

The Hydrogeological Characterization of Vegter Region 39: Eastern Upper Karoo

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Author

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Abstract

Over the past 50 to 60 years the Geological Survey and Department of Water and Sanitation (DWS) have carried out numerous local groundwater investigations as well as a number of regional surveys and studies. A large volume of data, reports, and information have thus been accumulated to which other organizations have contributed as well. The last 10 to 15 years saw the establishment of an electronic National Groundwater Archive (NGA) currently containing in excess of 200 000 boreholes. Despite the amassed data and information, the goal of characterising the country's groundwater resources still remain out of reach.

The focus of this study was to establish a methodology for the delineation of hydrogeological regions within the eastern upper Karoo, South Africa, based on the method that was employed by Vegter (2001). The methodology is based on three parameters, namely water level, strike depth, and EC. The delineation of the sub-regions will provide a rough estimate for the siting of boreholes and additionally provide more manageable hydrogeological units for future events.

Satisfactory model calibration was achieved, although the lack of appropriate data necessitated various assumptions in the model setup. The application of the calibrated model assisted in the interaction as well as the estimation of the available groundwater in the region.

Keywords: hydrogeological regions; numerical modelling; groundwater – surface water interaction; eastern upper Karoo, South Africa

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List of Abbreviations

CFB	Cape Fold Belt
CMB	Chloride Mass Balance
CRD	Cumulative Rainfall Departure
CWB	Channel Water Budget
DWS	Department of Water and Sanitation
EARTH	Extended model for Aquifer Recharge and Moisture Transport through Unsaturated Hardrock
EC	Electrical Conductivity
EV-SF	Equal Volume - Spring Flow
FCC	False Colour Composite
Fm.	Formation
GD	Groundwater Dating
GIS	Geographic Information System
GM	Groundwater Modelling
GRDM	Groundwater Resource Directed Measures
HS	Hydrograph Separation
K	Hydraulic Conductivity
KGEG	Karoo Groundwater Expert Group
M.	Member
MAP	Mean Annual Precipitation
NGA	National Groundwater Archive
RMD	Resource Directed Measures
SVF	Saturated Volume Fluctuation
TDS	Total Dissolved solids
UFM	Unsaturated Flow Modelling
VES	Vertical Electrical Sounding
WTF	Water Table Fluctuation
ZFP	Zero Flux Plane
NSE	Nash-Sutcliffe Efficiency

1 INTRODUCTION

Water is crucial for all of man's activities on earth, particularly fresh and potable water. Although the Earth's surface consists of 71% water, only a small fraction, approximately 2.8% of the total water on Earth, can be used as fresh water by mankind. Approximately 75% of the total volume of fresh water on Earth occurs in glaciers, while 0.33% of the fresh water is contained in lakes and rivers. Groundwater occurs as the remaining 24.67% (Botha *et al.*, 1998). The fresh water that is frozen in the glaciers are not available for general consumption, therefore the largest source of fresh water for mankind is in the form of groundwater.

The aquifers in South Africa occur mainly in hard rock formation, which complicates the situation, due to this the groundwater in South Africa is usually regarded as an unreliable source of fresh water. Due to the under-utilization of the groundwater, the surface water resources have now almost been exploited to its limits. The expanded use of groundwater in South Africa thus plays an important role in relieving the strain on the over-exploitation of the surface water. This is especially true in the arid western and central region, which covers approximately 66% of South Africa, where there are no major rivers or other surface sources (Botha *et al.*, 1998). The majority of the inhabitants in this region therefore rely heavily on groundwater for daily use such as, irrigation, livestock, and domestic water supply. The largest geological formation in South Africa is the Karoo Supergroup, which covers approximately 50% of the country. The possibility thus exists that the aquifers located within the Karoo Supergroup can make a momentous contribution to the water budget of the country. The general view is that the Karoo aquifers are not a reliable source of water. There are however occurrences of boreholes that have provided the residents of towns and farms with water successfully on a sustainable basis for many years.

The majority of boreholes drilled in the Karoo sediments have a very low yield which is $< 3.6 \text{ m}^3 \text{ h}^{-1}$. This is due to the characteristics of the Karoo Supergroup which mainly consists of mudstone, sandstone, siltstone, and shales (Botha *et al.*, 1998). Vegter (2001) thus developed a methodology to effectively describe the occurrence of groundwater in a largely complicated geological area as in South Africa by the delineation and division of sub-regions that have uniform occurrence characteristics.

1.1 AIMS

The aim of the study is to develop a methodology to subdivide Vegter region 39: Eastern Upper Karoo into smaller, more manageable units to determine how groundwater conditions differ over the immense region.

1.2 RESEARCH OBJECTIVES

To achieve the aim of this research project, the following objectives are set:

- Analyze and present the related groundwater data in a concise manner
- Delineation of the subdivisions of the region
- Estimate groundwater recharge and discharge (including groundwater/surface-water interactions) to determine the available yield.

2 LITERATURE REVIEW

Over the past 50 to 60 years the Geological Survey and Department of Water and Sanitation (DWS) have carried out numerous local groundwater investigations as well as a number of regional surveys and studies. A large volume of data, reports, and information have thus been accumulated to which other organizations have contributed as well. The last 10 to 15 years saw the establishment of an electronic National Groundwater Archive (NGA) currently containing in excess of 200 000 boreholes.

Groundwater characterisation entails (Vegter, 2001):

- Ascertaining the hydrogeological characteristics of groundwater occurrence
- Delineating hydraulic groundwater units
- Determining the hydraulic characteristics - transmissivity, storage etc.
- Estimating groundwater recharge and discharge
- Ascertaining chemical composition and potability of groundwater
- Establishing the current state of and potential for development
- Predicting the effect of groundwater exploitation on the environment and of environmental change on groundwater availability and quality

Despite the amassed data and information, the goal of characterising South Africa's groundwater resources as defined by the above, still remains out of reach. This fact, however, does not discount the desirability, if not necessity of compiling and synthesizing what is currently available.

2.1 CRITERIA FOR THE DIVISION OF SOUTH AFRICA IN GROUNDWATER REGIONS

Fundamental to groundwater hydrology is the concept of interstices, the open spaces that form receptacles and conduits for groundwater, their origin, shape, and interconnection (Vegter, 2001). The types and origins of openings, therefore may be considered to be a basis for the delineation of Vegter's sub-areas.

Primary openings or pores originate contemporaneously with genesis of the sedimentary formation and igneous rocks in which they occur. Primary openings in igneous and metaphoric rocks are generally of no consequence in groundwater hydrology, owing to their minute size and lack of interconnection (Vegter, 2001). During the lithification of sediments, primary openings are reduced in size by the physical-chemical processes of consolidation, compaction, cementation and re-crystallisation. The degree of diagenesis and metamorphism determines to what extent a sedimentary rock retains primary porosity and permeability or is converted into solid rock (Vegter, 2001).

Secondary openings originate from processes that affect rocks after they were formed. These processes are tectonic deformation, weathering, and unloading by degradation of the land surface

(Vegter, 2001). Secondary openings are planar, where formed along cleavage, joint, bedding and fault planes. They also consist of pores in disintegrated and decomposed rock.

From the water bearing point of view, geological formation, therefore, may be divided in two groups, those that are water bearing, basically as a result of:

- Primary openings or
- Secondary openings.

The transmissivity of primary water bearing rock may be enhanced by the presence of secondary openings. In the case of secondary water bearing rocks primary openings, if present, contribute to storage capacity.

Note that the term "aquifer" has been avoided because it describes that only part of a body of water bearing rocks, which is capable of transmitting groundwater rapidly enough to directly supply a borehole or spring. The term water bearing as used in this context describes saturated material consisting of highly variable proportions of permeable (aquifer), semi-permeable (aquitard), and impermeable (aquifuge) material.

Approximately, over nine tenths of the country's area, rocks are water bearing by virtue of secondary openings, for example, water is obtained from weathered and fractured hard rock formations ranging in age from earliest Pre-Cambrian to Jurassic and comprising sedimentary, metamorphic, extrusive and intrusive igneous rocks (Vegter, 2001). Therefore, the division of South Africa on the basis of primary and secondary water bearing hard rock formations clearly will be ineffective.

Extensive primary water bearing strata are confined to the coastal belt. They are readily divisible into separate entities. This does not apply to the patchy occurrence of narrow strips of water bearing alluvial deposits along rivers (Vegter, 2001). In the context of a regional subdivision, the alluvial deposits have to be treated as components of larger secondary water bearing units. The basis of subdividing the secondary water bearing hard rock formations will be discussed below (Vegter, 2001).

The occurrence and availability of groundwater at any locality is determined by (Vegter, 2001):

- the storage and transmissive properties of the geological formation;
- the volume and frequency of recharge;
- the rate of groundwater movement to discharge points/areas;
- the rate of groundwater discharge as springs and effluent seepage in streams; and
- loss through evapotranspiration.

Because rock type and locally developed structural and other characteristics govern, to a certain extent, the water bearing properties, lithostratigraphic subdivision may well serve as a primary basis for subdivision into groundwater regions. A lithostratigraphic unit is one which is unified by consisting dominantly of a certain rock type or a characteristic combination of rock types or by possessing other significant unifying lithological features, for example - distinctive colour, primary structures etc. (Kent, 1980).

Recharge, on the other hand, depends on:

- rainfall: volume, intensity, frequency, and temporal distribution;
- availability of surface water;
- land surface configuration:
- soil and vegetative cover and;
- subsurface moisture retention and evapotranspiration.

These factors are naturally related to climate and physiography. By restricting the size of regions, wide variation of climate and rainfall are obviated.

Besides transmissivity, the rate of groundwater movement is determined by the hydraulic gradient, which, in turn depends on topographic relief. Surface configuration is, furthermore, one of the factors controlling discharge and loss of groundwater. Conformity between lithostratigraphic units and physiographic features strengthens the case of lithostratigraphy as a primary basis of subdivision.

In delineating groundwater regions, Vegter's aim therefore, was to obtain some degree of uniformity in respect of lithostratigraphy, physiography and climate without ending up with an unmanageable number of regions.

2.2 SUBDIVISION INTO GROUNDWATER REGIONS

As stated above Vegter used the origin of the interstices for his initial division of the groundwater regions, namely:

- A.** Regions consisting mainly of primary water bearing formation. Hard rock formations underlying primary water bearing formation may act in places as aquifers.
- B.** Regions consisting mainly of secondary water bearing formations. Fluvial deposits are included. Regions have been classified further into principle rock type and erathem/system.

2.2.1 A. Regions consisting mainly of primary water bearing formation.

A summary of these regions are documented in **Error! Reference source not found..**

Table 1: Regions composed of tertiary/ quaternary formation (Vegter, 2001)

Groundwater regions		Principal rock types
No.	Name	
60	Die Kelders Embayment	Bredasdorp Group calcarenite, sandstone, conglomerate, sand underlain by Bokkeveld Group shale
61	Bredasdorp Coastal Belt	Bredasdorp Group calcarenite, sandstone, conglomerate, sand underlain by Bokkeveld Group shale
62	Stilbaai Coastal Belt	Bredasdorp Group calcarenite, sandstone, conglomerate, sand underlain by Bokkeveld Group shale
65	North Zululand Coastal Plain	Maputoland Group conglomerate, calcarenite, limestone, sand underlain by Cretaceous Zululand Group formations.

2.2.2 B. Regions consisting mainly of secondary water bearing formations.

The hard rock area of South Africa was subdivided into groundwater regions on the basis of both lithostratigraphy and physiography (Vegter, 2001). The regions in turn were classified according to the main type of water bearing rock as follows:

- B1** Crystalline metamorphic and igneous
- B2** Intrusive
- B3** Extrusive
- B4** Sedimentary
- B5** Composite - Regions where no major rock type is preponderant, several major lithostratigraphic units are involved, and more extensive primary aquifers than alluvial deposits are present.

2.3 METHODS FOR ESTIMATING RECHARGE AND DISCHARGE

Groundwater-surface water interaction and recharge in fractured rock aquifers are poorly understood phenomena. The number of studies focusing on these phenomena have been scarce. These studies point out that basic assumptions regarding groundwater recharge and discharge in porous media are not necessarily relevant in a fractured bedrock environment (Praamsma *et al.*, 2008).

2.3.1 Recharge

The term groundwater recharge was defined in a broad sense by Xu *et al.* (2003) as "an addition of water to a groundwater reservoir" and can be expressed in various forms, such as a percentage of Mean annual precipitation (MAP), or in mm/year. There are four modes of recharge that can be distinguished (Xu *et al.*, 2003):

1. Downward flow of water through the unsaturated zone reaching the water table
2. Lateral and/or vertical inter-aquifer flow
3. Induced recharge from nearby water bodies resulting from groundwater abstraction
4. Artificial recharge, such as from borehole injection or man-made infiltration ponds

One of the most important mode of recharge in semi-arid and arid region is that of natural recharge by the downward flow of water through the unsaturated zone. Mechanisms of moisture transport and infiltration that are expected to occur for this mode are illustrated in Figure 1. The major sources of recharge are surface water bodies (Perennial and non-perennial rivers, estuaries, and lakes), rainfall and irrigation losses.

Determining the groundwater recharge in arid and semi-arid region is neither easy nor straightforward. This is due to the time variability of rainfall in arid and semi-arid climates, and topography, land use, spatial variability in soil characteristics and vegetation (Lerner *et al.*, 1990). Furthermore, recharge amounts are generally small in comparison with the resolution of the investigation methods. The recharge flux is smaller and potentially more variable with an increase in the aridity of the climate (Allison *et al.*, 1994).

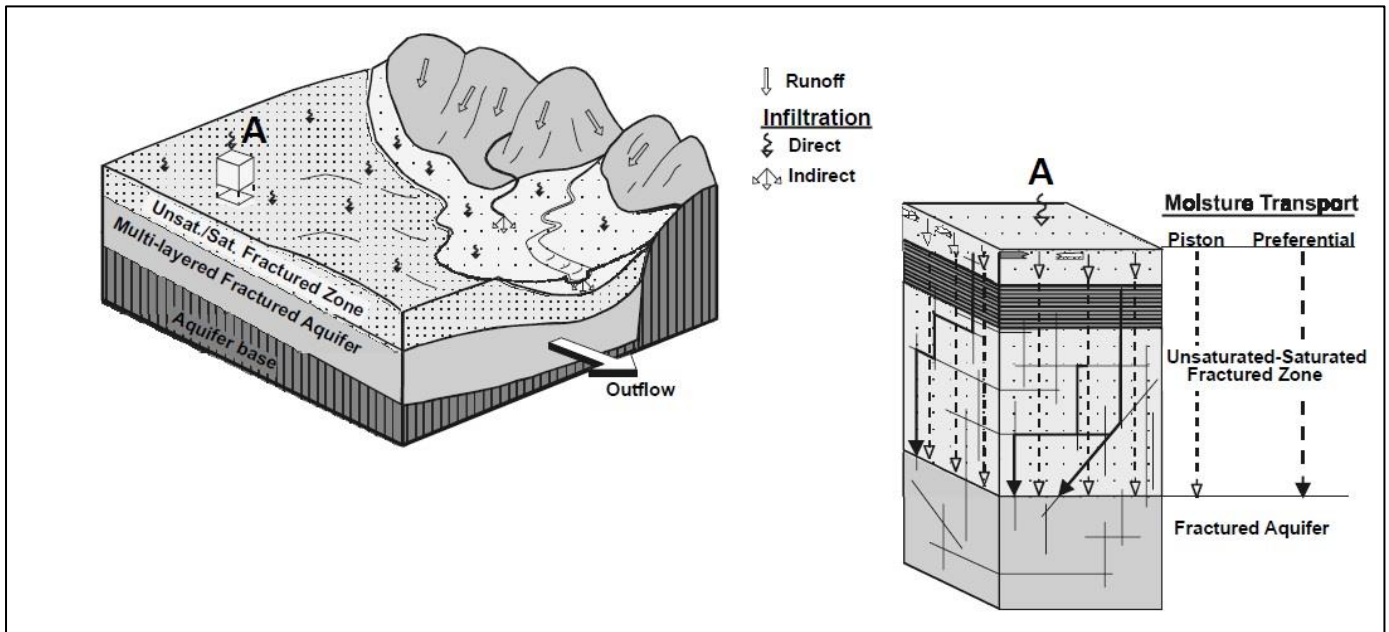


Figure 1: Mechanisms of infiltration and moisture transport (Beekman *et al.*, 1996)

There are as many methods available for estimating groundwater recharge as there are different processes and sources of recharge. All of these methods have its own limitations in terms of reliability and applicability. An overview of recharge estimation methods generally used in Southern Africa was summarized by Xu *et al.* (2003)

The methods mentioned in Xu *et al.* (2003) are grouped according to hydrological zones and further sub-divided into tracer and physical approaches. A short description is given for each method. Methods referring to the saturated zone, estimate the actual recharge, whereas methods referring to unsaturated zones and surface water estimate the potential recharge (Xu *et al.*, 2003).

2.3.2 Discharge

Discharge is the volumetric flow rate at which water flows through a given cross sectional area and is usually expressed in m^3/s (Gordon *et al.*, 2004). Most natural discharges occur as flow into surface water bodies, such as lakes, streams, and oceans, while flow to the surface appears as natural springs. One of the major constituents of artificial discharge of groundwater is the abstracting borehole.

Methods of measuring discharge generally fall into four categories, namely:

- Volumetric measurements
- Methods involving cross-sectional area and average stream velocity
- Dilution gauging methods using a salt or dye
- Stream-gauging methods where water levels are measured and a stage-discharge relationship is established

Volumetric measurements are most suitable for small flows, artificial structures or natural control sections for permanent gauging sites, and dilution gauging for turbulent flows (Gordon *et al.*, 2004). The velocity-area methods using a current meter are the recognized standard for direct discharge measurement.

Volumetric measurement is the most precise method of measuring small flows, such as those from springs. The discharge is calculated by measuring the time taken to fill a container of known a volume (Gordon *et al.*, 2004). Volumetric measurements are usually made where the flow is concentrated. Discharge is simply calculated as:

$$Q = \frac{V}{t}$$

Where: Q = Discharge in m³/s

 V = Volume in m³

 t = Time (seconds)

Numerous measurements should be taken to check for consistency of both the stream flow and the person conducting the test.

The velocity-area methods can be measured by water flowing through an open pipe or channel, where the discharge, Q, is equal to the product of the cross-sectional area, A, and the velocity, v:

$$Q = Av$$

One can apply the same logic to Darcy's law for flow through a porous medium. Darcy's law states that *"the rate of flow through a porous medium is proportional to the loss of head, and inversely proportional to the length of the flow path and is defined by the following equation"* (Todd, 1956):

$$Q = KiA$$

Where: Q = Discharge (m³/d)

 K = Hydraulic Conductivity (m/d)

 i = Groundwater gradient

 A = Cross sectional area (m²)

2.4 GROUNDWATER/SURFACE-WATER INTERACTIONS

Groundwater and surface water are not isolated components of the hydrologic system, but rather interact in a range of climatic and physiographic landscapes. Therefore, the contamination or development of one commonly affects the former. Thus, an understanding of the basic concept of the interaction between groundwater and surface water is needed for the effective management of water resources. Quantifying groundwater/surface water interaction is a difficult task to achieve, but is particularly complex in the South African context where much of the usable groundwater flows through fractured-rock aquifers (Levy, 2012). The sustainable development of groundwater depends in part on determining the potential impact of that development on the groundwater contribution to estuaries, wetlands, lakes, and rivers. Such groundwater - surface-water interactions are among the most vital aspects in the protection of valuable aquatic ecosystems and consequently in land-use planning.

To understand groundwater/surface water interaction, it is necessary to understand the effects of the hydrogeological environment on the groundwater flow system, this entails the effect of topography, climate, and geology (Sophocleous, 2002). An area with a uniform precipitation and infiltration rate over an undulating surface, will develop a groundwater flow system driven by a water table surface that is a subdued replica of the area's topography (Hubert, 1940). The resulting groundwater flow pattern is thus controlled by the configuration of the water table as well as by the distribution of the hydraulic conductivity in the region geology. In addition to geologic and topographic effects, groundwater flow is affected by climate, mainly through precipitation being the source of recharge (Sophocleous, 2002). The main regulator of surface water stage and the water table depth is climate, thus it is also a major driving force for interactions that depend on the hydraulic head difference between groundwater and surface water (Levy, 2012).

A flow system is formed when groundwater moves along flow paths that are organized in space. In the environment, the available subsurface flow domain of an area with an irregular topography contains multiple flow systems of diverse orders of magnitude and relative, nested hierarchical order (Sophocleous, 2002). Based on their relative position in space, Tóth (1963) acknowledged three distinct types of flow systems, namely - local, regional, and intermediate. Within a groundwater catchment these types of flow can be superimposed on one another. The water within a local flow system will flow to a close by discharge area, for instance a stream or lake. Water in a regional flow system travels a larger distance than a local flow system and often discharges to large lakes, major rivers, or to the ocean (Sophocleous, 2002). An intermediate flow system is categorized by one or more topographic highs and lows located between the discharge and recharge areas of the system, however, unlike the regional flow system, it doesn't occupy both the major topographic high and the bottom of the basin. The regional flow systems are at the peak of the hierarchy organization and all other flow systems are nested within the regional flow systems (Sophocleous, 2002).

Hydrological interactions between subsurface and surface water occur by the subsurface lateral flow through the unsaturated soil and by exfiltration from or infiltration into the saturated zones.

Furthermore, in the case of fractured terrain or karst formations, interactions occur through flow in fracture/solution channels. Water that enters a surface-water system rapidly, in response to singular water input events such as precipitation or snowmelt. These water input events are known as event flow, storm flow, direct flow, or quick flow (Sophocleous, 2002). This water is distinguished from baseflow, or water that goes into a stream from constant, slowly altering sources and maintains stream flow between water input events. Even though some baseflow is derived from drainage of wetlands or lakes, or from the slow drainage of moderately thin soils on high ground hillslopes, most of the baseflow is supplied from groundwater flow (Sophocleous, 2002). Subsurface storm flow or interflow, occurs when the subsurface flow enters a stream rapidly to contribute to the event response.

2.4.1 Large-Scale interaction

The large scale hydrological exchange between surface water and groundwater in a landscape is controlled by (Woessner, 2000):

1. The magnitude and the distribution of hydraulic conductivities, both inside the associated alluvial plain sediments and the channel;
2. The relation of the stream stage to the neighbouring groundwater level; and
3. The position and geometry of the stream channel inside the alluvial plain.

The course of the exchange processes varies with the hydraulic head, while the flow (volume/unit time) depends on the hydraulic conductivity of the sediment. Substantial precipitation events and seasonal patterns can change the hydraulic head. These precipitation events and seasonal patterns induce changes in the flow direction. In Figure 2 two net directions of water flow are notable, namely: the influent condition (losing stream), where the surface water contributes to the subsurface flow, and the effluent condition (gaining stream), where the groundwater contributes or drains into the stream (Sophocleous, 2002). Then again, variable flow regimes could change the hydraulic conductivity of the sediment by means of deposition and erosion processes and thus affects the intensity of the groundwater/surface water interactions.

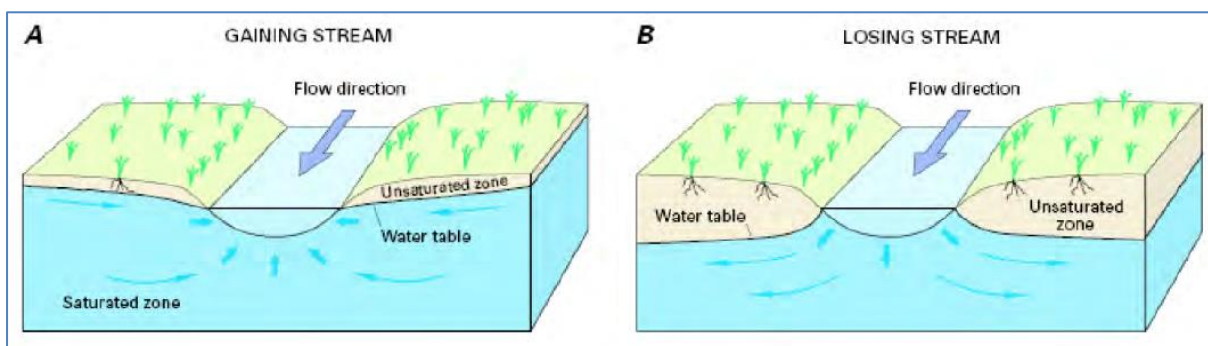


Figure 2: Example of a gaining stream and a losing stream (Winter et al., 1998)

Brunke and Gonser (1997) methodically summarized the interaction between groundwater and rivers. Under conditions of low precipitations, the baseflow in numerous streams constitutes the discharge for the majority of the year namely, effluent conditions. In comparison the surface runoff and interflow steadily increase under conditions of high precipitation, leading to elevated hydraulic pressures in the lower stream reaches, which in turn causes the stream to change from effluent to influent condition, infiltrating the stream banks and recharging the aquifer. During flooding, the stream loses water to bank infiltration, resulting in water loss that reduces the flood level and recharges the aquifer. The volume of this bank storage depends on the height, duration and shape of the flood hydrograph, as well as on the storage capacity and transmissivity of the aquifer. This stored water when release, during dry periods, compensates for a decline in stream discharge. In a number of river reaches, the water released to the river from the bank storage originating from flood runoff exceeds the groundwater discharge under baseflow conditions. Therefore, the consecutive recharge and discharge of the aquifer has a buffering effect on the runoff regimes of rivers (Brunke *et al.*, 1997).

Rivers are multifaceted, hierarchical systems with three main interlinked components. The geomorphological and geological components which form the basic physical template. The hydrological and climatic component which are key abiotic drivers of the system through water flow regimes, water temperature and water quality, and the biological component with a suite of species and communities which have adapted to the conditions created by their interaction with the abiotic component (Poff *et al.*, 1997).

Based on the understanding that baseflow was an indication of the minimum recharge to an area, Vegter (1995) attempted to estimate the groundwater contribution to baseflow (Figure 3). The map provides an initial indication of groundwater contribution to flow in river by using the GRDM software. Not all baseflow is derived from rivers, thus this map should be treated with caution and is only an initial indication of the groundwater contribution to flow in rivers, and more detailed and site-specific information should be used.

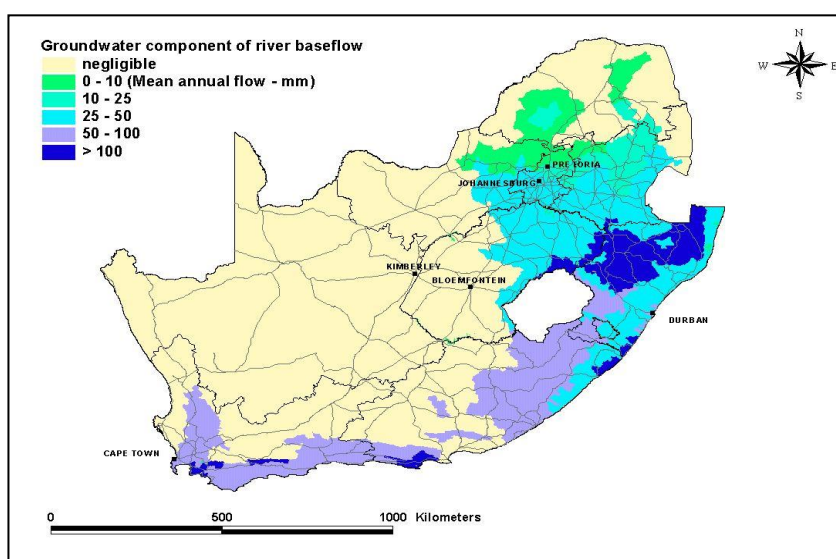


Figure 3: Estimation of groundwater contribution to river flow by Vegter (1995)

2.5 ELECTRICAL CONDUCTIVITY (EC) AND TOTAL DISSOLVED SOLIDS (TDS)

The total amount of material dissolved in a water sample is commonly referred to as total dissolved solids (TDS), or salinity and can be derived by measuring the electrical conductivity of the sample (Davies *et al.*, 1998). Dallas and Day (2004) define conductivity as the measurement of the ability of a sample of water to conduct an electrical charge, while TDS represents the total amount of dissolved material, inorganic and organic, un-ionized and ionized, in a water sample. It has been found that there is a correlation between conductivity and the concentration of the TDS in solution. The electrical conductivity is directly proportional to the TDS and can thus convert electrical conductivity to TDS according to Richards (1969) method. This method has become more practical to use because EC is simple to measure. Conductivity is mainly dependant on the geology of the area through the water flows in streams and rivers. The degree of dissociated ions, the distance from upstream, the amount of electrical charge on each ion and its mobility, the temperature of the water, and organic matter from decomposing plants all play a role (DWAF, 1996a).

Streams and rivers that flows through a surface that is characterized by clay soils have higher conductivity due to the presence of materials that ionize when dissolved into water, while rivers that flow through areas with a granite bedrock show lower conductivity due to granite being composed of more inert materials that do not dissolve (Hubert *et al.*, 2015). All rivers and stream flowing through rock that are bordering Malmesbury shales are characterized by high TDS, due to the rock containing a considerable number of leachable ions (Brown *et al.*, 2009). Mineral salts elements which provide water with the ability to conduct an electrical current include dissolved ions such as Mg^{+2} , Ca^{+2} , K^{+} , Na^{+} , Cl^{-} , HCO_3^{-} , SO_4^{-} , and CO_3^{-} in the aquatic environment (Leske *et al.*, 2003). The salinity may also be influenced by natural phenomena, namely rainfall and evaporation (DWAF, 1996a). The water quality and possible source of the water can be quantified on the basis of TDS and EC using Table 2.

Table 2: Water classes based on salinity

Class	Source	TDS, mg/L
Fresh	Rivers, lakes, groundwater	<500
Slightly saline	Ground, river, lake	500 - 1000
Mildly saline	Estuaries	1000 - 2000
Moderately saline	Inland and brackish mix	2000 - 10000
Severely saline	Inland and coastal	10000 - 30000
Sea water	Offshore seas and oceans	30000 - 36000

When calculating TDS from an EC measurement, a conversion factor is used. This conversion factor is dependent on the type of solids that is dissolved in the water and can be changed depending on the water source.

$$TDS = A \times EC$$

Where: A = Conversion factor, 0,55 to 0,75

EC = Electrical Conductivity, micromhos or microS

TDS = Total dissolved solids, mg/L

The majority of freshwaters typically have TDS levels between 0 and 1000 mg L⁻¹, however it is undeniably true that these levels can exceed 1000 mg L⁻¹ in polluted water or waters receiving large quantities of land run-off (Davies *et al.*, 1998). The TDS levels of rivers that flow through Paleozoic and Mesozoic sedimentary rock formations can vary between 200 and 1100 mg L⁻¹ and may surpass 1100 mg L⁻¹ at high evaporation (DWAF, 1996a).

2.6 AQUIFER HYDRAULICS

The characterization of a groundwater system is a vitally important first step in solving aquifer problems. Designing a hydrogeological test, conducting the test in the field, and analysing the data require a thorough knowledge of aquifer hydraulics. Vertical and horizontal hydraulic conductivities, and specific storage are the main hydraulic characteristics (Batu, 1998). Drawdown, hydraulic head, discharge velocity and groundwater velocity, porosity, permeability and transmissivity, hydraulic conductivity, capillarity and capillary fringe are the key hydraulic and hydrogeological quantities used to characterise aquifers (Batu, 1998).

Fractured aquifers can be considered to fall between a conduit system and a porous medium. In porous media the groundwater flows between the grains, whereas in fractured media the groundwater flows through the original interstices of the geological formations. If the rock matrix is permeable enough the groundwater in the fractured media will also flow through the rock matrix. This is referred to as fractured porous media. This is the most common type of aquifer in the world.

Modelling fractured porous media often presents a challenge since models either assume a homogenous porous or a purely fractured medium where the fractures are planar, parallel and often identical. Although these models do not represent the ideal world, together with pump tests, models provide borehole and reservoir hydraulics that will assist in deciding the efficient management of the well and that of the reservoir (van Tonder, *et al.*, 2002). Other more economically viable tests like the bail-down test as well as the slug test can be used in cases where the budget does not allow for a pump test.

2.7 STATISTICAL ANALYSIS

Statistics is the branch of mathematics which deal with the analysis of data and can be divided into inferential statistics (statistical inference) and descriptive statistics (Brown, 2012). Statistical analysis as applied in hydrological engineering consists of correlating interrelated hydrological variables and estimating the future probability or frequency of hydrological events based on information contained in hydrological records (Beard, 1962). In probability analysis, statistical methods allow the coordination of observed data to yield a more precise estimate of future frequencies than is pointed out by the raw data and can also provide a criteria for judging the reliability of the frequency estimates. By using statistical methods, a correlation analysis provides a means for obtaining the most probable relationship between two variables and can also offer a criteria for judging the reliability of estimates or forecasts based on the derived relationship.

When conducting a correlation analysis the term association is used to mean linear association. A statistical tool generally used for investigating relationships among variables in environmental and biological data sets is the Pearson correlation coefficients, which is performed on raw data between two variables of observations (Dutilleul *et al.*, 2000). Pearson's correlation coefficient takes on values between -1 and +1, ranging from being negatively correlated, -1, to uncorrelated, 0, and positively correlated, +1 (Zou *et al.*, 2002). The sign of the correlation coefficient describes the direction of correlation, while the absolute value specifies the strength of the relationship (Table 3) (Zou *et al.*, 2002).

Table 3: Interpretation of Correlation Coefficient

Correlation Coefficient Value	Direction and strength of Correlation
-1	Perfectly negative
-0.8	Strongly negative
-0.5	Moderately negative
-0.2	Weakly negative
0	No association
+0.2	Weakly positive
+0.5	Moderately positive
+0.8	Strongly positive
+1	Perfectly positive

2.8 METHODS OF DELINEATING HYDROGEOLOGICAL REGIONS

Hydrogeological regions are mappable bodies of rock and/or soil that have similar hydrological properties (Laney *et al.*, 1986). These regions are generally established due to an increase in population and modern industrial and agricultural activities that create a demand for groundwater resources and can provide a solution to this problem by the proper delineation and identification of the water bearing units. Hydrogeological regions can be delineated by using either geological, geophysical, or chemical data or a combination of all three techniques (Edet *et al.*, 2002).

2.8.1 Surface resistivity and hydrogeological data method

This method uses geo-electrical and borehole data to identify water bearing zones in an area. The resistivity data is derived from vertical electrical sounding (VES) measurements. The interpretation of the VES data is then carried out by using conventional partial-curve matching and auxiliary point techniques together with computer modelling (Edet *et al.*, 2002). A comparison must then be drawn between the geo-electrical models of the subsurface and the lithological logs of the area in question and if there is a good agreement between the two datasets it will enable the successful identification of the different water bearing units. The water bearing unit can then be further characterized by using hydrogeological parameters (Edet *et al.*, 2001).

2.8.2 Remote Sensing and Geographical Information System method

This method makes use of False Colour Composite (FCC) images and geological maps by generating thematic layers on lithology, structures (faults, folds, type of bedding ect.), geomorphology and hydrology based on their image characteristics, such as tone, pattern, texture, size, shape, association and drainage characteristics (Khan *et al.*, 2002). Secondary data on recharge conditions, groundwater level, hydrology and aquifer material are then collected to support the mapping. A lineaments map is then generated by using satellite images and geological logs to identify the possible relationship between lineament distribution and their influence on the groundwater.

Geographic Information System (GIS) is then used to map the individual layer as mentioned above. The different hydrogeological units is then obtained by the final integration of the maps, their overlays and individual correlation between layer (Khan *et al.*, 2002)

3 STUDY AREA

3.1 LOCATION

The location of the Vegter Region to be investigated is shown in Figure 4. It is located to the south of the Karoo Basin. The main towns in Region 39 are Victoria West, Hanover, Colesburg, Noupoort, Philippolis, Venterstad, Bethulie and Springfontein.

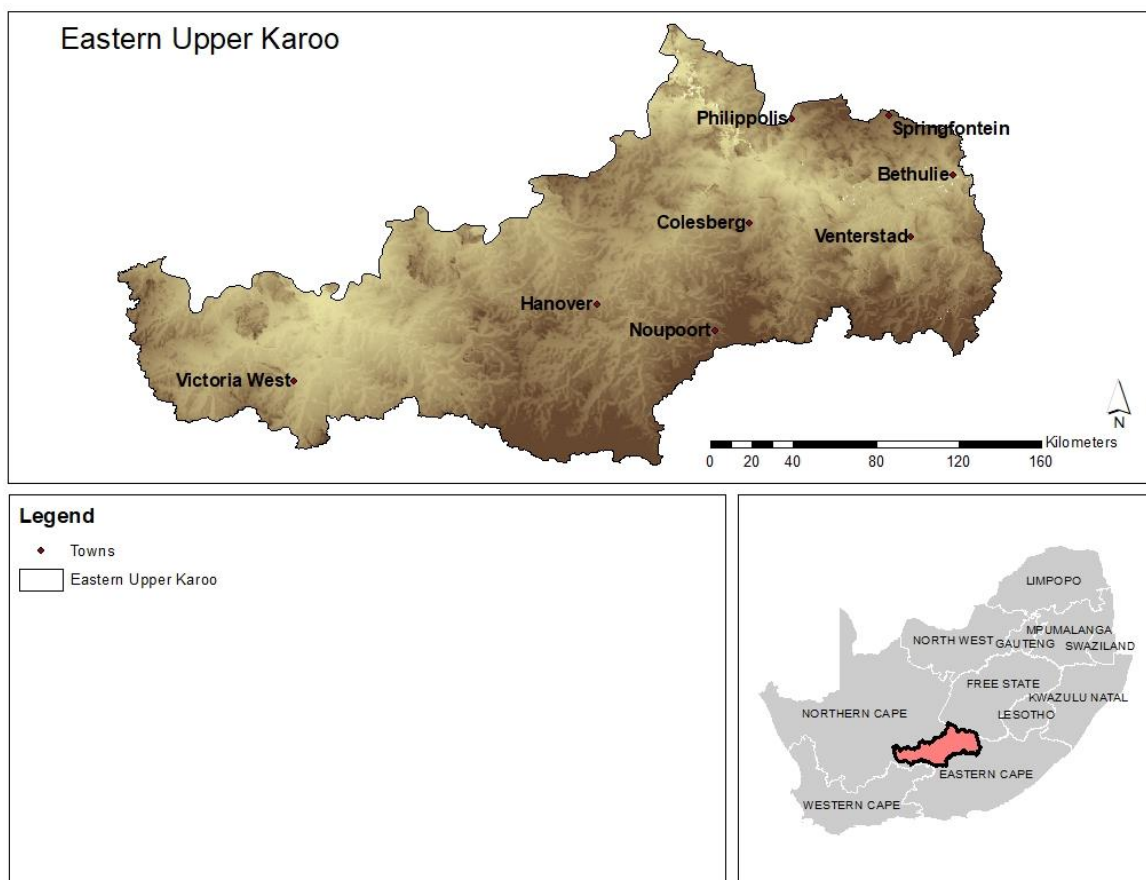


Figure 4: Location

3.2 PHYSIOGRAPHY

The Main Karoo basin covers a large part (35 902 km²) of the central region of South Africa. Surface altitudes range from 1132 to 2175 m above mean sea level (Figure 5). Altitudes are highest in the east decreasing gradually towards the west as the surface slopes. The generally flat to undulating topography is broken up by the unwrapped plateau edge and the escarpment, most prominent in the eastern portion of the region. The Lesotho Drakensberg has hard erosion resistant upper surfaces and therefore has a very high and rugged appearance, combining steep-sided blocks and pinnacles. The KwaZulu-Natal - Free State Drakensberg escarpment consists of softer rocks and thus has a more rounded, softer appearance from below.

A distinctive feature of the landscape of the Eastern Upper Karoo region is the flat topped hills, which are often capped by more resistant dolerite sills or sandstone beds, which rises above the featureless and flat to undulating plains. Outcrops are not common between the hills due to the surface being covered by windblown sand, calcrete, colluvium, alluvium, and soil (Golder Associates, 2011).

Dolerite sills and ring-complexes are seldom prominent features of the region's landscape. These structures are recognized without any difficulty on satellite images, where they often display a sub-circular saucer-like shape, the rims of which are commonly exposed as topographic highs forming ring-like outcrops.

There are numerous rivers within the regions (Figure 6). The major rivers in Region 39 include the Orange, Seekoei and Ongers Rivers. The Van der Kloof and Gariep Dams are located in Region 39.

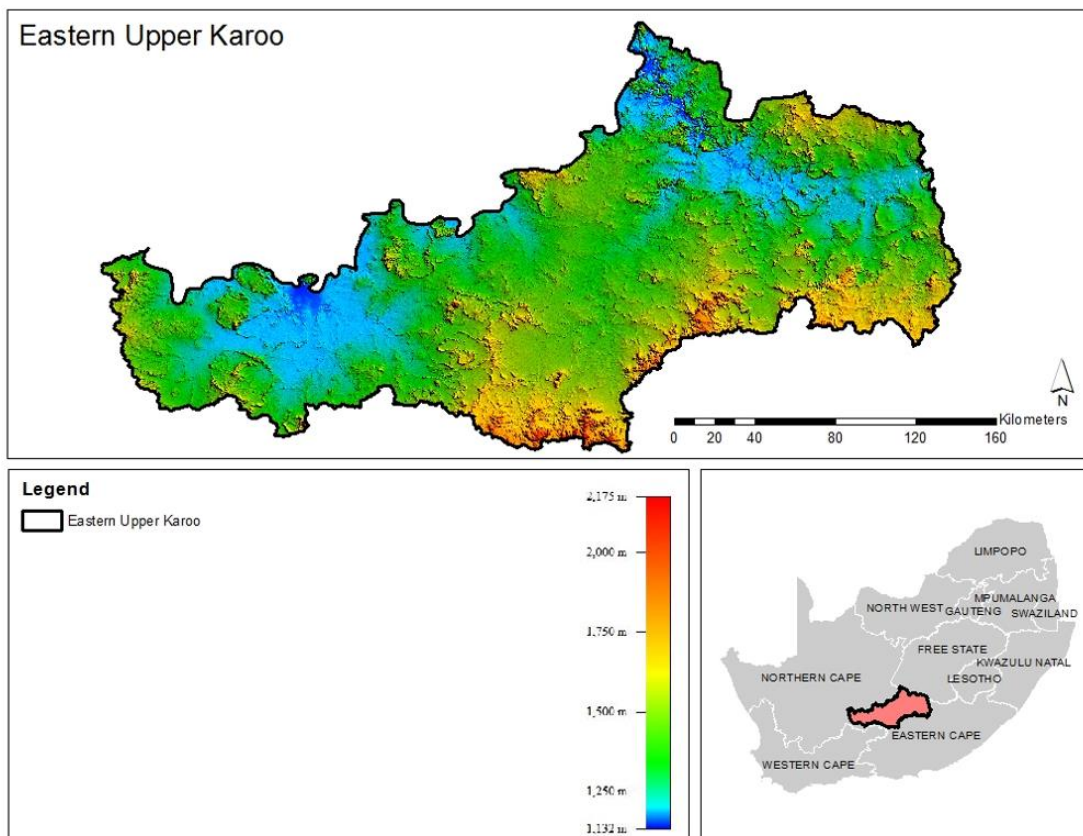


Figure 5: Topography

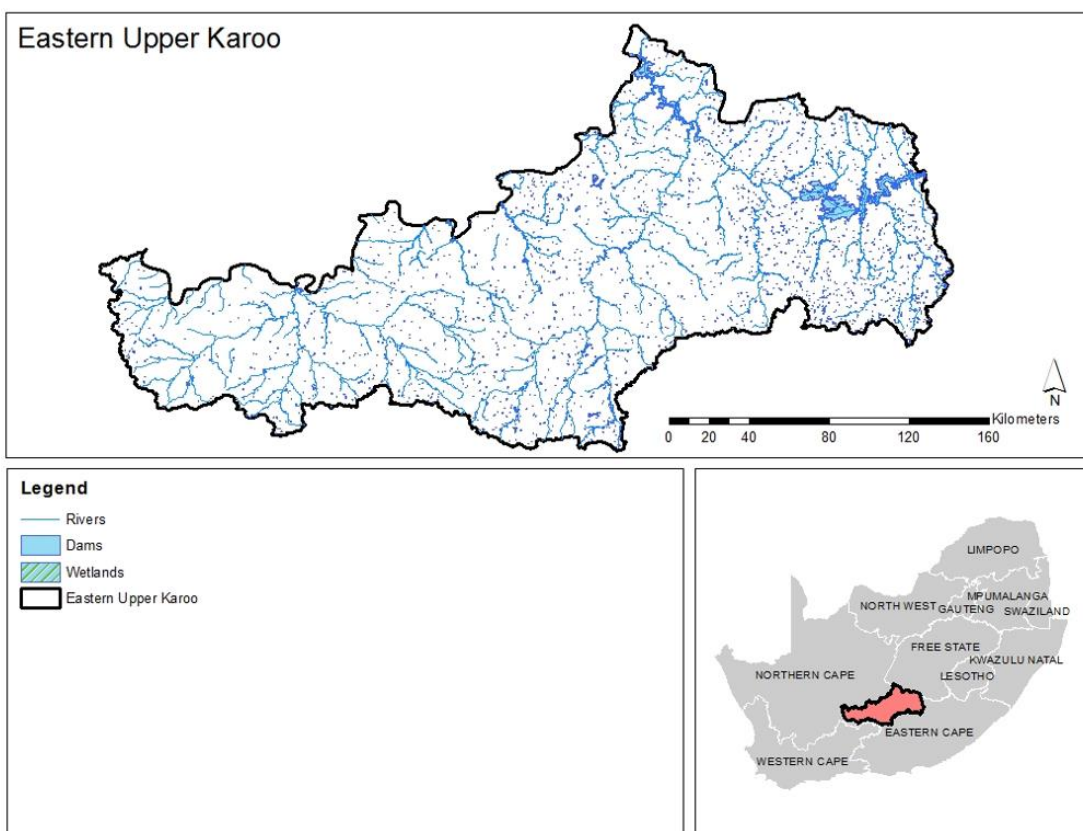


Figure 6: Water bodies

3.3 CLIMATE AND RAINFALL

The climate of the South Western Karoo basin ranges from arid, with a MAP of <200mm, to semi-arid, with an MAP of <500mm, and is classified as a summer rainfall region (Midgley *et al.*, 1994) (Figure 7). The rain typically comes in the form of thunderstorms, due to moisture-laden air flows from the Indian Ocean, and largely falls during the summer months of October to April. Mean annual rainfall increases from west (<200mm) to the east (500mm). The rivers in the region are seasonal and only flows for short periods of time following a heavy rainfall event. Evaporation is the highest during the summer months, further reducing the available moisture in arid areas. The main source of groundwater recharge is precipitation.

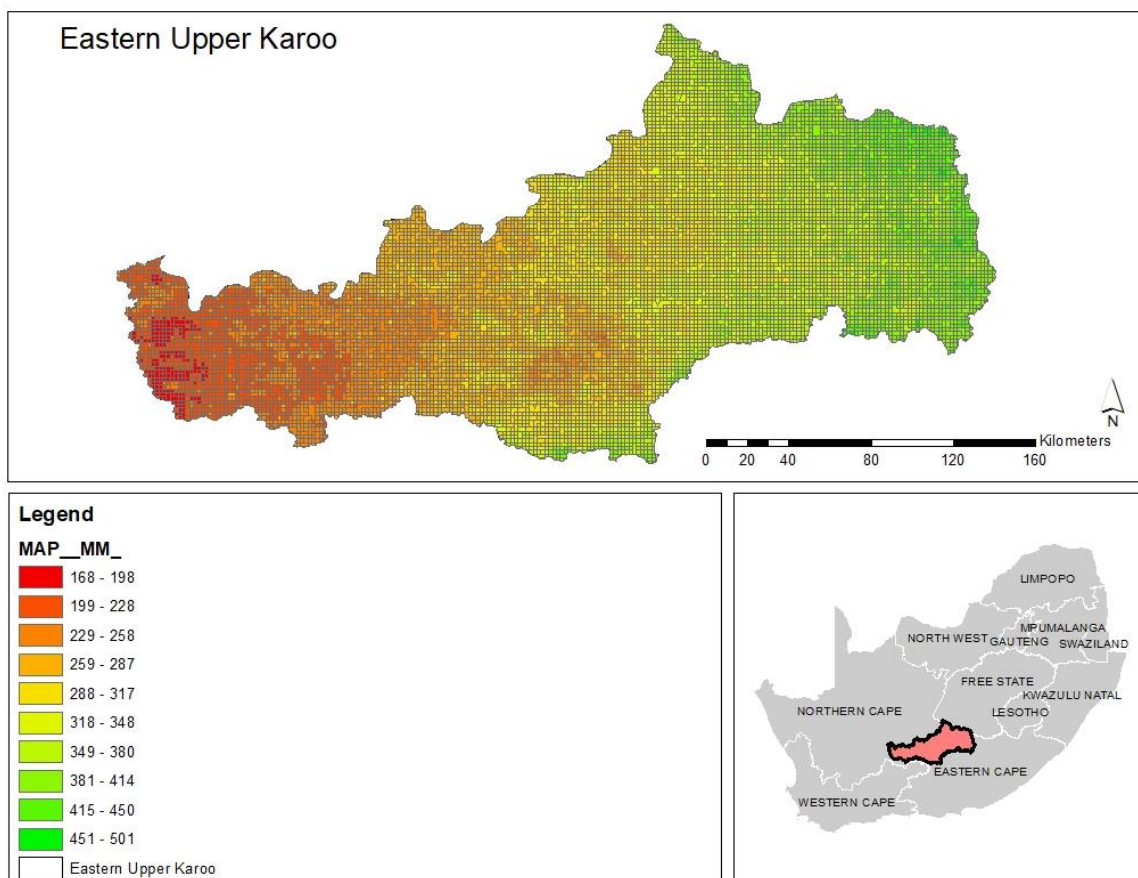


Figure 7: MAP of Study Area

Rainfall patterns in arid to semi-arid regions are uneven in terms of depth (mm), footprints (km²), and intensities (mm/hr). During the wetter seasons the footprint is generally larger and intermittently generates local flash flooding and depression storage (Van Wyk, 2010). Indirect recharge in these instances occurs as point source recharge zones in an otherwise low potential diffuse recharge environment. Intermittent or episodic recharge events in semi-arid regions are associated with extraordinary rainfall events and prompt medium-term aquifer replenishment. As stated by Vegter (1995), the recharge in this type of climate does not necessarily happen annually.

The Karoo is prone to wide spread variations in temperature and can vary greatly at different altitudes, because the temperature can drop by 6.5°C for every 1000m gain in altitude. Even though

the annual average maximum and minimum temperature are 25°C and 10°C respectively, the climate is considered one of an extreme nature, due to temperature ranging from -15°C on the plateau in winter to over 40°C on the plain in the summer.

The climate for the main towns in the study area are discussed in Appendix A.

3.4 REGIONAL GEOLOGY OF THE KAROO SUPERGROUP

The geology of the Karoo Basin was extensively covered by Woodford *et al.* (2002). The Karoo Basin (Figure 8 and Table 4) covers around 300 000 km² of South Africa and represents approximately 100 million years of sedimentation, from ca. 280Ma to ca. 180Ma (Geel *et al.*, 2013). The beginning of the deposition of the Karoo sedimentary rocks occurred during the late Carboniferous across Gondwana, and continued until the start of the break-up of this supercontinent during the Middle Jurassic approximately 183 Ma (Geel *et al.*, 2013). The Karoo basin has been interpreted as a foreland trough formed during the shallow-angle subduction of the paleo-Pacific plate beneath Gondwana. This led to the building of the wide fold thrust belt, which is now referred to as the Cape Fold Belt (CFB).

Glaciation of southern Africa took place when Gondwana drifted over the South Pole and a large ice-sheet covered the southern end of the continent. When this glaciation period ended an extensive shallow lake formed, which was fed by the ice-sheet that melted resulting in the deposition of the Dwyka diamictites (Geel *et al.*, 2013). Dropstones are found at the bottom of the overlying Ecca group, Price Albert formation, due to gradational contact with the Dwyka Group. The Prince Albert formation consists of mudstone with shale and a number of sandstone units. The overlying Whitehill formation comprises of fine-grained, finely laminated black organic rich shale which weathers due to sub-aerial pyrite oxidation to gypsum. The majority of the Karoo basin's sediments are considered to be deposited in an anoxic environment.

Table 4: Lithostratigraphy of the Karoo Supergroup

Gp		West of 24°E			East of 24°E		Free State/KwaZulu-Natal			
BEAUFORT GROUP	Tarkastad Subgroup				Burgersdorp Fm.		Driekoppen Fm.			
					Katberg Fm.		Verkykerskop Fm.			
	Balfour Fm.								Palingkloof M.	
					Elandsberg M.				Schoondraai M.	
					Barberskrans M.				Rooinekke M.	
					Daggaboersnek M.		Frankfort M.			
		Oudeberg M.		Volksrust Fm.						
	Middleton Fm.									
					Koonap Fm.					
Adelaide Subgroup	Teefloof Fm.	Steenkampsvlakte M.								
		Oukloof M.								
		Hoedemaker M.								
	Abrahamskraal Fm.		Poortjie M.		Koonap Fm.		Volksrust Fm.			
	Waterford Fm.			Waterford Fm.						
	Tierberg/Fort Brown Fm.			Tierberg/Fort Brown Fm.						
Laingsburg/ripon Fm.			Ripon Fm.							
Collingham Fm.			Collingham Fm.							
Whitehill Fm.			Whitehill Fm.							
Prince Albert Fm.			Prince Albert Fm.							

Apart from the pyrite, the shales contain dolomite lenses near the base, these rocks are highly faulted and folded, and is thus, interpreted as decollement (Geel *et al.*, 2013). The Collingham Formation comprises of dark grey mudstone, intercalated with thin yellow clay-like layers of ashfall tuff, along with zircons that have been dated at ca. 274-270 Ma. The mudstone beds are normally parallel laminated, but often display flaser and wavy bedding at the contact of the mudstone and the tuff. Pyrite is common in the lower half of the Collingham Formation.

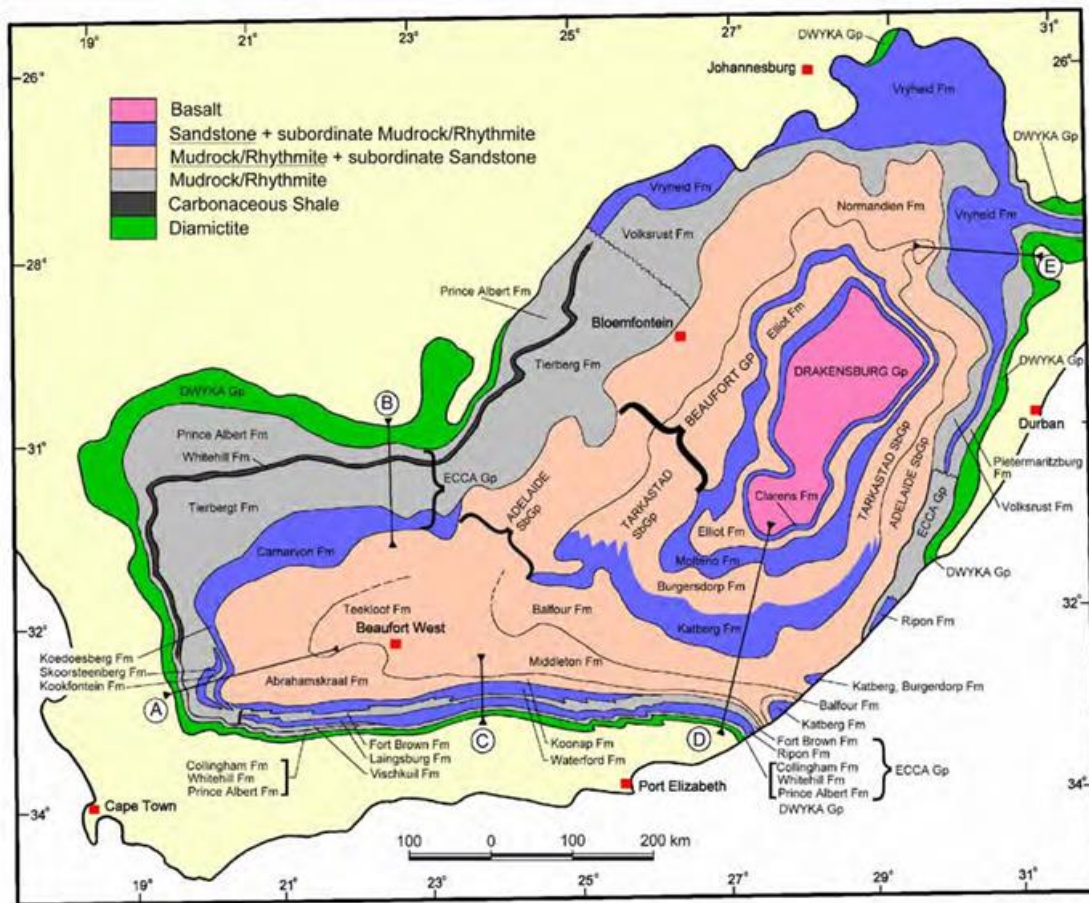


Figure 8: Schematic areal distribution of lithostratigraphic units in the Main Karoo Basin (Johnson *et al.*, 1997)

The early Ecca deposition took place during the early stages of the Cape Orogeny, roughly 250 Ma, when mountain ranges developed in the far south. Subsequently, the material from these mountain ranges, as well as from the highland areas in the north east and the west, drained into the basin to form the upper Ecca turbidites and prograding delta (Geel *et al.*, 2013). Numerous authors have inferred that the Dwyka diamictites and lower Karoo were deposited in an open marine setting (Smith, 1990., Visser, 1993) while other authors have proposed a marine lacustrine setting (Faure *et al.*, 1999). Alternatively, only a short marine incursion related to eustatic sea level rise occurred as a response to global deglaciation (Milani *et al.*, 2008). Following the later progressive basin filling and the deposition of the delta-slope sediment, the lacustrine period changed to a fluvial environment during the deposition of the Beaufort Group. The northerly progression of the Cape Fold Belt resulted in the mountain range encroaching inland and forcing the fluvial deposition for most of the overlying Stormberg Group farther northwards. During that time period the climate of the region changed to a semi-arid environment. The increase of more clastic sediment resulted in a coarser-grained sandstone that comprises of the upper sequences such as the Molteno formation and the Katberg Member (Geel *et al.*, 2013). In the final stages of deposition there were playa and wadi lake type environments forming the Elliot Formation, and sand dunes that dominated the Clarens Formation. The Karoo depositional sequence was brought to an end by the volcanic activity of the Drakensberg Group at ca 183 Ma (Johnson *et al.*, 2006).

3.4.1 Ecca Group

The Ecca group sediments comprises of a total of 16 formations, reflecting lateral facies changes that characterise this succession, of these 16 formations only 3 formations are of importance to the study area, namely the Prince Albert Formation, the Whitehill Formation, and the Waterford Formation of the North-Western zone. These formations are discussed in detail below.

3.4.1.1 The Prince Albert Formation

The Prince Albert Formation is confined to the south-western half of the Karoo Basin. Towards the northeast the Prince Albert formation thins and locally pinches out against the basement or merge with the Pietermaritzburg and/or the Vryheid Formations (Woodford *et al.*, 2002). Along the southern and western outcrop belt its thickness varies substantially from 40 to 150 m, while borehole data indicate a maximum thickness of up to 300 m (Veever *et al.*, 1994).

It is possible to distinguish between a northern and a southern facies in the Formation. The northern facies is characterised by the predominance of greyish to olive green, micaceous shale and grey, silty shale, as well as a distinct transition from the underlying glacial deposits. Dark-grey to black carbonaceous shale and fine to medium grained feldspathic arenite and wacke are also present (Woodford *et al.*, 2002). The southern facies is characterised by the predominance of dark grey, pyrite bearing, splintery shale, siltstone and the presence of dark chert and phosphatic nodules and lenses (Woodford *et al.*, 2002).

The shale represents the suspension settling of mud and the siltstone represents turbidites (Visser, 1991), whereas the wacke and arenite in the northern part of the basin are probably the result of deltaic sedimentation (Cole *et al.*, 1991). The lower part of the formation was deposited following the subsequent melting of the Dwyka ice-sheets and the presence of marine invertebrate fossils and phosphorite are indicative of marine condition in the formation (Visser, 1991).

3.4.1.2 Whitehill Formation

The Whitehill Formation contains mudrocks that weather white on the surface, making it a very useful marker unit. In fresh outcrop and in the subsurface the predominant facies is black, carbonaceous, pyrite-bearing shale (Woodford *et al.*, 2002). The shale contains up to 14% carbonaceous material and is very thinly laminated (Du Toit, 1954). The thickness of the shale layer varies in thickness, from 10 to 80 m, and contains the fossilized remains of the reptile Mesosaurus.

The Whitehill Formation loses its characteristic lithology towards the northeast with its lower part containing very fine-grained sandstone and siltstone. It can be regarded as a distal equivalent of part or all of the Vryheid Formation (Cole *et al.*, 1991).

3.4.1.3 Waterford Formation of the North-Western Zone

The Waterford Formation, which was previously named the Carnarvon Formation, outcrops along the north-western margin of the basin, with a thickness of approximately 250m in the vicinity of

Carnarvon. The sediments of the formation consist of fine- to very fine grained tabular sandstone that are up to 8m thick, shale, rhythmite, and siltstone (Siebrits, 1987). Brown-weathering, calcareous concretions with a maximum diameter of 2m are present in all the rock types in the formation. Wavy bedding, including symmetrical ripples and hummocky cross-bedding are predominant, in addition to ball-and-pillow structures, slump structures, and load casts (Woodford *et al.*, 2002). The different facies commonly form upward-coarsening sequences ranging in thickness from 4 to 38m.

The deposition most likely took place in a shallow sea environment, where wave action was controlling the deposition process (Rust *et al.*, 1991). The closest shoreline was more than 200 km towards west in the surrounding area of Calvinia.

3.4.2 Beaufort Group

The geology of the study area falls mainly within the confines of the Beaufort Group, specifically in the Adelaide and Tarkastad subgroups. The sediment of the Beaufort Group was deposited in an intracratonic basin receiving detritus from a source area located to the south a west (Ryan, 1967). Sedimentation was initiated by source area uplift, particularly in the south, possibly due to a collision between two lithospheric plates reproducing a cordilleran type orogenic event as foreseen by the modern plate tectonic theory (Dewey *et al.*, 1970). The sediments of the Beaufort group consist mainly of siltstones, sandstones, and mudstone, and along the length of the southern margin of the basin these sediments have been caught up in the Cape orogeny and extensively folded. Towards the northern area of the study area the folding decreases in intensity and disappears completely on approaching the northern boundary of the study area, where the sediment is flat lying (Turner, 1981).

3.4.2.1 Adelaide Subgroup

In the south-eastern part of the study area, the late Permian Adelaide Subgroup comprises of the Middleton, Balfour, and Koonap Formations. In the west the Teekloof and Abrahamskraal Formations are approximate equivalents of the Middleton and Koonap Formations, respectively. While the Teekloof and Middleton Formations are characterized by a larger relative abundance of red mudstone compared to the underlying and overlying units, in practice the boundaries are linked to specific sandstone rich marker units, namely members (Woodford *et al.*, 2002). The arenaceous Poortjie and Oudeberg Members forms the base of the Teekloof and Balfour formations. In the northeastern region only a single formation is present, namely the Normandien formation.

The Adelaide Subgroup reaches a maximum thickness of roughly 5 000m in the southeast, which decreases rapidly to approximately 800m in the centre of the Basin and subsequently more gradually to about 100-200m in the extreme north. The Koonap Formation reaches a maximum thickness of approximately 1 300m, the Middleton Formation around 1 600m, and the Balfour Formation about 2 000m. The Abrahamskraal and Teekloof Formations, in the west, are up to 2 500m and 1 400m thick, respectively, while the Normandien formation in the northeastern region is approximately 320m thick (Groenewald, 1989).

In the central and southern area of the basin the Adelaide Subgroup consists of alternating bluish-grey, greyish-red, or greenish-grey mudstone and grey, very fine to medium grained, lithofeldspathic sandstone (Woodford *et al.*, 2002). In the northern area of the basin, coarse to very coarse sandstone, or even granulestone, are common in the Normandien Formation. In certain areas the sandstone comprises as little as 10% of the total thickness, while normally being 20-30%, while some sandstone-rich interval may in part be up to 60% sandstone.

Individual sandstone units are thickest in the south, averaging approximately 6m reaching a maximum thickness of 60m, and becomes thinner northwards, except for the northeast where thick, laterally extensive units are also present in the Normandien Formation (Woodford *et al.*, 2002). The units usually extend laterally for a few hundred metres to a few kilometres, but numerous units are markedly lenticular. Some Sandstone layers contains Calcareous concretions of various sizes, 20-100cm in diameter. In the Daggaboersnek Member, which occurs towards the centre of the Balfour Formation in the south-eastern part of the basin, the sandstones tend to be tabular and thin, which possibly reflects a lacustrine depositional environment (Woodford *et al.*, 1998).

The palaeo-current data indicate that the bulk of the sediment was derived from a source area situated to the south southeast of the basin, with subordinate influxes from the southwest, west-northwest and northeast. The source area that is situated to the south, southwest, and southeast of the basin coincides with the second major tectonic paroxysm of the Cape Fold Belt, which dates back to approximately 258 Ma (Hälbich *et al.*, 1983). The border of the basin was probably close to the present coastline of South Africa (Cole, 1998). Source area were sited on the continental regions of western Namaqualand and the Mozambique Ridge to the west-northwest and northwest (Cole, 1998).

Apart from the lower part of the Normandien Formation, where coarsening-upward cycles of sedimentation are present, the sandstone units normally form fining-upward cycles (Woodford *et al.*, 2002). The cycles can vary in thickness, from a few metres to a few tens of metres and were probably formed by the lateral migration of meandering rivers. The subordinate, horizontally bedded sandstone units that show no upward change in grain size were deposited by ephemeral sheet-floods (Woodford *et al.*, 2002). The mudstone represents deposition in a flood plain and lacustrine environment.

3.4.2.2 Tarkastad Subgroup

The early Triassic Tarkastad Subgroup is characterized by a larger abundance of both red mudstone and sandstone when compared to the Adelaide Subgroup. The boundary between these two subgroups is the only one in the Beaufort Group that can be traced with certainty throughout the Main Karoo Basin. The Tarkastad Subgroup has a maximum thickness of approximately 2 000m in the south and decreases to approximately 800m in the central basin and 50m or less in the far northern extremity of the Basin (Groenewald, 1989).

In the south the Tarkastad Subgroup comprises a lower sandstone-rich Katberg Formation and an upper mudstone-rich Burgersdorp Formation. The Katberg Formation comprises of over 90%

sandstone in southern part of the study area, where the unit is over 900m thick, however the sandstone: mudstone ratio decreases gradually northwards until the Formation becomes indistinguishable from the Burgersdorp Formation (Woodford *et al.*, 2002). The Burgersdorp Formation is approximately 1 000m thick in the southern outcrop area, with the overall sandstone content declining from roughly 50% in the coastal exposure to around 20 - 30% or less further north within the main outcrop area. Groenewald (1989), recognized a lower Verkykerskop Formation in the extreme northeast, comprising up to 80m of fine- to very coarse-grained sandstone and an upper Driekoppen Formation, which is approximately 70m thick and consists almost entirely of mudstone.

The sandstones of the Katberg Formation are light brownish grey to greenish grey, fine- to medium grained and contain scattered pebbles up to 15cm in diameter within the coastal outcrop (Woodford *et al.*, 2002). Spherical to oval calcareous with a diameter of 3-10 cm are also common. The sandstones of the Burgersdorp Formation are greenish grey to light brownish grey and are fined-grained. The sandstone units in the central portion of the Formation in the main outcrop area has an average thickness is 2m (Woodford *et al.*, 2002).

Intraformational mud-pellet conglomerates are common in both the Katberg and Burgersdorp Formation. The mudstone units in both Formations are predominantly red coloured.

The mudstone and the sandstone units in the Tarkastad Subgroup tend to form fining-upward cycles similar to those of the Adelaide Subgroup, except for the Katberg Formation in the south, which was probably deposited in a braided stream environment. Meandering streams or, in the of the Burgersdorp formation, flood basin and lacustrine palaeo-environments may therefore be predominated (Woodford *et al.*, 2002).

The palaeo-current data for the Tarkastad Subgroup suggests a northerly to northwesterly regional palaeo-slope comparable to that prevailing during deposition of the underlying Adelaide Subgroup. Once more, the main source area must have been located to the southeast of the basin. The rapid increase in the quartz content at the expense of feldspar in the Katberg formation would appear to reflect strong uplift and denudation of the Cape Fold Belt, located between the magnetic arc and the basin. Catuneanu *et al.* (1998), hypothesised that the Tarkastad Subgroup was deposited during a period of orogeny loading and foredeep subsidence that ended with a tectonic paroxysm dated at approximately 239 Ma.

3.4.3 Dolerite Intrusion

The Dolerites of the Karoo consists of an interconnected network of sills and dykes and it is not possible to single out any tectonic or intrusive event responsible for these intrusions. It, however, appears that multiple fractures within the Karoo Supergroup were intruded simultaneously by magma and that the dolerite intrusive network acted as a shallow "stockwork-like" network (Woodford *et al.*, 2002)

The emplacement of dykes within the western portion of the Karoo Basin appears to be lithologically controlled where a decrease in intrusion density is noted at the boundary between the upper and lower Ecca group (Woodford *et al.*, 2002). This boundary corresponds to the appearance of the first sandstone unit within the Karoo Basin. The mass of the intrusions are strata bound and concentrated in the Beaufort and the upper Ecca Group, although some intrusions are present in the Dwyka and lower Ecca group (Woodford *et al.*, 2002).

A map of the different lithologies together with the lineaments (including dolerite dykes) are shown in Figure 9.

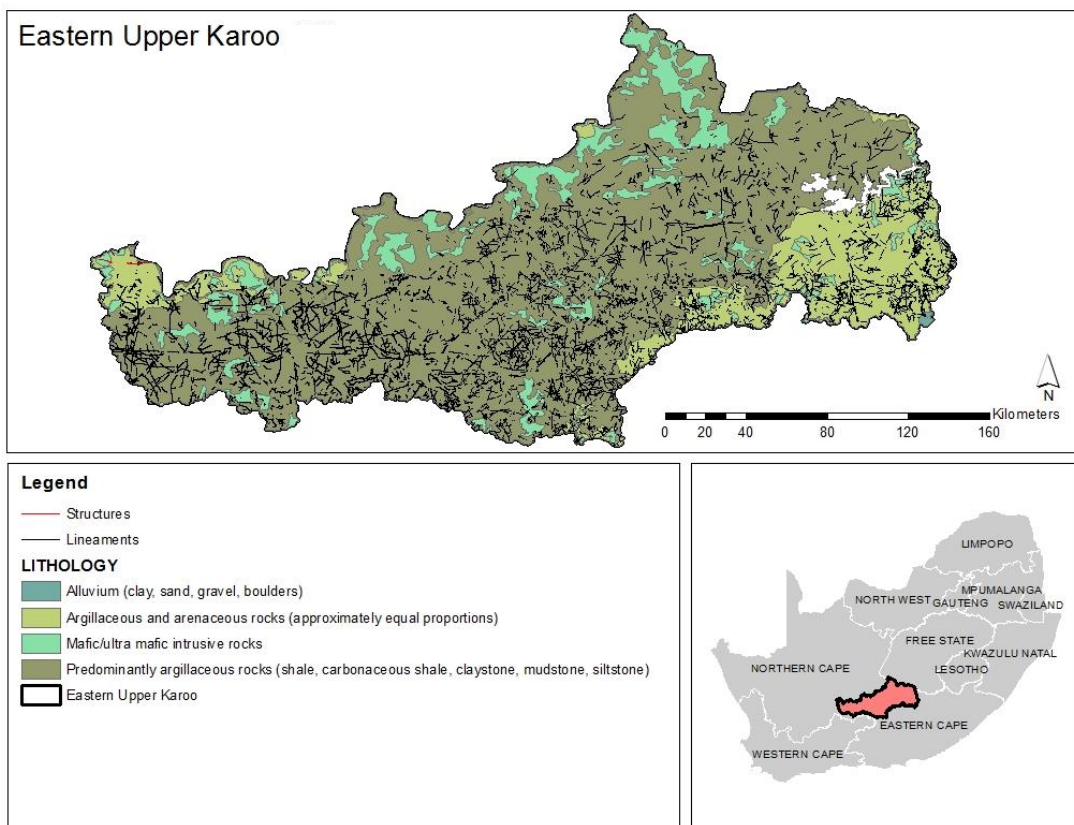


Figure 9: Geology map

3.5 GEOHYDROLOGY AND HYDROLOGY

Groundwater is normally viewed as a renewable resource because it is continuously being recharged from precipitation and surface water sources. In an arid environment this is often not the case as recharge is limited. The hydrogeology of an area is determined by the rock's ability to transmit and store water and the relationship between water bearing and non-water bearing rock.

The Karoo aquifers are secondary in character, and owe their transmission and storage capabilities to fracturing, weathering, faulting, and the intrusion of dolerite bodies. These secondary aquifers are both anisotropic and heterogeneous, resulting in properties altering significantly over short distances (Vermeulen, 2012). A dual porosity model is considered appropriate for these groundwater systems,

where most of the groundwater is stored in the matrix and the transmission of the groundwater takes place in secondary openings such as fractures and joints (Vermeulen, 2012).

There is a great deal of knowledge regarding the relatively shallow aquifer (<300 m) which supply many local municipalities and farmers with groundwater for domestic, irrigation, and stock use. On the other hand, the deeper formations (>500 m) and associated groundwater occurrence and its possible interconnection to the shallow aquifer systems is lacking in knowledge (KGEG, 2011). In this section these two distinct systems will be discussed.

3.5.1 Shallow Aquifers

These shallow aquifer systems are well understood based on decades of detailed research, use, monitoring and groundwater exploration, much of it by members of the KGEG (Karoo Groundwater Expert Group). Some linear or point features, such as dykes and boreholes, have potential capture or preferential pathway zones, respectively, for groundwater flow. The application of a surrounding 'consideration zone' to take into account the areas of influence beyond the boundaries of the features or mapped coordinates was therefore proposed Rosewarne *et al.* (2013). Within these consideration zones, exclusion zones may be identified where no gas wells should be sited (Table 5).

The aquifer potential in the study area increases, dolerite intrusion becomes more common, groundwater quality improves and the water levels get shallower from west to east, and from south to north in the study area. The occurrence of methane gas in existing supply boreholes and thermal spring in the study area are a relatively common phenomenon. Available isotope data confirms a deep origin for the methane gas (KGEG, 2011).

Structure	Consideration Zone Width (m)
Dykes	250
Other intrusions	250
Faults	250
Production boreholes	1000
Hot springs	1000
Hydrothermal plugs	100
Kimberlites	100

Table 5: Consideration zone widths (Rosewarne *et al.*, 2013)

3.5.2 Deep Aquifers

There is very little to no publicly available data for hydrogeological models for the main Karoo basin for depth of >300m to >4 000m (KGEG, 2011). However, Soeker undertook a deep, up to 4 658m, exploration drilling project in the 1960's that did provide some insight in the characteristics and nature of the deep aquifer of the main Karoo basin.

The deep exploration drilling by Soeker indicated isolated occurrences of deep, saline groundwater contained within the Karoo formations and fresher groundwater from the underlying Witteberg Group. In addition, fairly weak, hot (43 - 76°C) free flowing groundwater at a rate of 0.3 to 3.0 l/s was reported from a small number of such boreholes in the southern Karoo, within the zone of influence of the Cape fold belt and below the Great Escarpment. However, the flow only started after drilling into the Dwyka Group.

Groundwater is not likely to occur in a continuous aquiferous zone from the shallow aquifer zone to the deep formation where warm brackish to saline water occur under pressure. The shallow aquifer zones may be separated from deeper groundwater by zones of low Hydraulic conductivity (K) rock, probably hundreds to thousands of metres thick, altering from area to area. In general, the groundwater salinity increases with depth due to a combination of longer residence time due to longer flow path, lower K-values direct recharge from rainfall to the shallow aquifer.

The dyke in the area and their contact zones extend for up to ten, even hundreds of kilometres on the surface but their vertical continuation is uncertain at this time. Region east-west trending shear dykes could possibly extend to the base of the Karoo sediments. The K-value along dyke contact zones will differ with depth and strike dependant on the host rock and it is not likely that K-values will be constant along such zones given multiple layer of alternating siltstone, mudstone, sandstone, and shale that make up the Karoo sedimentary sequence.

3.5.3 Borehole information

Borehole information was obtained from the National Groundwater Archive (NGA). The locations of the boreholes are plotted in Figure 10. There are 2 aquifer types found in the regions, namely fractured and, intergranular and fractured (Figure 11). For most of the region's the borehole yields are less than 2 l/s. Groundwater use was obtained from the Water Resource Management System (WARMS) database as shown in Figure 10. As evident from these figures the registered groundwater use is not high.

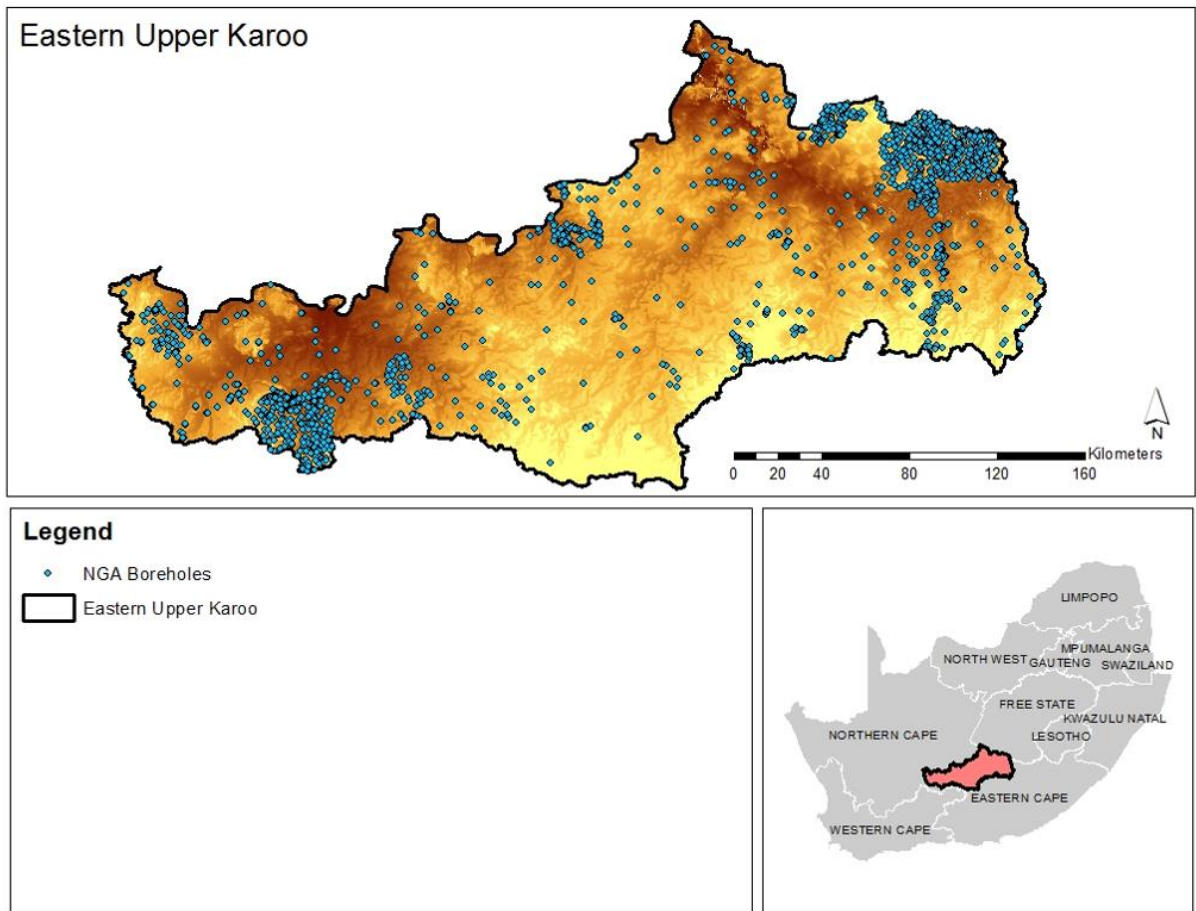


Figure 10: Boreholes for Region 39

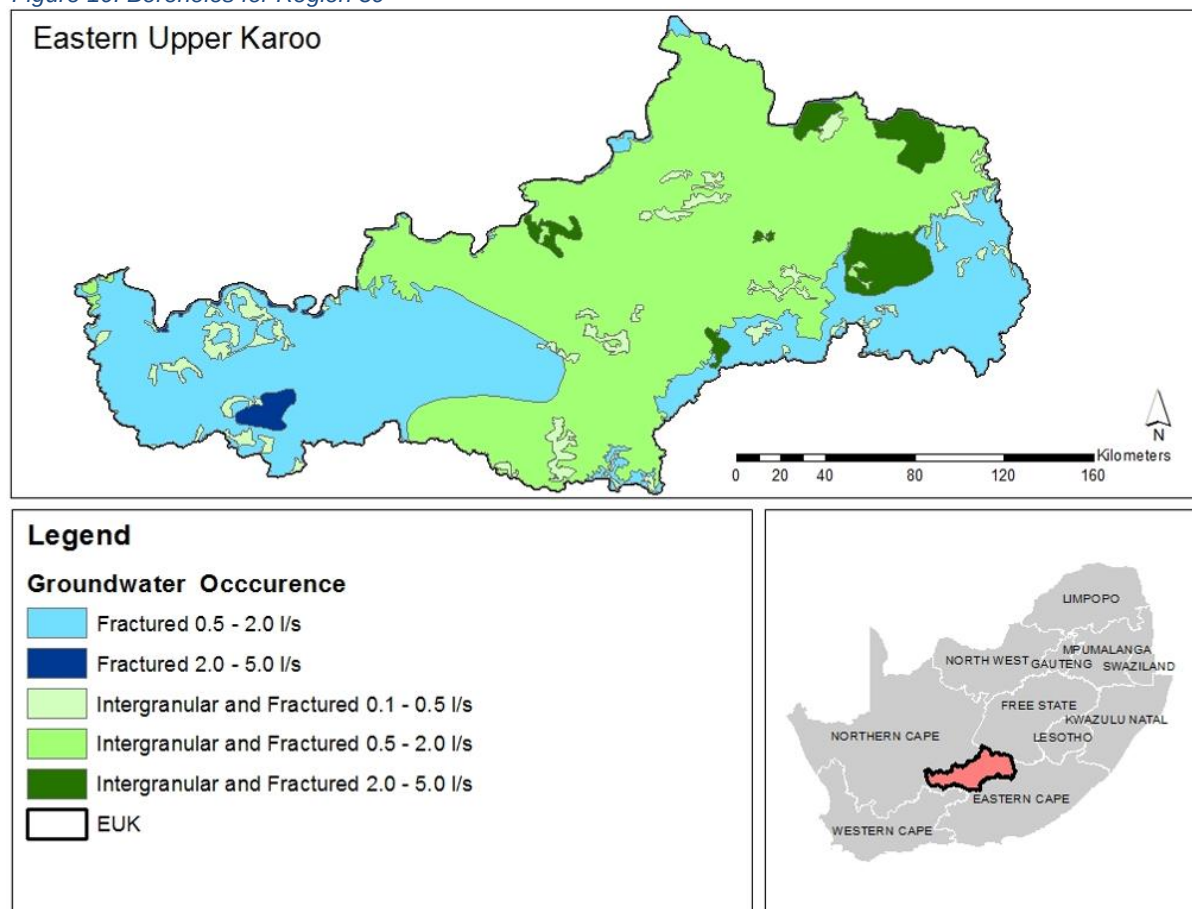


Figure 11: Aquifer types for Region 39

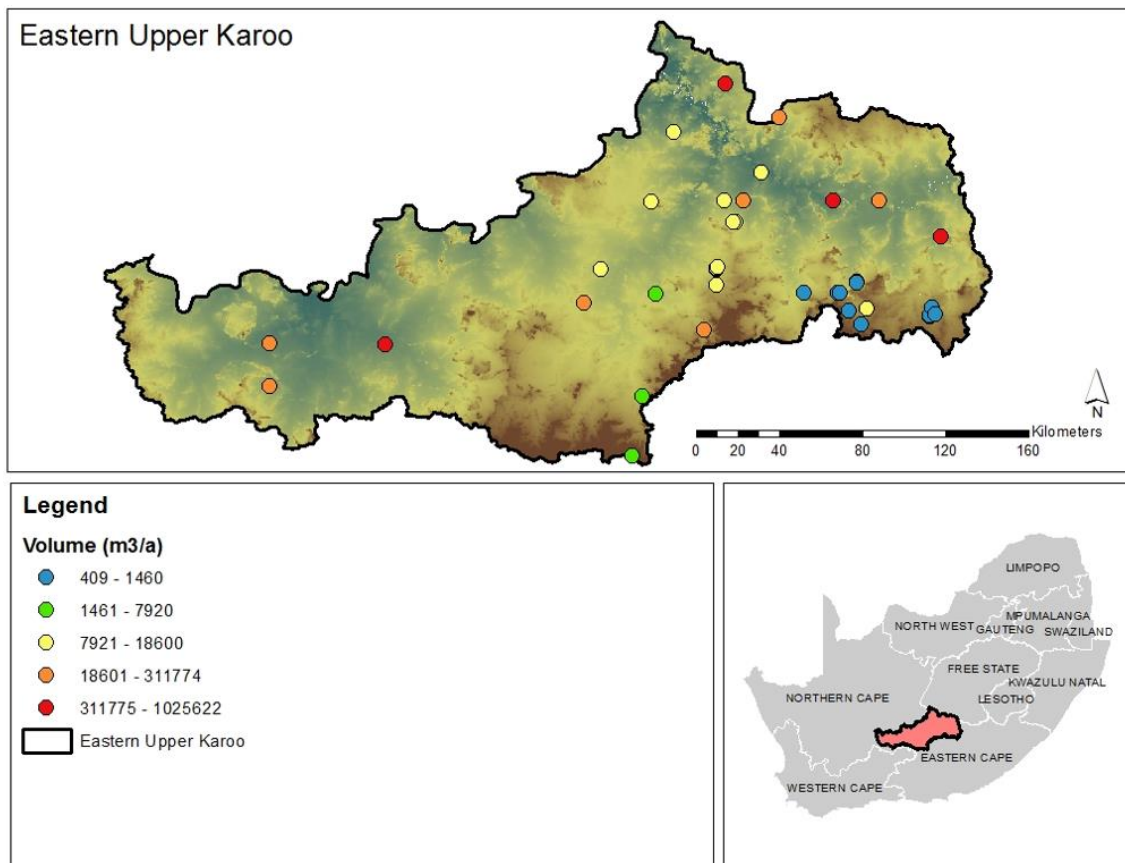


Figure 12: Groundwater use for Region 39

3.6 WATER QUALITY

The Karoo formation display variable water quality properties, due to their ubiquity throughout Southern Africa. Lateral changes in climatic patterns may be the main factor controlling the water types and diversity of the mineralization occurring in the Karoo rocks. This variability is caused by differences in rainfall, evaporation, recharge, topography, vegetation cover, soil type and thickness, and human activities (Woodford *et al.*, 2002).

The groundwater flow can vary significantly from area to area, due to this nature the local groundwater quality variations are significant and anomalies to the large scale generalisations are prevalent.

The general concentrations of the dissolved constituents increase from east to the west, following a comparable decrease in precipitation (Figure 13). The geometric mean concentration of the dissolved solids ranges from less than 100 mg/l at the base of the North-East slope of the Drakensberg Mountains to more than 3 400 mg/l in the Western Karoo, representing a concentration factor in surplus of 30 fold due to decreasing precipitation towards the Western Karoo.

The Karoo Basin largely has a TDS that ranges from 450-1 000 mg/l, which is not excessive by any standard. High concentrations are limited to the westernmost and southernmost edges of the Basin, in particular to the groundwater in the Dwyka Formation. This water is partly of a connate origin.

pH is an important parameter to consider when studying the quality of groundwater. Unfortunately, one has to rely on pH measurements made in the laboratory that may have been tainted by subpar aseptic condition (Woodford *et al.*, 2002). According to these measurements the study area has a rather high pH, in the range of 7.75-8.25 (Woodford *et al.*, 2002).

High pH values are rather distinctive for dry desert-like climates. The pH values have an increasing value from east to west, this may be due to the flattening out of the topography where the groundwater circulation is comparatively lower (Woodford *et al.*, 2002)

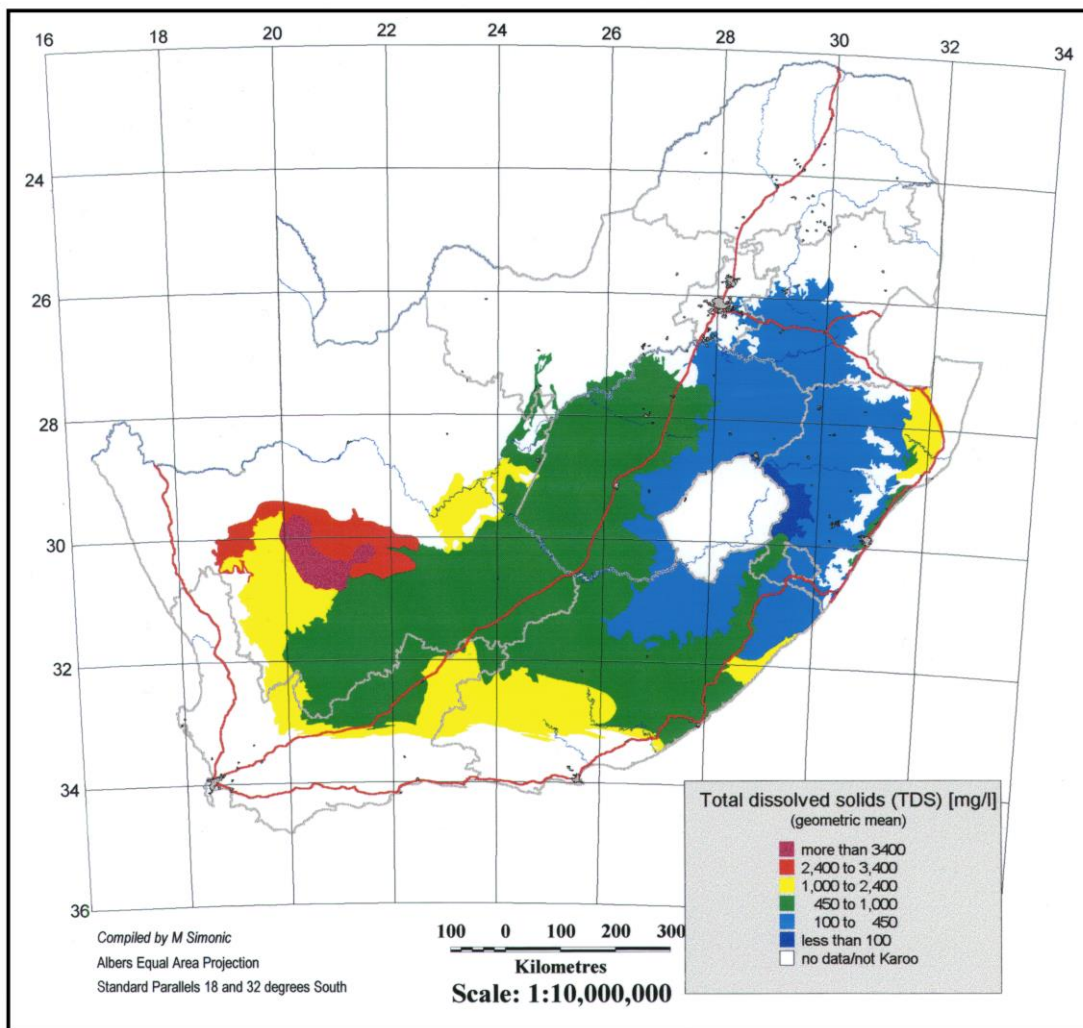


Figure 13: Total dissolved solids of Karoo Basin (mg/l) (WoodFord *et al.*, 2002)

Bicarbonate and calcium are usually the dominant ions in recharge water at the beginning of groundwater cycle. For the most part the study area calcium occurs in relatively low mean concentrations, usually between 30-80 mg/l (Woodford *et al.*, 2002). Calcium is balanced by alkalinity in the central area of the study area and by sulphate in the western portion.

Magnesium reveals a comparable distribution pattern to calcium but does not occur at the same concentration levels as calcium. Relatively low ranges, 30-80 mg/l, are encountered in the study area in comparison to the rest of the Karoo basin. Magnesium is rarely more abundant than calcium,

suggesting that magnesium minerals are not as readily soluble as calcium. The Ca/Mg ratio for most part of the study area is between 1.1 and 2. Magnesium and Calcium ions participate in a property known as total hardness. Based on this property the majority of the groundwater in the study area is regarded as hard. The extreme western portion of the study area contains groundwater that is considered very hard to extremely hard (Woodford *et al.*, 2002).

The concentration of Sodium is more variable than that of magnesium and calcium, range between 20-100 mg/l. Most of the study area has sodium concentrations within the acceptable drinking limits, i.e. below 100 mg/l (Woodford *et al.*, 2002). The distribution of sodium almost exactly mirrors that of chloride, suggesting the ions are closely associated. This can also suggest that the process of Ca-Na exchange is not significant on a regional basis.

Potassium concentration rarely exceed 10-20 mg/l in the study area. Potassium ions are adsorbed without any difficulty by the aquifer material and therefore can rarely reach significant concentration in groundwater.

Carbonate and bicarbonate are represented by the total alkalinity. In the dynamic systems they are formed by the introduction of carbon dioxide with rainfall and by the biological activities in soils (Woodford *et al.*, 2002). Further dissolution of carbonates in the aquifer material introduces additional alkalinity into the solution until the solubility limit is reached. The majority of the total alkalinity in the study area ranges between 200-300 mg/l, while a small portion in the south-west range between 100-200 mg/l, this is probably due to the solubility limits of CaCO_3 and part of the alkalinity may be lost to precipitation of carbonate minerals (Woodford *et al.*, 2002). Calcite fracture incrustation are widespread in the Western portion of the study area.

Sulphate and Chloride concentration seem to be well correlated, however chloride dominates over sulphate in most part of the study area (Bond, 1946). In the north-western portion of the study area both ions show relatively high concentration- exceeding 1 000mg/l. Long groundwater residence times, saline influxes via river, and poor irrigation practices are noted as the probable causes for these high concentrations.

High nitrate concentration does not pose any regional health-risk problems, but do occur in excessive concentrations in the study area (Woodford *et al.*, 2002). This however does not mean that the nitrate dilemma can be completely overlooked. Several locally elevated nitrate concentrations have been reported from different parts of the study area - most of which are linked to point source contamination of the groundwater from the surface.

4 METHODOLOGY

4.1 STATISTICAL ANALYSES

A total of 3184 boreholes were obtained for the study. It should be noted however that not all boreholes had the same dataset. The borehole statistics in later sections will highlight this fact.

Borehole data was obtained from the following sources:

- NGA
- GRIP
- Private Consultants

The 1:1 000 000 Simplified Geological Map available from the Council for Geoscience was used in the analysis. This was done to reduce the complexity of the data available in the 1:50 000 geological maps in relation to the available borehole data. The lithostratigraphic definitions in the Simplified Geological Map are listed in Table 6.

Table 6: Geological map label definition

Geology	Stratigraphy	Lithology 1	Lithology 2	Lithostratigraphic Unit	Group / Formation / Complex
Jd	Karoo Dolerite	Dolerite		Dolerite Dyke	KAROO SUPERGROUP
Pa	Karoo Dolerite	Mudstone	Arenite	Adelaide	KAROO SUPERGROUP - BEAUFORT
Pc	Koedoesberg	Arenite	Shale	Koedoesberg	KAROO SUPERGROUP
Pvo	Volksrust	Shale		Volksrust	KAROO SUPERGROUP - ECCA
TRt	Tarkastad	Mudstone	Arenite	Tarkastad	KAROO SUPERGROUP - BEAUFORT

Water level correlation with surface topography was analysed for each of the surface geologies where boreholes were present. The methodology followed was to rank the boreholes based on water level depth to determine if multiple systems can be identified.

4.1.1 Water Strike Analysis

The water strikes were ranked according to their depth to determine the number of boreholes passing through the determined water strike depth range. By doing this the strike frequency can be used to determine the depth of the predominant strike frequency.

This is formulated as follows:

$$\textit{Strike Frequency} = \frac{\textit{Number of strikes per depth range below surface}}{\textit{Number of boreholes passing through depth range}}$$

4.2 DELINEATION OF SUB-REGIONS

Vegter's methodology for the delineation of sub-regions within a groundwater region was followed as closely as possible, but due to data insufficiency Vegter's methodology was altered to some extent.

4.2.1 Skewness of Data

In statistics and probability theory, skewness is a measure of the asymmetry of the probability distribution of a real-valued random variable about its mean (Oja, 1981). The skewness value can be either negative or positive, or even undefined. Many models may assume normal distribution, for example if the data is symmetric about the mean. The normal distribution has a skewness of zero, but in reality, data points may not be perfectly symmetrical.

For the purposes of this dissertation it is important to understand some of the factors that can influence the skewness of the data in question. The three major anthropogenic influences are listed as follows:

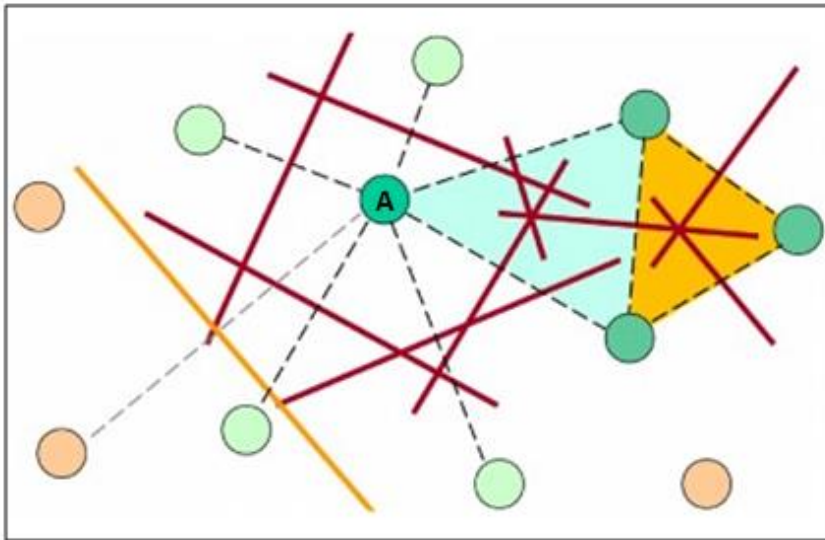
- The density of the boreholes will affect the proposed delineation as a high concentration of boreholes in certain regions will result in a more detailed delineation as opposed to regions where the borehole distribution is less dense.
- Only records of boreholes that have a good yield are normally kept, for example when drilling for water supply takes place, the 'dry' boreholes do not get logged as these are not considered important.
- Some of the data is time dependant and various borehole records are outdated. This will lead to discrepancies in the data as a whole and will skew the end result.

4.2.2 Voronoi Diagram

In mathematics, the Voronoi diagram is the partitioning of a plane with a set amount of points into convex polygons such that each polygon contains precisely one generating point and every point in a given polygon is closer to its generating point than to any other. A Voronoi diagram is sometimes referred to as a Dirichlet tessellation. The cells are called Thiessen polytopes, Dirichlet regions, or Voronoi polygons (Weisstein, 2015).

A Voronoi diagram is created by taking pairs of points that are close together and drawing a line that is equidistant between them and perpendicular to the line connecting them. All points on the lines in the diagram are equidistant to the nearest two, or more, source points. A graphic representation of the creation of the Voronoi diagram is shown in Figure 14, where the first Voronoi polygon is constructed around point A.

Figure 14: Creation of a Voronoi diagram



4.2.3 Frequency Analysis of Borehole Parameters

A frequency analysis of all available borehole parameters is conducted on the scale of the study area. The final borehole parameter set considered in the delineation is presented in Table 7.

Data availability was a major factor in identifying the borehole parameters used in the delineation. Borehole discharge was also taken into consideration, but was excluded due to the poor distribution of data. Bin sizes were selected for each of the parameters to yield four bins per parameter that described at least 90% of the total dataset.

Table 7: Borehole parameters considered in the delineation process

Parameter	Comment
Water Level	Average borehole water level measured from surface to water level position.
Water Strike Depth	During the process of drilling, water strikes are encountered at specific depths. For the purposes of delineation the deepest water strike for each borehole was used.
Water Quality (EC)	The EC (Electrical Conductivity) of a borehole is an indication of the salinity of the water. Very saline water is associated with deep stagnant water, but can also be due to the mineralogy of the host rock.

A Voronoi diagram was constructed for each of the identified borehole parameters, where the borehole position and bin number were used. The bin number enabled a classification of 1 to 4 for each of the parameters in question.

A simplified Voronoi diagram was created for each of the three borehole parameters (Table 14). As very little blow yield data was available, Equation 1 which was used in previous investigations was replaced with Equation 2.

$$Delineation\ Class = \frac{Level + (5 - Yield) + Depth + EC}{4} \quad (1)$$

$$Delineation\ Class = \frac{Level + Depth + EC}{3} \quad (2)$$

4.3 CALCULATION OF INFLOWS AND OUTFLOW

4.3.1 Discharge and Recharge

Discharges and recharges are calculated with a calibrated numerical flow model discussed in Section 4.4. These values are then used together with the surface groundwater interaction to determine the allocable yield.

4.3.2 Surface water – groundwater interactions

The groundwater - surface water interaction was determined for the two major rivers and their tributaries in the study area, namely the Orange River in the east and the Brak River in the west.

Herold's method was used to determine the baseflow for each quaternary catchment. The Herold method was used by Vegter (1995) to separate monthly flow into a surface runoff and a groundwater contribution component. Parsons (2004) challenged the contention that the baseflow component is

entirely derived from groundwater, but recognised that with great care, hydrograph separation techniques could be used to quantify the groundwater contribution to flow. Pitman and Vegter (Xu *et al.*, 2003) explained the Herold method as follows:

$$Q_i = Q_{Gi} + Q_{Si}$$

Where: Q_i = Total flow during month i
 Q_{Gi} = Groundwater contribution
 Q_{Si} = Surface runoff

The assumption is made that all flow below a specified value (called GGMAX) is groundwater flow, hence:

$Q_{Si} = Q_i - GGMAX$ (for $Q_i > Q_{GMAX}$)
or $Q_{Si} = 0$ (for $Q_i \leq Q_{GMAX}$)
and hence $Q_{Gi} = Q_i - Q_{Si}$

The value of GGMAX is adjusted each month according to the surface runoff during the previous month and is assumed to decay with time, hence:

$$GGMAX_i = DECAFY.GGMAX_{i-1} + PG.QS_{i-1}/100$$

Where: subscripts i and $i - 1$ refers to the current and previous months.
DECAFY = groundwater decay factor ($0 < DECAFY < 1$)
PG = groundwater growth factor ($0 < PG > 1$)

An added restraint is that GGMAX may not fall below the value specified by QGMAX. The calibration of this model is achieved by selecting an appropriate value of PG, QGMAX, and DECAFY so that a realistic division between groundwater and surface runoff is obtained (Figure 15).

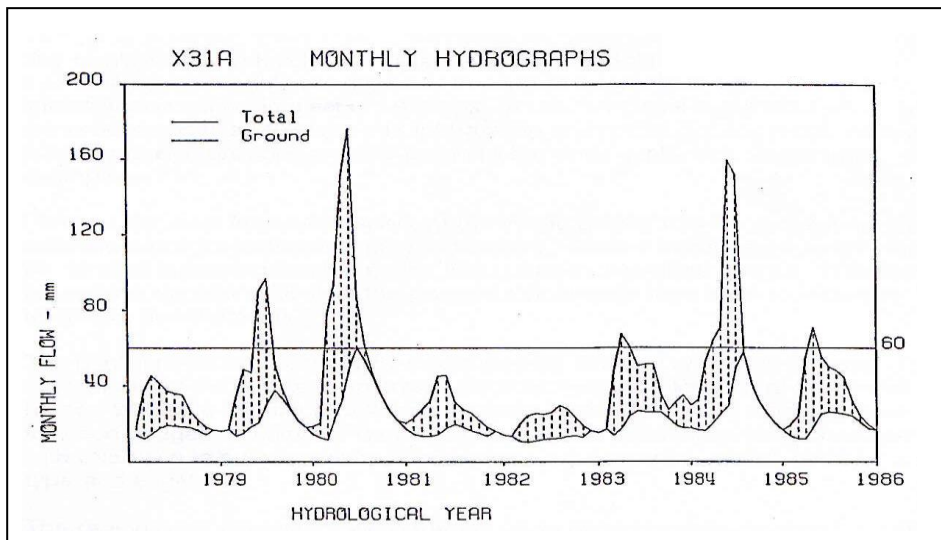


Figure 15: An example of the graphic output of a hydrograph separation using the Herold method (Xu *et al.*, 2003)

4.4 NUMERICAL MODELS

Numerical Models provide the most versatile approach to groundwater problems, due to this they have outclassed all other types of groundwater models. The popularity of numerical models, however, may lead to the overestimation of their potential. Groundwater systems are complicated beyond our capability to evaluate them in detail (Spitz *et al.*, 1996).

The purpose of this numerical model is to calculate the simulated water level of the area. This will be achieved through the process of adjustment of the model parameters, which in this case is transmissivity and the recharge of the area, and forcing within the margins of uncertainties to obtain a model representation where the calibration curve of the simulated water level and observed water level has the best goodness-of-fit.

4.4.1 Creating Numerical Model

As previously stated the Eastern upper Karoo is a vast region of 35 902 km² in size, this scale may prevent accurate simulation of the water level due to an immense lack of data. Each model grid cell is 500 m x 500m consisting of 424 rows and 732 columns.

The geology of the study area consists of various geological layers. These geological units were grouped together to form 5 layers within the model each varying in layer thickness, with a maximum model thickness of approximately 200 m (Table 8).

The study area contains 5 perennial rivers namely; the Brak, Visgat, Laken, Orange, and Seekoei rivers. The study area also contains 2 large dams namely, The Gariep and Vanderkloof dams. For the cell status array of the flow model these areas were assigned a constant hydraulic head. Furthermore, constant heads were also assigned to the boundary of the study area. This was applied only to the top layer of the model.

Table 8: Geological layer of Numerical model

Layer Unit	Geological unit
1	-Soil -Sand -Alluvium -Clay
2	-Shale -Silt +Clay
3	-Dolerite -Mudstone
4	-Siltstone
5	-Sandstone

The study area had no clear specified vertical hydraulic conductivity, thus the vertical hydraulic conductivity had to be calculated by using the following equation:

$$K = \frac{T}{D}$$

Where :

K	=	Hydraulic conductivity (m/d)
T	=	Transmissivity (m ² /d)
D	=	Unit thickness (m)

It is assumed that the horizontal hydraulic conductivity is higher than that of the vertical conductivity in the study area, thus the resulting value of the vertical anisotropy is 10, meaning that the above mentioned equation changes to:

$$Vertical\ K = \left(\frac{T}{D}\right) \div 10$$

The transmissivity of the model layers that was used in the calculation of the vertical hydraulic conductivity was obtained by using the average observed transmissivities of the geological units that occurs in nature.

5 MODEL CALIBRATION

Groundwater models are typically applied to understand and conceptualize a hydrologic system or to predict the outcome of future changes to the system. In order to provide some assurance that the model reflects the appearance or behaviour of the flow system, the model must be calibrated prior to using it as a predictive tool. Calibration is accomplished by finding a set of parameters, in this case transmissivity and annual recharge, which produce simulated heads that match the measured values within an acceptable range or error.

Model construction and calibration involved the following:

- Model construction during which the model boundaries was identified and quantified, the project sub-catchment was discretized into a model grid, error criteria for heads and the balance were set.
- Calibration of the flow model refers to the demonstration that the model is capable of reproducing field measured heads and flows under steady state and transient conditions. Calibration is achieved when a set of parameters, boundary conditions and stresses are found to produce simulated heads that match field measured data. This is a crucial step in the modelling project, which aided in ensuring that model results are reliable.

5.1 MODEL EVALUATION RESULTS

A number of performance measures have been proposed in the past to indicate when a model fits historical field measurements closely enough to be acceptable for use in future predictions. These may include parameters such as Root mean squared error (RMSE) and Absolute residual mean (ARM).

The following performance measurements were evaluated during the calibration of the Eastern Upper Karoo model:

- Figure 17 shows the relationship between the simulated and observed heads at the individual boreholes. For data point where the calculated groundwater levels and the observed groundwater levels correspond 79 % and the dots plot on the roughly a 45 degree angle. The figures indicate acceptable levels of agreement between the calculated and observed groundwater levels for such a large study area.
- Quantitative measures: the steady state calibration was regarded as sufficient at $ARM = 32.4m$ and $RMSE = 34.5m$.

Due to the sheer size of the study area various assumption are made in the model due to a lack of groundwater data. Groundwater level data availability was directly correlated to population density thus, groundwater level was interpolated across a vast area assuming that the aquifer and geology

would be homogenous. Geological intrusion for example, with higher K-values surrounding them, are not included in the numerical model.

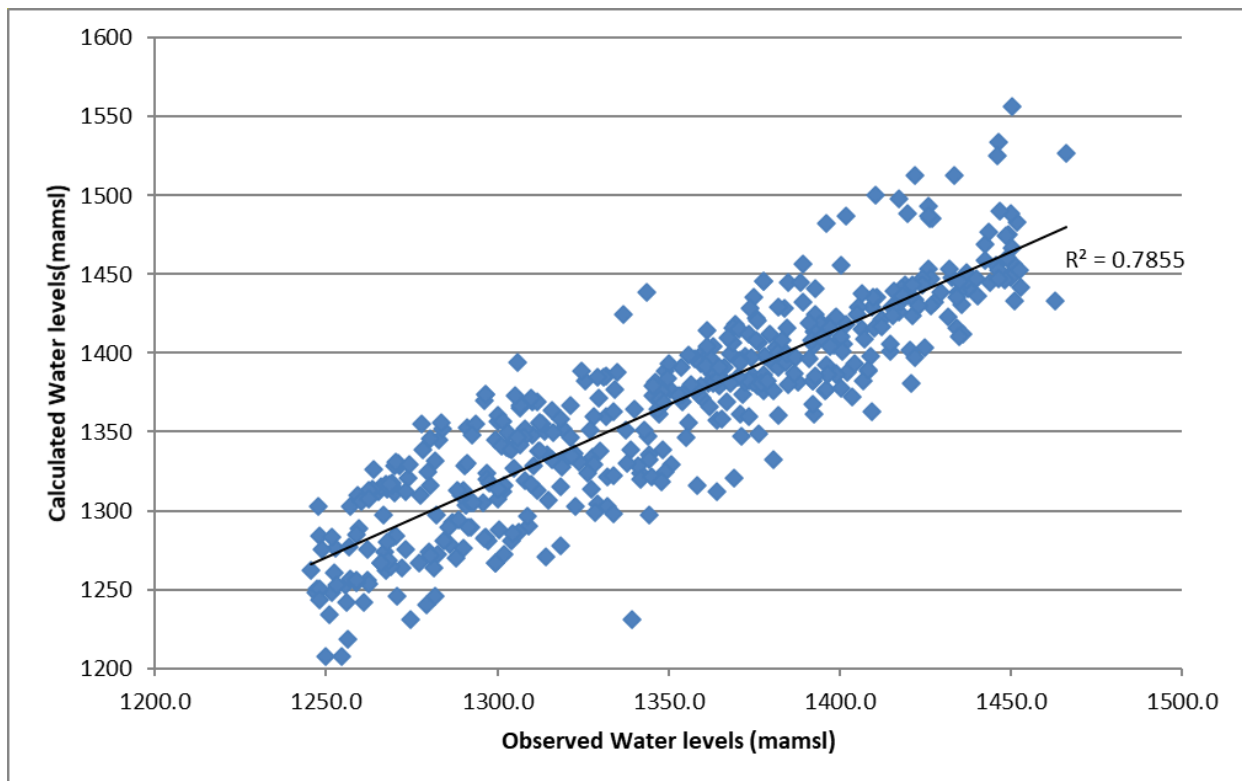


Figure 17: Steady state calibration results

6 STATISTICAL ANALYSIS

The geostatistical analysis for the study area as a whole is discussed and also the individual analysis of the different geological units as identified in the 1:1 000 000 simplified geological map of the area. The data used in the analysis comprises of borehole information from the NGA (National Groundwater Archive) and data obtained from various consultants that have done work within the study area – mostly water supply. Vegter's methodology as discussed in the previous section is followed as closely as possible, but due to the absence of certain datasets not all Vegter analyses could be repeated. Production costs and associated drilling control procedures are not addressed in this report.

6.1 SIMPLIFIED GEOLOGY

The 1:1 000 000 Simplified Geological Map available from the Council for Geoscience was used in the analysis. This was done to reduce the complexity of the data available in the 1:50 000 geological maps in relation to the available borehole data. The quaternary catchments within the area are shown in Figure 17 and Figure 18. The lithostratigraphic definitions in the map are listed in Table 9.

Table 9: Geological map label definitions

Geology	Stratigraphy	Lithology 1	Lithology 2	Lithostratigraphic Unit	Group / Formation / Complex
Jd	Karoo Dolerite	Dolerite		Dolerite Dyke	KAROO SUPERGROUP
Pa	Karoo Dolerite	Mudstone	Arenite	Adelaide	KAROO SUPERGROUP - BEAUFORT
Pc	Koedoesberg	Arenite	Shale	Koedoesberg	KAROO SUPERGROUP
Pvo	Volksrust	Shale		Volksrust	KAROO SUPERGROUP - ECCA
TRt	Tarkastad	Mudstone	Arenite	Tarkastad	KAROO SUPERGROUP - BEAUFORT

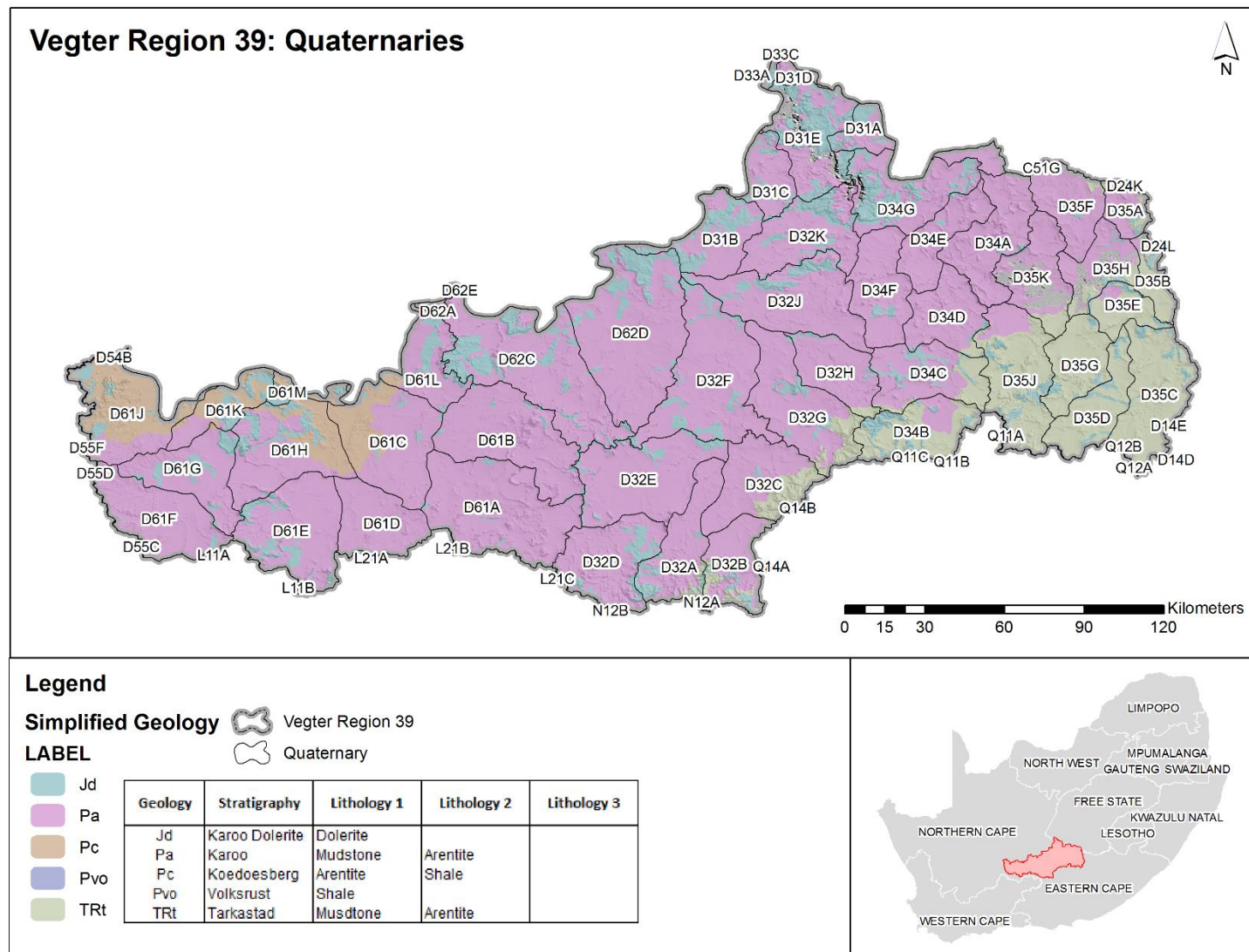


Figure 18: quaternary catchments

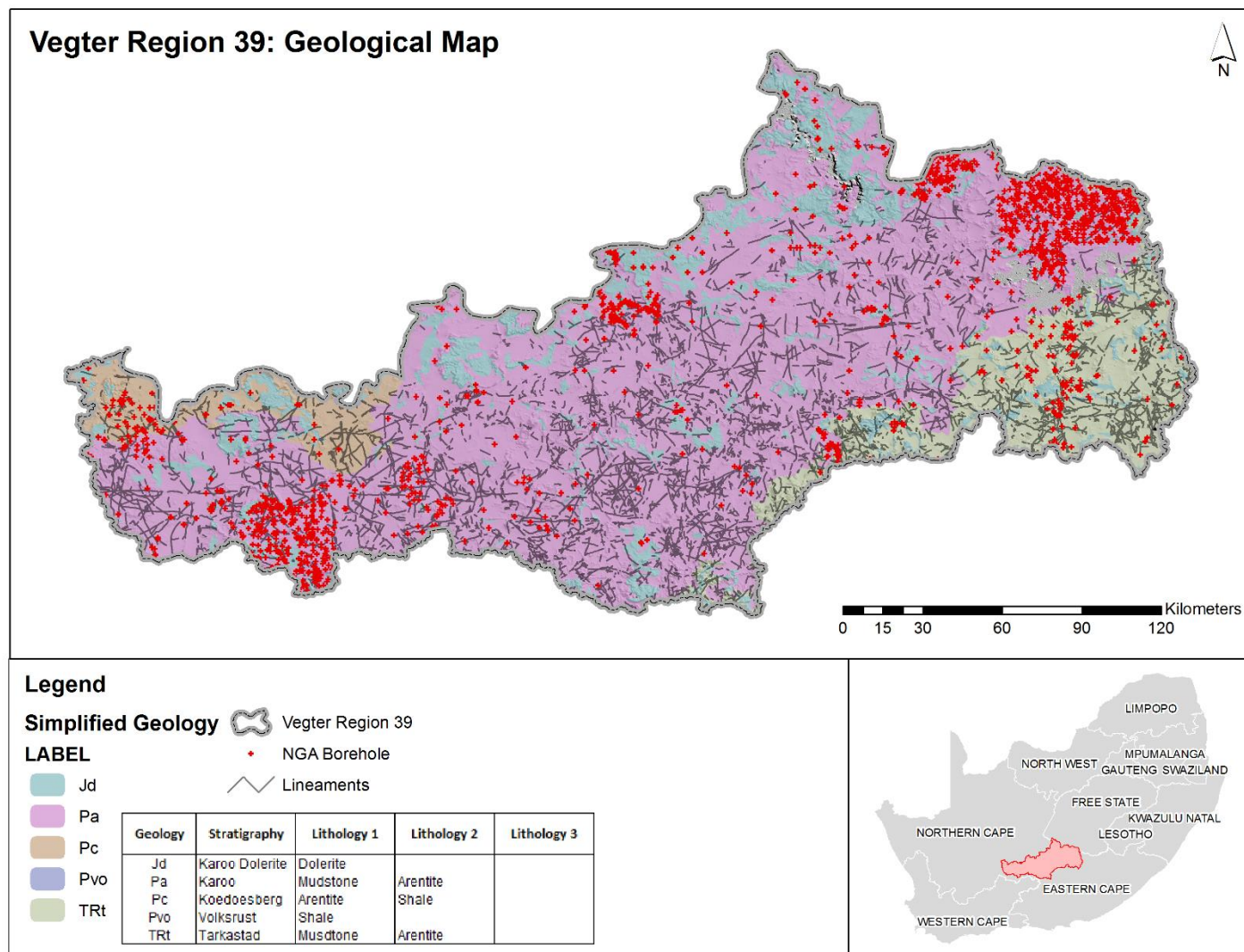


Figure 19: Simplified geological map

The lithology associated with each of the geological units as well as an aquifer rating are given in Table 10. From the aquifer ratings it is clear the Shales are the poorest aquifers.

Table 10: Lithologies and aquifer rating

Geology	Stratigraphy	Lithology 1	Lithology 2	Aquifer Index
Jd	Karoo Dolerite	Dolerite		4
Pa	Karoo	Mudstone	Arentite	2
Pc	Koedoesberg	Arentite	Shale	2
Pvo	Volksrust	Shale		1
TRt	Tarkastad	Mudstone	Arentite	2

It is expected that boreholes in similar geologies should behave in a similar fashion therefore all analyses done, were done in the context of the different lithostratigraphic units. The behaviour of each lithostratigraphic unit will become clear in subsequent analysis.

6.2 BOREHOLE DISTRIBUTION

Borehole data was obtained from the following sources:

- NGA
- GRIP
- Private Consultants

A summary of the borehole densities per quaternary and surface geology is given in Table 11 and Table 12 respectively, assuming a uniform distribution of boreholes over the area.

Table 11: Borehole summary per quaternary

Quaternary	Boreholes	Clipped Area (km2)	Density (BH/km2)
D14D	0	0.3	0.00
D31A	37	379.4	0.10
D31B	18	652.1	0.03
D31C	2	399.4	0.01
D31D	2	89.7	0.02
D31E	34	860.1	0.04
D32A	0	710.8	0.00
D32B	1	569.1	0.00
D32C	12	843.2	0.01
D32D	4	844.1	0.00
D32E	8	1155.4	0.01
D32F	16	1441.3	0.01
D32G	92	1041.3	0.09
D32H	19	571.8	0.03
D32J	37	1112.5	0.03
D32K	52	823.4	0.06
D34A	104	792.2	0.13
D34B	20	696.8	0.03
D34C	18	760.0	0.02
D34D	19	598.9	0.03
D34E	0	518.8	0.00
D34F	75	691.3	0.11
D34G	136	856.7	0.16
D35A	141	245.5	0.57
D35B	14	247.1	0.06
D35C	22	920.8	0.02
D35D	18	583.4	0.03
D35E	5	311.8	0.02
D35F	301	552.8	0.54
D35G	181	551.8	0.33
D35H	59	498.2	0.12
D35J	67	999.0	0.07
D35K	155	674.1	0.23
D61A	53	1456.2	0.04
D61B	28	1196.8	0.02
D61C	40	1117.2	0.04
D61D	20	640.7	0.03
D61E	460	1079.6	0.43
D61F	77	863.2	0.09
D61G	67	744.1	0.09
D61H	28	1086.1	0.03
D61J	162	950.4	0.17
D61K	38	439.6	0.09
D61L	11	558.1	0.02
D61M	0	140.1	0.00
D62A	4	56.9	0.07
D62C	8	1670.8	0.00
D62D	516	1810.3	0.29
Total	3181	35803	

Table 12: Borehole summary per geology

Geology	Boreholes	Clipped Area (km ²)	Density (BH/km ²)
Jd	320	4456	0.07
Pa	2301	25058	0.09
Pc	144	1565	0.09
Pvo	16	163	0.10
TRt	402	4561	0.09
Total	3183	35803	

6.3 GEOPHYSICAL MAPS

Little geophysical information is available for the area. The aerial magnetic map together with the boreholes intersecting dykes are shown in Figure 20. It is clear that there exists a strong correlation between the boreholes intersecting dykes and the proximity to magnetic features.

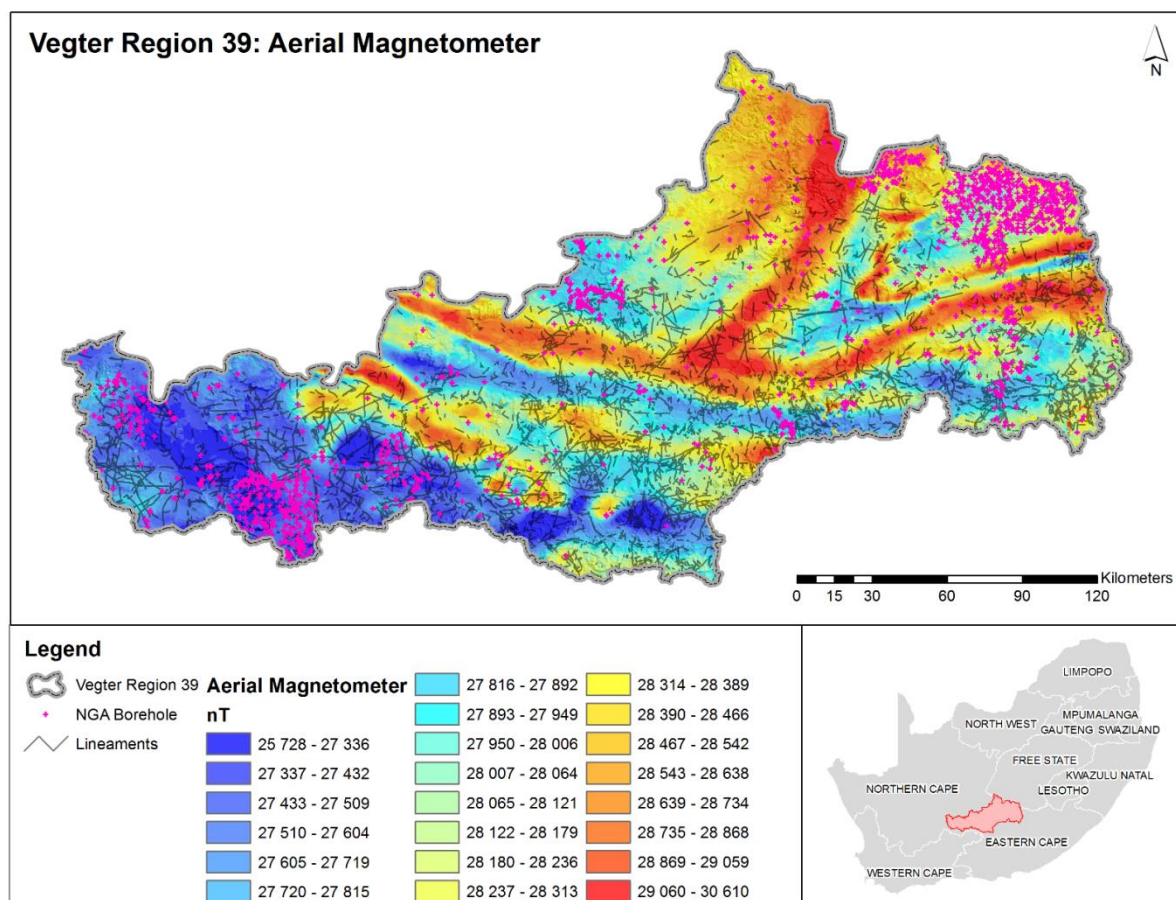


Figure 20: Aerial magnetic map and boreholes intersecting dykes

6.4 WATER LEVEL ANALYSIS

Water levels versus topography have been analysed for each of the surface geologies where boreholes are present. The methodology followed was to rank the boreholes based on water level depth, and different systems were identified from the ranking plots. Water level correlation with surface topography was analysed for each of the identified systems.

6.4.1 Jd Water Levels

The Jd comprise a total number of 168 boreholes and two different systems are identified as shown in Figure 21, each exhibiting a high correlation between water level and surface topography as shown in Figure 22.

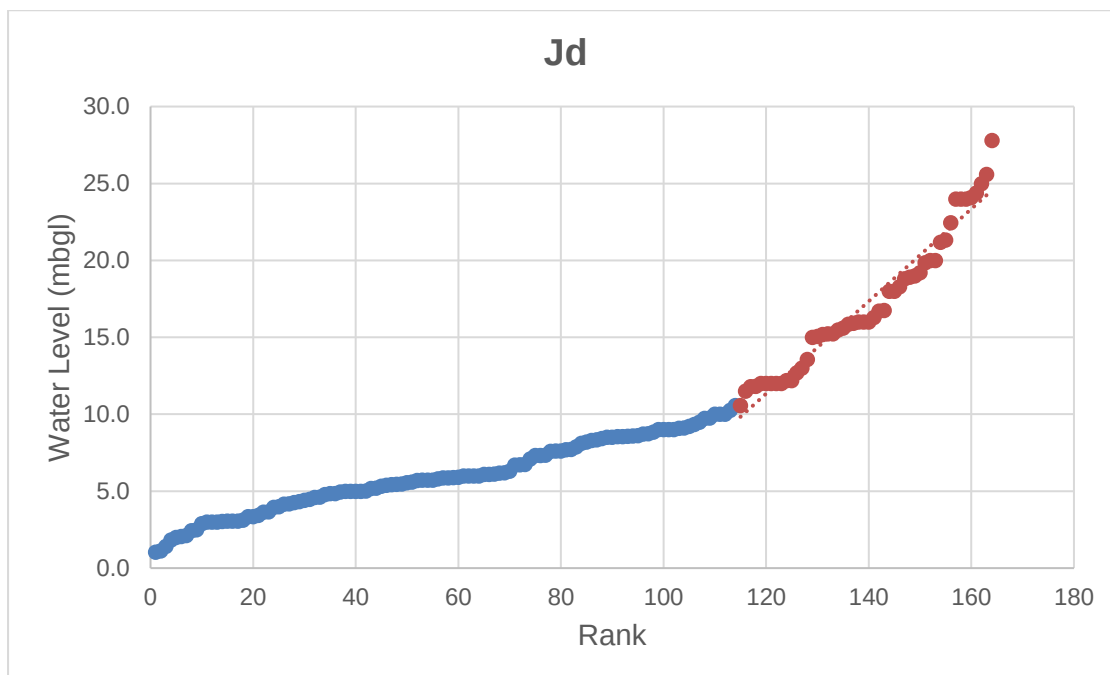


Figure 21: Jd water level vs rank

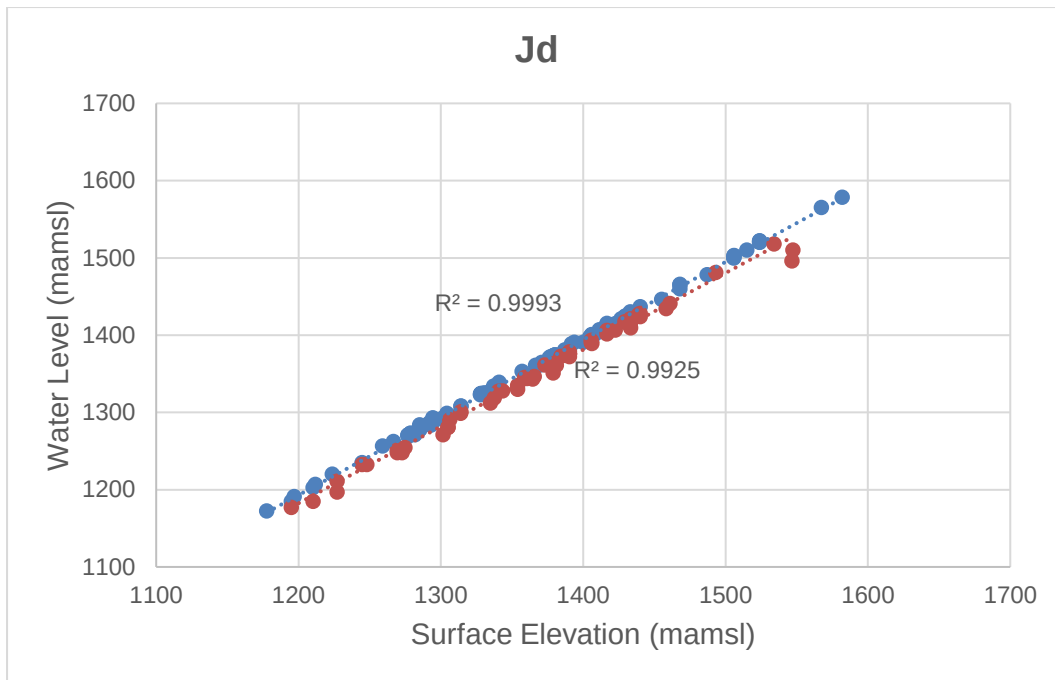


Figure 22: JD groundwater level vs surface elevation

The distribution of groundwater levels per depth and the number of boreholes passing through the depth range is shown in Figure 23.

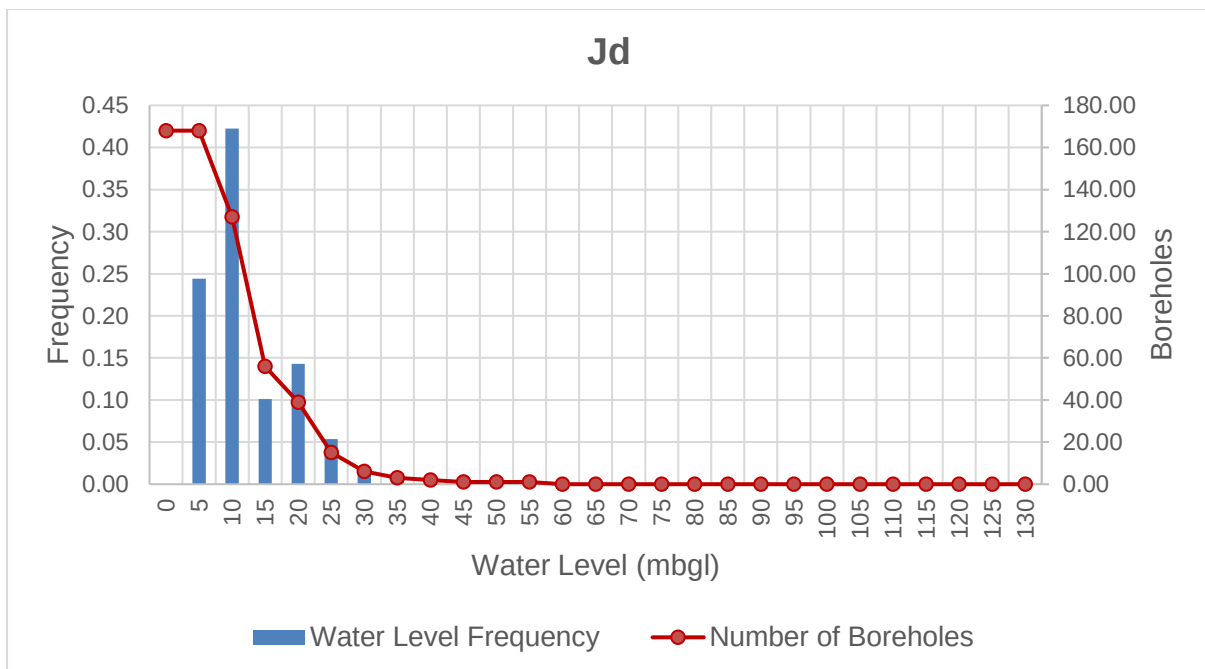


Figure 23: JD distribution of groundwater levels

6.4.2 Pa Water Levels

The Pa comprise a total number of 1153 boreholes and four different systems are identified as shown in Figure 24. All systems show a high correlation between groundwater levels and surface elevation as shown in Figure 25.

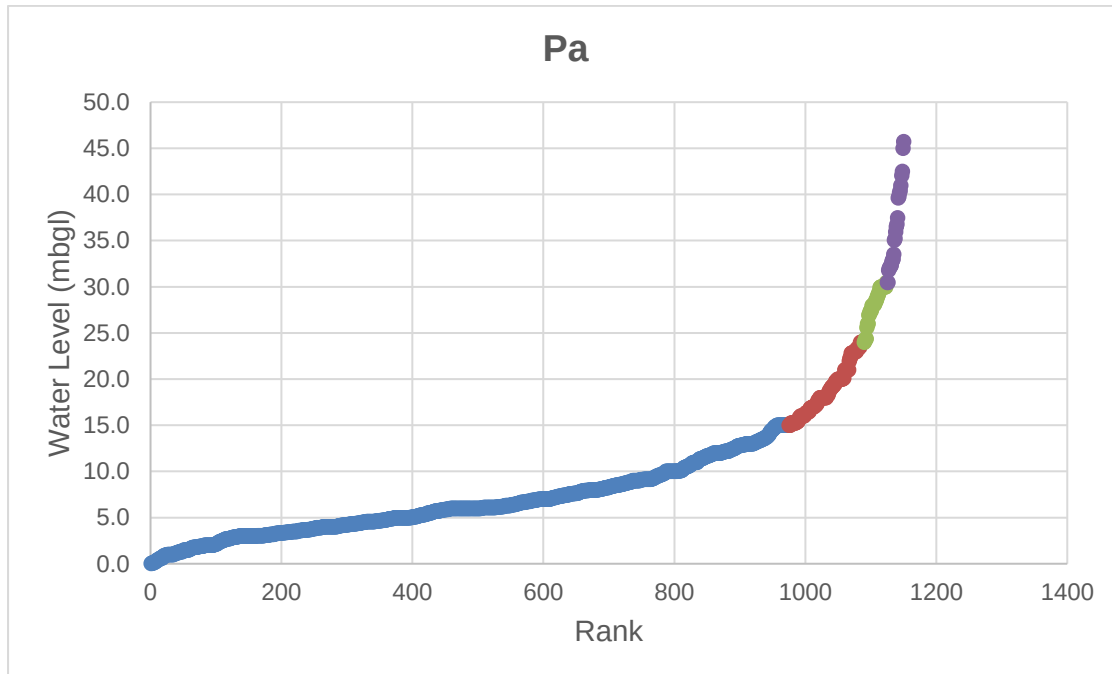


Figure 24: PA water levels vs rank

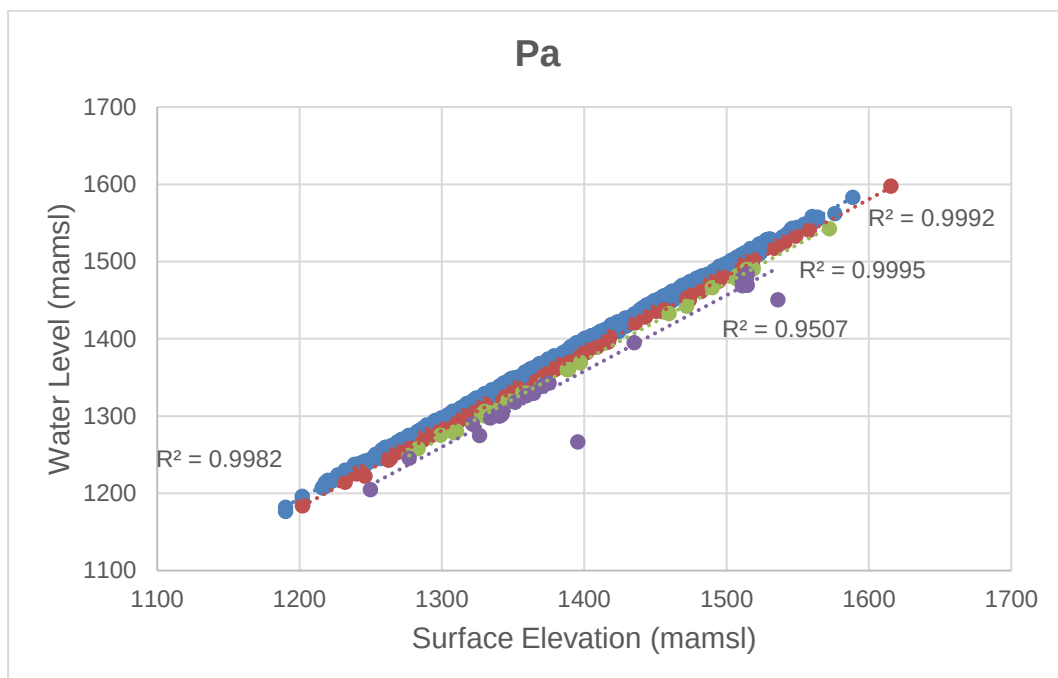


Figure 25: PA groundwater level vs surface elevation

The distribution of groundwater levels per depth and the number of boreholes passing through the depth range is shown in Figure 26.

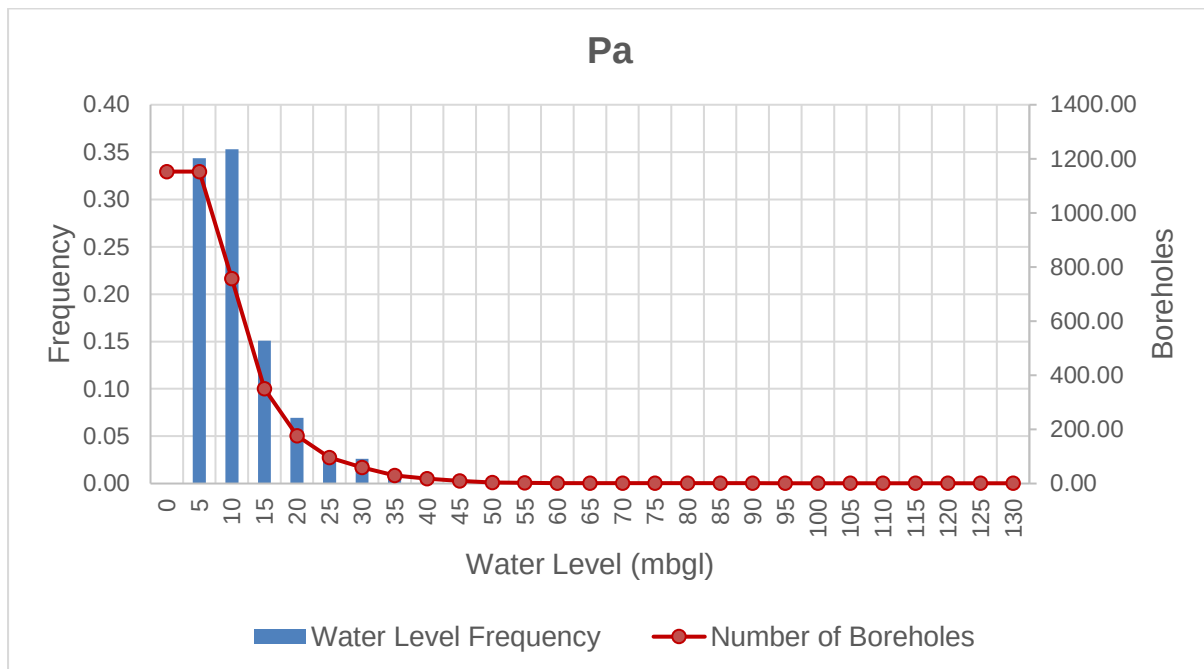


Figure 26: PA distribution of groundwater levels

6.4.3 Pc Water Levels

The Pc comprise a total number of 81 boreholes and 3 systems are identified as shown in Figure 27, exhibiting a very high correlation between water level and surface topography as shown in Figure 28.

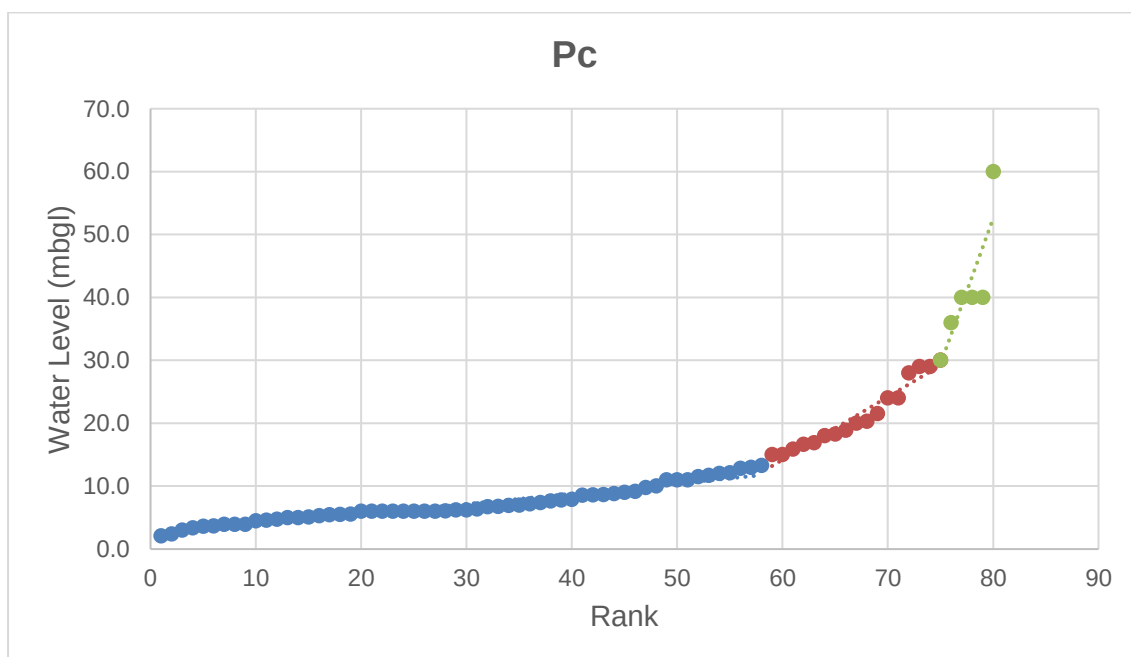


Figure 27: Pc water levels vs rank

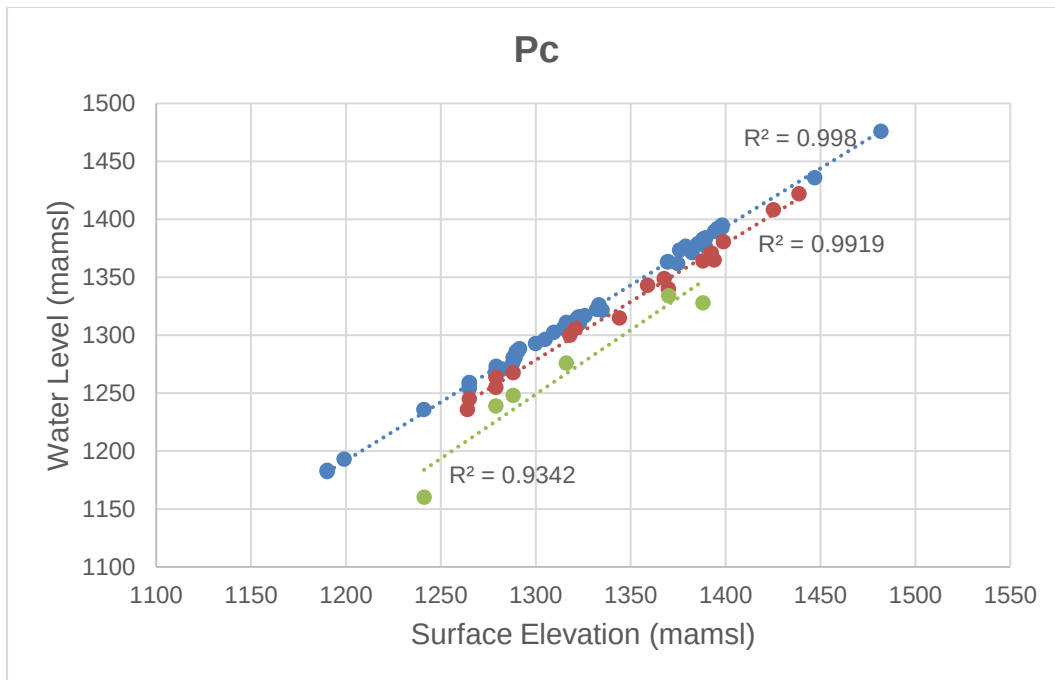


Figure 28: Pc Groundwater levels vs surface elevation

The distribution of groundwater levels per depth and the number of boreholes passing through the depth range is shown in Figure 29.

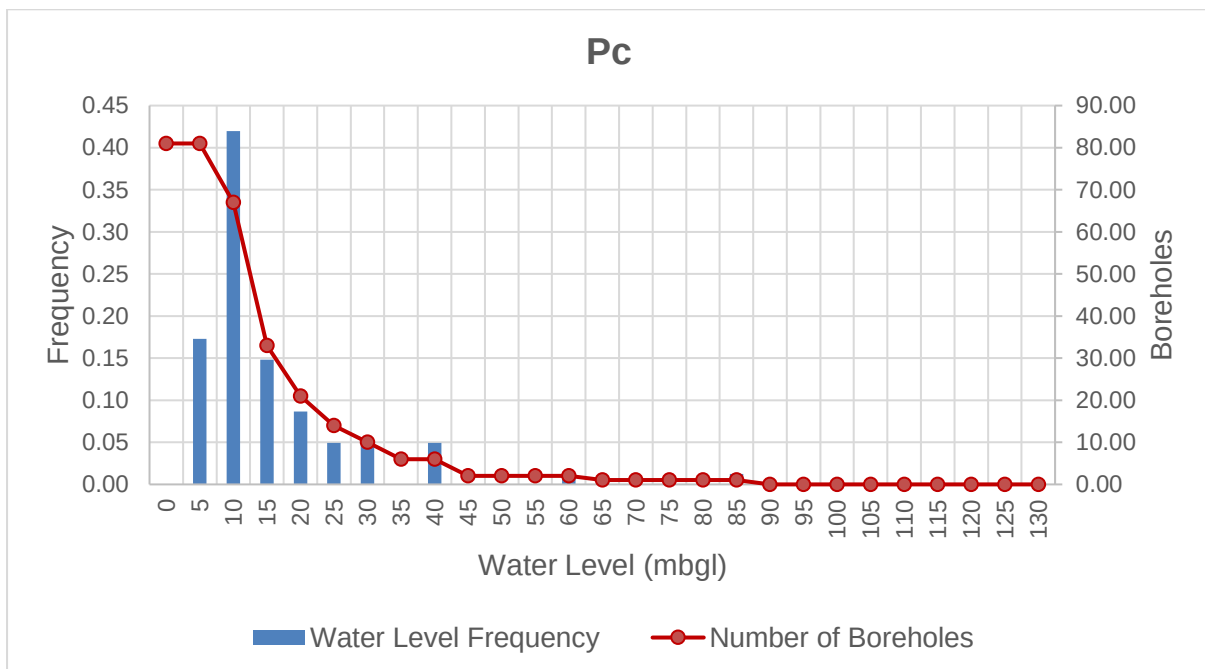


Figure 29: Pc distribution of groundwater levels

6.4.4 Pvo Water Levels

The Pvo boreholes comprise a total number of 10 boreholes and one system is identified as shown in Figure 30, with a high correlation between water level and surface topography as shown in Figure 31.

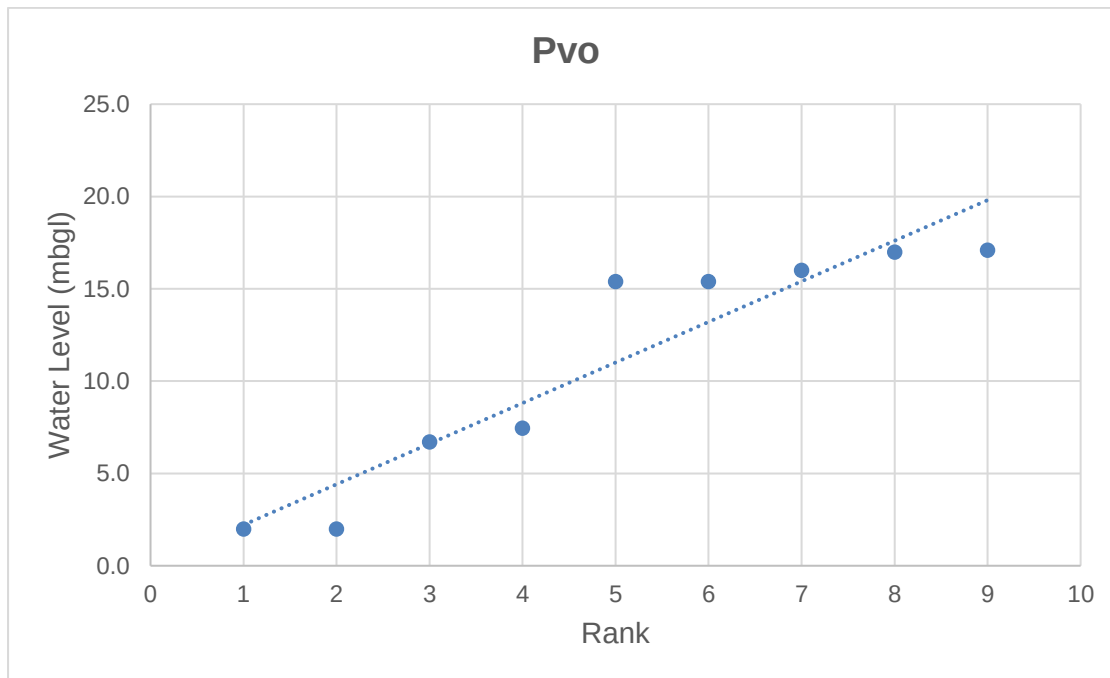


Figure 30: PVo water levels vs rank

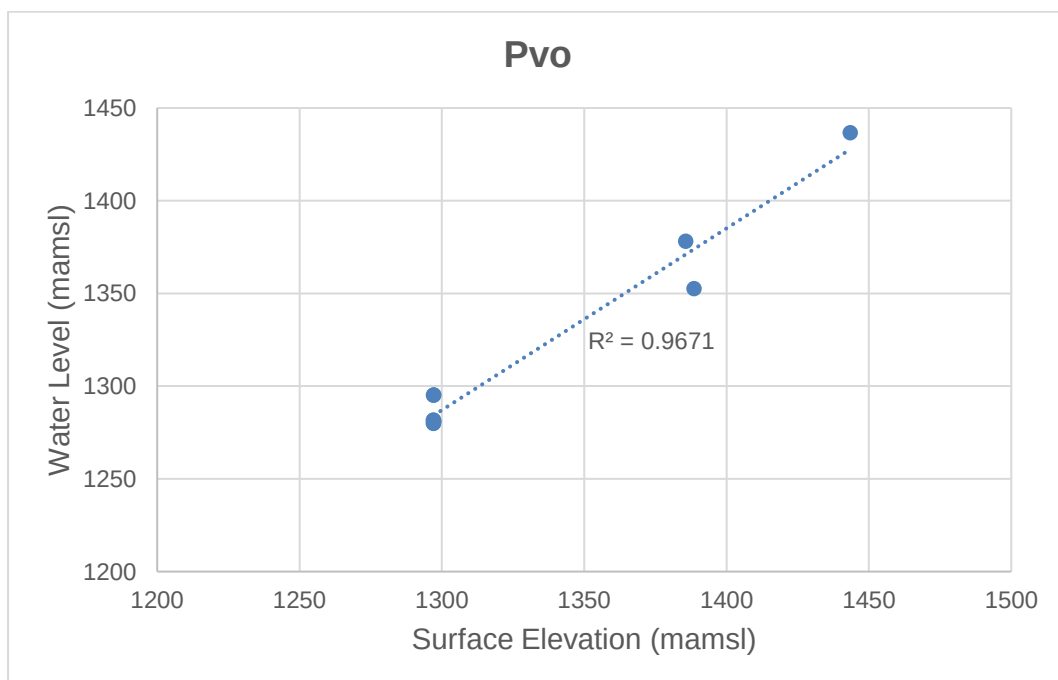


Figure 31: PVO groundwater levels vs surface elevation

The distribution of groundwater levels per depth and the number of boreholes passing through the depth range is shown in Figure 32.

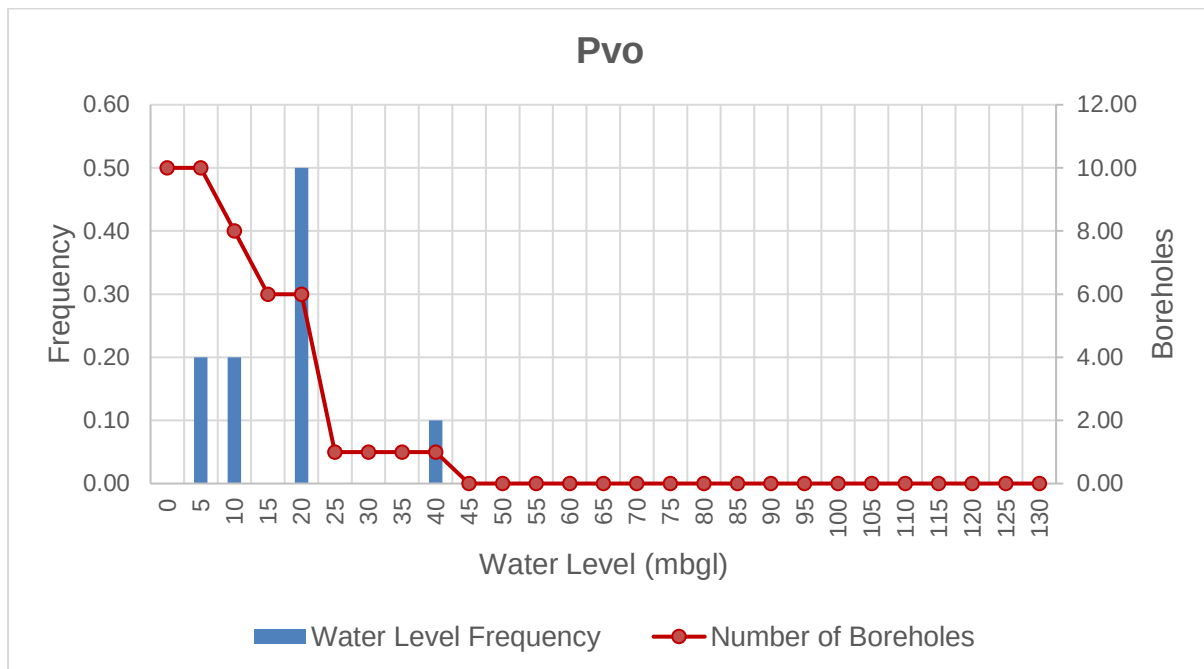


Figure 32: PVO distribution of groundwater levels

6.4.5 TRt Water Levels

The TRt comprise a total number of 231 boreholes and five different systems are identified as shown in Figure 33, each exhibiting a high correlation between water level and surface topography as shown in Figure 34.

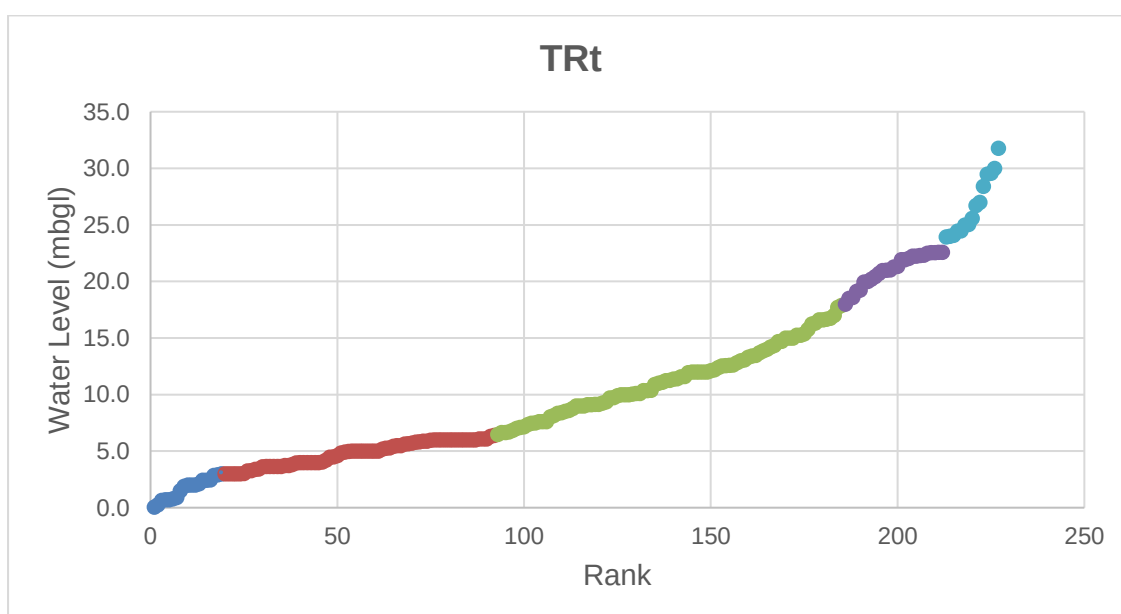


Figure 33: Trt water level vs rank

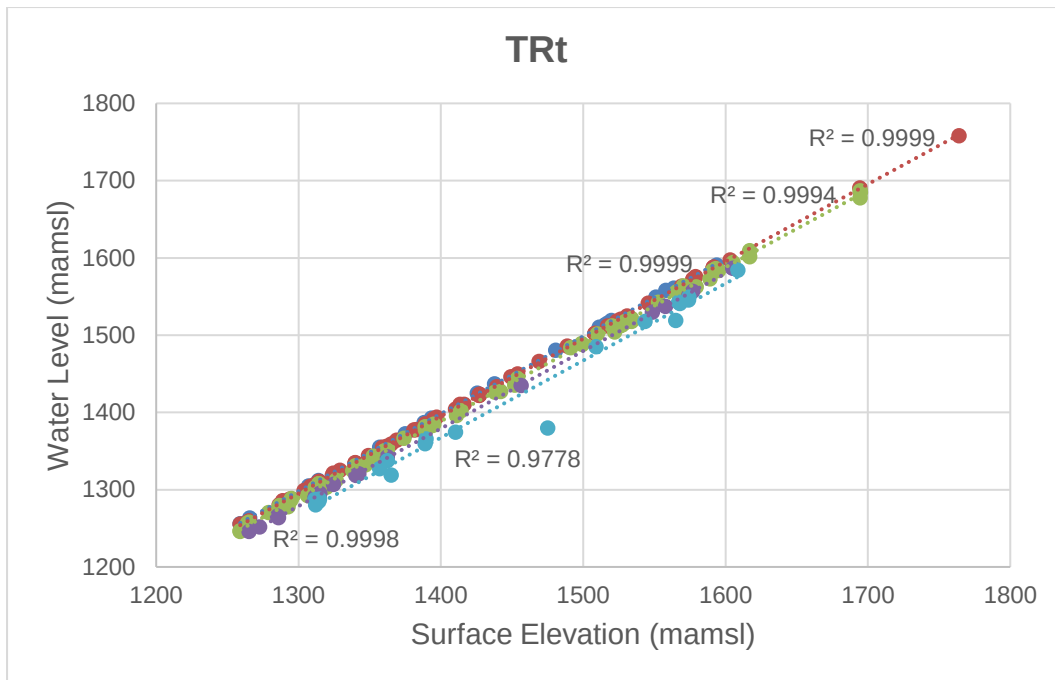


Figure 34: Trt groundwater level vs surface water elevation

The distribution of groundwater levels per depth and the number of boreholes passing through the depth range is shown in Figure 35.

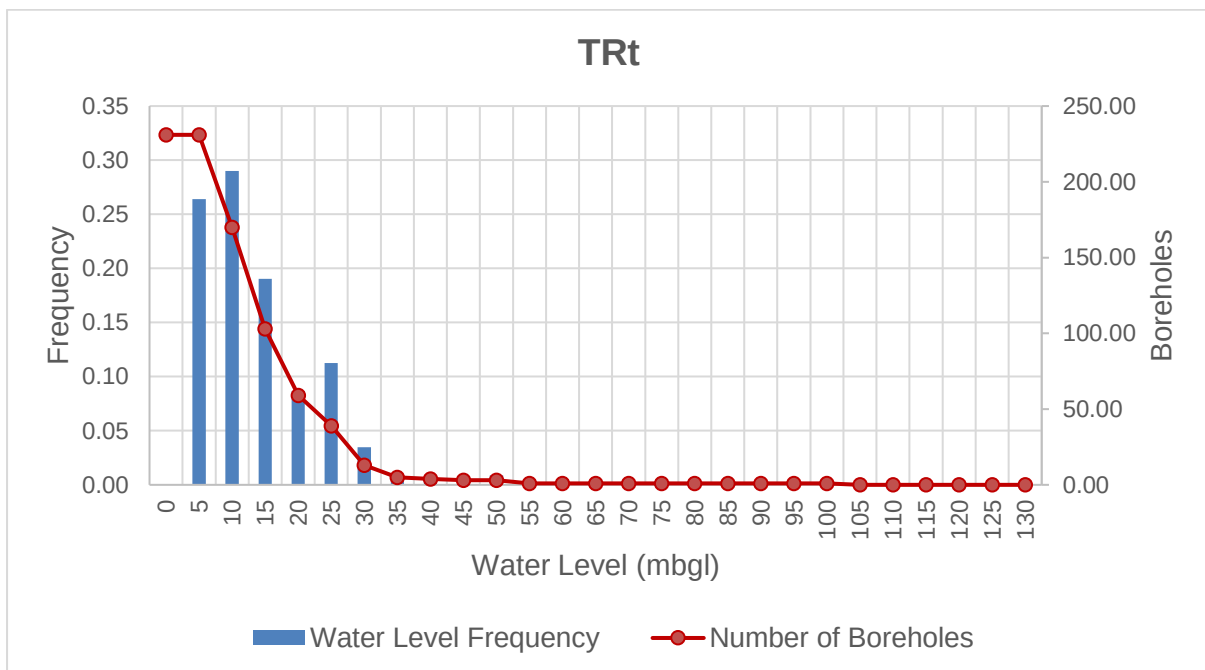


Figure 35: Trt distribution of groundwater levels

6.5 BOREHOLE YIELDS

A main characteristic of the study area, which consists mainly of mudstone, sandstone, siltstone, and shale, is its low permeability. The majority of the boreholes drilled in the study area therefore have very low immediate yield, <1 l/s. The general view is that Karoo aquifers do not contain large quantities of groundwater, thus very few borehole yields were available and therefore a geostatistical analysis was not possible.

6.6 BOREHOLE DEPTHS

A summary of average borehole depths and water levels is shown in Table 13.

Table 13: Summary of average borehole depths and water levels

Geology	% Area	Borehole Depth (mbgl)			Borehole Water Level (mbgl)		
		Average	Std. Dev	Count	Average	Std. Dev	Count
Jd	12.4	46	47	312	10	7	168
Pa	70.0	37	39	2035	9	9	1153
Pc	4.4	44	26	140	13	13	81
Pvo	0.5	51	19	15	14	10	10
TRt	12.7	46	28	382	11	10	231

The borehole depth values in descending order is presented in Figure 36.

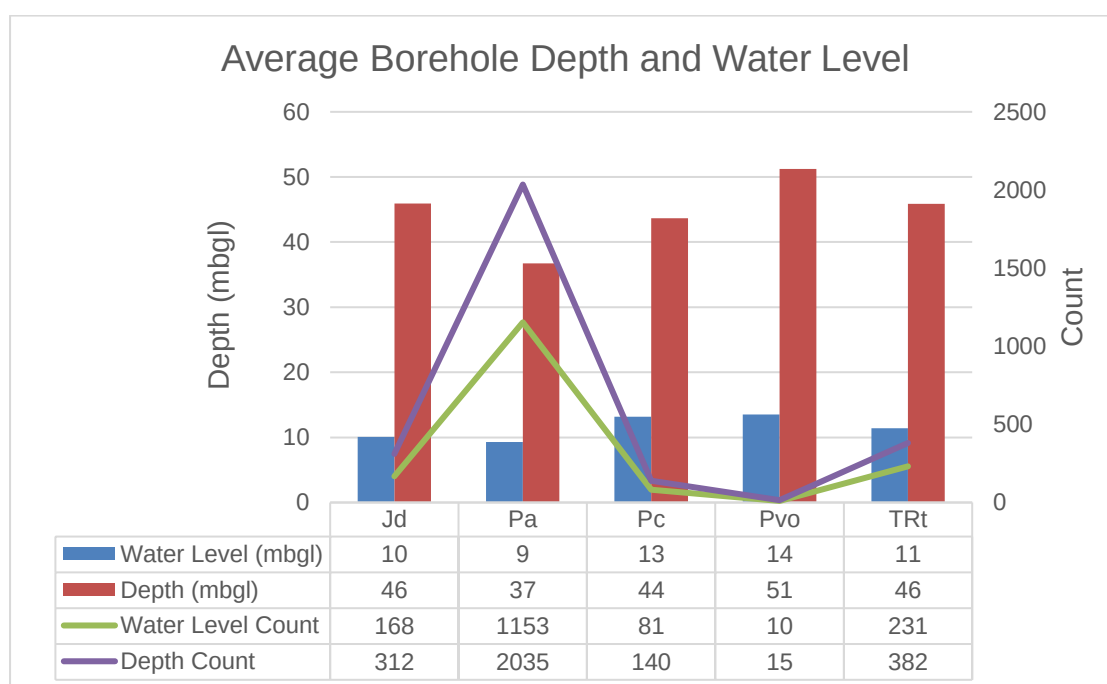


Figure 36: Average borehole depth and water level

The borehole frequency per depth range for each of the lithostratigraphic units in the study area are presented in the following sections.

6.6.1 Jd Depth Frequency

The depth frequency for the Jd lithostratigraphic units is shown in Figure 37. A total of 312 of which 37 boreholes have a depth deeper than 90m.

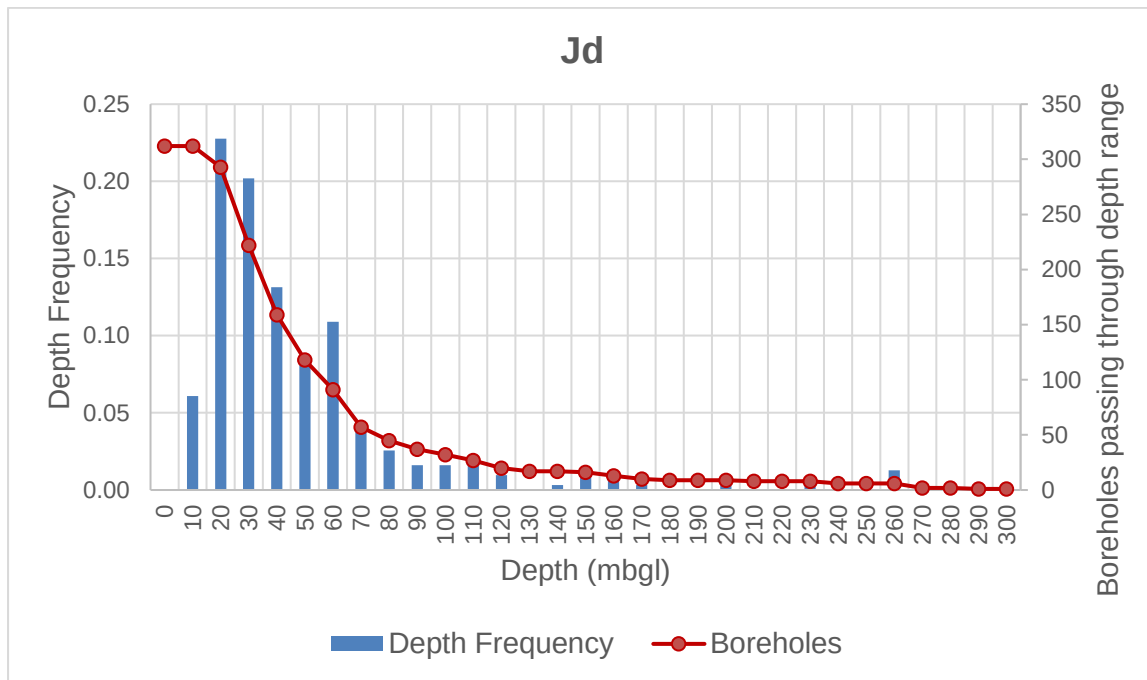


Figure 37: Jd depth frequency plot

6.6.2 Pa Depth Frequency

The depth frequency for the Pa lithostratigraphic units is shown in Figure 38. Some total of 2035 boreholes exist with varying depths between 1m and 190m.

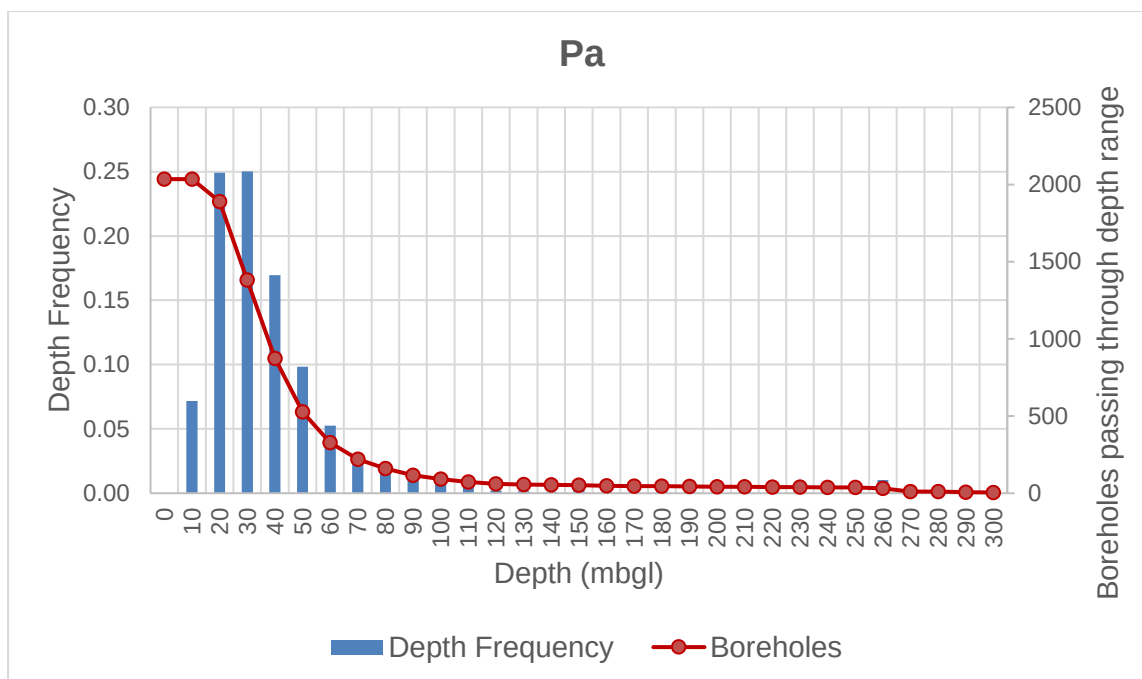


Figure 38: Pa depth frequency plot

6.6.3 Pc Depth Frequency

The depth frequency for the Pc lithostratigraphic units is shown in Figure 39. A total of 140 boreholes exist with 11 being deeper than 90 m.

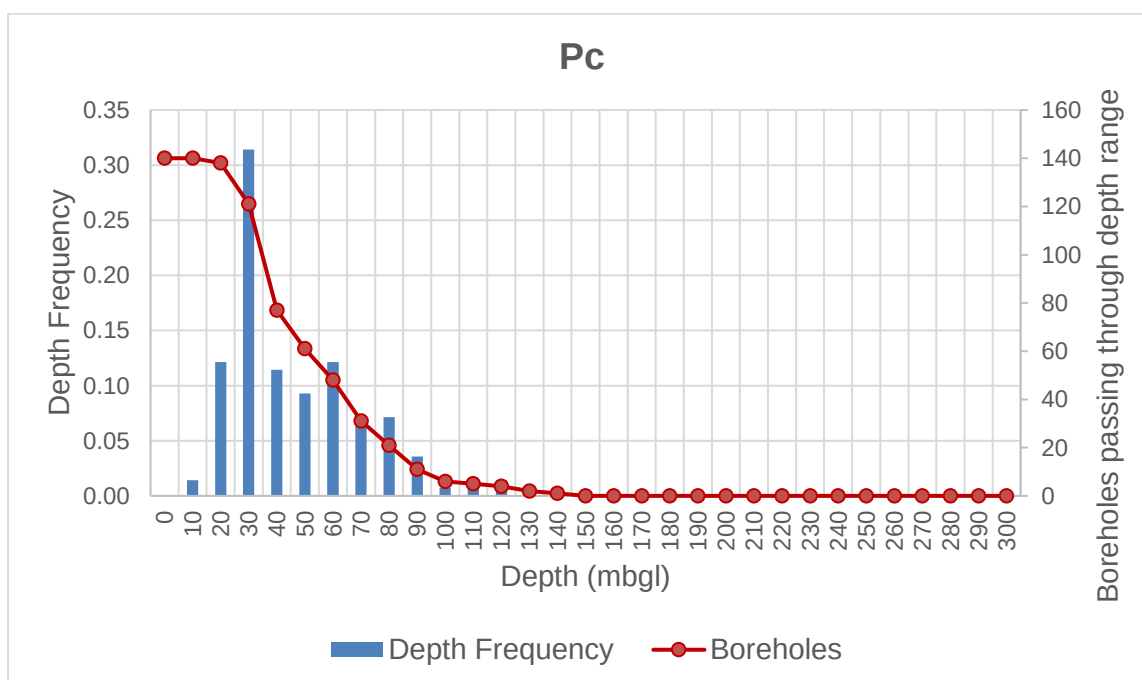


Figure 39: Pc depth frequency plot

6.6.4 Pvo Depth Frequency

The depth frequency for the Pvo lithostratigraphic units is shown in Figure 40. A total of 15 boreholes exist of which only one has a depth deeper than 90m.

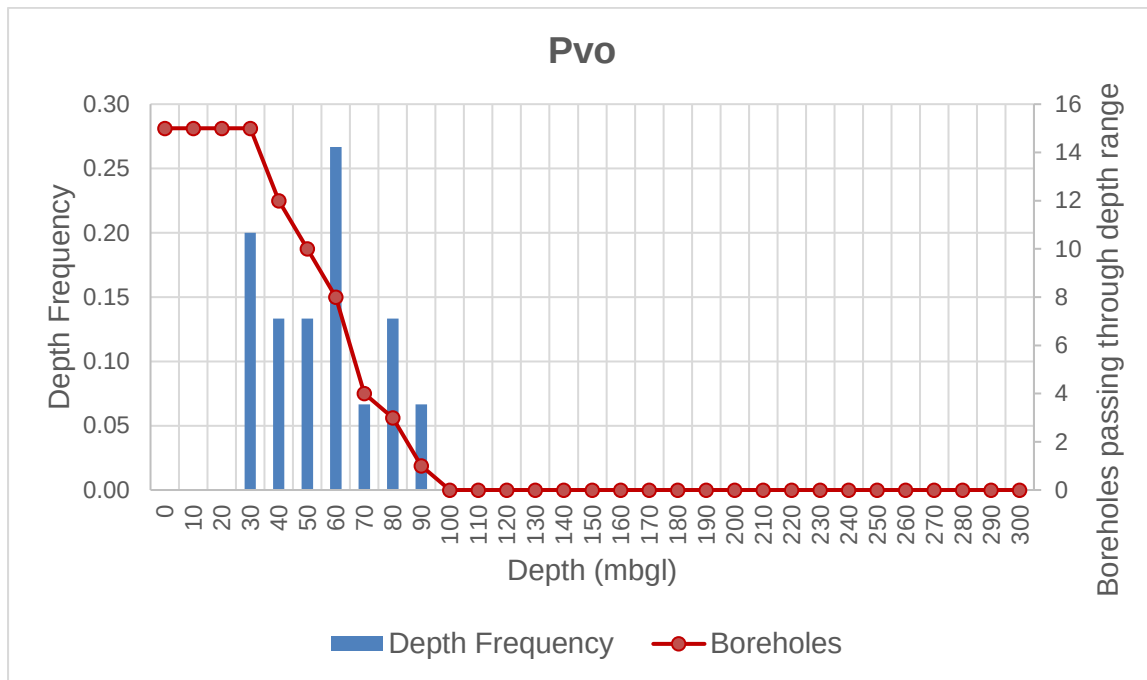


Figure 40: Pvo depth frequency plot

6.6.5 TRt Depth Frequency

The depth frequency for the TRt lithostratigraphic units is shown in Figure 41. A total of 382 boreholes exist with a 51 of them being deeper than 90 m.

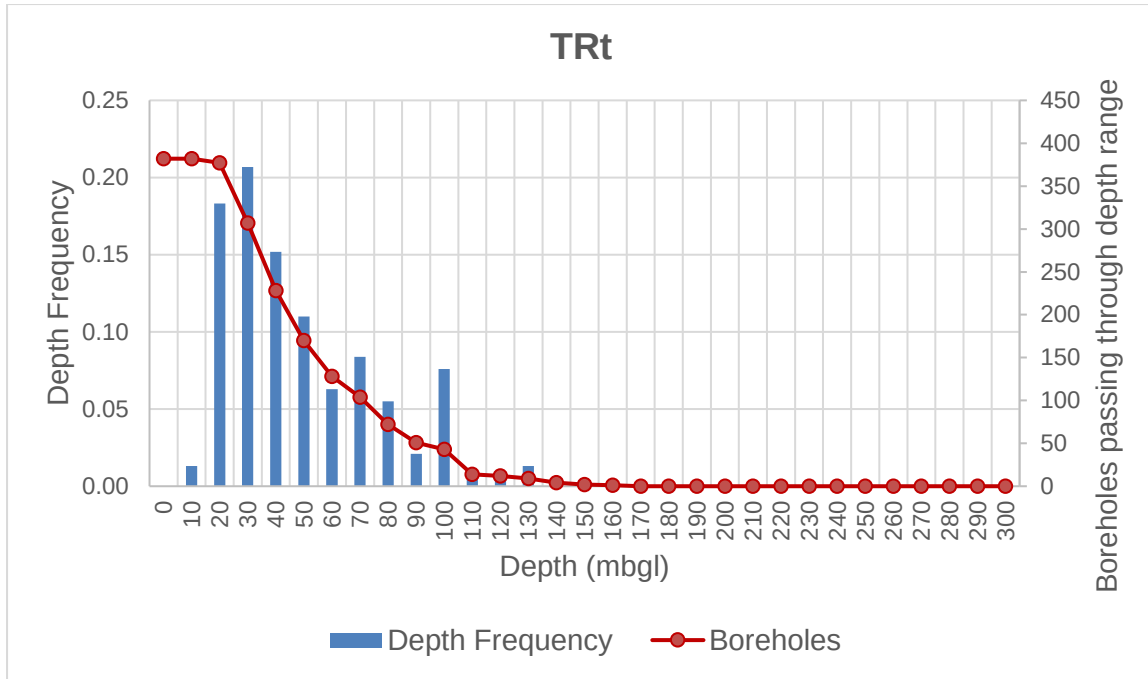


Figure 41: Trt depth frequency plot

6.7 WATER STRIKES

The strike frequency used in the sections that follow is formulated as follows:

$$\text{Strike Frequency} = \frac{\text{Number of strikes per depth range below surface}}{\text{Number of boreholes passing through depth range}}$$

The cumulative strike frequency is defined as the sum of the all the preceding strike frequencies per depth range.

6.7.1 Jd Strike Frequency

The strike frequency and the cumulative strike frequency for the Jd unit are shown in Figure 41 and Figure 42 respectively. Note only 232 boreholes with strike information were used. From the available data the predominant strike frequencies are within the first 160 m below surface.

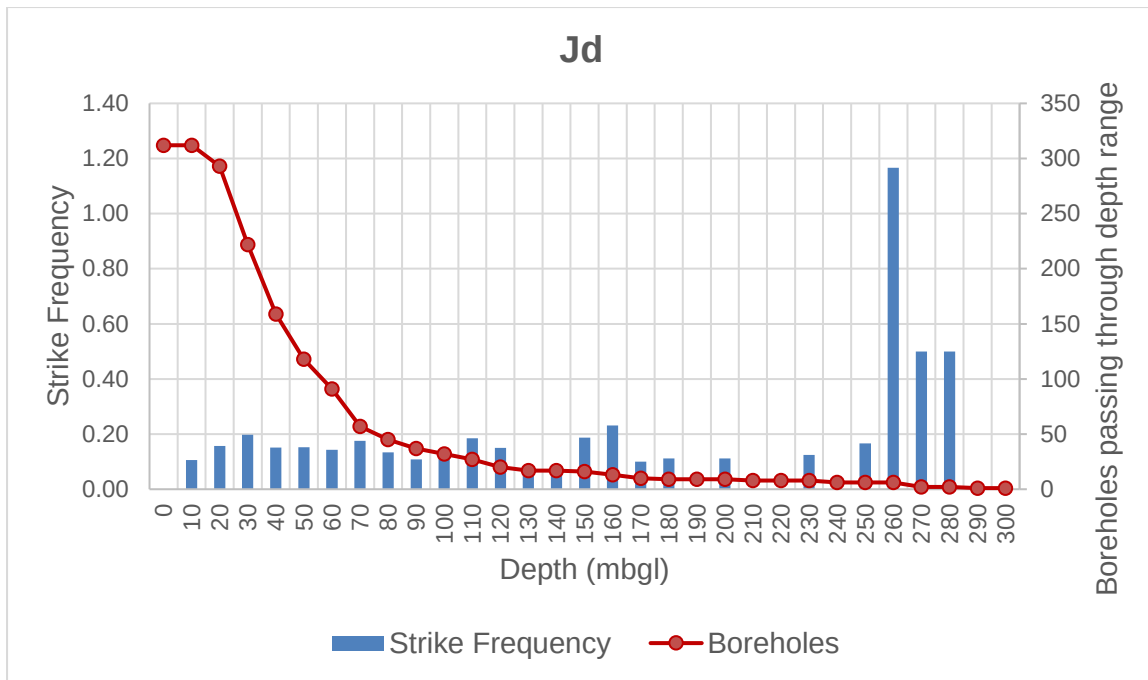


Figure 42: Jd strike frequency graph

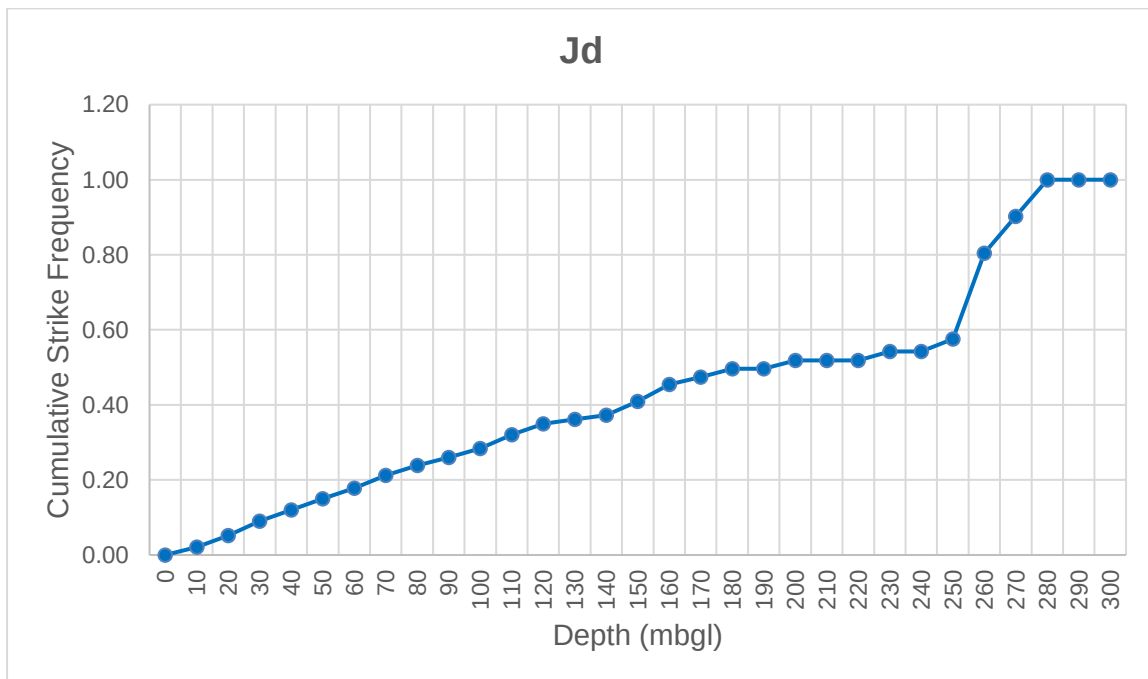


Figure 43: JD cumulative strike frequency graph

6.7.2 Pa Strike Frequency

The strike frequency and the cumulative strike frequency for the Pa unit are shown in Figure 43 and Figure 44 respectively. Note 1280 boreholes with strike information were used to generate the graph. From the available data the predominant strike frequencies are within the first 120 m below surface.

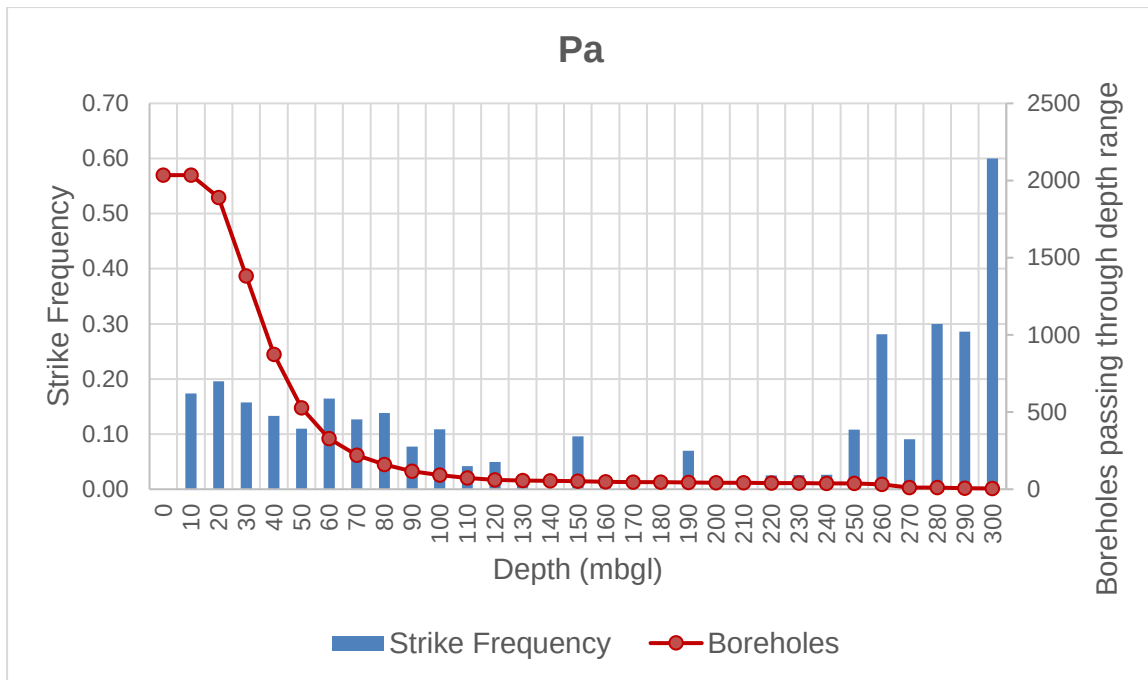


Figure 44: Pa strike frequency graph

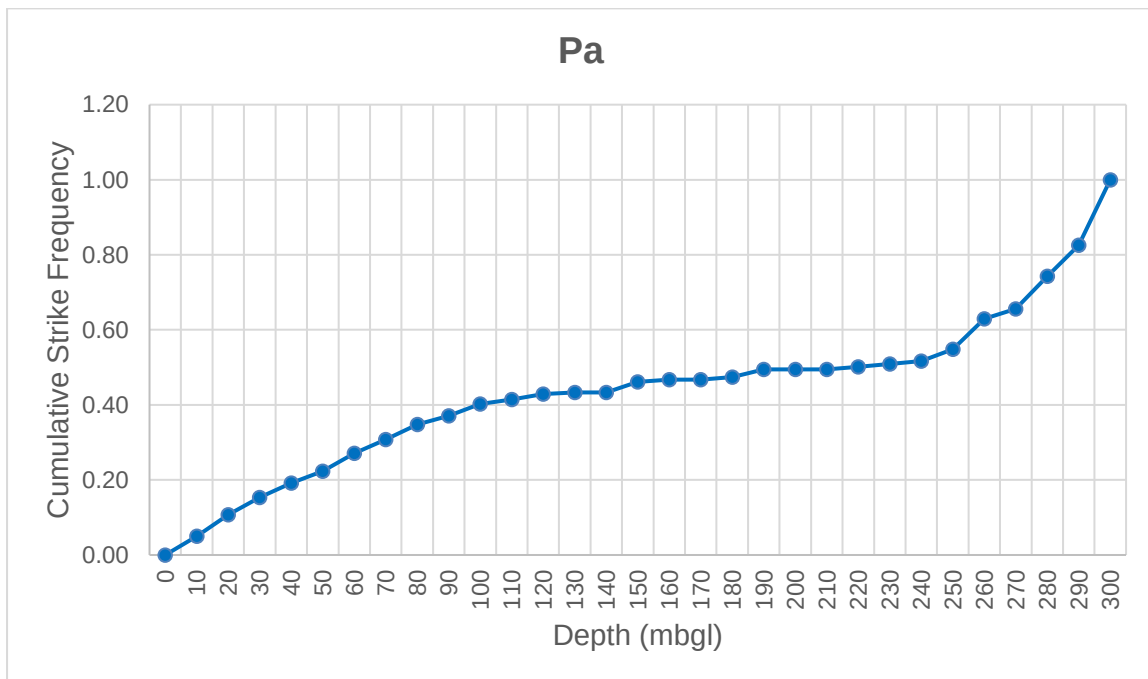


Figure 45: Pa cumulative strike frequency graph

6.7.3 Pc Strike Frequency

The strike frequency and the cumulative strike frequency for the Pc unit are shown in Figure 45 and Figure 46 respectively. Note 55 boreholes with strike information were used to generate the graph. From the available data the predominant strike frequencies are within the first 100 m below surface.

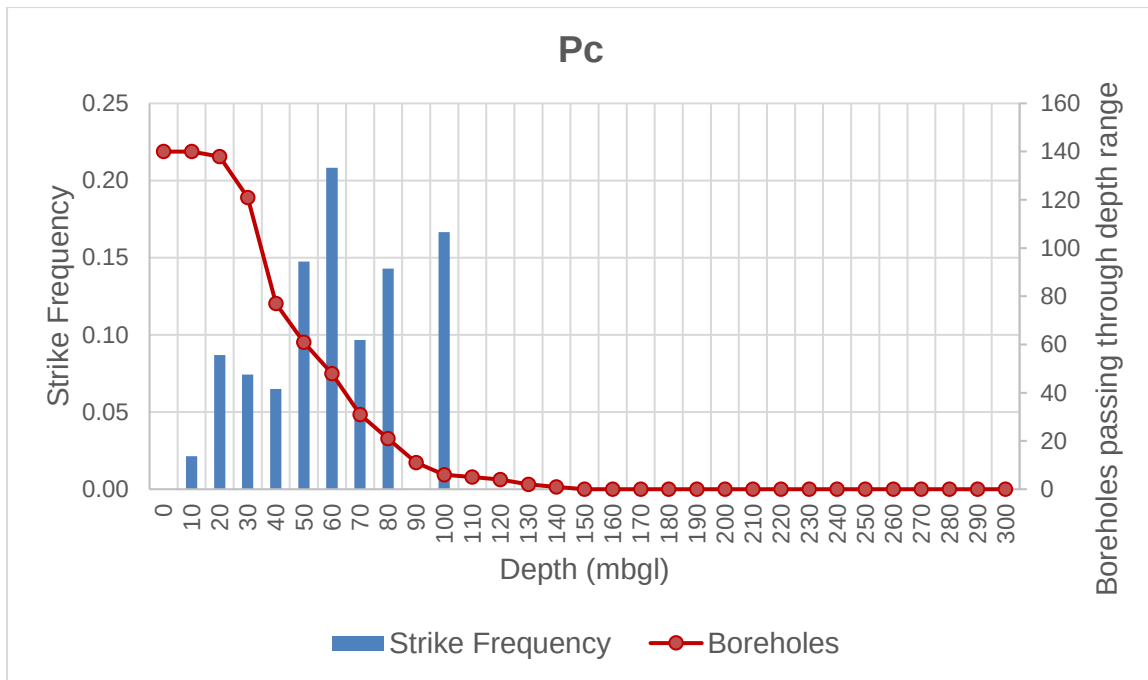


Figure 46: PC strike frequency graph

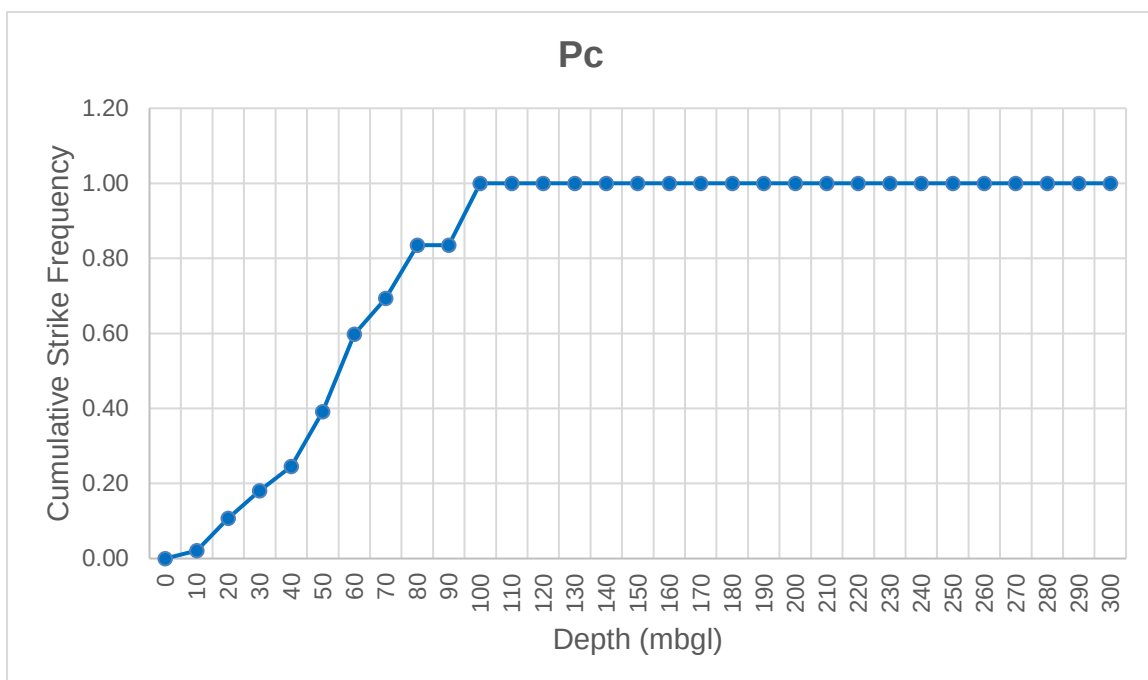


Figure 47: PC cumulative strike frequency

6.7.4 Pvo Strike Frequency

The strike frequency and the cumulative strike frequency for the Pvo unit are shown in Figure 47 and Figure 48 respectively. Note only 8 boreholes with strike information were used hence the stepwise nature of the cumulative graph.

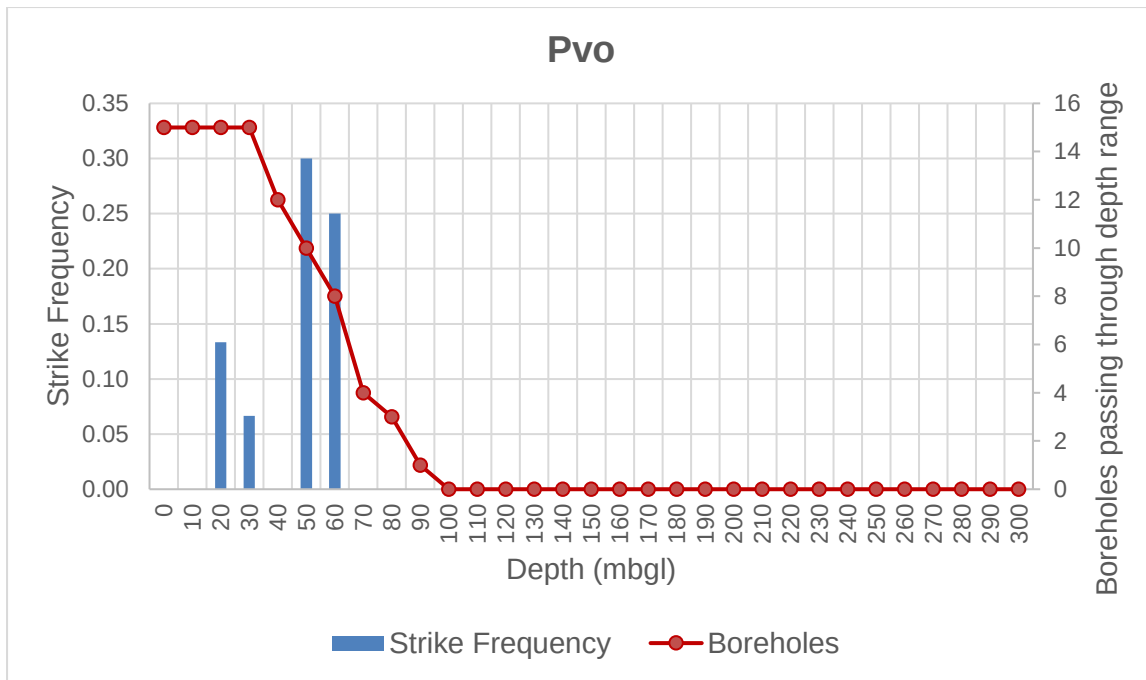


Figure 48: Pvo strike frequency graph

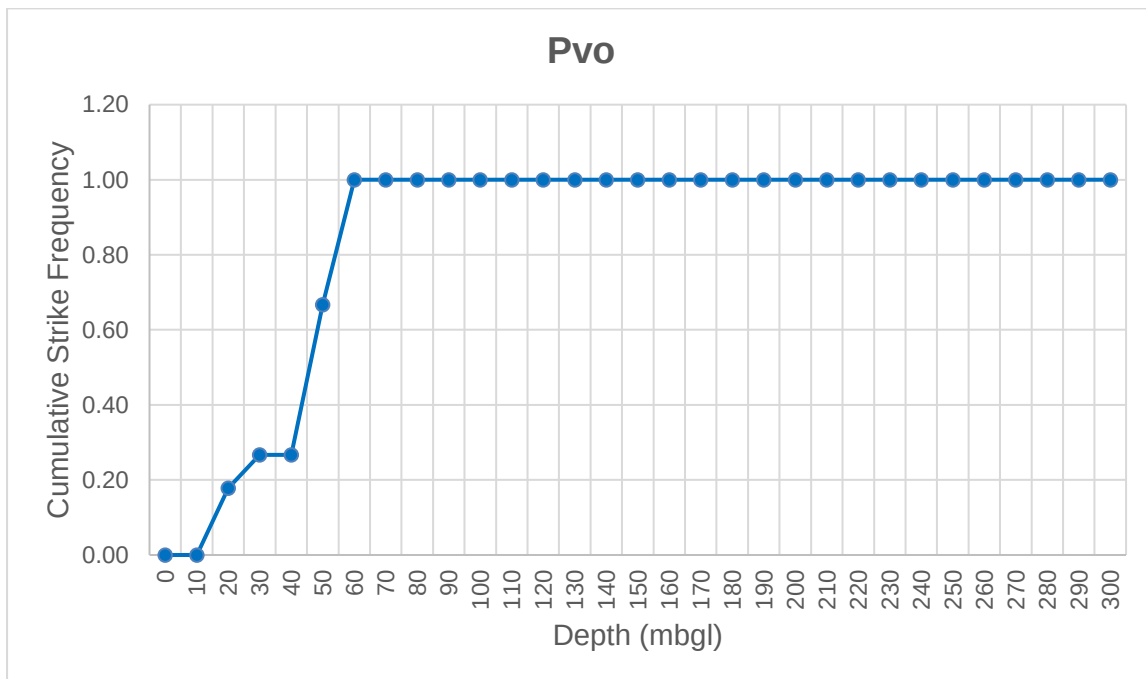


Figure 49: Pvo cumulative strike frequency graph

6.7.5 TRt Strike Frequency

The strike frequency and the cumulative strike frequency for the TRt unit are shown in Figure 49 and Figure 50 respectively. Note only 231 boreholes with strike information were used hence the stepwise nature of the cumulative graph. From the available data the predominant strike frequencies are within the first 120 m below surface.

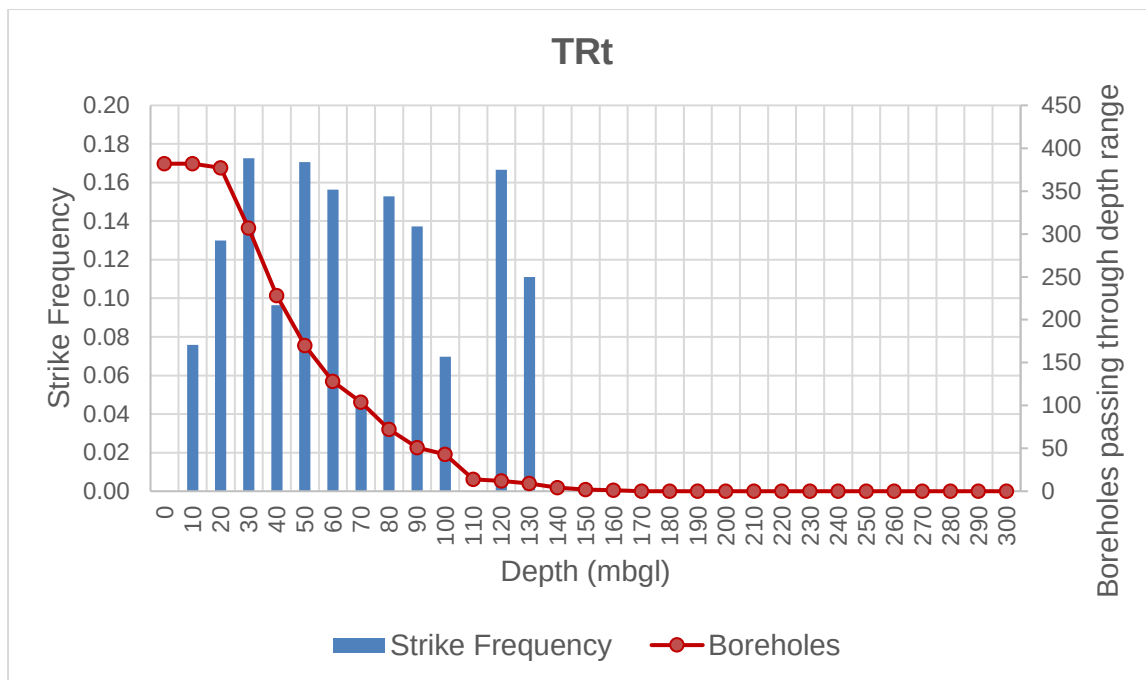


Figure 50: TRt strike frequency graph

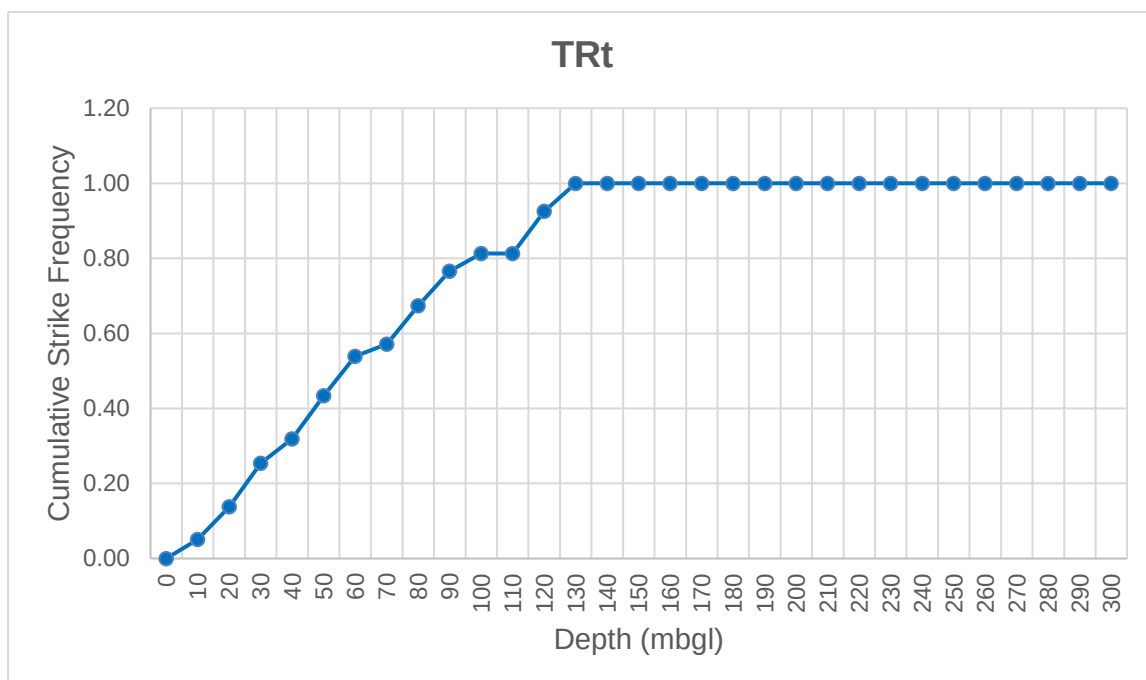


Figure 51: TRt cumulative strike frequency graph

6.8 WATER STRIKES AND DYKE STRUCTURES

In this section the number of water strikes in dykes are compared to the surrounding geologies to estimate the water bearing capabilities of the dyke structures. This will help indicate the potential sitting of future borehole.

6.8.1 Jd Water Strikes

The number of water strikes with depth are shown in Figure 52. There are more water strikes in the dolerites at a depth of 40 m below surface.

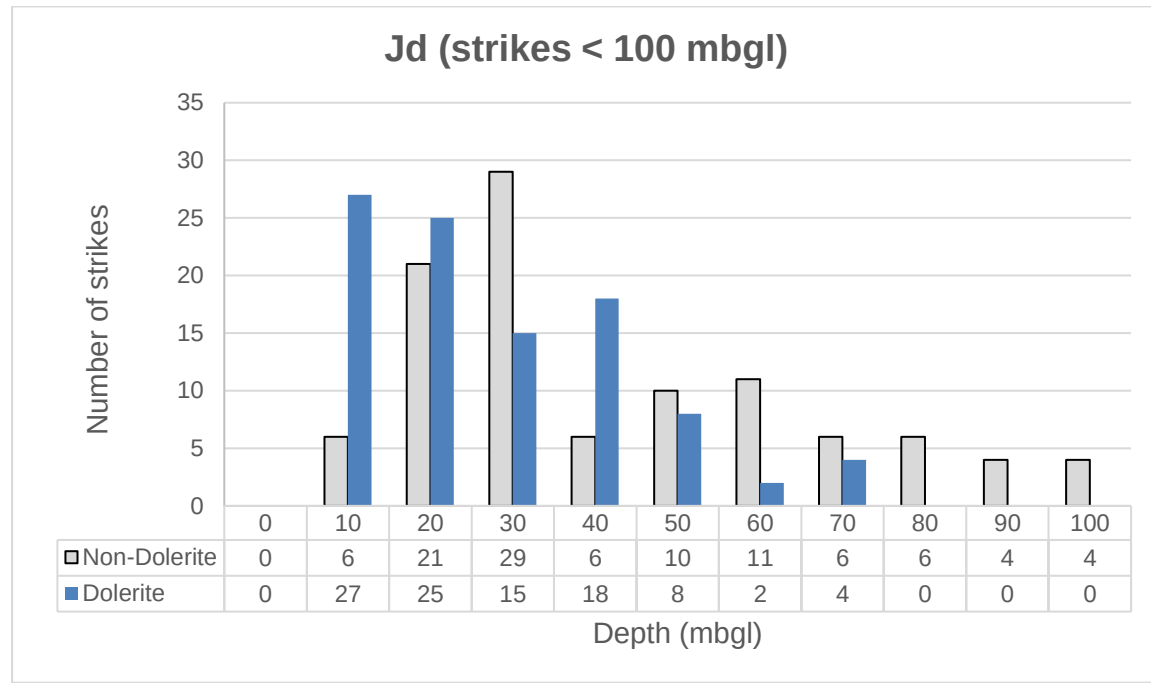


Figure 52: Jd Water strike graph

6.8.2 Pa Water Strikes

The number of water strikes with depth are shown in Figure 53. At all depths there are less strikes in the dolerites.

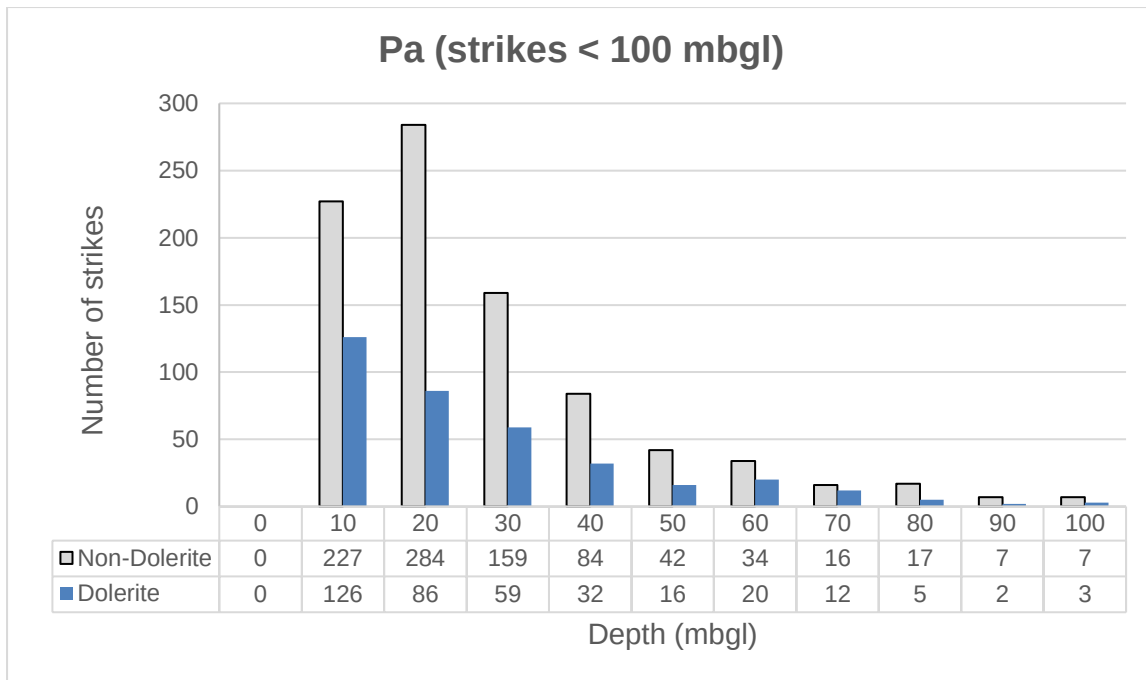


Figure 53: Pa Water strike graph

6.8.3 Pc Water Strikes

The number of water strikes with depth are shown in Figure 54. At 20 m below surface there are more water strikes in the dolerites.

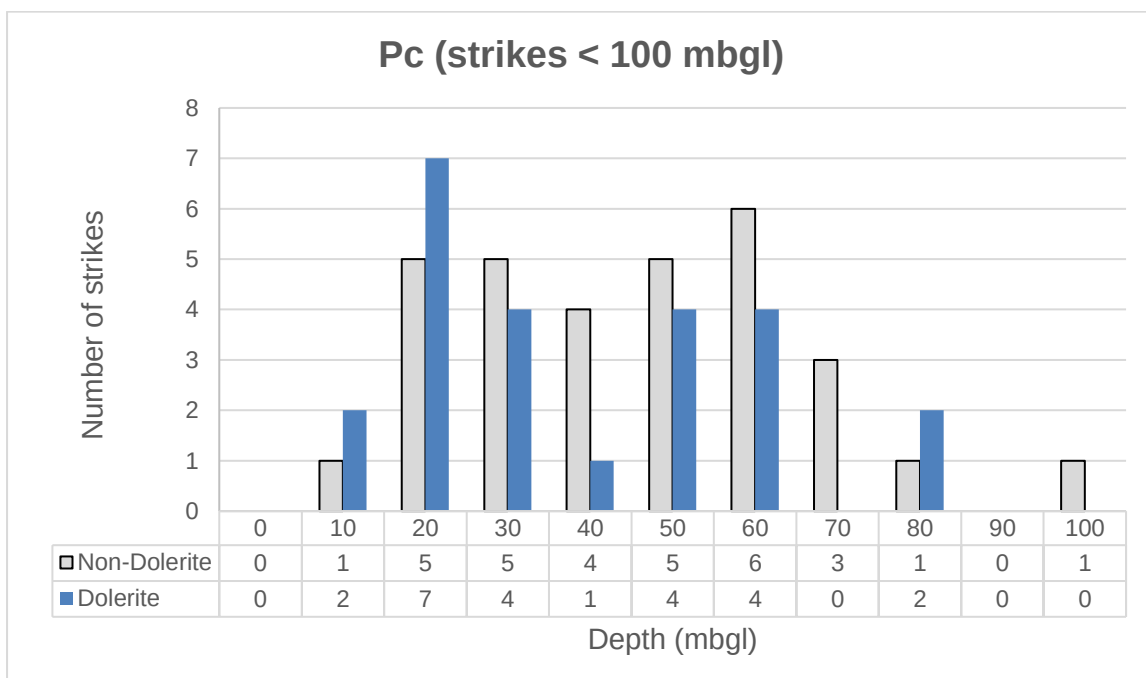


Figure 54: Pc Water strike graph

6.8.4 Pvo Water Strikes

The number of water strikes with depth are shown in Figure 55. At 50 m below surface there are more water strikes in the dolerites.

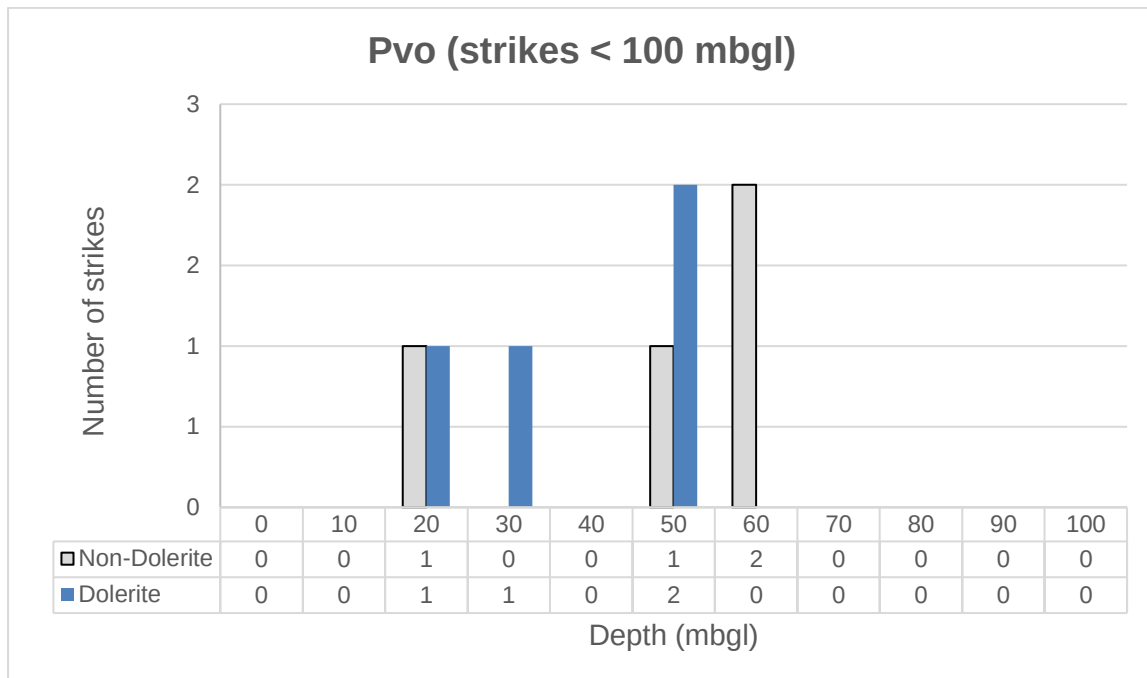


Figure 55: Pvo Water strike graph

6.8.5 TRt Water Strikes

The number of water strikes with depth are shown in Figure 56. At all depths there are less strikes in the dolerites.

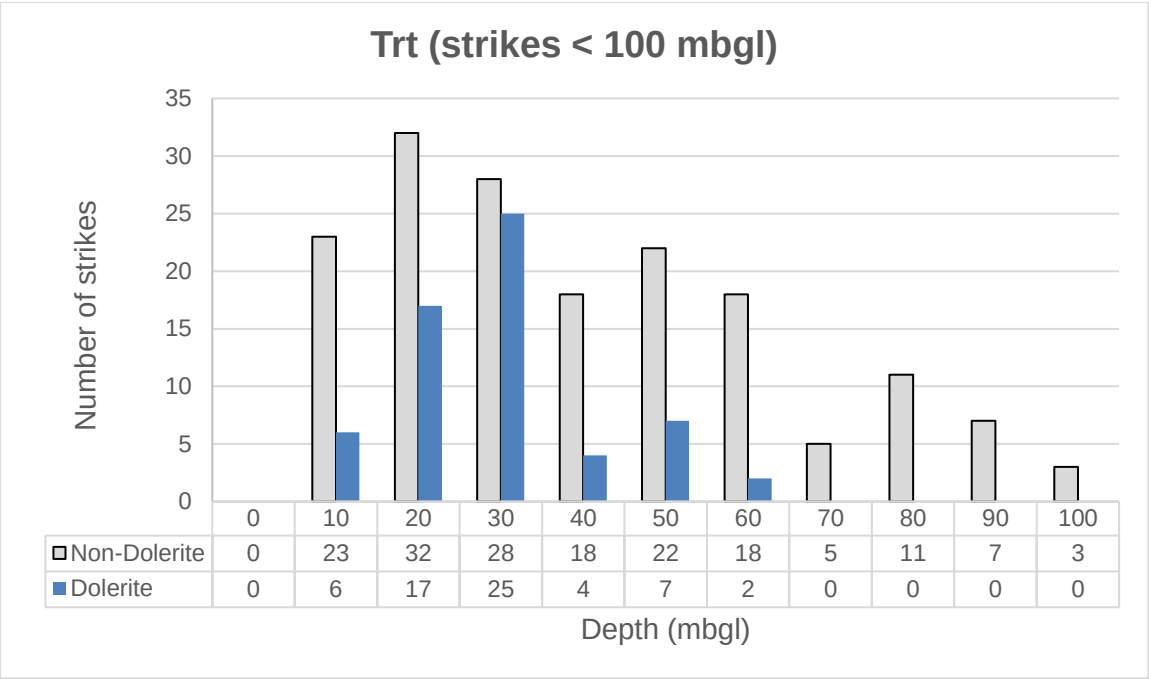


Figure 56: Trt Water strike graph

7 DELINEATION OF SUB-REGIONS

In the preceding sections the statistical analysis of various borehole parameters per surface geology type was discussed. The aim of this section is to make use of the individual borehole information as basis for delineation of sub-regions.

7.1 FREQUENCY ANALYSIS OF BOREHOLE PARAMETERS

A frequency analysis of all available borehole parameters is conducted on the scale of the study area. The resultant frequency analysis of the borehole parameters used is presented in Figure 57 to Figure 58. Please note, there was insufficient data to produce a realistic histogram for blow yield. Therefore, blow yield was not taken into account in the delineation process.

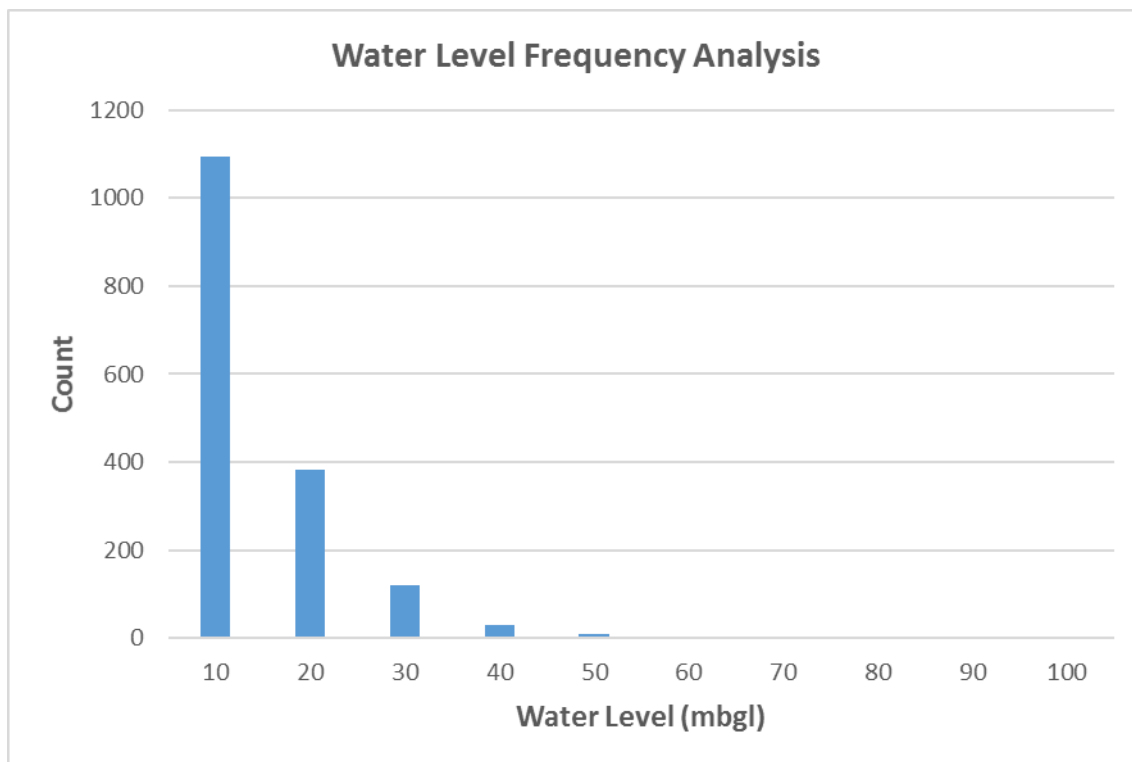


Figure 57: Water level frequency analysis

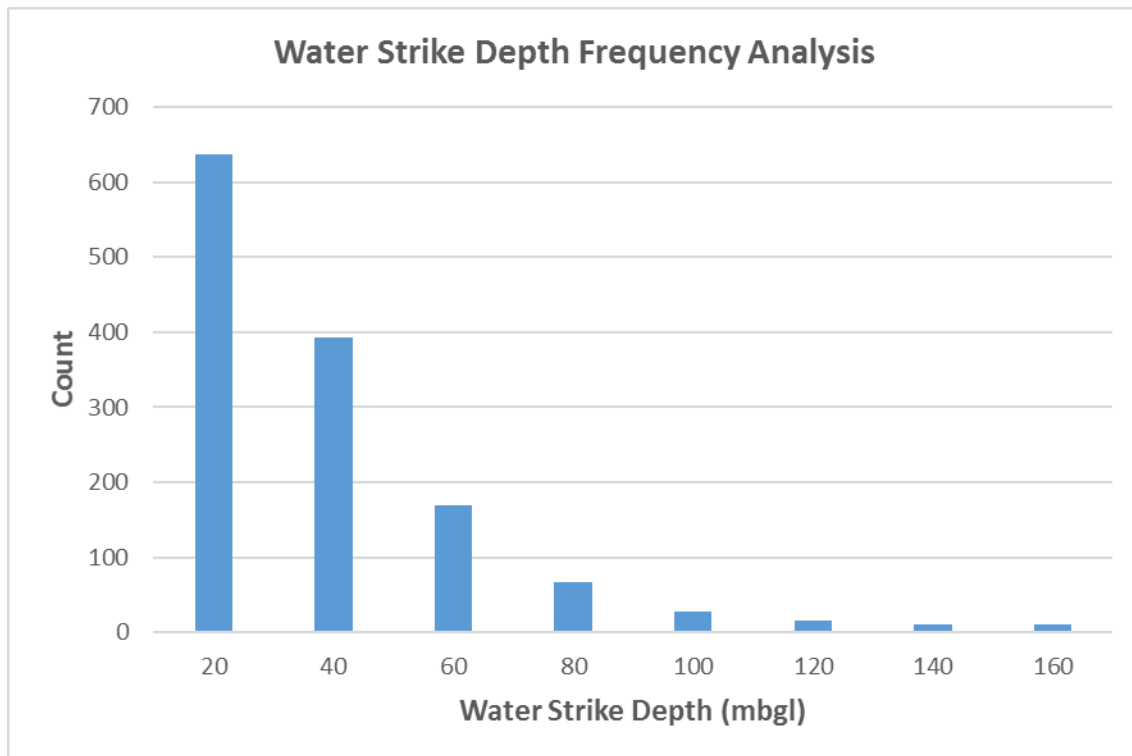


Figure 58: Water strike frequency analysis

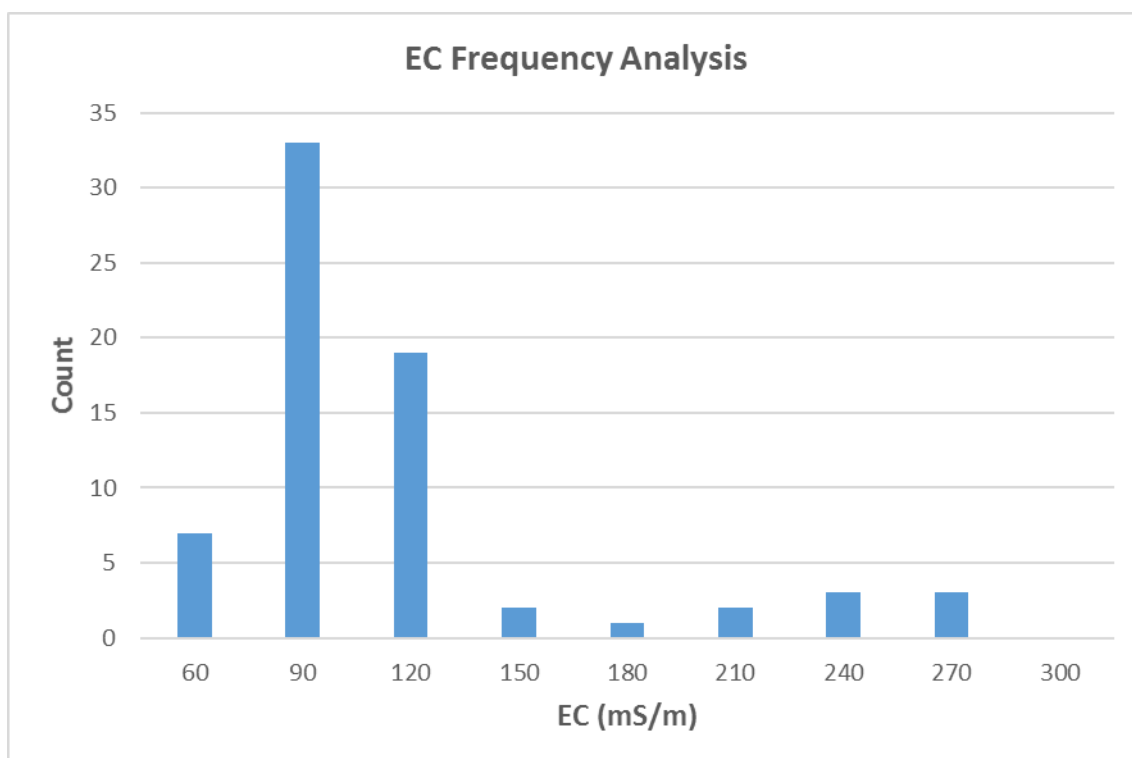


Figure 59: EC frequency analysis

Bin sizes were selected for each of the parameters to yield four bins per parameter that described at least 90% of the total dataset.

A summary of the selected bins per parameter is presented in Table 14.

Table 14: Summary of selected bins per specified borehole parameter

Bin No.	Water Level (mbgl)		Water Strike (mbgl)		EC (mS/m)	
	Bin	Count	Bin	Count	Bin	Count
1	10	1095	20	637	60	7
2	20	383	40	392	90	33
3	30	120	60	170	120	19
4	40	29	80	67	150	2
		1627		1266		61

Once the Voronoi diagram was created it was simplified through the grouping of Voronoi cells with the same bin number as illustrated in Figure 59.

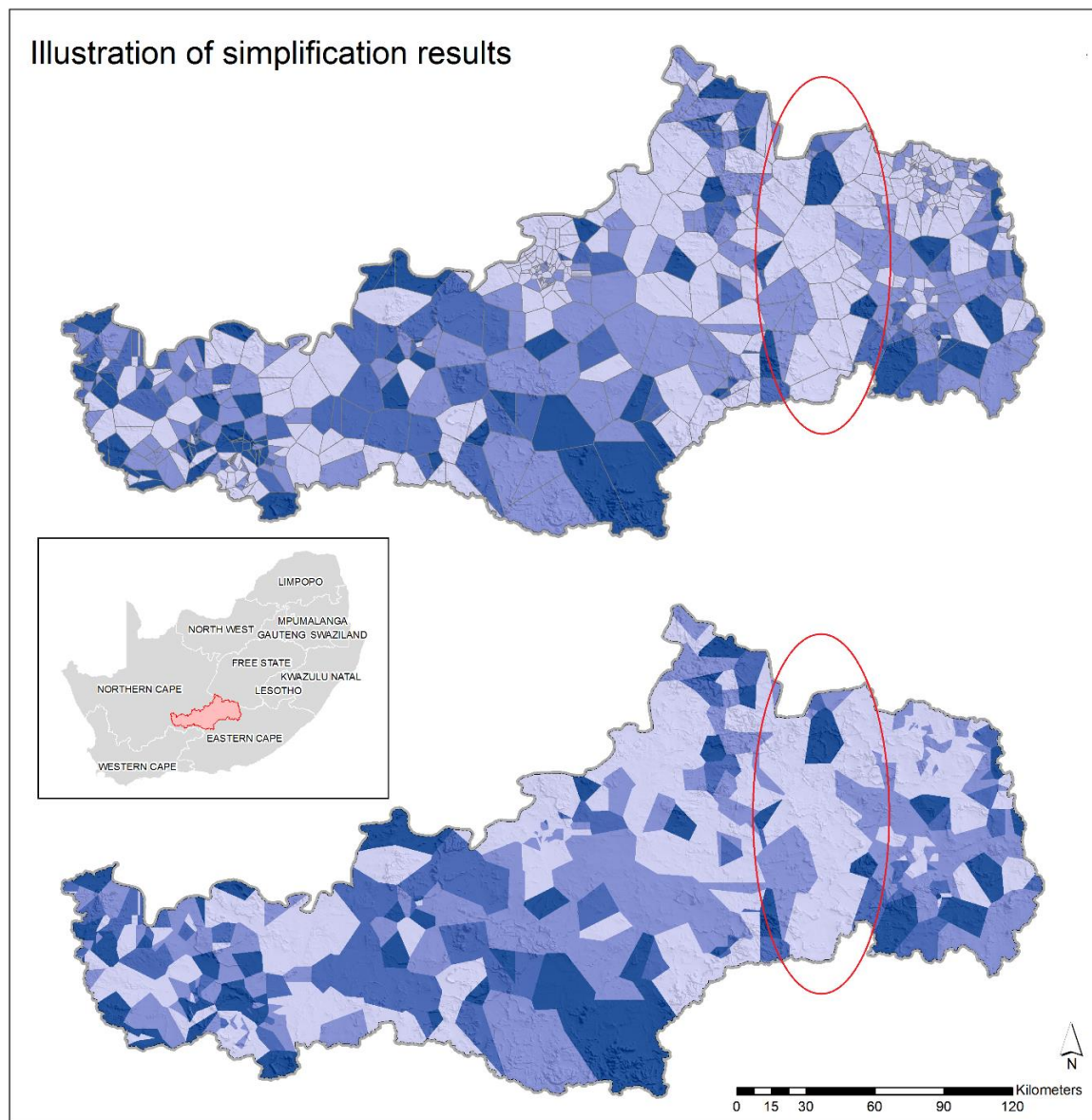


Figure 60: Simplification of Voronoi diagram based on bin numbers

The resultant map suffered from a few slivers that were removed by hand. This is a result of combining Voronoi diagrams that do not align with respect to their individual Voronoi cells due to the fact that the borehole positions differ from diagram to diagram.

The final delineation map is shown in Figure 61. The Vegter sub-region delineation with the borehole sets used that represent the three parameters (Equation 2) is shown in Figure 62 to Figure 64.

For the purposes of comparison Vegter sub-regions were overlaid on the simplified surface geology and the result is shown in Figure 65.

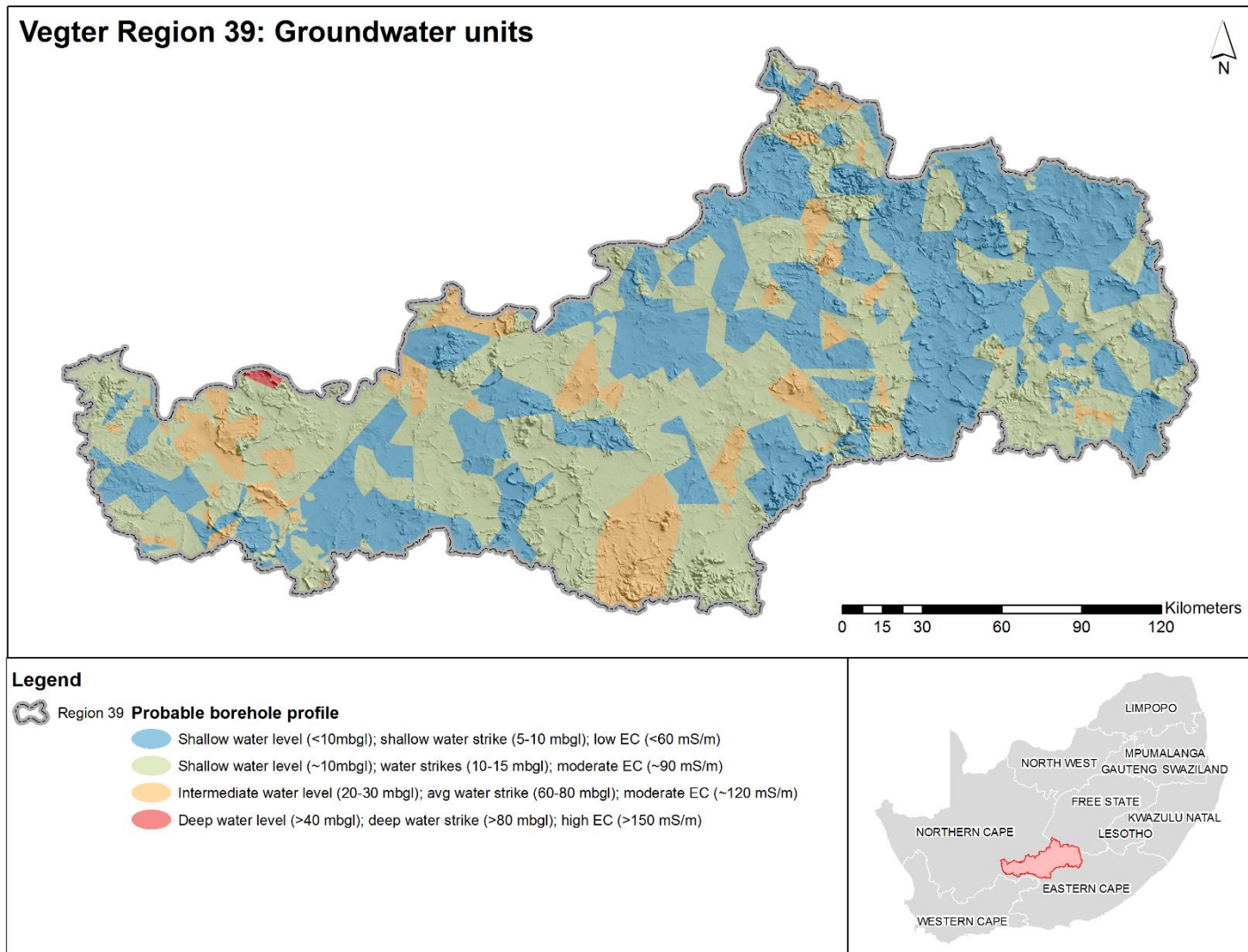


Figure 61: Final sub-region map

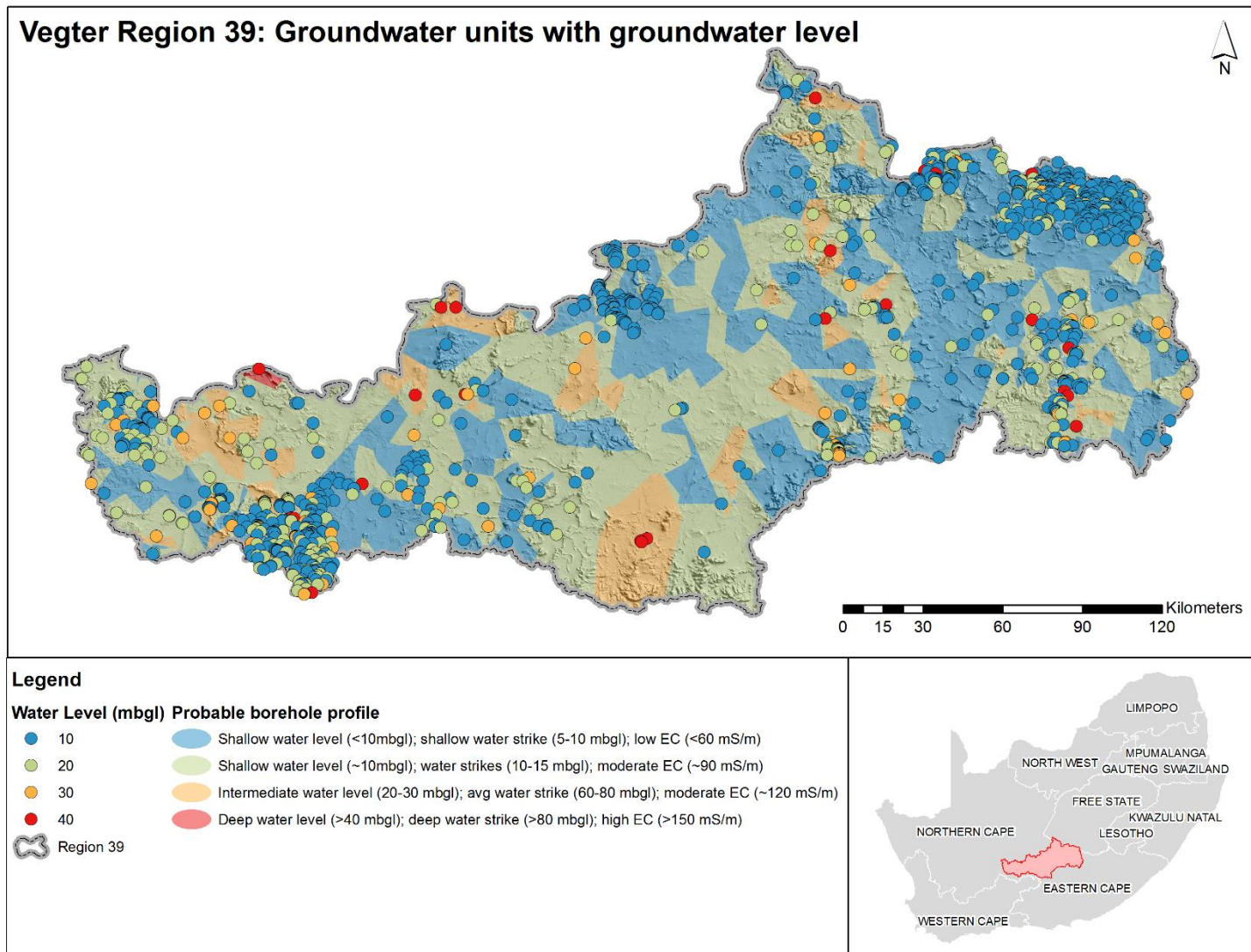


Figure 62: Sub-region map with probable borehole water levels

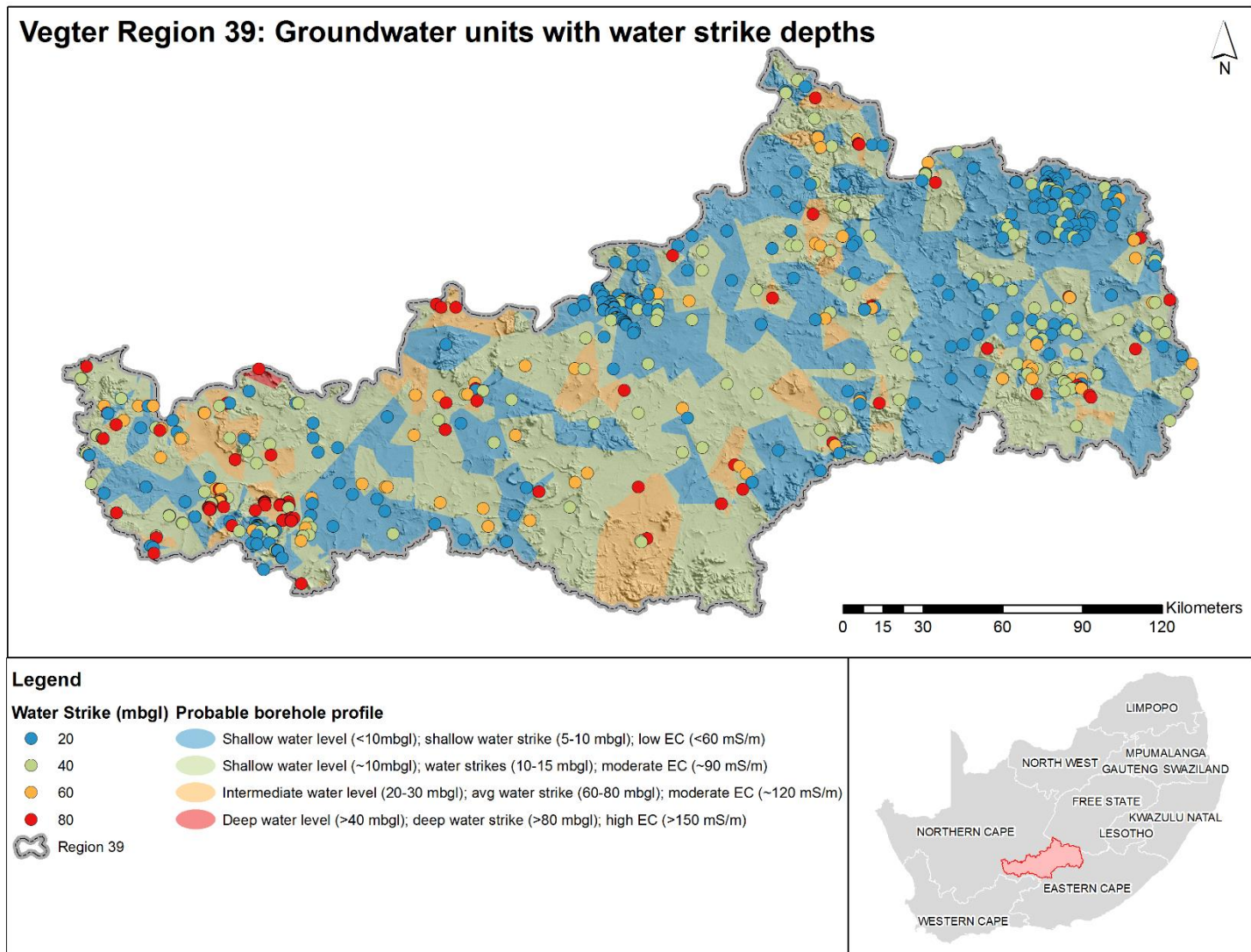


Figure 63: Sub-region map with probable borehole water strike positions

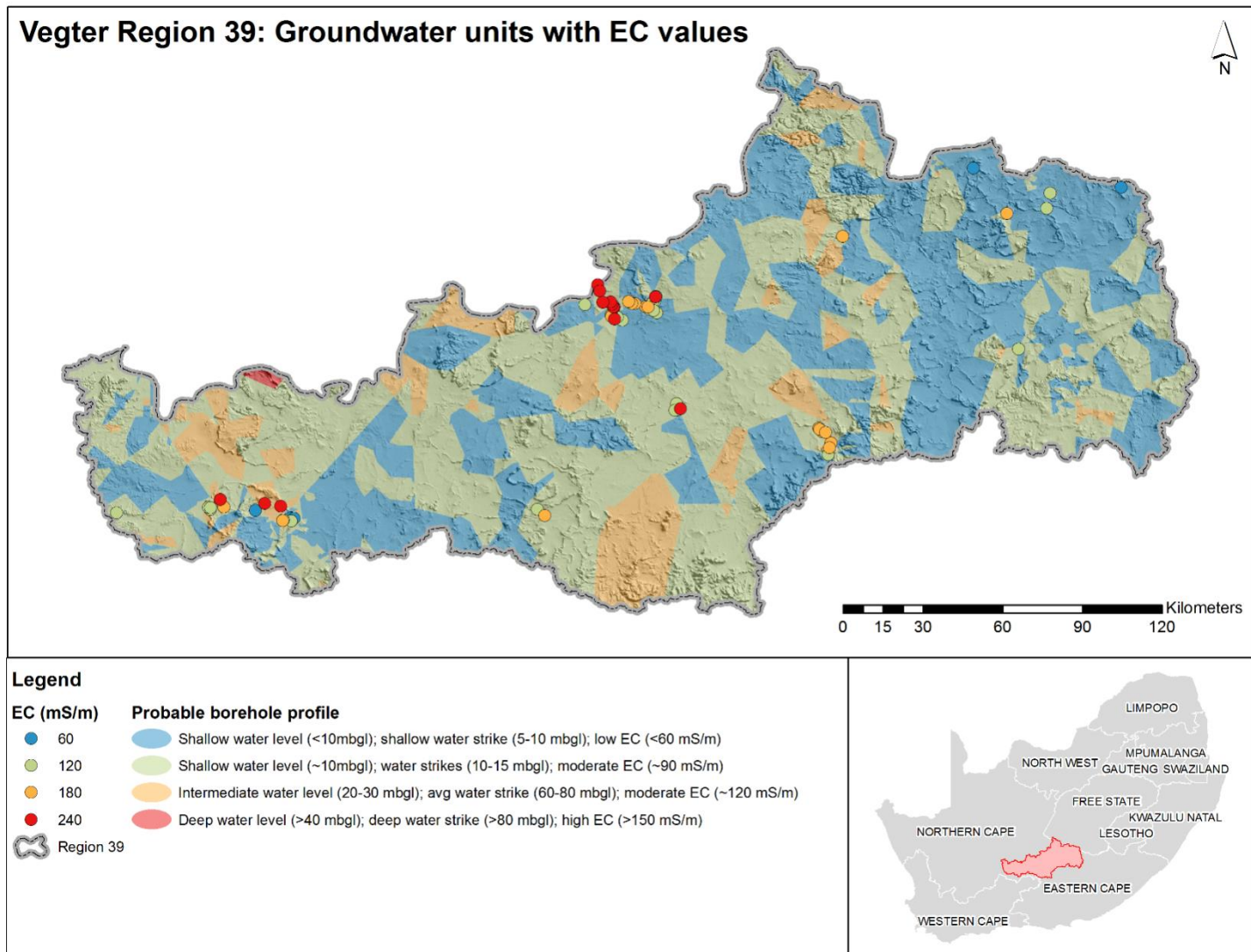


Figure 64: Sub-region map with probable borehole EC values

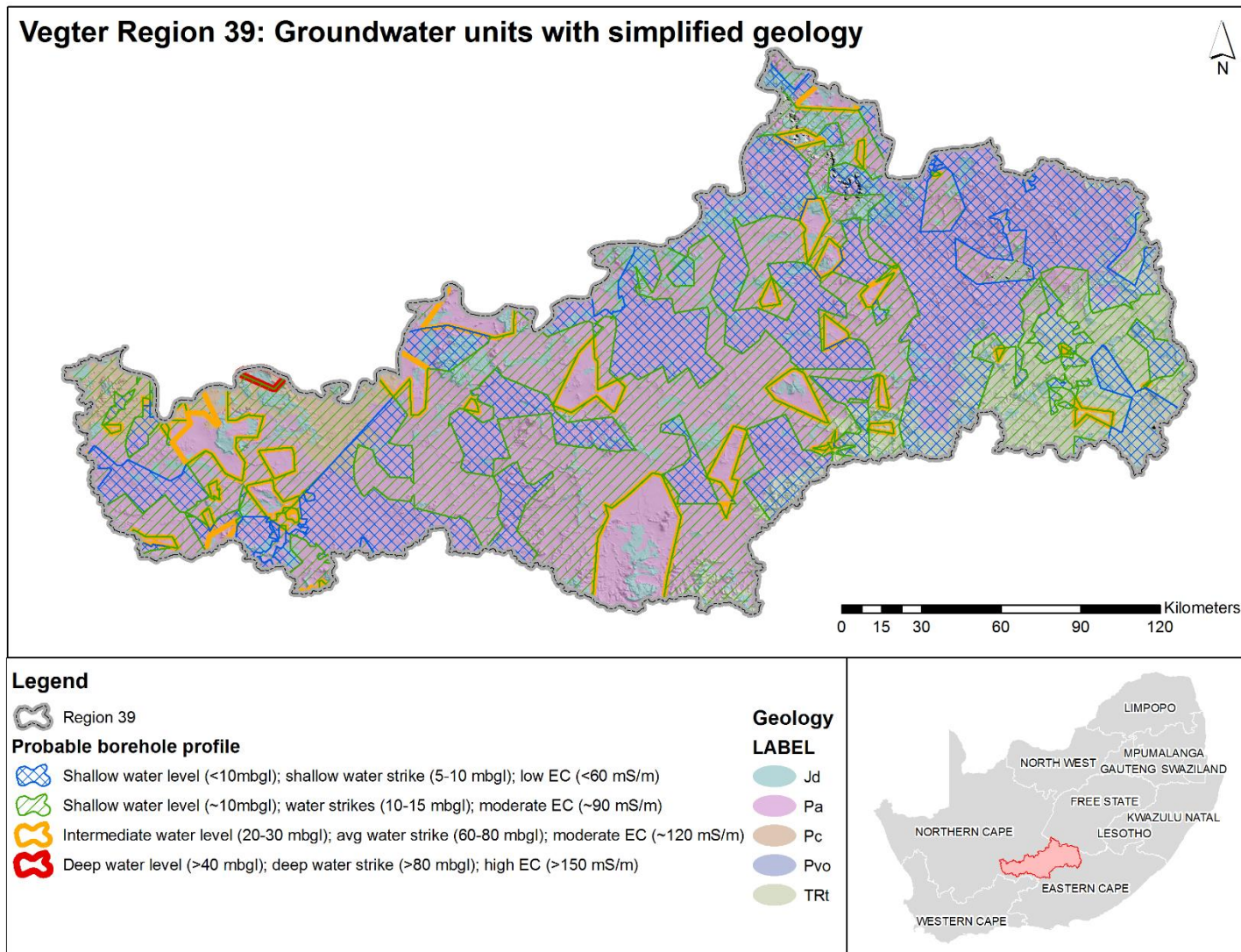


Figure 65: Sub-region comparison with the simplified surface geology

8 CALCULATION OF INFLOWS AND OUTFLOWS

8.1 GROUNDWATER - SURFACE WATER INTERACTION

The groundwater – surface water interaction was determined for the two major rivers and their tributaries namely the Brak River in the west and Orange and its tributaries in the east.

The tributaries of the Brak River include the Klein Brak, Visgat, Ongers and Elandsfontein Rivers. The area falls within the following quaternary catchments: D61A, D61B, D61C, D61D, D61E, D61F, D61G, D61H, D61L, D62C and D62D (Figure 65). The average rainfall for the area is 255 mm/a and the average percentage no flow in the rivers is 62% (WR90; Midgley *et al.*, 1994). Herold's method was used to determine the baseflow for each quaternary catchment. The curve fitting method estimated that the average groundwater contribution to baseflow would be 0.24 Mm³/a. See Appendix B for curve fits.

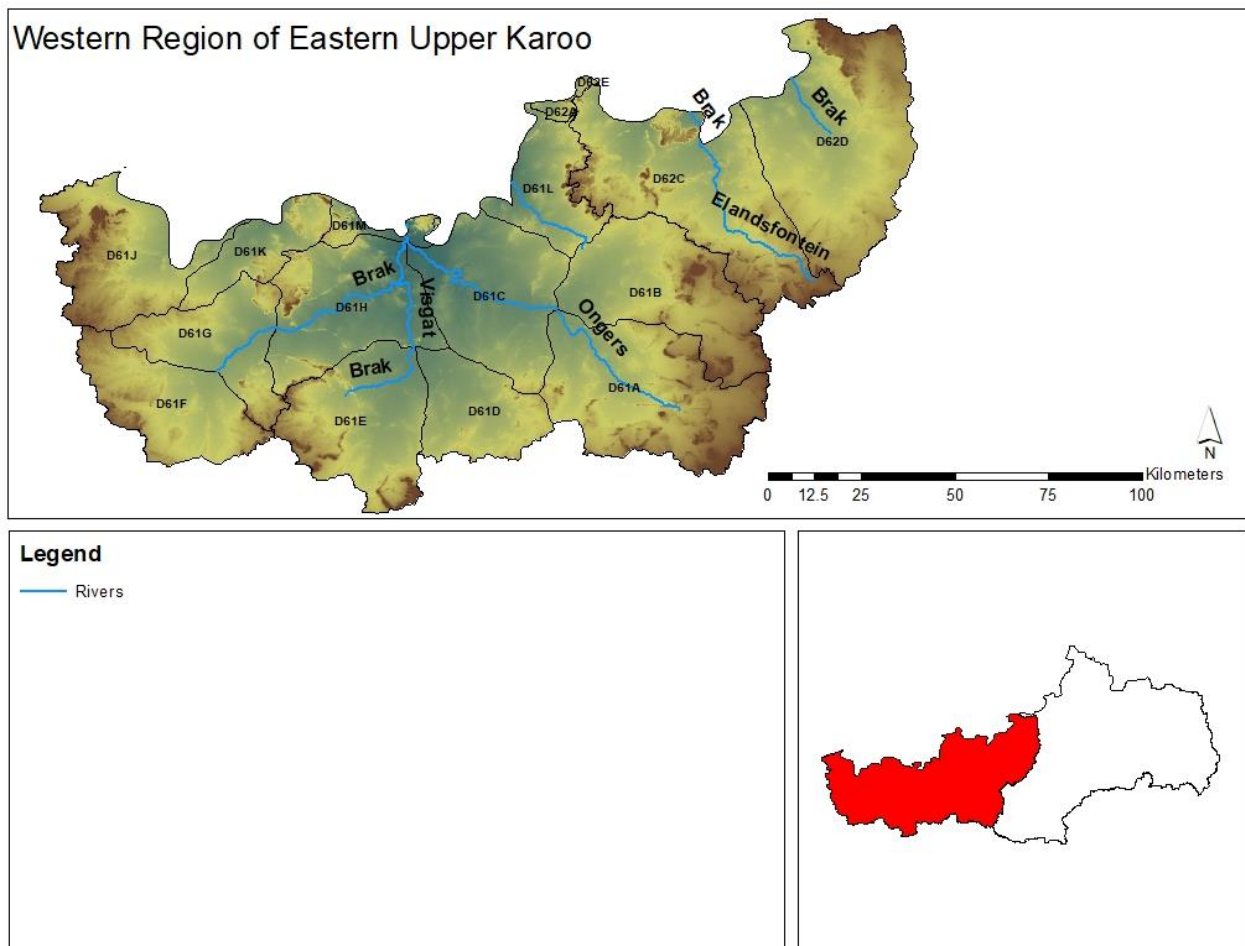


Figure 66: Rivers and Quaternary catchment for the Western region of the Eastern Upper Karoo

A numerical groundwater model was developed to simulate the groundwater – surface water interaction. The model estimates the groundwater contributes 0.2 Mm³/a.

The tributaries of the Orange River in the study area include the Hondeblaf, Oorlogspoort, Seekoei, and Broeks Stream. The area falls within the following quaternary catchments: D32A, D32B, D32C, D32D, D32E, D32F, D32G, D32H, D32J, D32K, D34A, D34B, D34C, D34D, D34E, D34F, D34G, D35A, D35B, D35C, D35D, D35E, D35F, D35G, D35H, D35J and D35K (Figure 66)

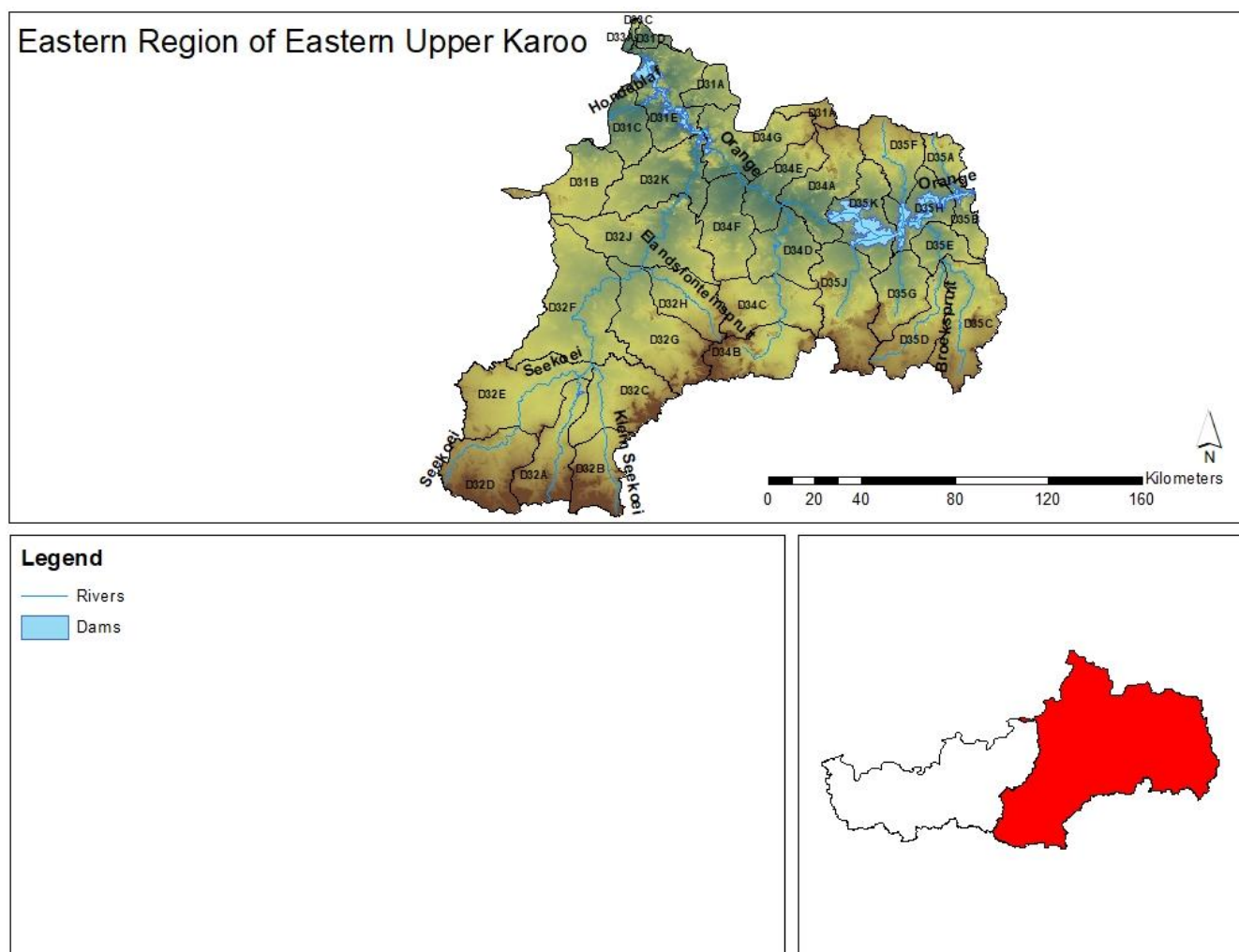


Figure 67: Rivers and Quaternary catchment for the Eastern region of the Eastern Upper Karoo

The average rainfall for the area is 360 mm/a and the average percentage no flow in the rivers is 49% (WR90; Midgley *et al.*, 1994). Herold's method was used to determine the baseflow for each quaternary catchment. The curve fitting method estimated that the average groundwater contribution to baseflow would be 0.66 Mm³/a.

A numerical groundwater model was developed to simulate the groundwater – surface water interaction. The model estimates the groundwater contributes 0.71 Mm³/a. See Appendix B for curve fits.

8.2 AVAILABILITY FOR GROUNDWATER FOR USE

Quaternary catchments are used as the primary delineation of water resource units in Resources Directed Measures (RMD), as this is the boundary that the Department of Water and Sanitation (DWS) uses for reporting. However, due to insufficient information the refining of resource units further is not possible. This has led to the quaternary catchments being used as the basis for GRDM calculations, even though the surface water boundaries and groundwater aquifers are rarely the same. Furthermore, due to the vastness of the region an unspecified amount of borehole is not registered, thus the WARMS data is normally an underestimation of groundwater use.

The National Water Act (36 of 1998) states that water must be set aside for basic human needs (set at 25 l per person per day) and the protection of aquatic ecosystems. If the current use is taken into account, then the allocatable amount of water can be determined according to Parsons and Wentzel (2007) as:

$$GW_{allocatable} = Re - GW_{use} - GW_{Reserve}$$

Where:	Re	=	Recharge
	GW _{use}	=	Current groundwater use
	GW _{Reserve}	=	Groundwater contribution to the Reserve
	GW _{allocatable}	=	Allocatable groundwater

Available groundwater in the Western area (Figure 67):

$$\text{BHNs} = 15\,426 \text{ people} \times 25 \text{ l/d} = 0.14 \text{ Mm}^3/\text{a}$$

Groundwater contribution to baseflow (ecological Reserve) = 0.2 Mm³/a (obtained from numerical model)

$$\text{Groundwater use} = 5.74 \text{ Mm}^3/\text{a}$$

$$\text{Recharge} = 68.5 \text{ Mm}^3/\text{a}$$

$$\text{Available groundwater} = 62.4 \text{ Mm}^3/\text{a}$$

Available groundwater in the Central area (Figure 67):

$$\text{BHNs} = 32\,663 \text{ people} \times 25 \text{ l/d} = 0.3 \text{ Mm}^3/\text{a}$$

$$\text{Groundwater contribution to baseflow (ecological Reserve)} = 0 \text{ Mm}^3/\text{a}$$

$$\text{Groundwater use} = 21 \text{ Mm}^3/\text{a}$$

Recharge = 56.6 Mm³/a

Available groundwater = 35.3 Mm³/a

Available groundwater in the Eastern area (Figure 67):

BHNs = 67 709 people * l/d = 0.62 Mm³/a

Groundwater contribution to baseflow (Ecological Reserve) = 0.71 Mm³/a

Groundwater use = 41 Mm³/a

Recharge = 212 Mm³/a

Available groundwater = 170 Mm³/a

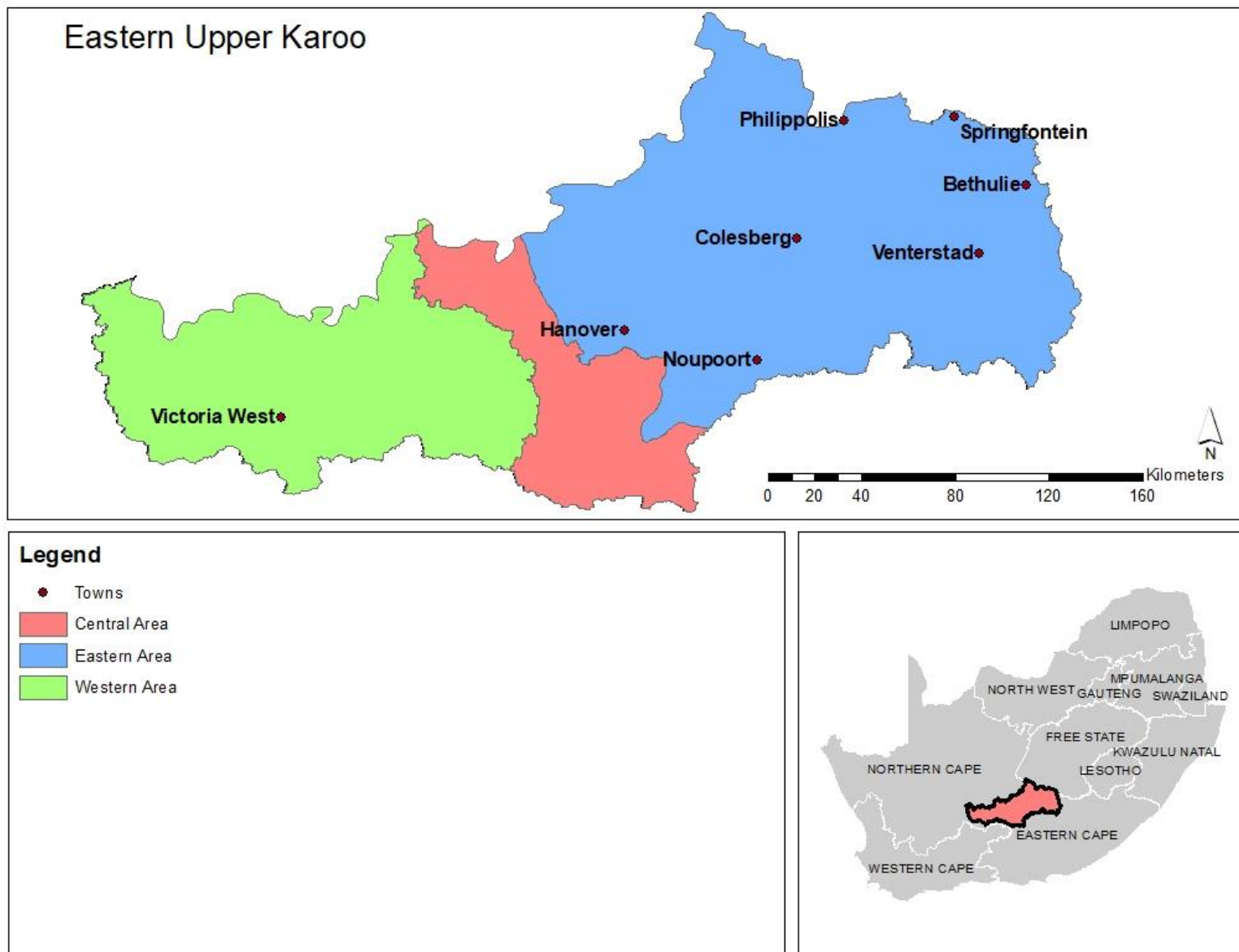


Figure 68: Resource units within Region 39

9 CONCLUSIONS AND RECOMMENDATIONS

The result of the statistical analyses, as applied to the hydrogeological data set, provides insight in the regional factors and processes controlling groundwater availability and recharge of the study area. The strong correlation between the water level and the topography for the region suggests that an unconfined aquifer consisting of various systems exists within the study area. The study area comprises of relatively shallow groundwater averaging between 9 mbgl and 14 mbgl and is classified as low yielding boreholes. To provide sufficient groundwater for basic daily needs and irrigation the boreholes are relatively deep to penetrate multiple water strikes. This is apparent in the predominant strike frequencies of the studies area, which ranges between 160 m and 100 m below surface level. The amount of water strikes found in dykes in comparison to those found in the surrounding geology, suggest it would be more profitable to drill in the regional geology rather than in a dolerite system. This may be true to the majority of the area, but is inconclusive due to the fact that most farmers of the Karoo area do not often drill boreholes on the dolerite systems.

Vegter's methodology for the delineation of sub-regions within a groundwater region was followed as closely as possible, but due to data insufficiency Vegter's methodology was altered to some extent. Three parameters were used for the delineation of the sub-regions, namely water level, strike depth, and EC. The results indicated that each parameter increases to some extent from the east to the west. This trend is likely due to multiple factors such as recharge, rainfall and geology. Through the delineation of these sub-regions a possible methodology can be implemented to provide a rough estimate for the siting of boreholes and additionally provide more manageable hydrogeological units for future events.

A numerical groundwater model was developed to simulate the groundwater – surface water interaction. The region was subdivided into three separate units for the calculation of the groundwater contribution to baseflow, namely western, central, and eastern areas. The model estimated that the average groundwater contribution to baseflow for these areas are, 0.14 Mm³/a, 0 Mm³/a, and 0.71 Mm³/a, respectively. The aperture and areal extent of the fractures in the Karoo formations are limited and therefore unable to contribute large amount of groundwater to the baseflow. This can be problematic. Due to the Karoo exhibiting arid to semi-arid climatic characteristics, the groundwater is most often the sole source of water to the rivers in the region. Although there is an abundance of available groundwater in the region it is often too deep or of low yield standards to provide a sustainable borehole.

The study area is characterized by fractured-rock aquifers that are bisected by numerous vertical and horizontal dolerite intrusions. These conditions create a complex and unique hydrogeological system, which complicated the study and development of groundwater. There was a major lack of borehole information and hydrogeological data. Therefore, the knowledge and information have to be passed onto water users and practitioners so that a program can be developed. The program will assess the

resources of the main Karoo basin by applying the scientific results that were gathered in the last 15 years to provide a better understanding of the hydrogeological characteristics of the region.

The development of accurate tools and technique to assess the impact that man's activities have on the water resource are essential for further sustainable management.

It seems necessary to generate a wider awareness of the impact that man's activities have on the environment and on the water resources. Therefore, to spread awareness of these issues a purposed environmental course should be included in the curriculum of primary and secondary schools along with short lecture at a community level to spread awareness amongst the older generation.

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APPENDIX A

Victoria West

Victoria West has a desert climate. Most of the rainfall occurs in autumn. The rainfall here averages 261 mm per year (Figure). The driest month is August, with 6 mm of rainfall. Victoria West, the average annual temperature is 14.9 °C. The warmest month of the year is January, with an average temperature of 22.3 °C. The lowest average temperatures in the year occur in July, when it is around 6.5 °C (Figure).

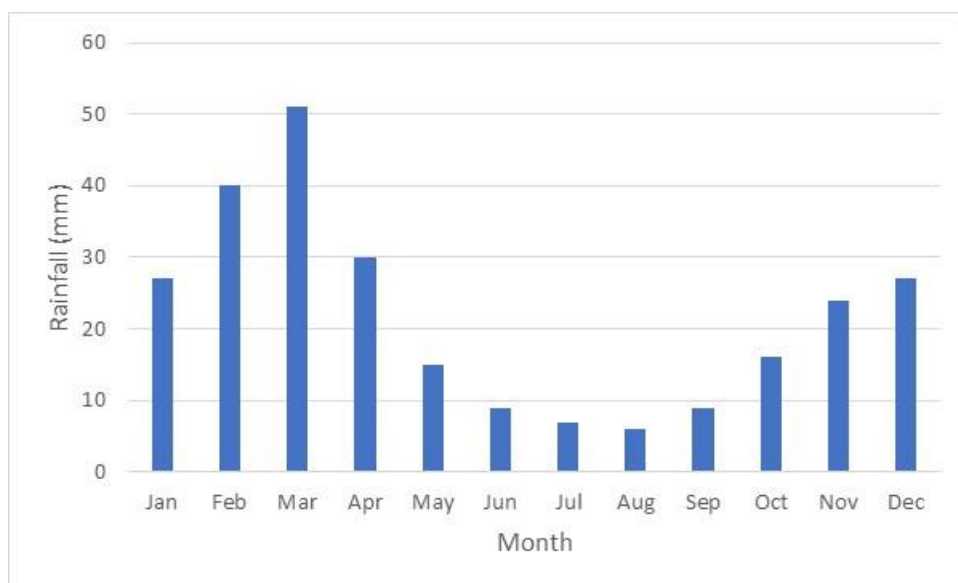


Figure: Monthly rainfall

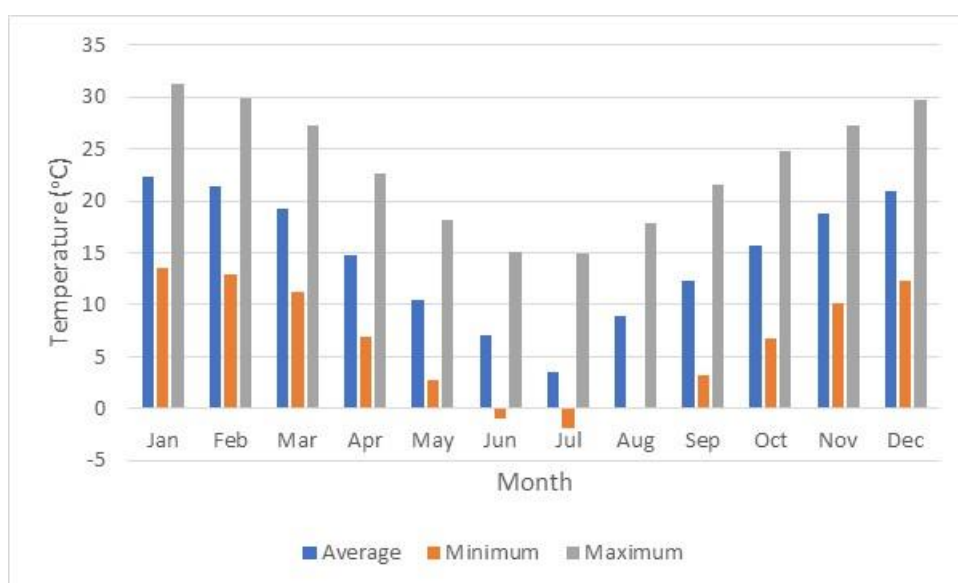


Figure: Monthly temperatures

Colesberg

In Colesberg, there is little rainfall throughout the year. About 392 mm of precipitation falls annually. The temperature here averages 13.9 °C. The temperatures are highest on average in January, at around 21.6 °C. July has the lowest average temperature of the year at 2.3 °C.

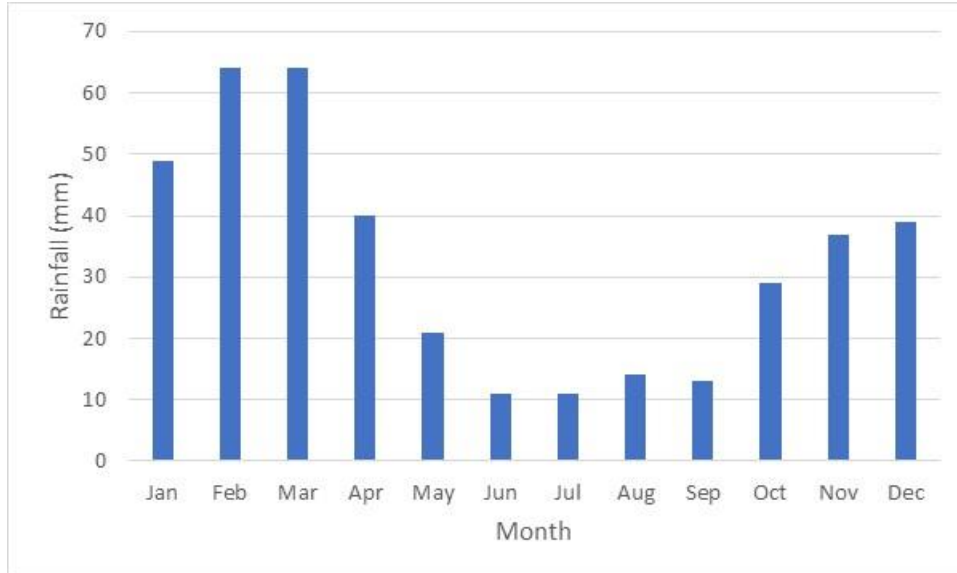


Figure: Monthly rainfall

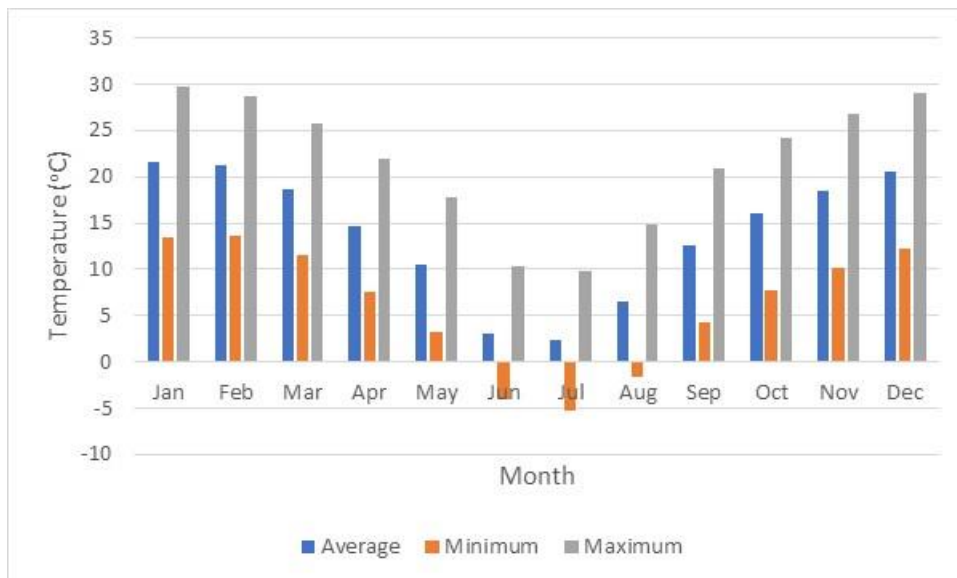


Figure: Monthly temperatures

Hanover

The average annual rainfall is 331 mm. The driest month is July, with 9 mm of rain. March has the highest precipitation average of 63 mm (Figure). The average annual temperature is 14.5 °C. January is the warmest month of the year. The temperature in January averages 21.8 °C. At 6.4 °C on average, July is the coldest month of the year (Figure).

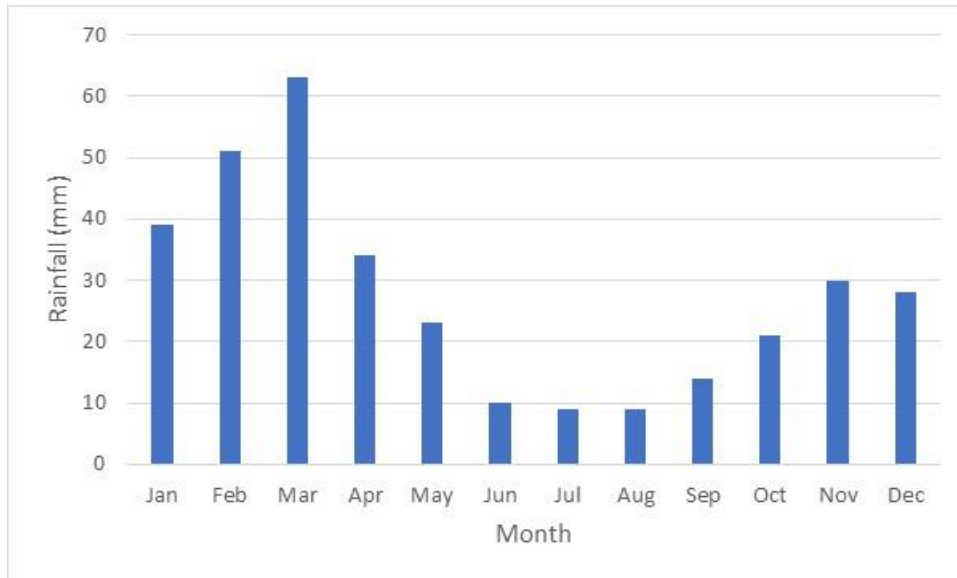


Figure: Monthly rainfall

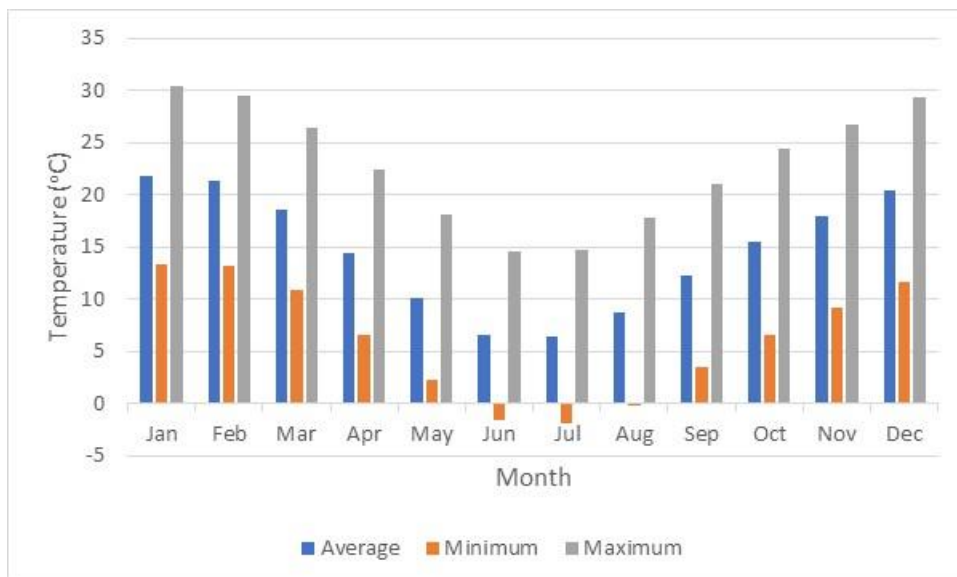


Figure: Monthly temperatures

Noupoort

The average annual precipitation is 417 mm. The driest month is July, with 11 mm of rain. Most of the precipitation here falls in March, averaging 72 mm.

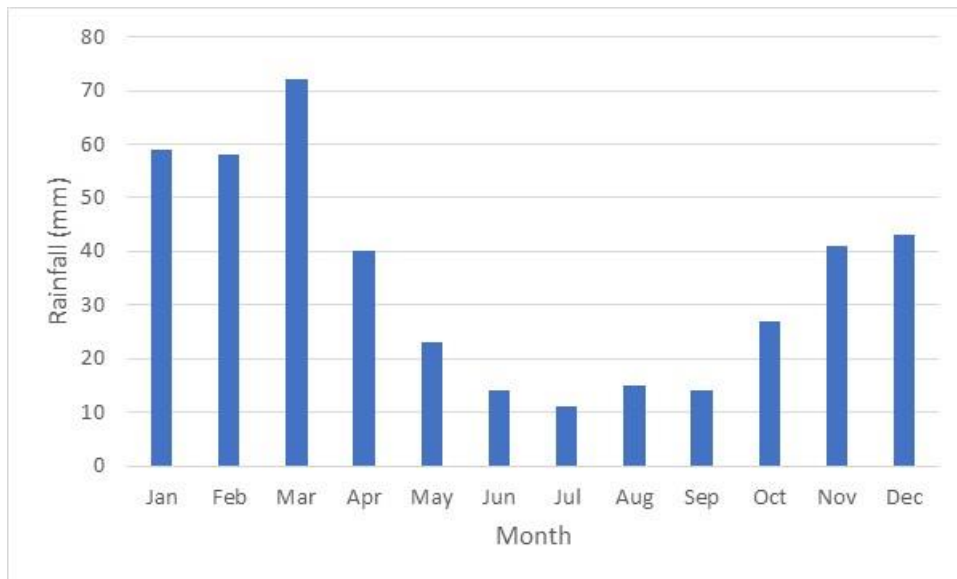


Figure: Monthly rainfall

January is the warmest month of the year. The temperature in January averages 20.6 °C. July is the coldest month, with temperatures averaging 5.2 °C.

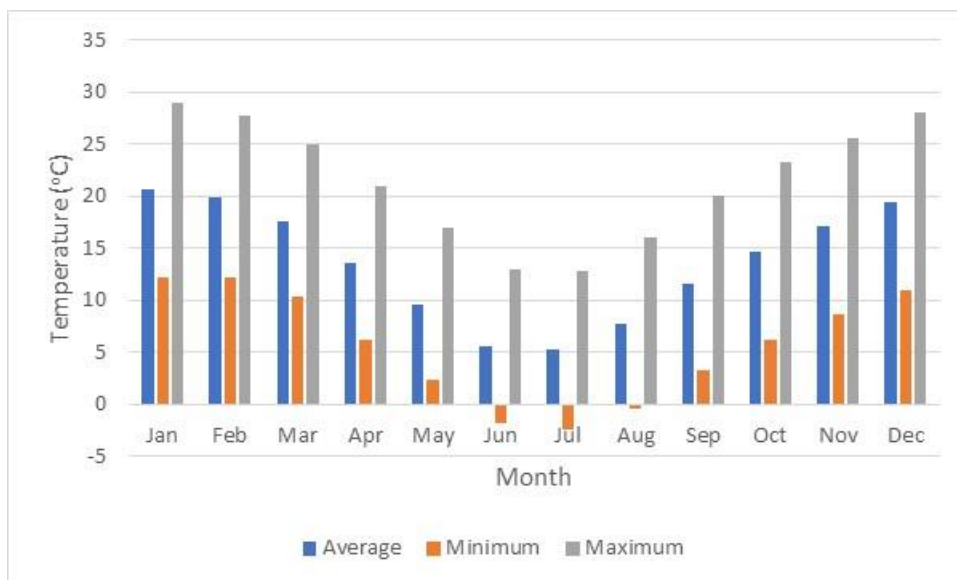


Figure: Monthly temperatures

Philippolis

Philippolis has an average rainfall of 391 mm per year. Precipitation is the lowest in June, with an average of 9 mm. With an average of 64 mm, the most precipitation falls in February (Figure). At

an average temperature of 23.0°C, January is the hottest month of the year. July has the lowest average temperature of the year at 6.4 °C (Figure).

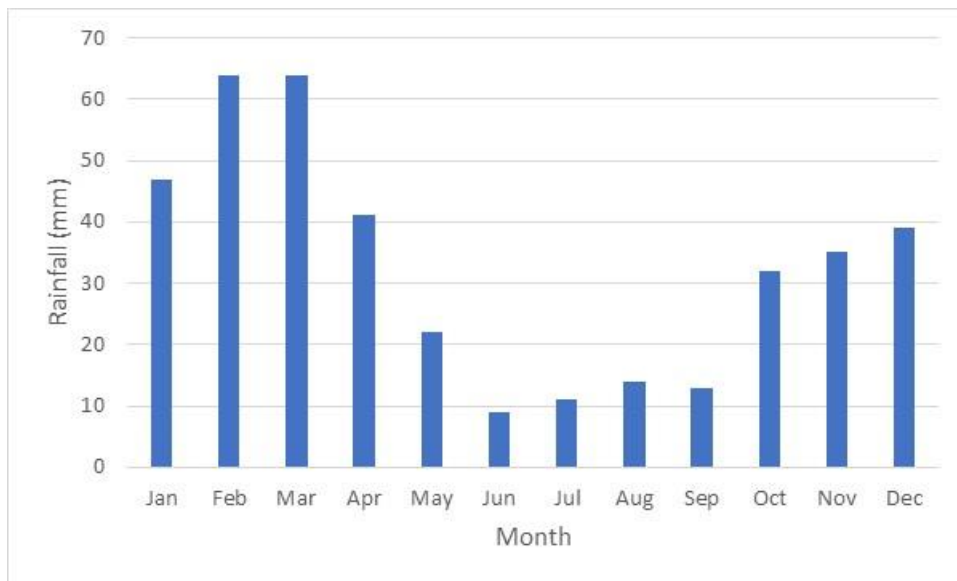


Figure: Monthly rainfall

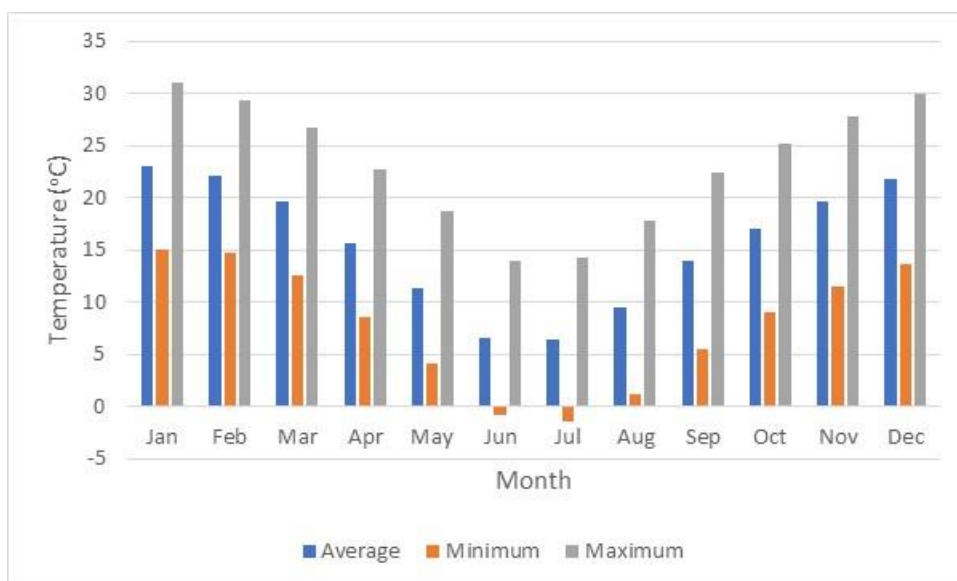


Figure: Monthly temperatures

Venterstad

Venterstad's average annual rainfall is 433 mm. The lowest rainfall occurs in July, with an average of 10 mm. The highest monthly rainfall occurs in March, with an average of 76 mm (Figure). The temperatures are highest on average in January, at around 23.1 °C. The lowest average temperatures in the year occur in July, when it is around 7.8 °C (Figure).

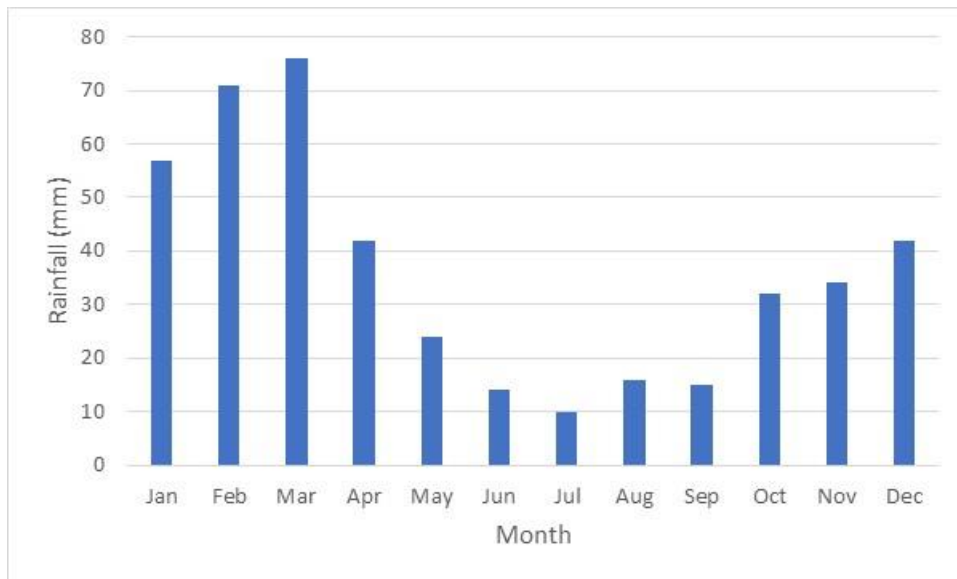


Figure: Monthly rainfall

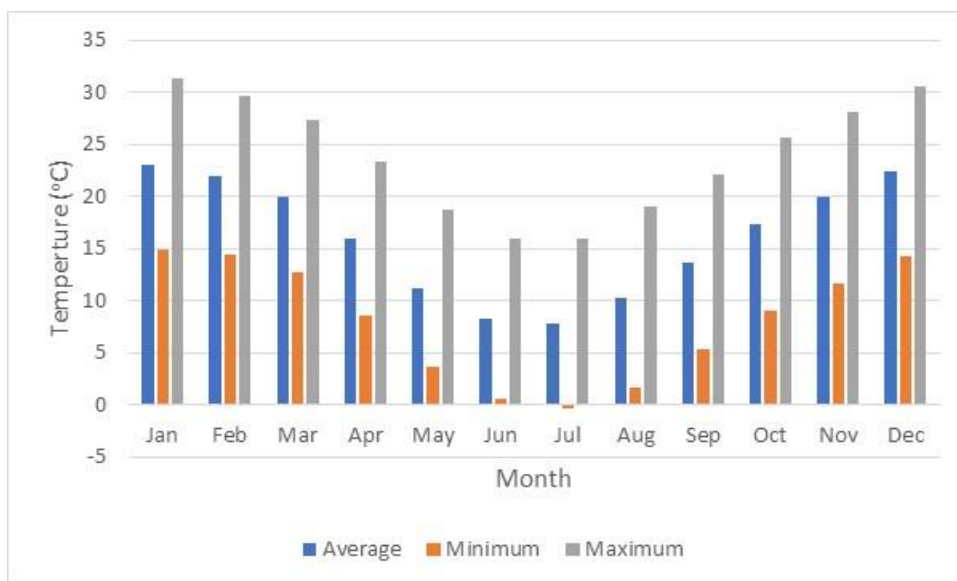


Figure: Monthly temperatures

Bethulie

The average monthly rainfall is 481 mm. The driest month is June, with 13 mm of rain. February has the highest rainfall with an average of 80 mm (Figure). January is the warmest month of the year with an average temperature of 22.7 °C. July has the lowest average temperature of 8.3 °C (Figure).

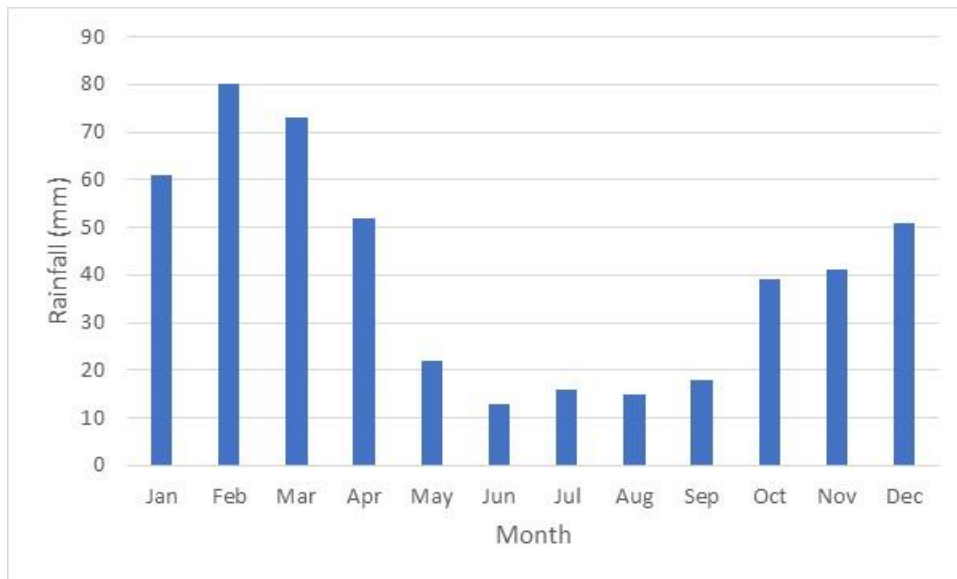


Figure: Monthly rainfall

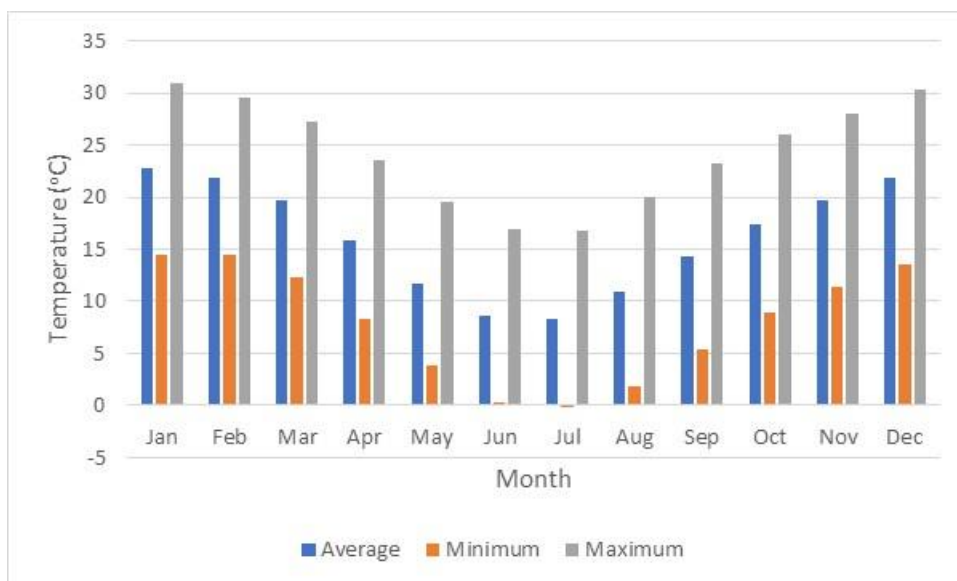


Figure: Monthly temperatures

Springfontein

Springfontein's average rainfall is approximately 448 mm per year. The driest month is June with 10 mm of rain. The month that receives the most precipitation is March with an average of 74 mm (Figure). January is the hottest of the year with an average temperature of 21.8 °C. July is the coldest month, with an average temperature of 6.2 °C (Figure).

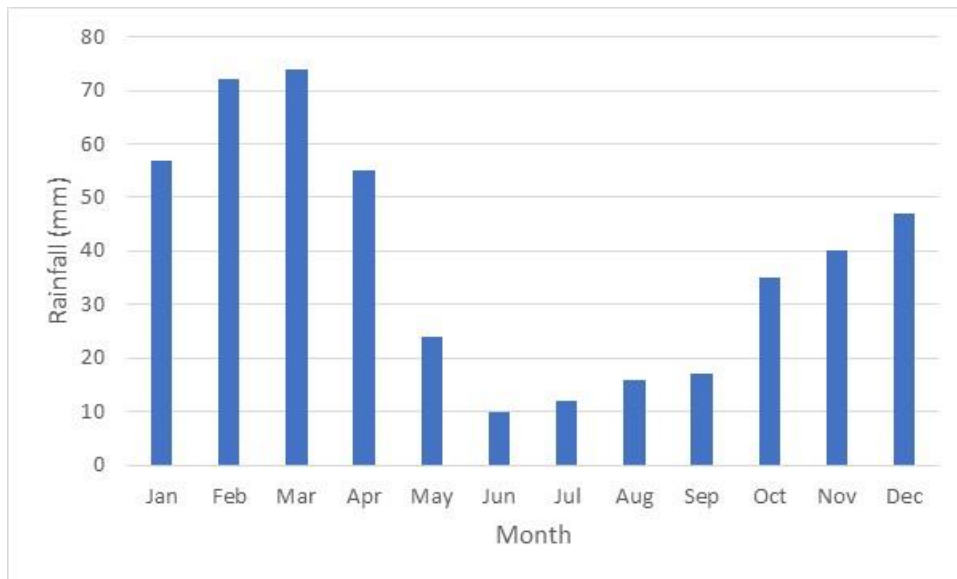


Figure: Monthly rainfall

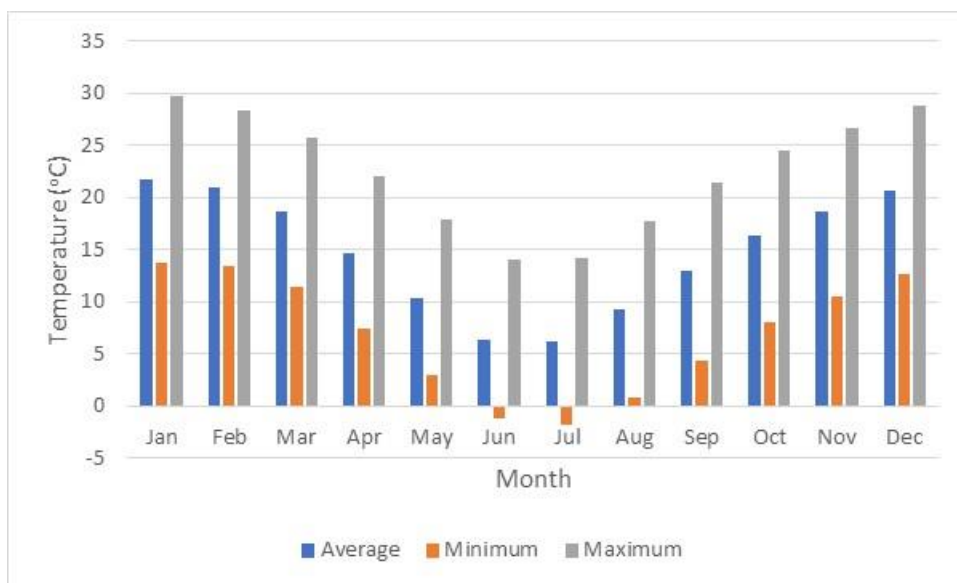


Figure: Monthly temperatures

APPENDIX B

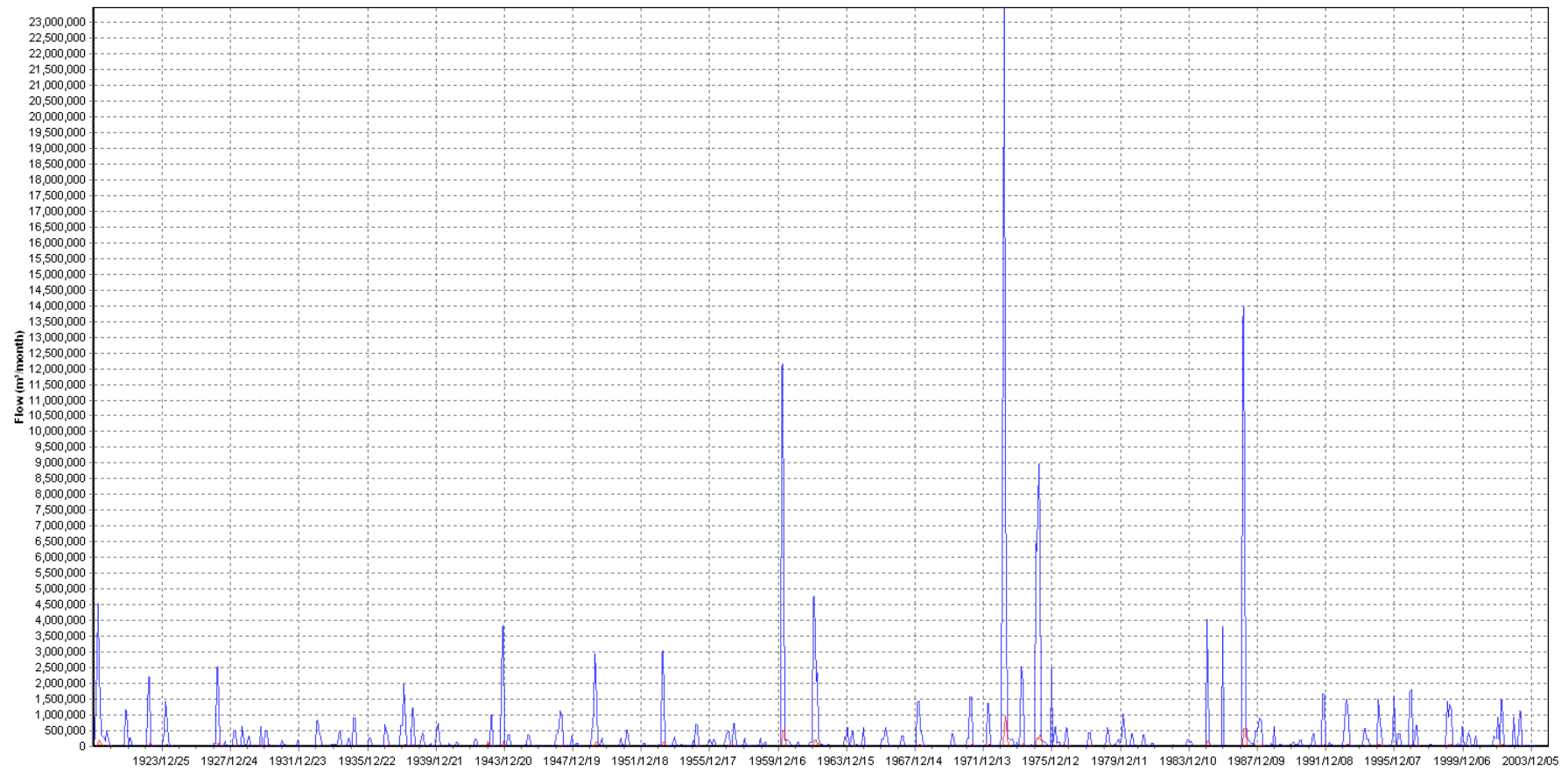


Figure: Groundwater contribution to baseflow (D61A)

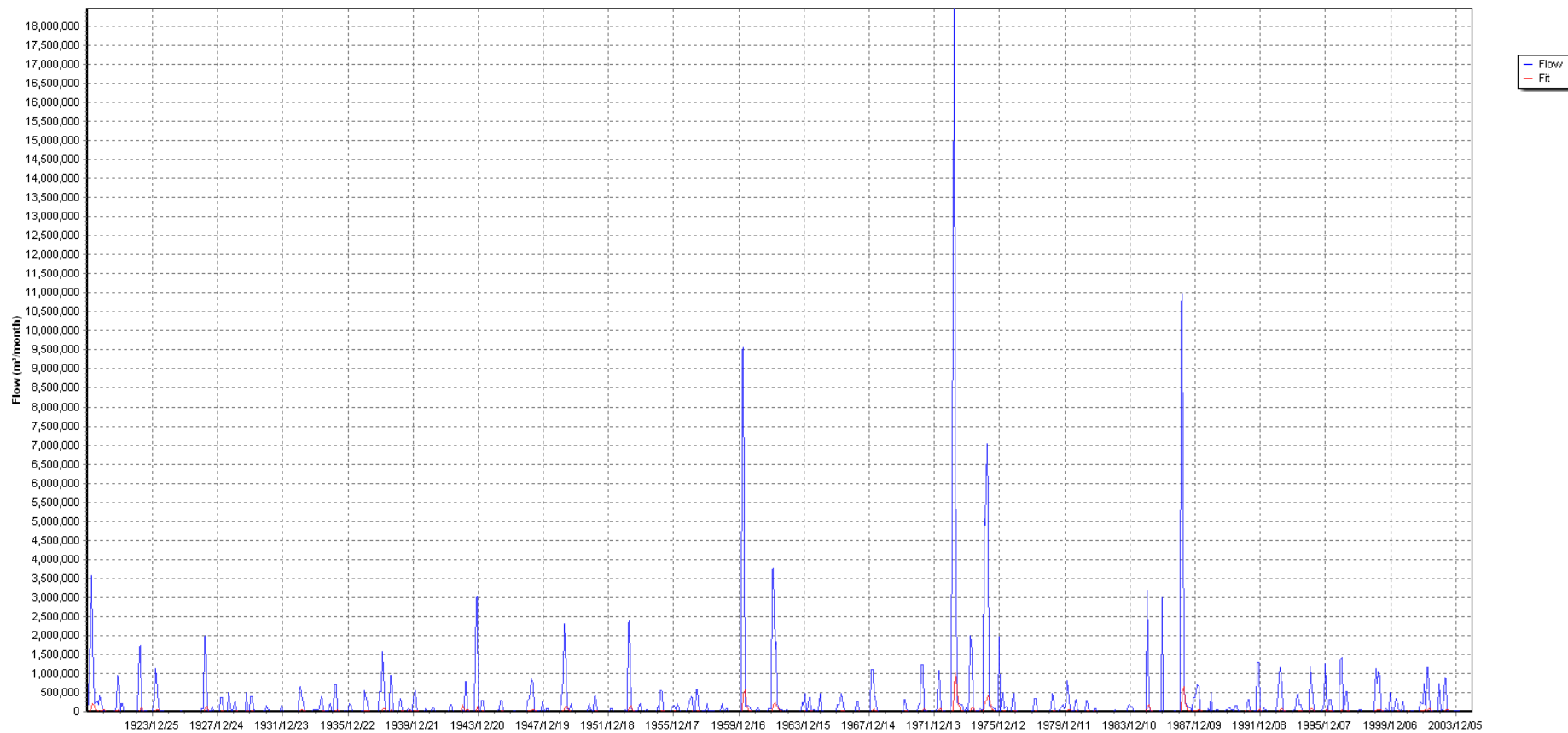


Figure: Groundwater contribution to baseflow (D61B)

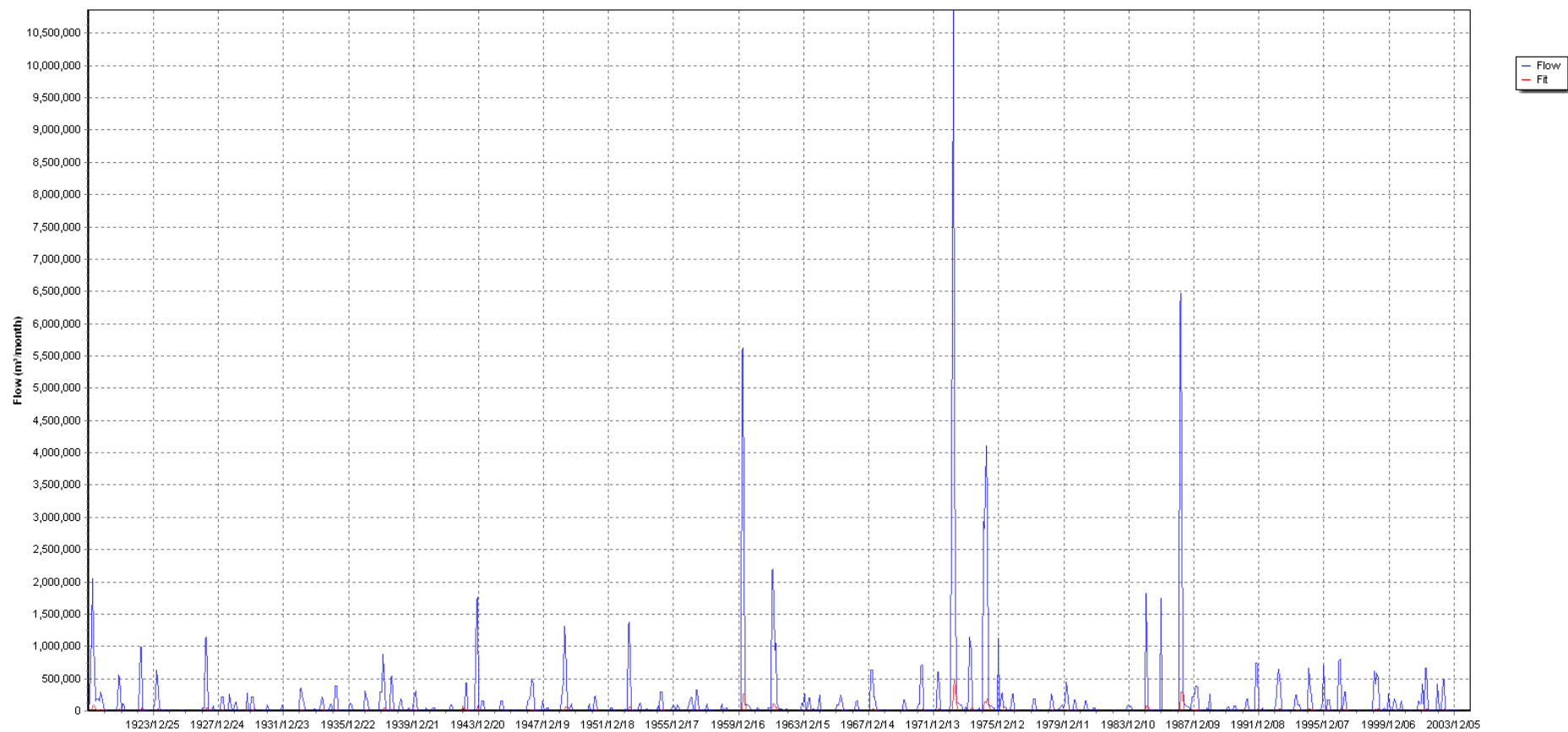


Figure: Groundwater contribution to baseflow (D61C)

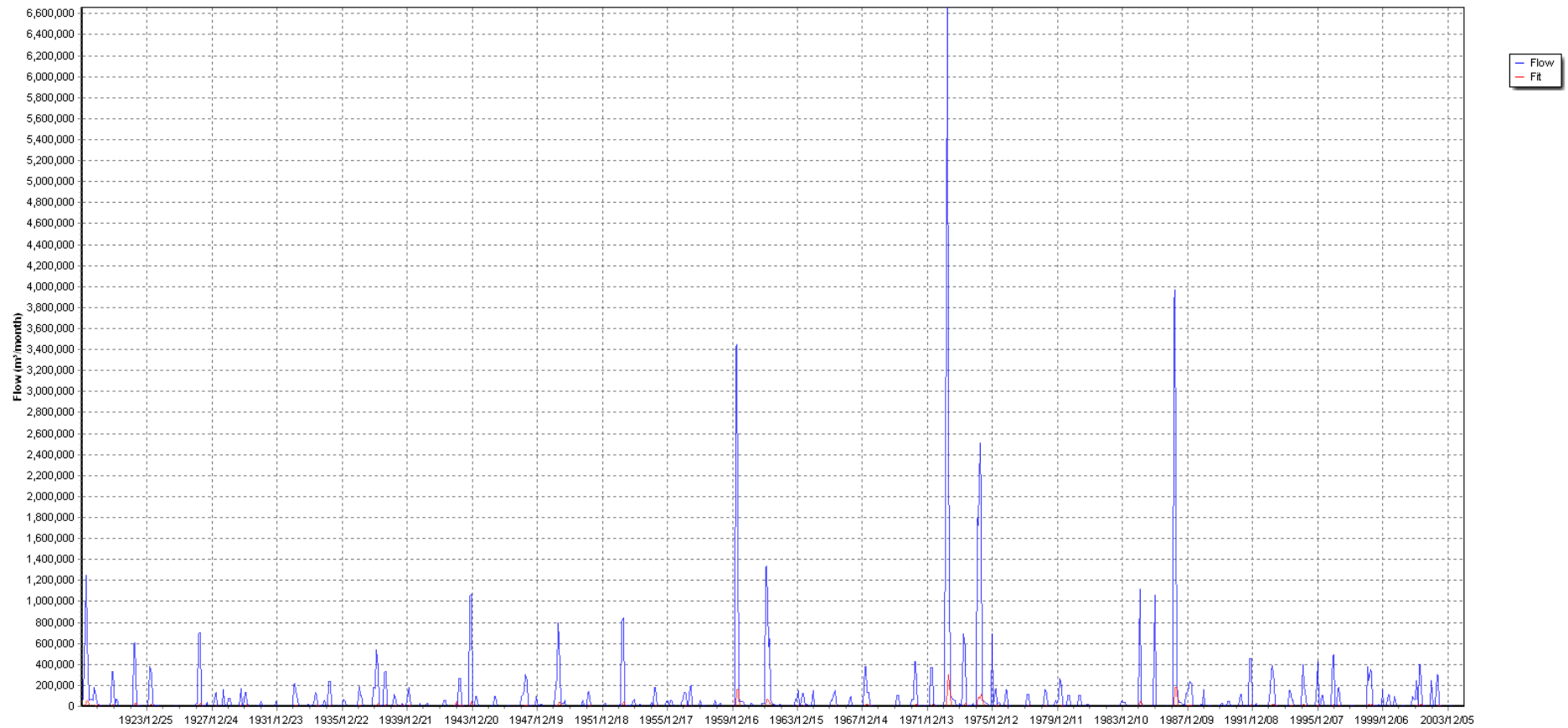


Figure: Groundwater contribution to baseflow (D61D)

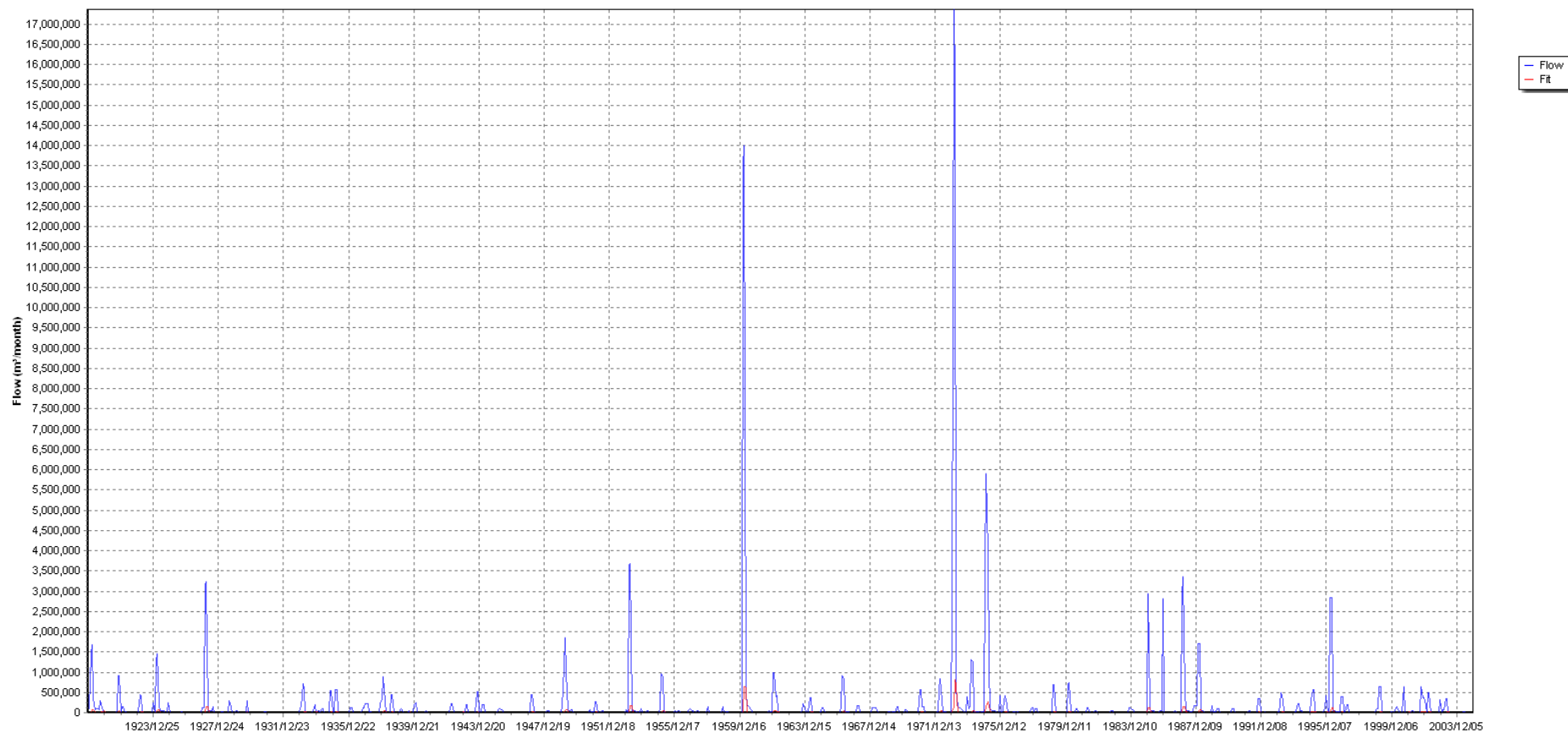


Figure: Groundwater contribution to baseflow (D61E)

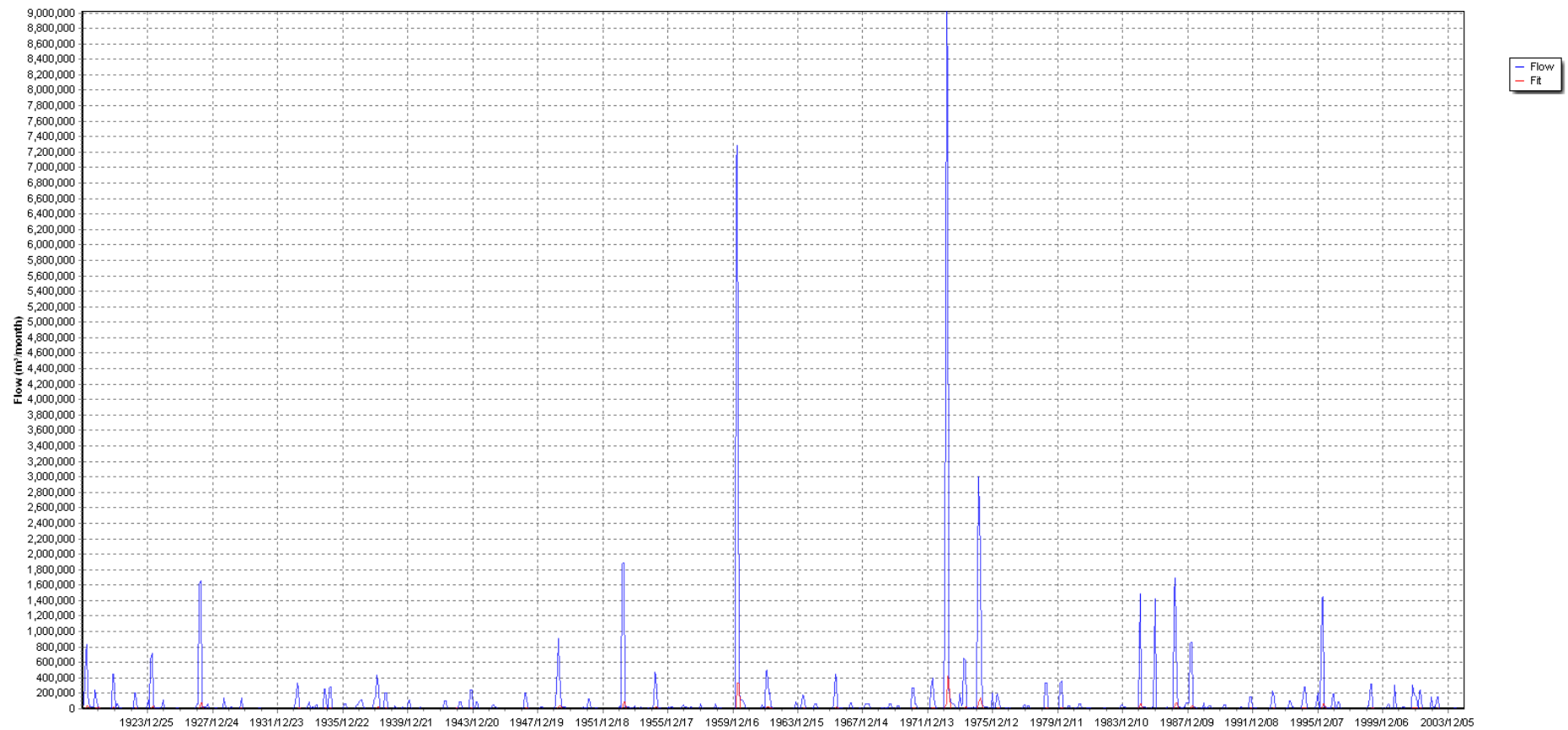


Figure: Groundwater contribution to baseflow (D61F)

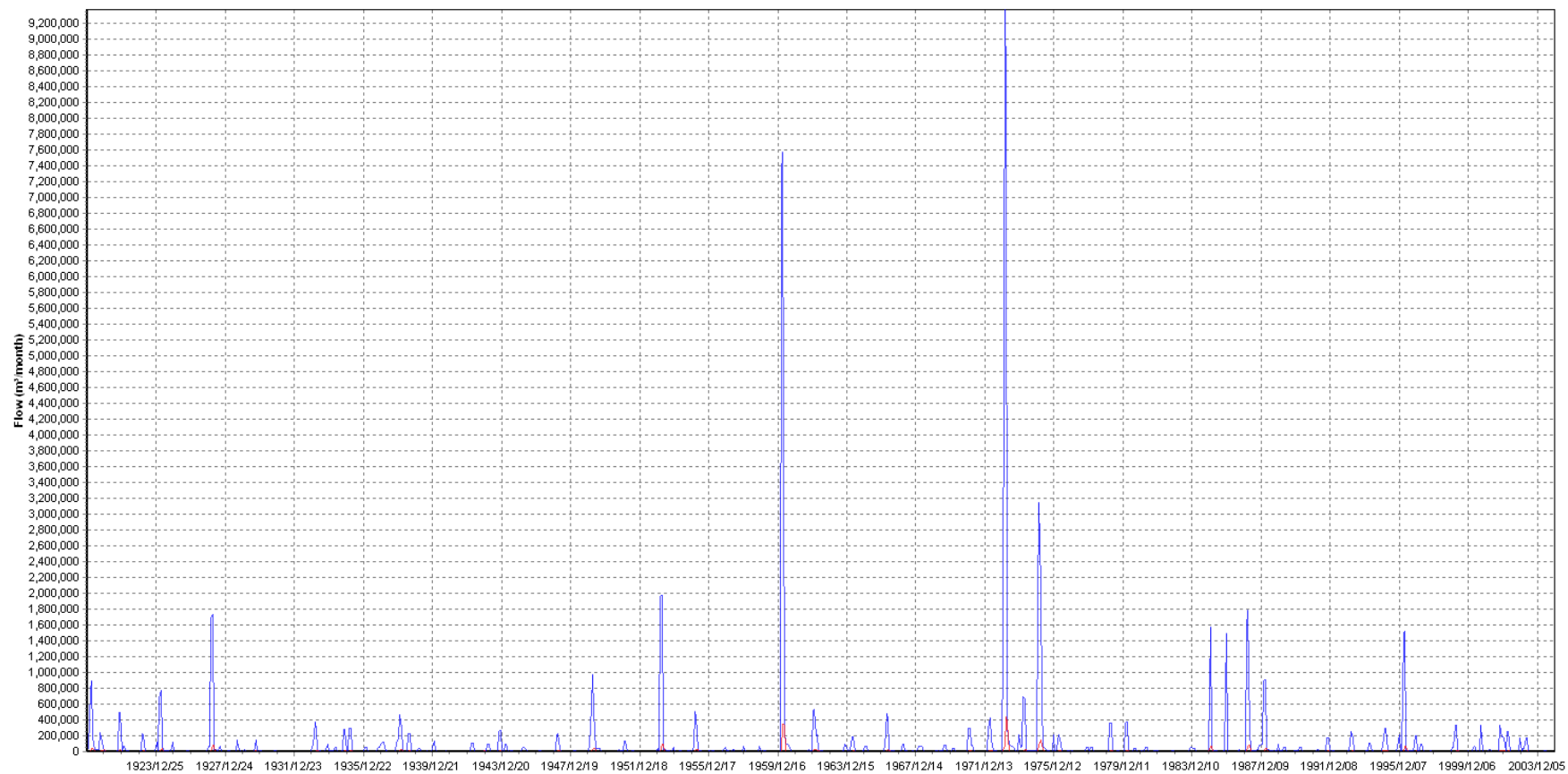


Figure: Groundwater contribution to baseflow (D61G)

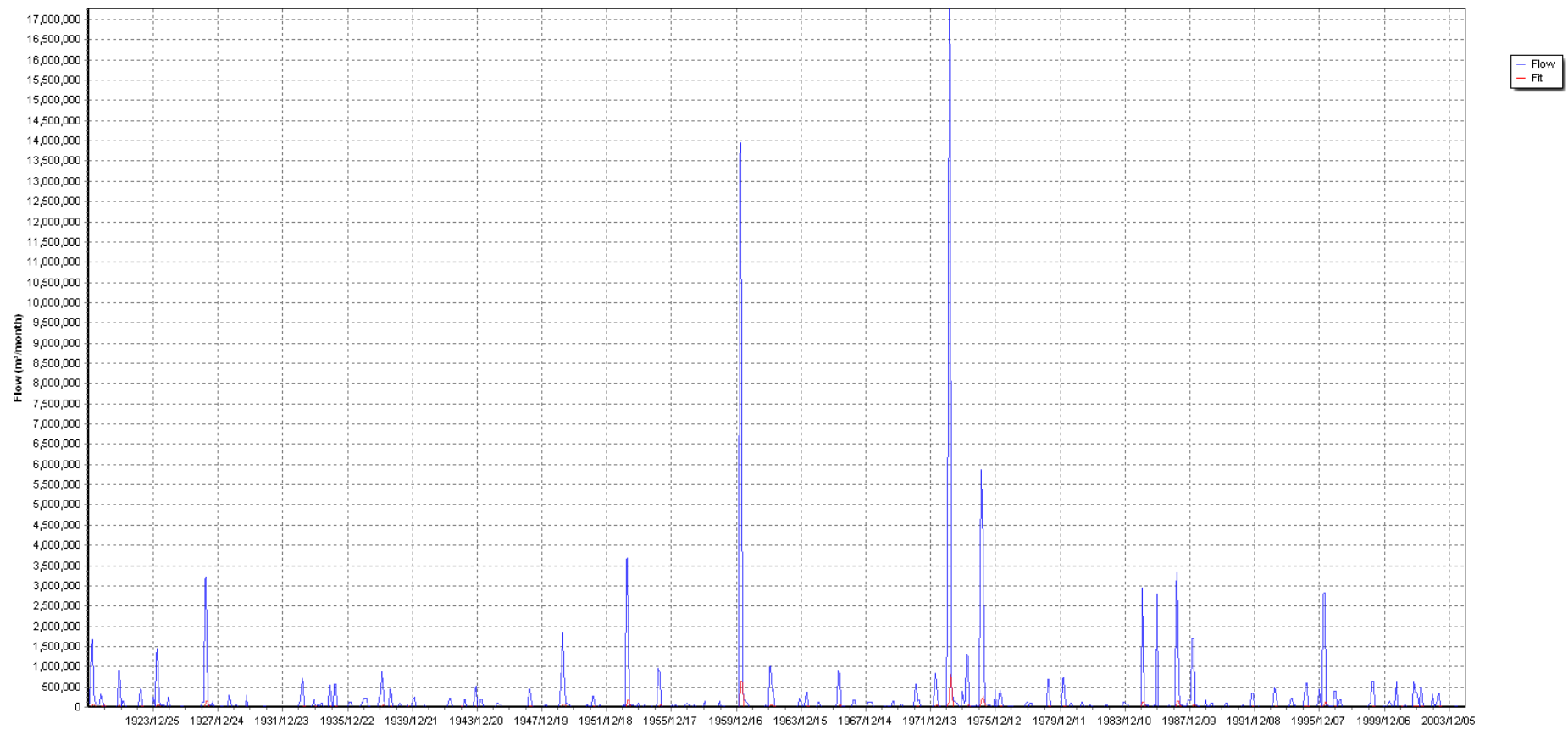


Figure: Groundwater contribution to baseflow (D61H)

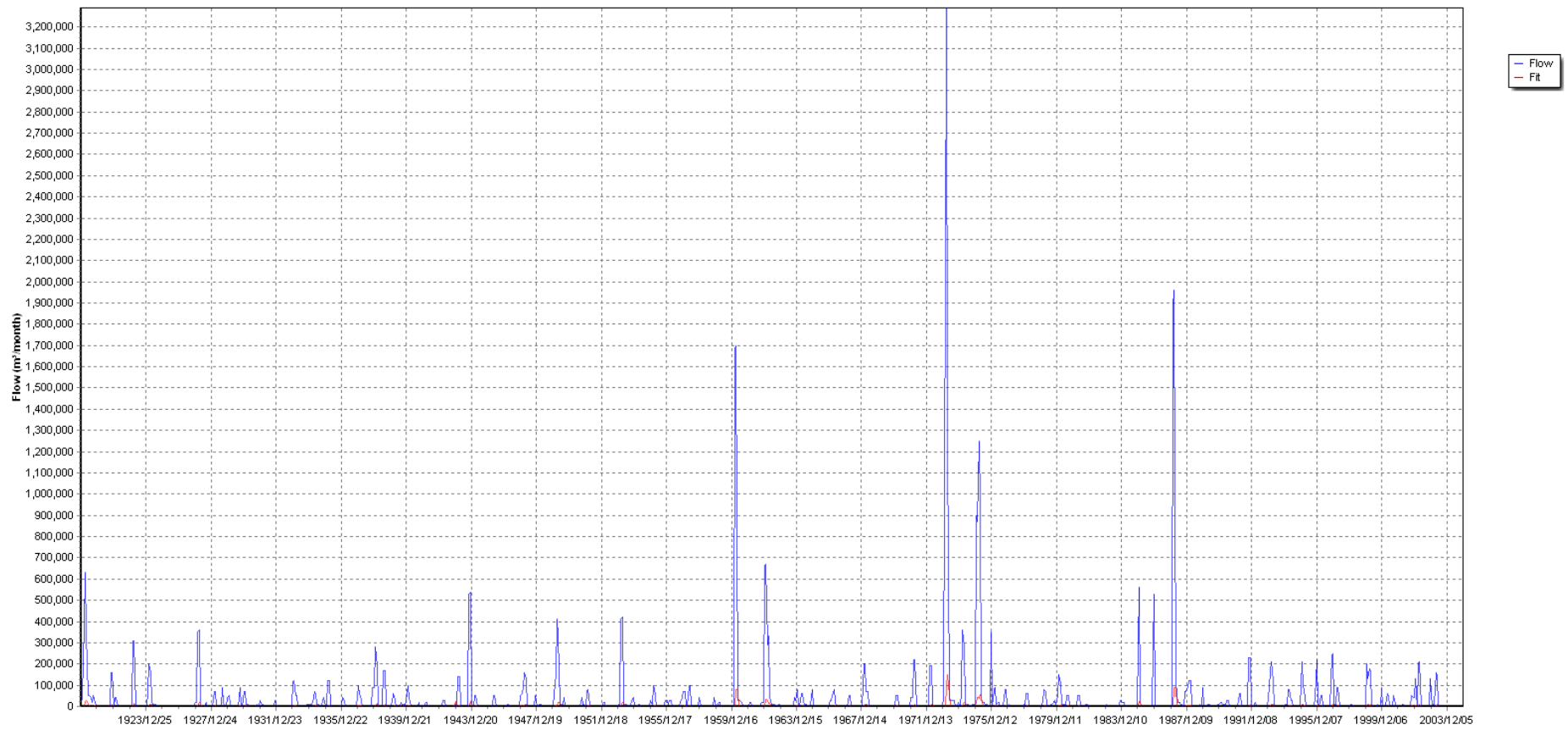


Figure: Groundwater contribution to baseflow (D61L)

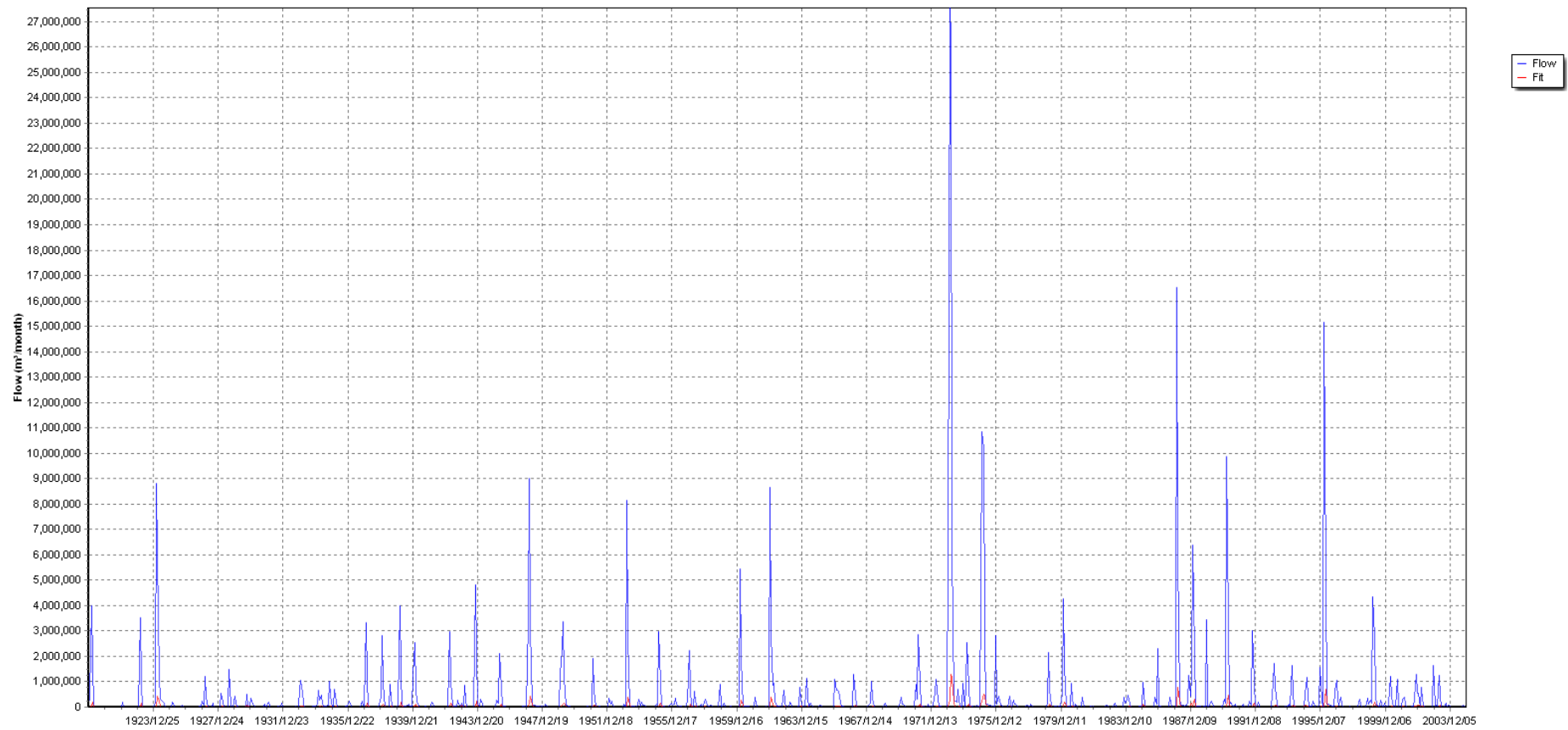


Figure: Groundwater contribution to baseflow (D62C)

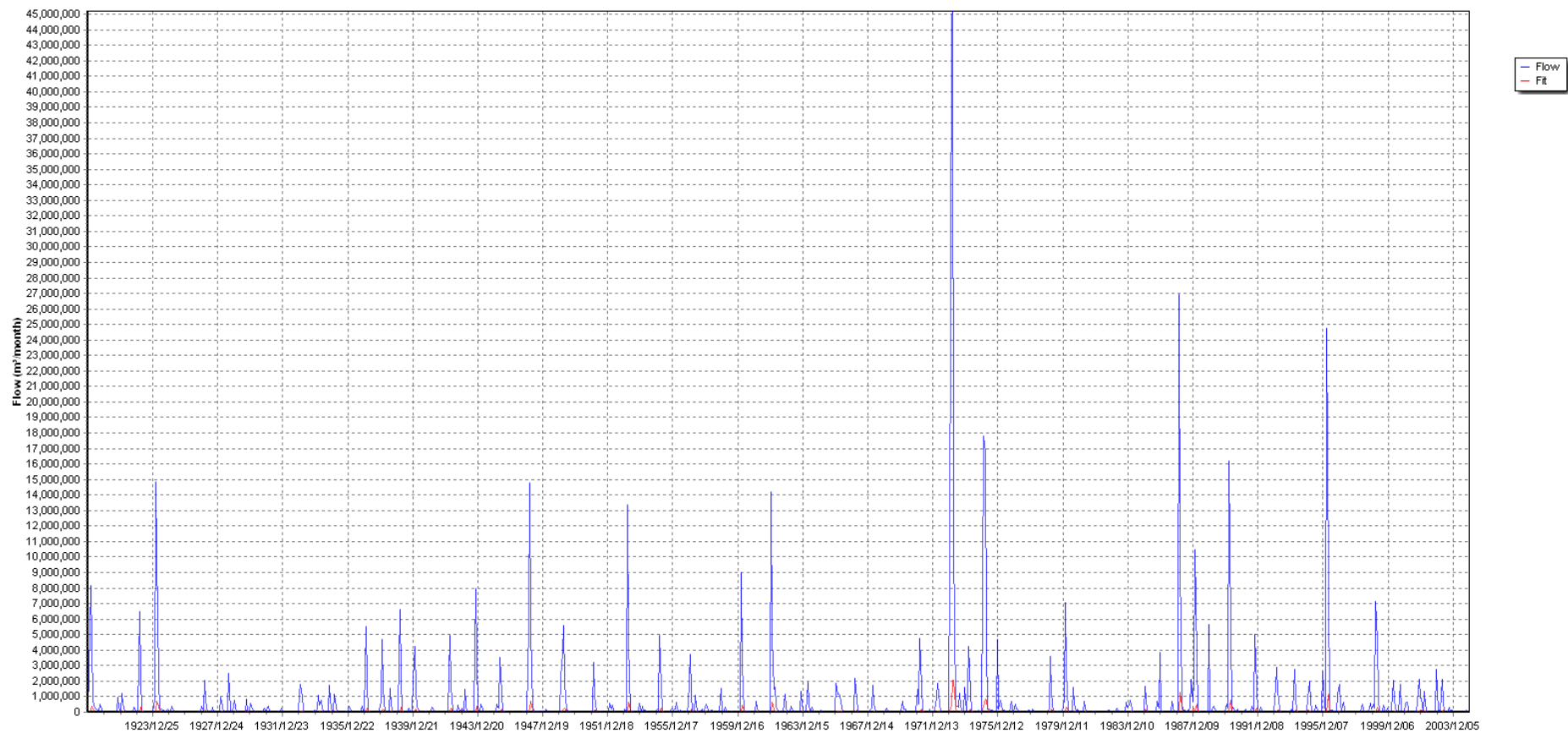


Figure: Groundwater contribution to baseflow (D62D)

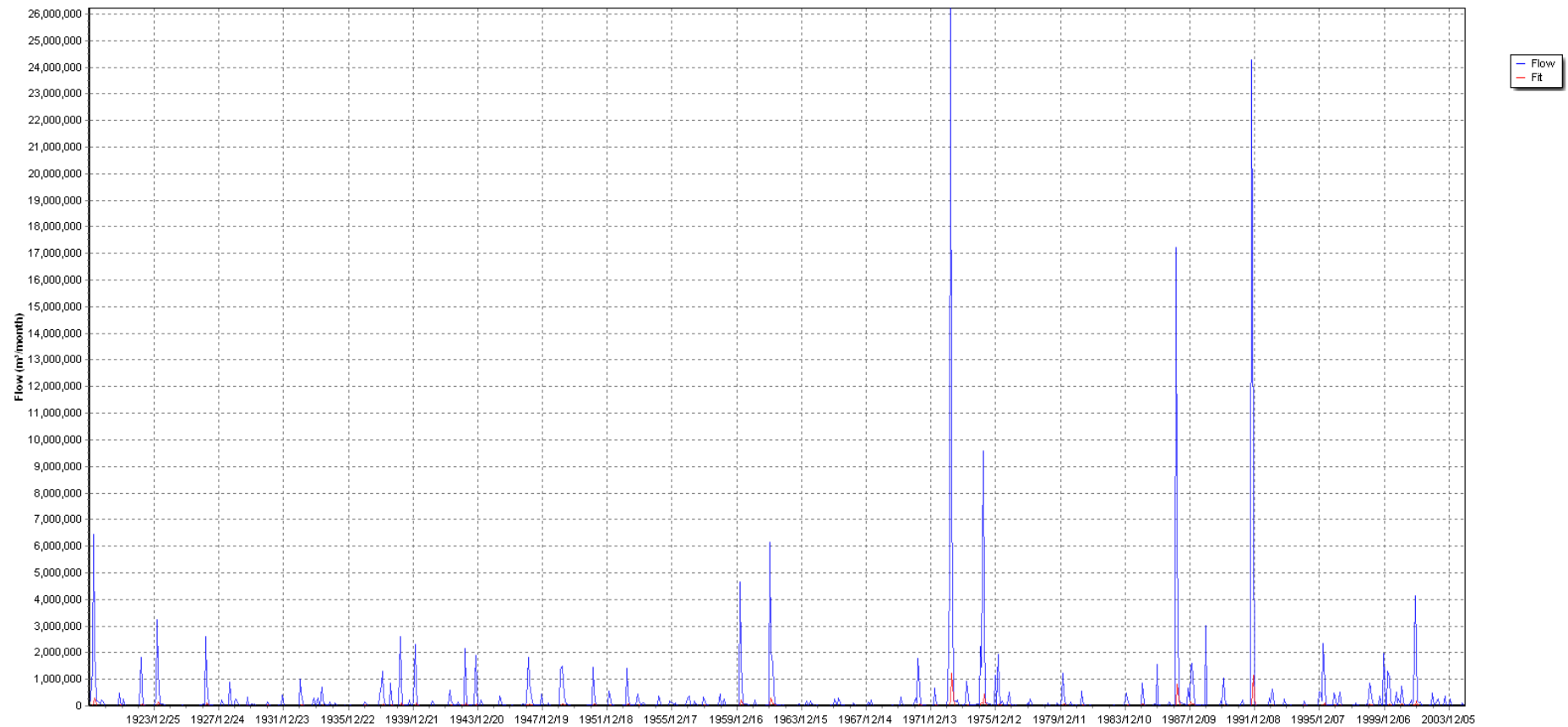


Figure: Groundwater contribution to baseflow (D32A)

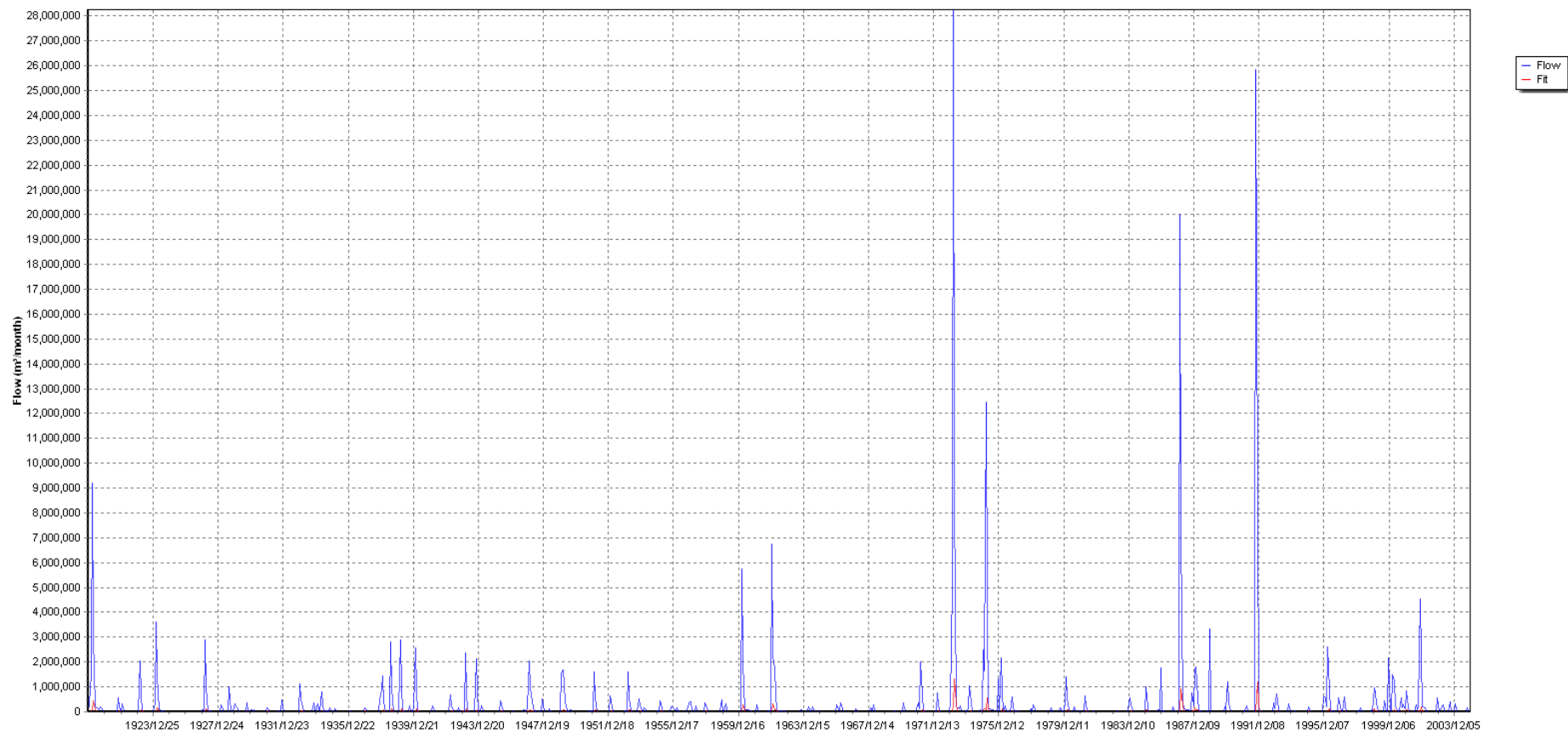


Figure: Groundwater contribution to baseflow (D32B)

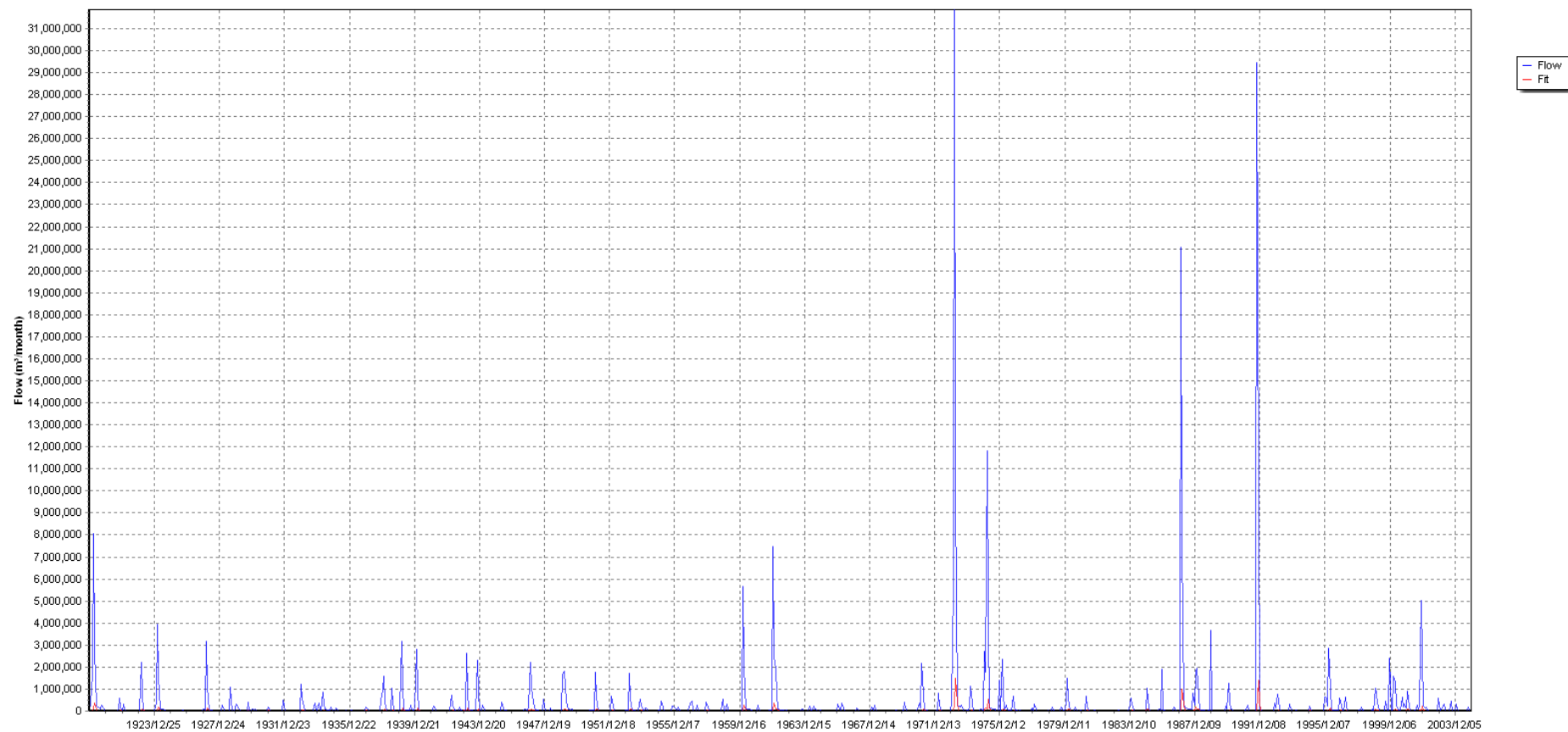


Figure: Groundwater contribution to baseflow (D32C)

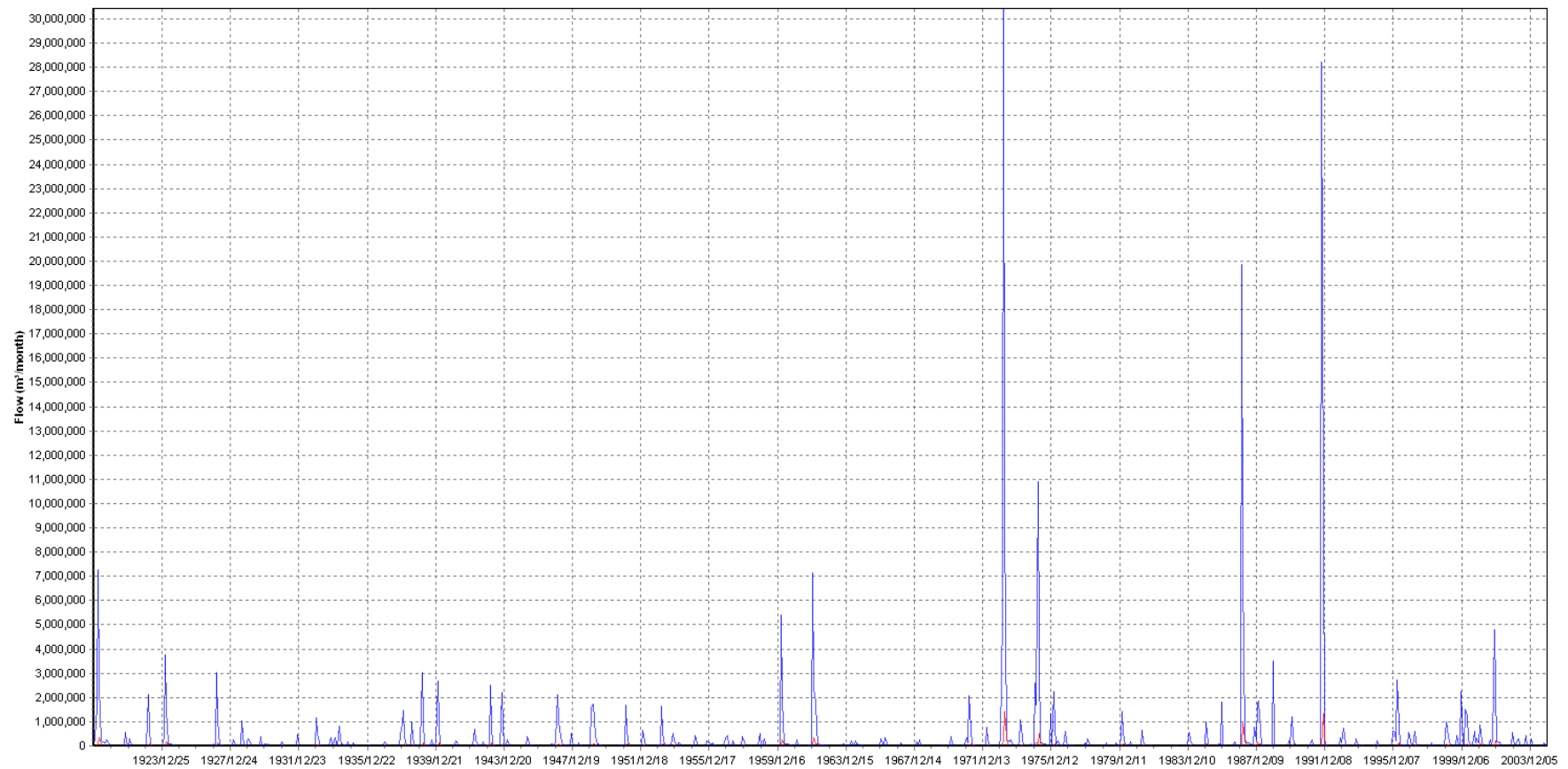


Figure: Groundwater contribution to baseflow (D32D)

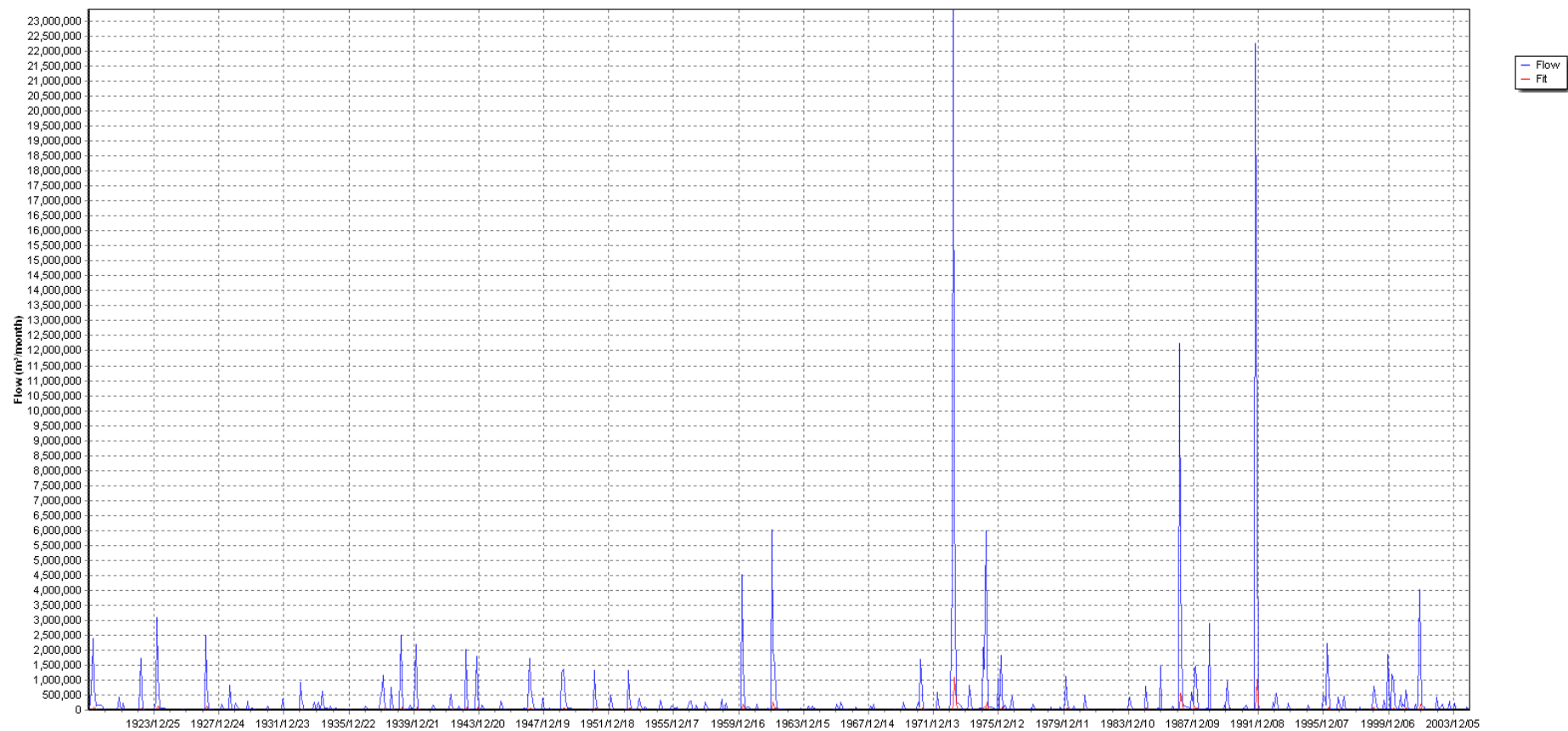


Figure: Groundwater contribution to baseflow (D32E)

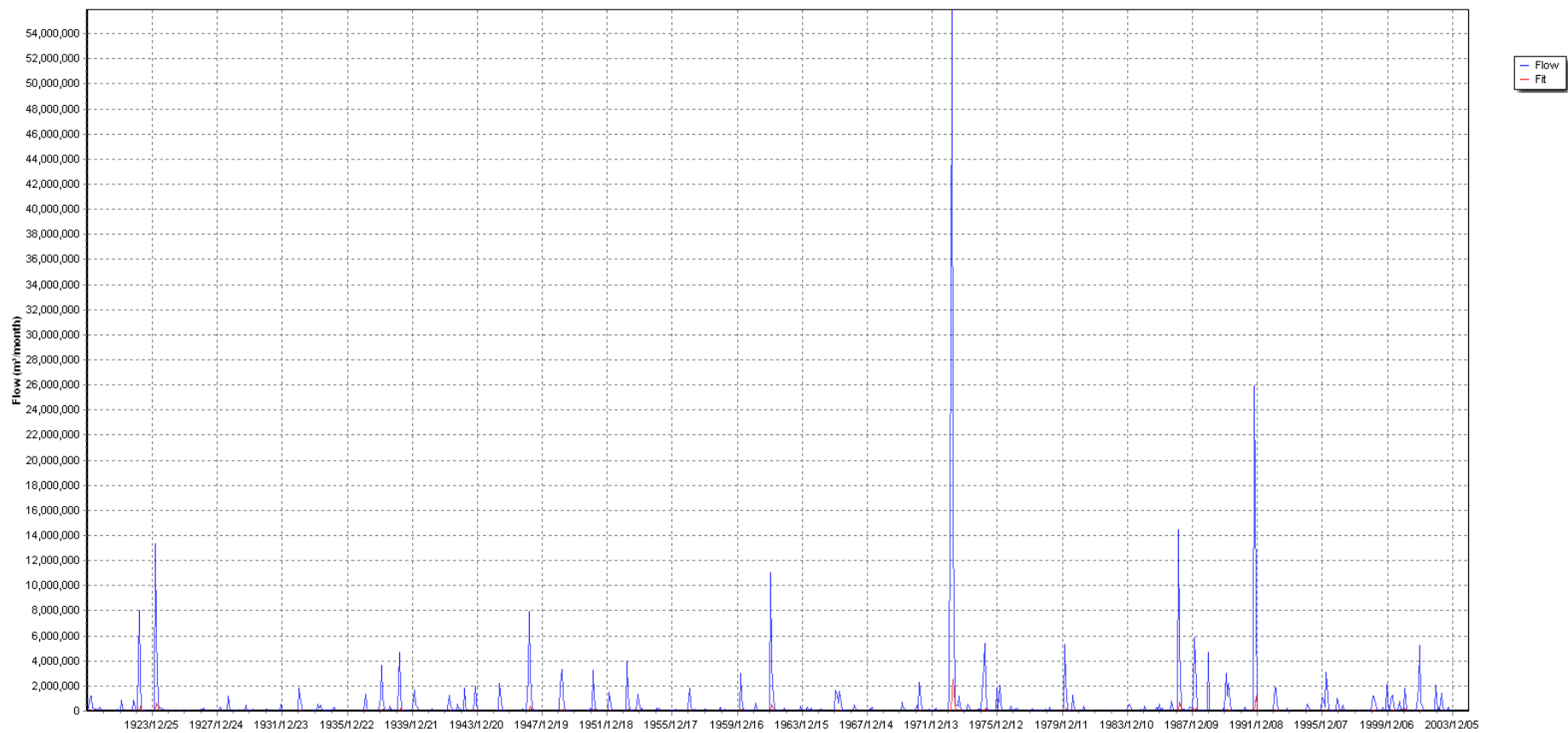


Figure: Groundwater contribution to baseflow (D32F)

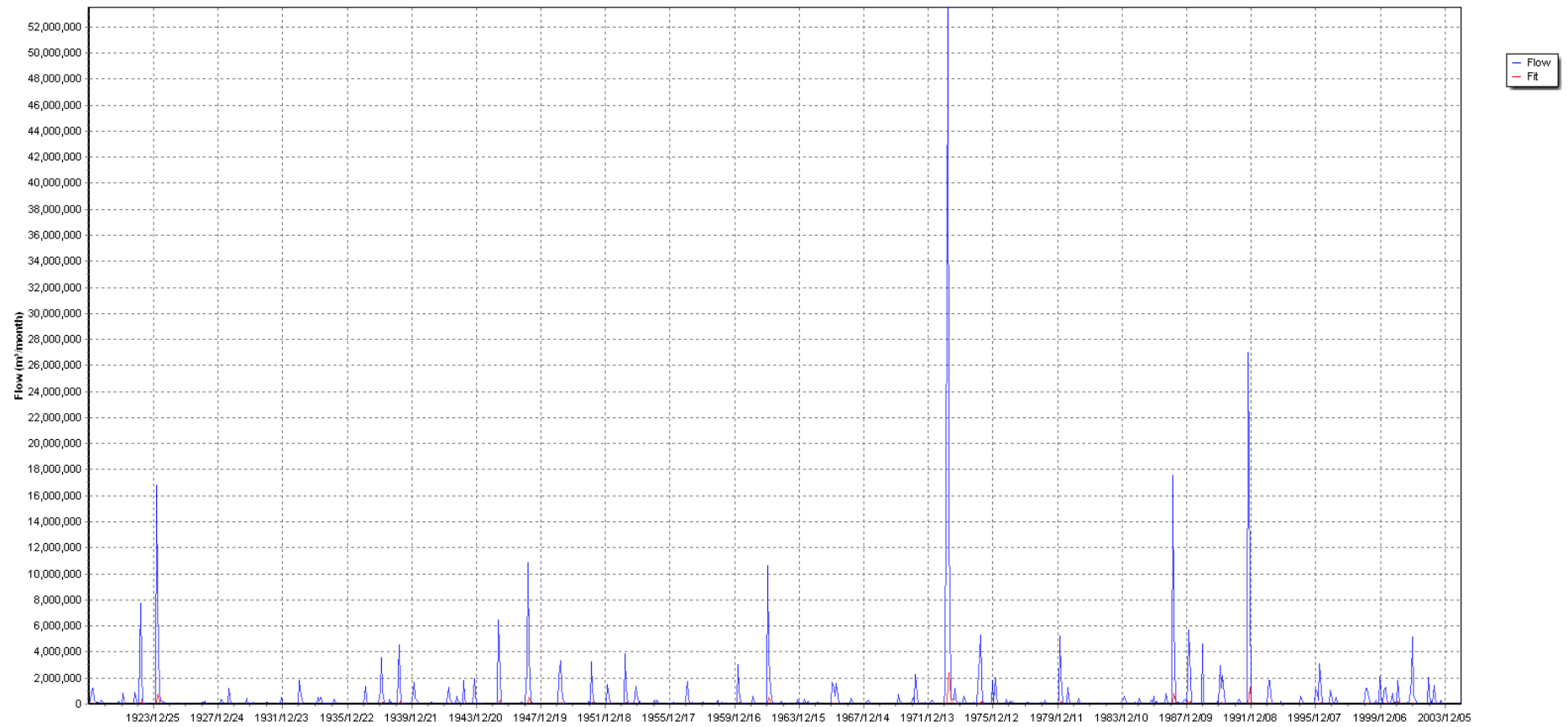


Figure: Groundwater contribution to baseflow (D32G)

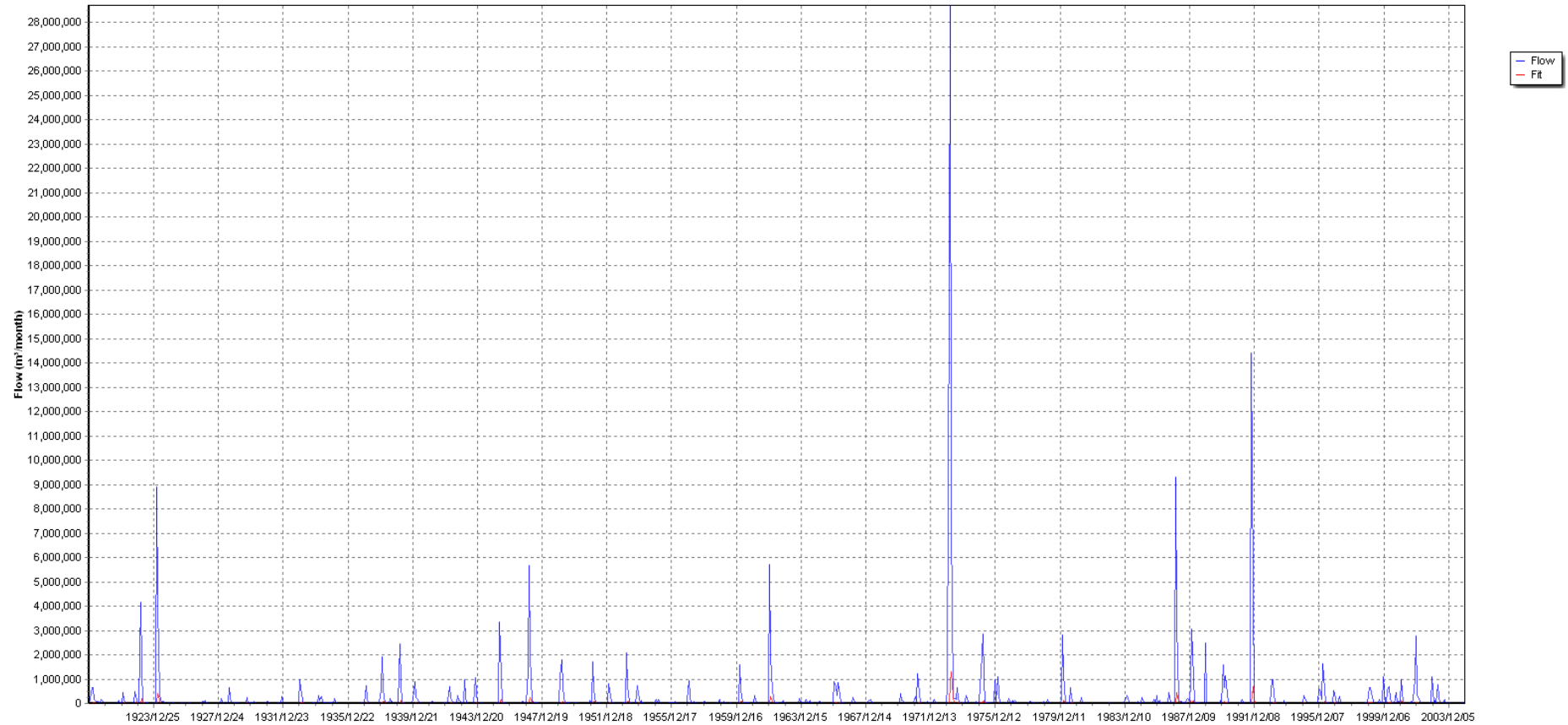


Figure: Groundwater contribution to baseflow (D32H)

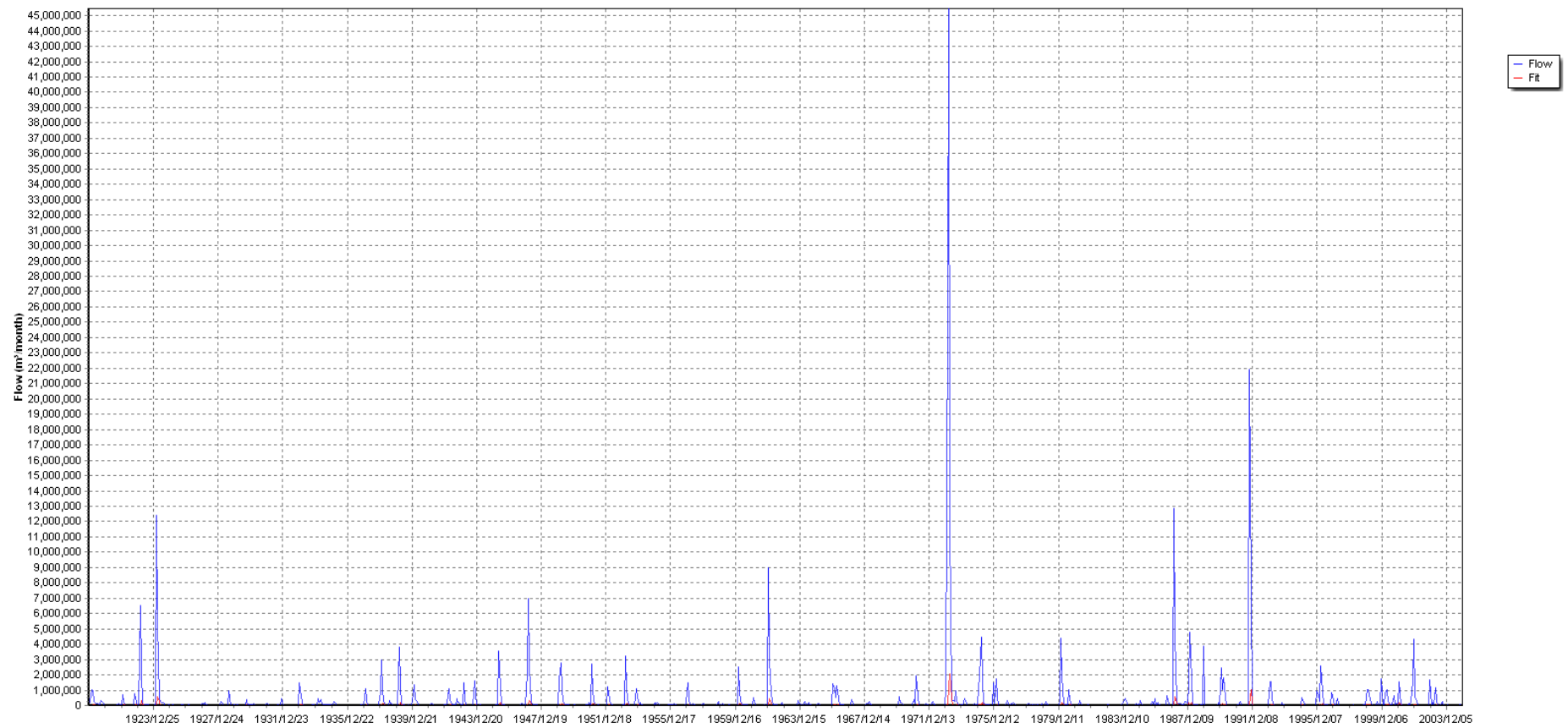


Figure: Groundwater contribution to baseflow (D32J)

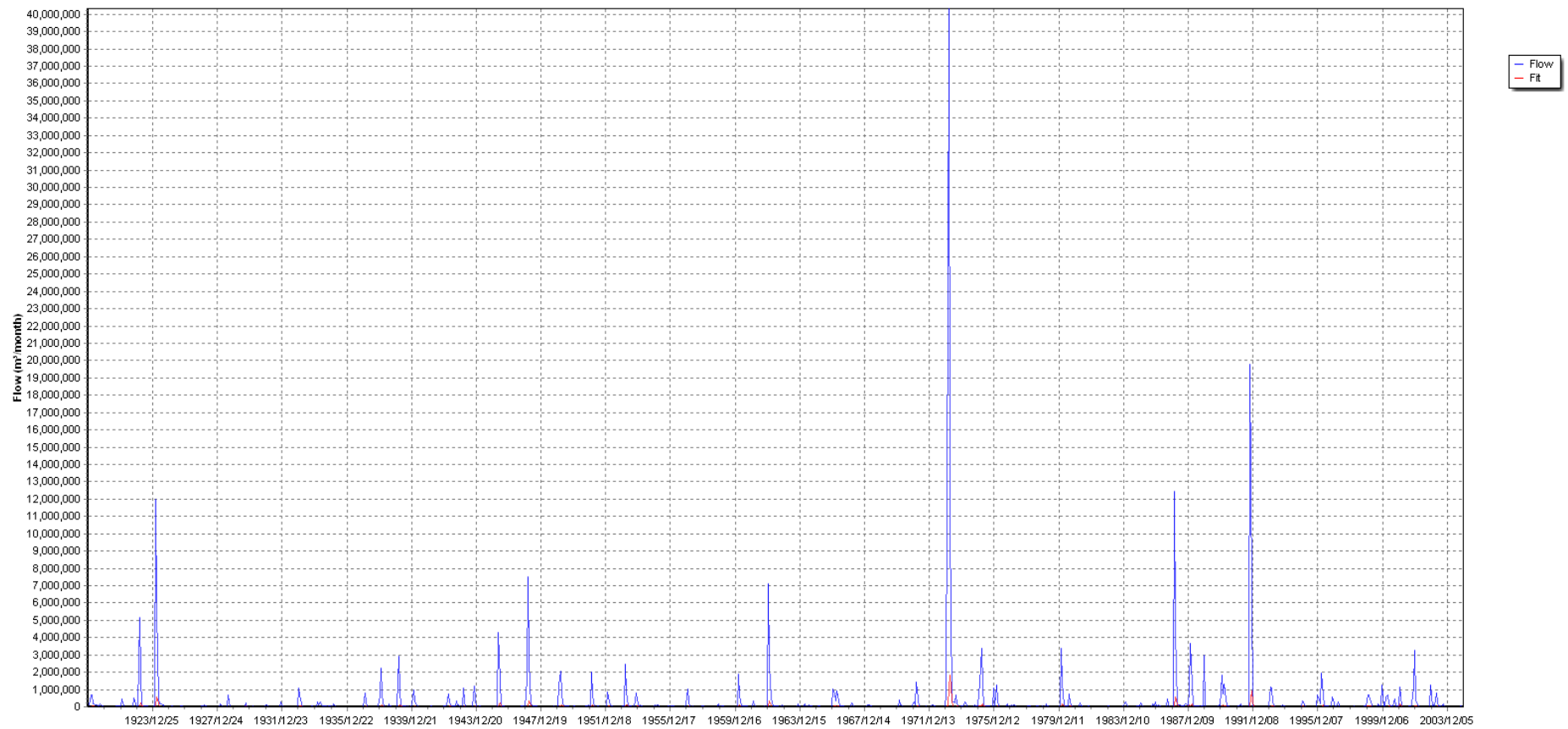


Figure: Groundwater contribution to baseflow (D32K)