to total flow, over groundwater (Figure 4.22). In comparison to $^{\delta 18}$O hydrograph separation, Si underestimates the contributions of groundwater and overestimates the contributions of surface runoff for Event 1. There was a small increase in total flow. During this period groundwater contribution increased slightly, whereas surface runoff contributions slightly decreased. After rainfall had ceased surface runoff continued to contribute to storm flow and groundwater contributions ceased. Surface runoff contributions for Event 1 were 98.6 %, whereas groundwater contributions for Event 1 were only 1.4 %. When rainfall started during Event 2, surface runoff contributions started to decrease, whereas groundwater contributions started to increase. However, this was not enough to readily increase total flow. As Event 2 continued a change in the dominating flow component occurred, which indicated that changes occured between events. Surface runoff contributions decreased and groundwater contributions increased. The contributions for surface runoff for Event 2 had decreased to 66.9 % and groundwater contributions had increased to 33.4 %. The changes in the contributions of surface runoff and groundwater indicate that under certain conditions groundwater may contribute more to total flow than surface runoff. These conditions may include increased soil moisture or increased rainfall. This is in the same as the one parameter algorithm results, whereby groundwater contributions become dominant only when a) there has been rainfall to induce flow within the river during previous storm events, and b) when significant rainfall occurs during a single Event such that groundwater may become the dominant contributor. Rainfall that occurred from the onset of Events 1 and 2 was enough to induce flow in the river. Groundwater contributions can only maintain storm flow for a short period. Groundwater contributions may be minimal due to low antecedent soil moisture conditions. Under higher soil moisture conditions, groundwater may become the dominant contributor to flow and increase flow within the river.

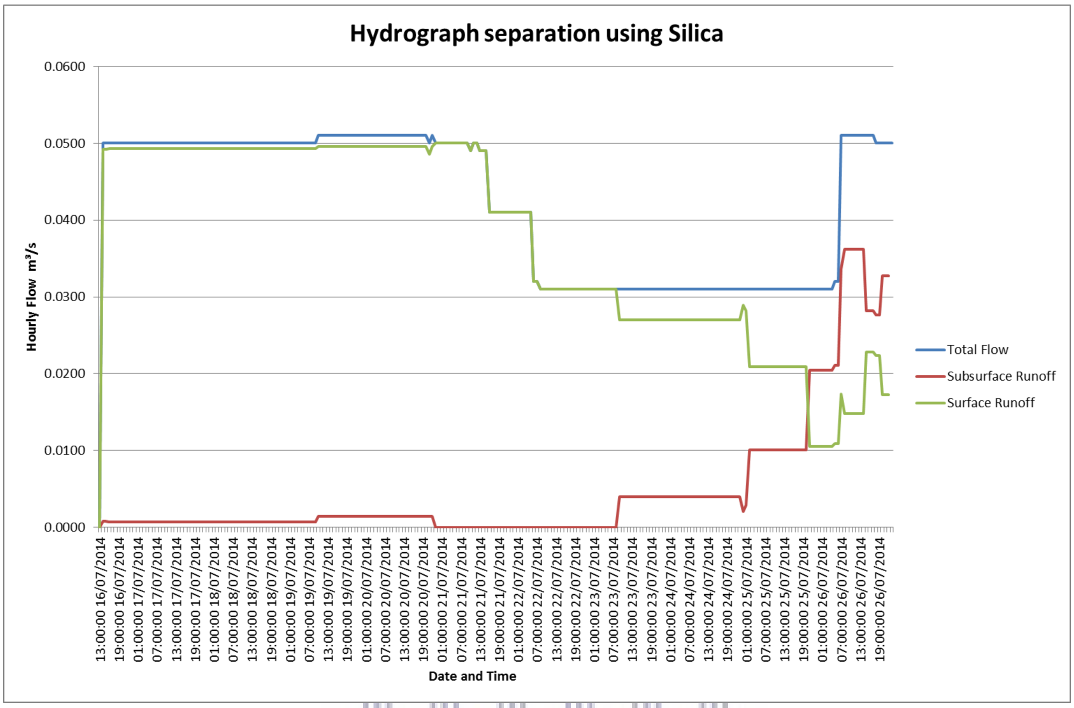


Figure 4.22: Two component hydrograph separation Using Silica for storm events 14-19 July and 22-26 July. The graph indicates a minor contribution of rain water to flow at the onset of the event. Groundwater is the dominant contributor to storm flow. During baseflow conditions storm water indicates a delayed contribution to flow.

A comparison between baseflow separation using a one parameter algorithm and tracer-based separations, indicates significant differences in the relative importance of surface runoff and groundwater contributions to storm flow (Figure 4.20). Baseflow separations indicate that surface runoff is the more dominant contributor to flow than groundwater. The observations made during tracer-based separations indicate differently. Tracer observations using both silica and δ18O indicate that at the onset of storm surface runoff is the dominant contributor to storm flow. Though the tracers indicate that the proportions of surface runoff and groundwater between the two tracers are different there is a general consensus that for Event 1 at least, surface runoff is the dominant contributor to storm flow. Due to the atypical nature of the hydrograph i.e. no clear peaks, the hydrograph for Event 2 and the low flow conditions of an isotope separation could not be done.

4.10 The Influence of catchment characteristics on the contributions of flow components

To determine the effects of catchment characteristics on surface and subsurface flow to the Sandspruit, water chemistry and groundwater levels were analysed in order to determine the influence of elevation and geology. This is presented in the below sections.

4.10.1 Elevation and geology

The change in elevation of the Sandspruit Catchment has an influence on the slope of the water table. Measured water levels at the boreholes within the catchment indicate a difference in the height of water above sea level. The below graphs indicate the changes in groundwater level from high elevations to low elevations (Figure 4.23 and Figure 4.24). Very little change in groundwater levels was observed between Event 1 and 2.

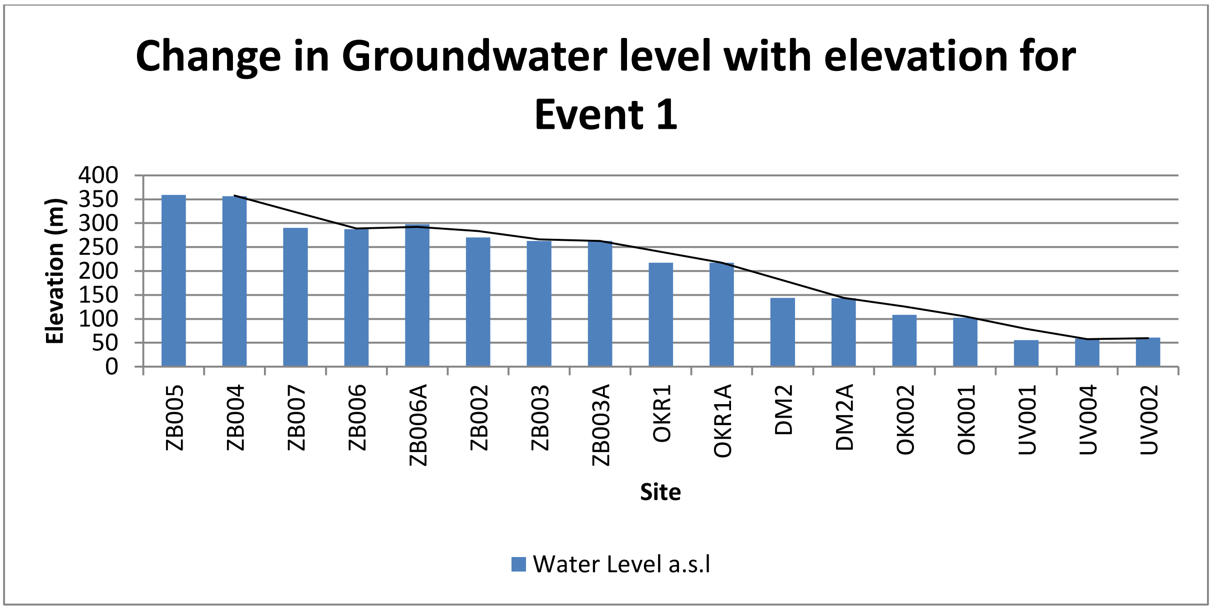


Figure 4.23: The above graph indicates the apparent slope in water level with decreasing elevation for Event 1.

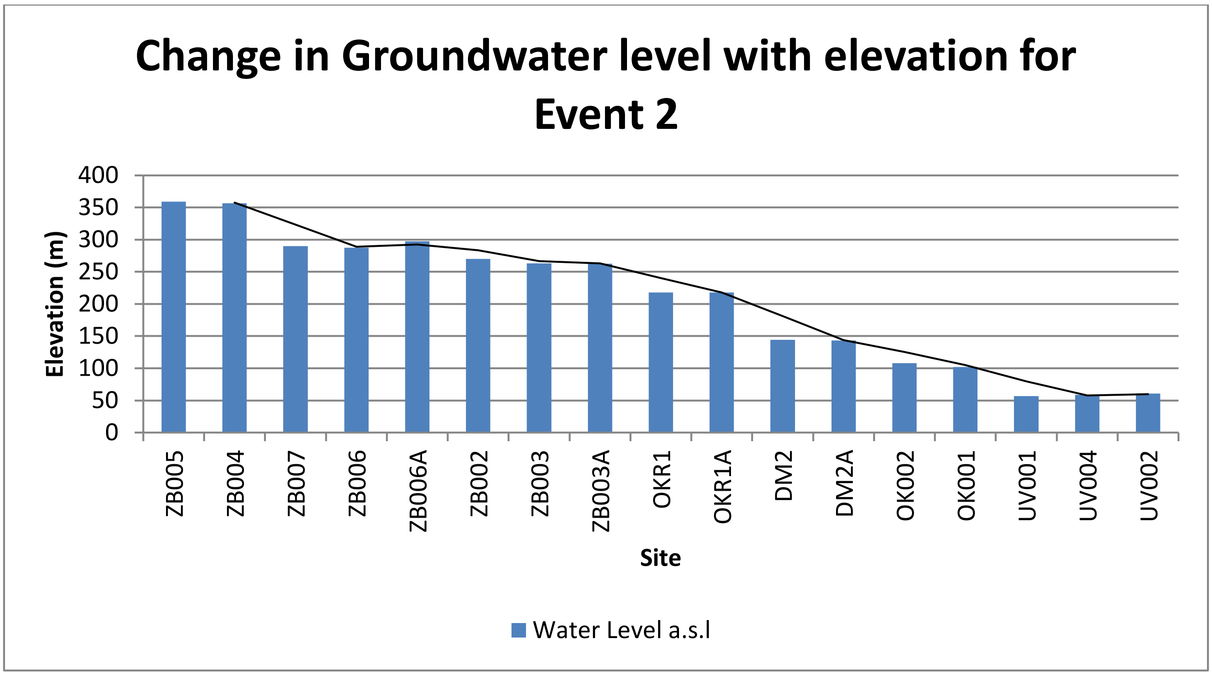


Figure 4.24: The above graph indicates the apparent slope in water level with decreasing elevation for Event 2.

Elevation also has a major influence on surface runoff. The upslope accumulated area map indicates that area of the catchment that directs water to the outlet (Figure 4.25). In the case of the Sandspruit, most of the catchment directs water towards the outlet. The fact that both surface runoff and sub-surface runoff follow elevation further indicates that there is some connectivity between the two components and that elevation has a strong influence on runoff production. The flow accumulation map that was generated indicates that the Sandspruit receives flux from another source of water other than surface runoff. This is indicated by the negative values received when the map was generated (Figure 4.26). This other source of water could be groundwater, as based on the hydrograph separation results groundwater does flow towards the stream.

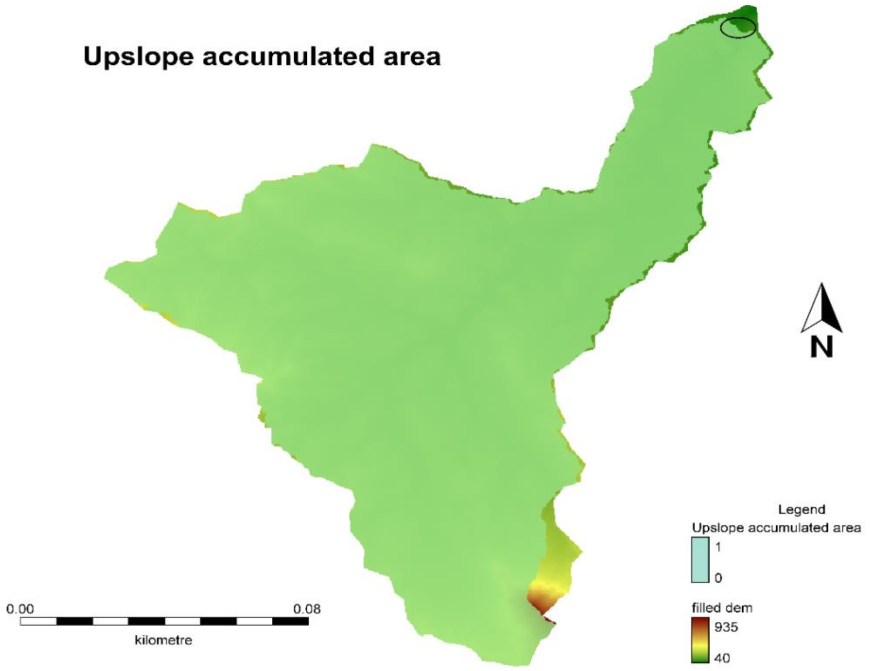


Figure 4.25: Upslope Accumulated area of the Sandspruit Catchment. The map indicates that water entering the Sandspruit Catchment flows downstream towards the Outlet. The catchment outlet is circled in black.

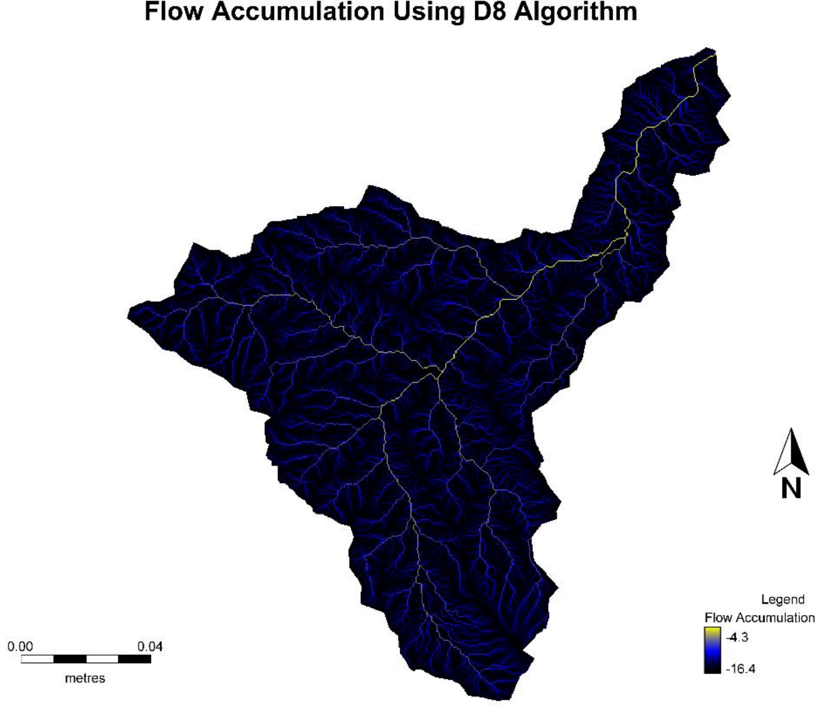


Figure 4.26: Flow Accumulation map of the Sandspruit Catchment. Negative values indicate that the Sandspruit receives flux from outside sources such as groundwater.

Boreholes within the Sandspruit Catchment penetrate the Malmesbury shales with the exception of two boreholes in the lowest reaches of the catchment which penetrate fine sediments of the Springfontyn Formation (Figure 4.27). Hydrologic connectivity of groundwater and surface water was determined by monitoring groundwater. Hydrologic connectivity was inferred from the measured groundwater levels and surface water levels above sea level. If groundwater levels were higher than stream level, then hydrologic connectivity was present. Table 4.5 indicates which boreholes indicated hydrologic connectivity.

Table 4.5: The table indicates the average measured water levels in boreholes across the catchment. Sites labled N/A have no stream reach nearby.

Borehole No.	Groundwater Level (m.a.s.l)	Surface water Level (m.a.s.l)	Geology of Borehole	Connectivity Yes/No
ZB005	358.803	364	Malmesbury Shale	No
ZB004	356.39	364	Malmesbury Shale	No
ZB007	289.971	N/A	Malmesbury Shale	N/A
ZB006	287.287	269	Malmesbury Shale	Yes
ZB006A	297.444	269	Malmesbury Shale	Yes
ZB002	269.975	269	Malmesbury Shale	Yes
ZB003	262.91	269	Malmesbury Shale	No
ZB003A	262.85	269	Malmesbury Shale	No
OKR1	217.49	218	Malmesbury Shale	No
OKR1A	217.507	218	Malmesbury Shale	No
DM2	144	N/A	Malmesbury Shale	N/A
DM2A	143.37	N/A	Malmesbury Shale	N/A
OK002	108.315	105	Malmesbury Shale	Yes
OK001	102.09	105	Malmesbury Shale	No
UV001	55.73	43	Malmesbury Shale	Yes
UV004	58.75	43	Fine sediment	Yes
UV002	60.87	43	Fine Sediment	Yes

Hydrologic connectivity between groundwater and surface water was observed at 7 locations across the Sandspruit Catchment. These areas included boreholes drilled into both Malmesbury shales and Fine sediments. Boreholes that indicate connectivity to the Sandspruit are circled in green (Figure 4.27). groundwater flows to the stream.

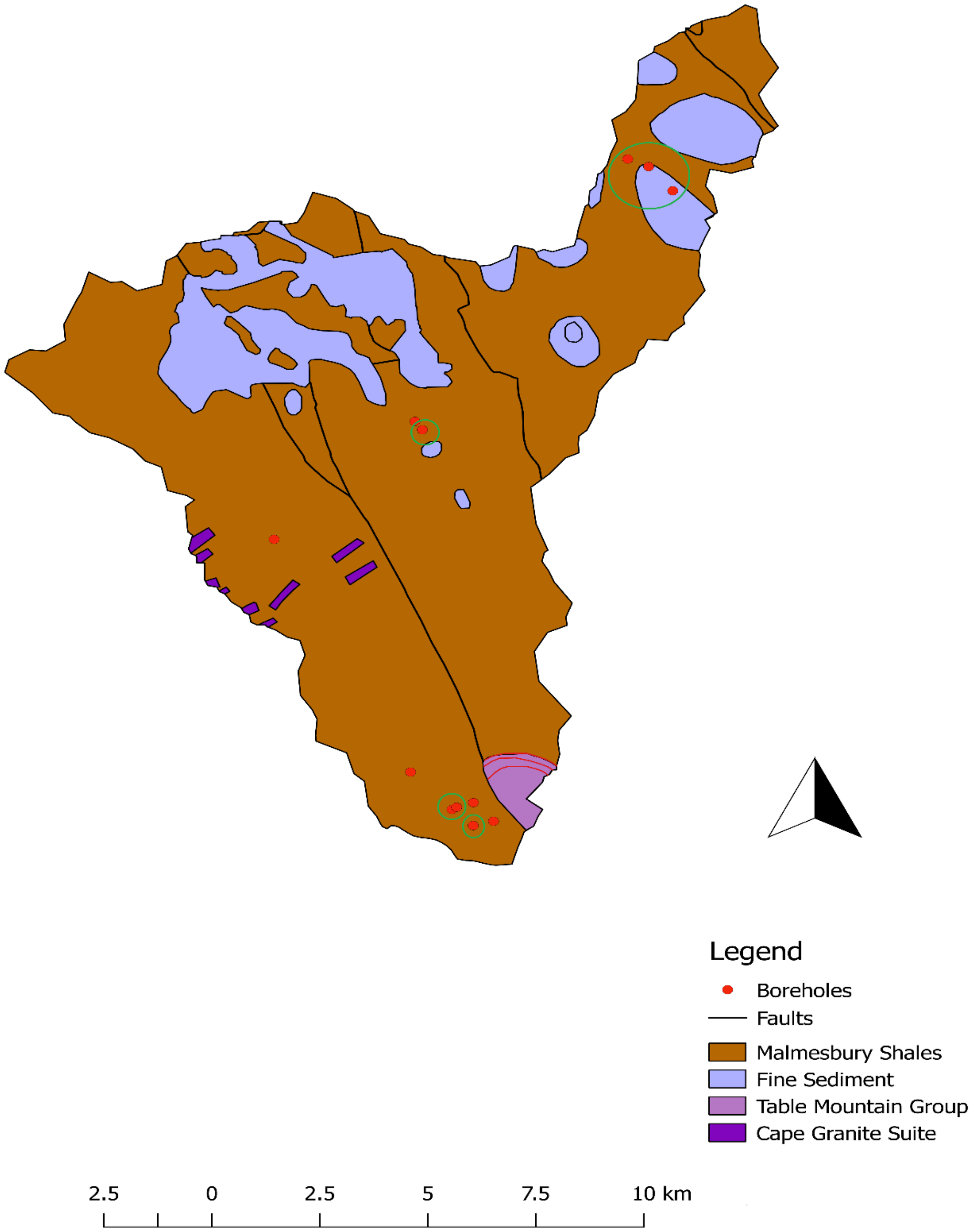


Figure 4.27: Location of boreholes in the Sandspruit Catchment and the geological layers they penetrate. Boreholes that indicate hydrological connectivity based on the water table height above sea level are circled in green.

According to the aquifer yield map, boreholes in the middle catchment have the highest yield. This is partly due to the presence of faults in that part of the catchment that serve as a preferential flow paths for groundwater. Consequently, areas where hydrologic connectivity was observed are also areas where faults occur within the Sandspruit Catchment. This indicates that there is a clear influence of geology on runoff generation (Figure 2.8).

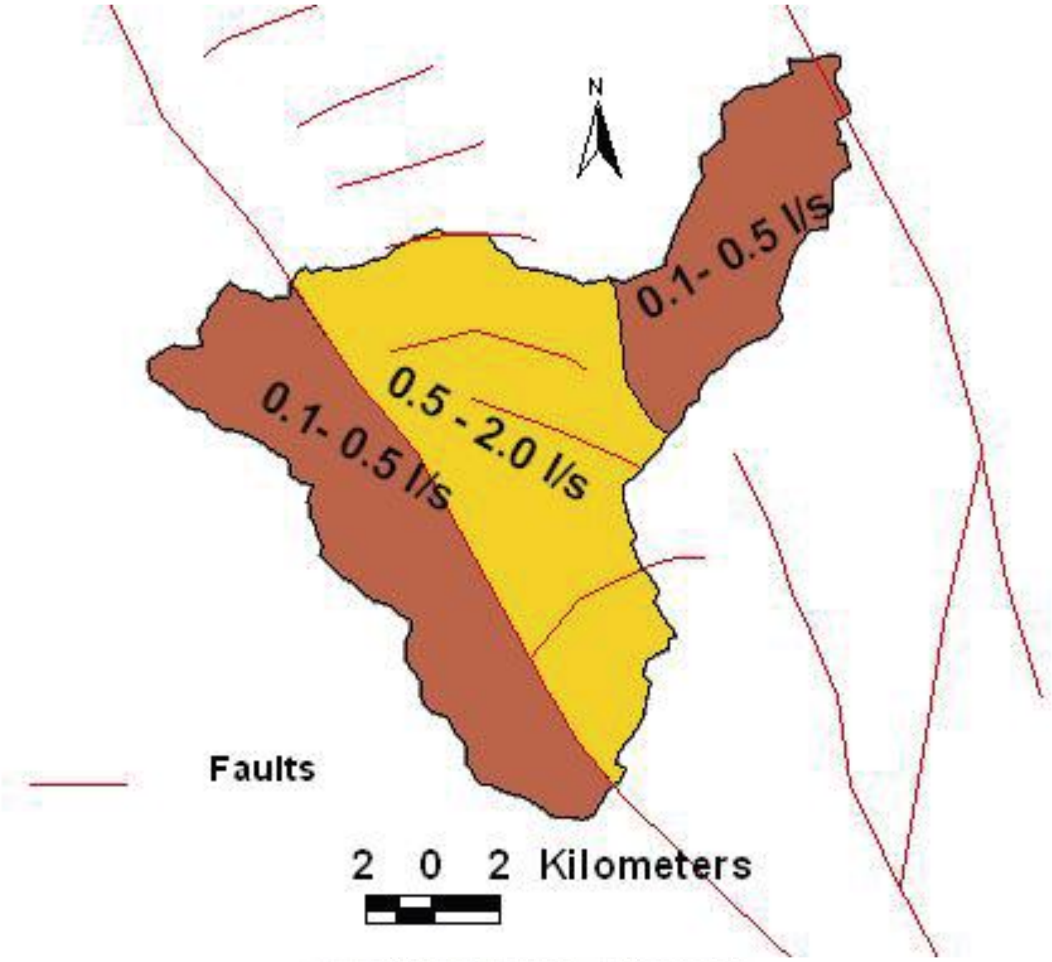


Figure 4.28: Fault zones and groundwater flow rates (Jovanovic *et al.*, 2011)

4.11 Conclusion

Hydrograph separations were done using two techniques, which included automated baseflow separation with a one parameter algorithm and a tracer-based separation using $\delta^{18}O$ and Silica. The automated baseflow separation indicates that at least one storm event is required before groundwater becomes the dominant contributor to flow. This could be indicative of a trigger effect such as increased soil moisture or increased water tables at such times. During this first storm event, surface runoff is the dominant contributor to flow. Tracer separations based on Silica indicate similarly, whereby at least one storm event is required before there is an increase in groundwater contributions. The relationship between silica tracers and flow is directly proportional, whereas with isotopes it is conversely proportional. Changes in flow are reflected in tracer concentrations. So if flow increases then silica concentrations increase, and isotope concentrations due to their complex nature, decrease.

Chapter 5 : Conclusion

An investigation was done to determine the relative importance of surface runoff and groundwater to storm flow and the influence of catchment characteristics, as well the variations of these contributions. In order to determine the relative importance of contributions, historical data was analysed using a one parameter algorithm and two individual storms were used and analysed. The influence of catchment characteristics was analysed using maps.

Rainfall was one of the important elements of each storm event that was observed and analysed. During the year 2014 there were 86 days of rainfall that occurred from January to September. Rainfall distribution during the rainy season from May to September occurs regularly with a minimum of 1 day between rain events and a maximum period of 6 days with no rain on two occasions only. The typical duration of rainfall events is usually for a few days and can last up to several hours during most days with rainfall.

The catchment experienced total rainfall of 405.4 mm/yr and only 8.01 mm/yr. The runoff coefficient was very low at 0.02, which means on 2% of rainfall became flow in the Sandspruit. This could be a result of a lack of rainfall prior to the study period. As a result rainfall most likely replenished soil moisture, before surface runoff could be induced. The Sandspruit is non-perennial, which is typical of a semi-arid region.

Runoff variations for the Sandspruit are dependent on rainfall. If no rain occurs for 7 to 10 days flow will cease. However if rain occurs within 7 days, the Sandspruit will continue to flow and increases in flow will be observed. Flow usually starts within a few hours up to a few days after a storm event within the Sandspruit. This is dependent on the amount of rainfall and the antecedent soil moisture at the time of rainfall. Flow in the Sandspruit Catchment normally stops after 7 days of cessation of rainfall. The magnitude of flows during the investigation period were very low as the maximum flow recorded was only 0.051 m^3/s. The duration of storm runoff for the investigation period was 5 days, thereafter flow would decrease rapidly. The Sandspruit's response to rainfall indicated that flows started within a few hours after the onset of rainfall. Flow recession starts 5 days after the onset of flow, and continues until flow ceases or the next storm event.

Water table variations within the catchment indicate an increasing trend from the start of the sampling period to the end of the sampling period. Water table variations observed in shallow boreholes indicated that these located in the upper part of the catchment increase gradually from the start to the end of the rainy season. Shallow boreholes in the middle of the catchment indicated minimal changes in water levels. Deep boreholes in the upper and lower catchment indicated increases in flow from the start of the end sampling period. Boreholes in the middle catchment zone indicated virtually no change in water level. This could be due to the borehole being located in a part of the catchment where groundwater flow is high. Water level changes indicated a clear response to the input of rainfall, but changes in water levels only increase gradually as the rainy season progresses. Water levels for boreholes in both the upper and lower catchment zones generally increased by a few centimetres per storm event. The observed water levels within the different zones in the catchment indicated varying responses. Boreholes in the upper catchment zone have the highest increases in the observed water levels. Water levels in the lower catchment zone increase but only by a few metres by the end of the rainy season, due to water being released from storage and low rainfall amounts.

Catchment characteristics play a significant role in the movement of water, as well as the direction in which water flows. Flow of water is controlled by geology, elevation and slope. In areas where faulting occurs flow of groundwater is higher than in areas where little to no faulting occurs. The influence of elevation on flow direction was also found to be significant. Elevation has a strong influence on the flow direction groundwater as it moves toward the catchment outlet.

The results from the one parameter algorithm indicated that when flow in the catchment starts, it is almost always composed of surface runoff predominantly. For changes in the proportion of contributions to occur and for groundwater to become the dominant flow component, at least a previous event should have “wet” the catchment or there should be a significant amount of rainfall in a single event in order for groundwater to become the dominant flow component.

Hydrograph separation was done using tracers and indicated a similar trend as that of the one parameter algorithm, whereby surface runoff is the dominant contributor to flow for the first event and groundwater is the least dominant. However, the calculated proportions of tracer-based separations in comparison to automated separations differ. The isotope results proved reliable for Event 1, surface runoff was the dominant contributor to storm flow. During Event 2, isotopes could not be used to separate the storm hydrograph, as flow at the start of the event was too low. Silica separations indicate that surface runoff for Event 1 was almost the only contributor to storm flow and that groundwater contributions were minor. At the end of Event 1 when rainfall had ceased and flow decreased, surface runoff became the dominant contributor to flow. During Event 2 conditions indicate a change towards the end of the event, whereby groundwater becomes the dominant contributor to flow. The best method for separating the hydrograph within the Sandspruit catchment is tracer-based, as it provides a more complete separation and is not biased to one specific component. In the instance whereby a tracer-based separation cannot be done, baseflow separation using the one parameter algorithm can be used, as similar trends were observed as tracer-based separations.

The influence of flow components on salinity is dependent on the dominant flow components. Salinity enters the Sandspruit Catchment by atmospheric deposition and is stored in the regolith, and existing salt which occurs in the catchment is derived from weathered shales. Considering the results obtained for hydrograph separations, salinity in the Sandspruit is likely to only increase when groundwater is the dominant contributor to flow as salt already exists in the water from weathered shales and soil. Under conditions where groundwater flow is dominant, water that moves down from the surface to the water table displaces salt to the water table. The increase in salts in the groundwater is more likely to leach out into the river. When the water table rises, salts stored in the upper layers of soil are also more likely to dissolve and be leached out into the river. Salts stored in upper soil layers by rising groundwater levels may also have an impact on river salinity especially when considering soil water contributions. In the instance where surface runoff is the dominant flow component, salinity may increase but not as much as when groundwater flow is the dominant flow component. The results obtained for the flow components may be used to direct water managers going forward in managing salinity. The types of techniques employable in order to reduce the release of salts from storage may thus be refined and tested. Possible techniques may include replanting of indigenous flora to reduce groundwater levels and a reduction in water abstractions.

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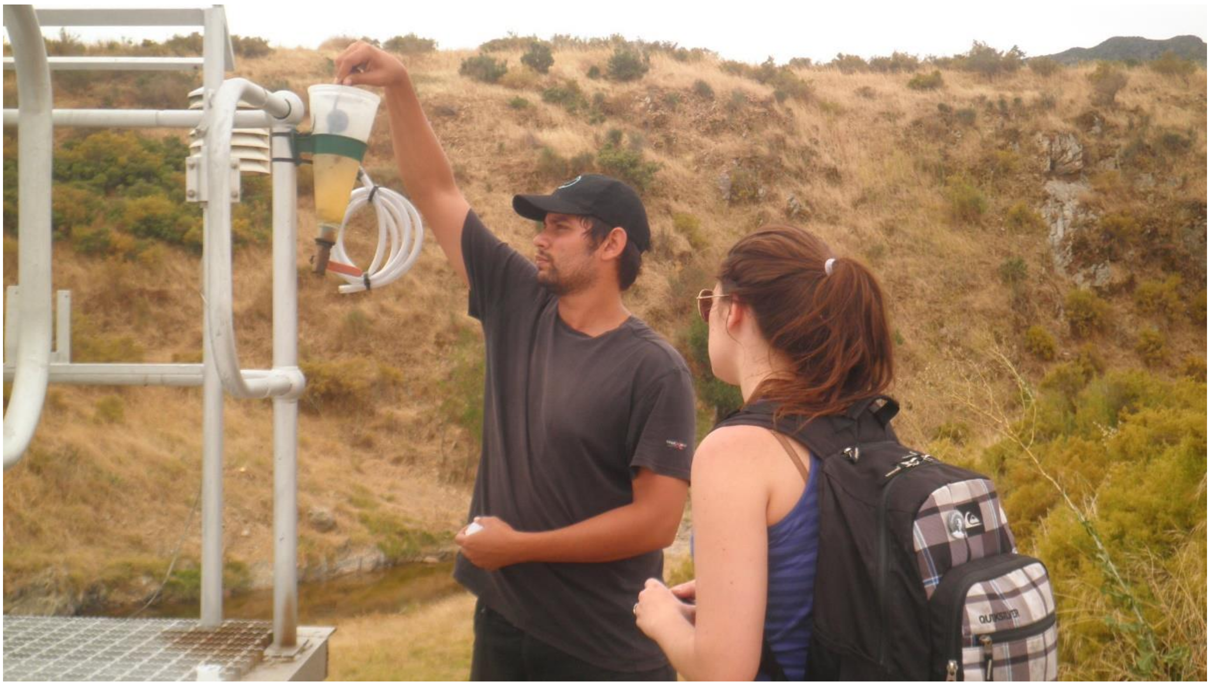
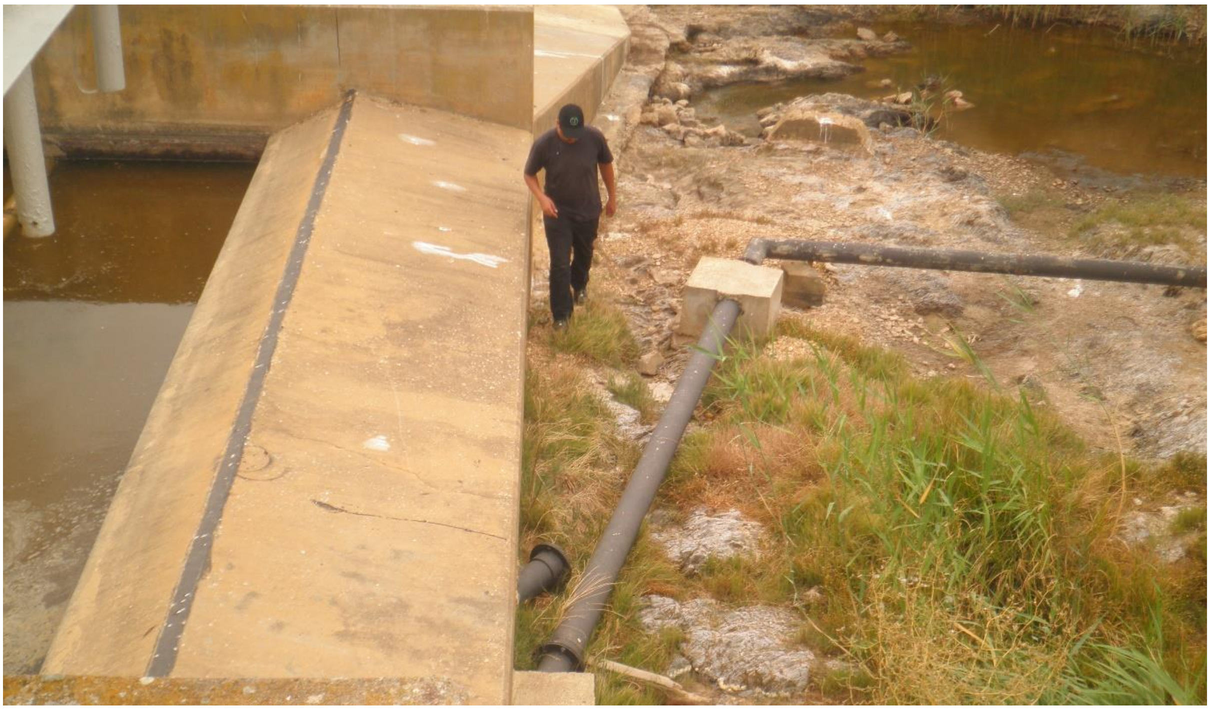
Appendices

Appendix 1: Borehole purging at UV002



Appendix 2: Rainwater Sampling in The Sandspruit Catchment



Appendix 3: Surface water Sampling in the Sandspruit Catchment

Appendix 4: Isotope Sample preparation and analysis