

The use of GIS, statistical and risk assessment tools to evaluate aquifer  
vulnerability to potential contaminants



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## Declaration

I Lucien Keith Barbeau declare that Assessment and evaluation of aquifer vulnerability to contaminants with GIS, statistical and risk assessment tools is my own work. This work has never been submitted before for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledged as complete references.

Lucien Keith Barbeau

Signed:.....



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## **Abstract**

An aquifer is a body of permeable rock which can contain or transmit groundwater. It is a low cost water supply for domestic and agricultural use. Routine monitoring of aquifers is important to prevent contamination and its consequences. One of the advantages of routine monitoring of aquifer is the provision of continuous information on quality and quantity of water. The research problem for the current study is the lack of implementing of routine monitoring interventions to provide continuous updated information on water quality and quantity for various uses. The impact of continuous decrease in the annual rain fall due to the global warming is mostly felt by the countries in the Sub-Saharan Africa and most especially in the water tight rural community of South Africa. Consequently, aquifers represents the only reliable source of water for economic sustainability, agricultural production and healthy living in this part of the world. Routine monitoring of aquifer is therefore very important for prevention of its vulnerability.

The aim of the present study was to provide information on the vulnerability of the study aquifer to potential contaminants through routine monitoring using DRASTIC method and risk assessment method. To achieve such aim, the study used the conceptual model of groundwater flow system to explain the potential vulnerability of the aquifer to contaminants, apply the DRASTIC method and risk assessment method to investigate the vulnerability status of the study aquifer, and thirdly, determined the suitability of groundwater quality for agricultural and drinking purposes. The Heuningnes catchment in the Western Cape Province of South Africa was used as a case study in order to evaluate vulnerability of coastal aquifers. The choice of Heuningnes catchment was based on the fact that it has a coastal aquifer that serves as a potable water source for the surrounding regions.

The integrated hydrogeological conceptual model allowed for describing the potential threats to groundwater. The conceptual model assisted with the broader understanding of the groundwater system in the Heuningnes catchment, by analysing and comprehending previous literature and studies within the present study area. The utilization of the conceptual model allowed for the estimation and expectation of certain characteristics of the groundwater in specific areas of the study area.

Spatial, vector and raster data was analysed through geospatial and geostatistical analysis tools within GIS. This analysis determined the groundwater's potential threat to contaminants in the Heuningnes catchment. The GIS analysis is utilized alongside DRASTIC in this present study, where each parameter of DRASTIC underwent GIS analysis. The parameters of the DRASTIC method were measured using GIS, where the findings of DRASTIC's seven parameters found that the study areas aquifer to be under potential threat to potential contamination.

The findings of the statistical analysis of the groundwater physicochemistry indicate that majority of the groundwater's physicochemical parameters have a linear relationship with one another. Furthermore descriptive statistics find that pH values (6.38 - 7.40) meet drinking and agricultural requirements for the use of groundwater in the study, which was expected. In accordance to DRASTIC the highly vulnerable and moderately vulnerable zones are proven to be 87% and 12% coverage of the total study area respectively. This is due to the fact that moving in a more easterly direction of the study area the depth to water becomes shallower. The soil media alters to a less permeable characteristic although the topography remained fairly constant. Less than 1% of the total study area is under low vulnerability as it contains both Soetendalsvlei and Voelvlei, which are classed as water bodies.

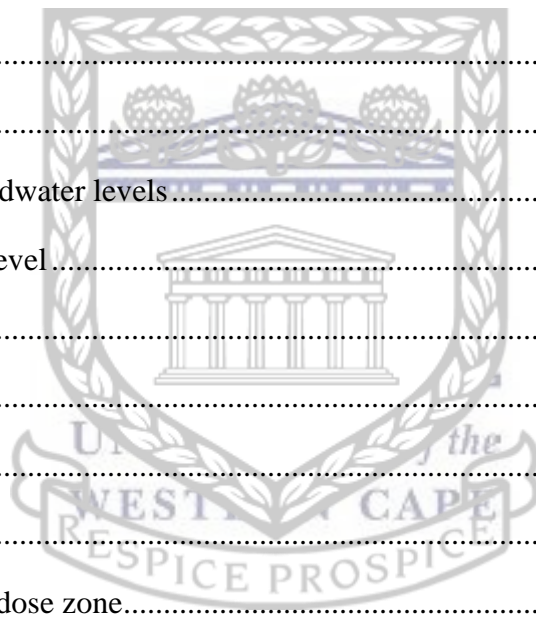
The aquifer under the current study is vulnerable to potential contamination. The groundwater quality within the study area remains of drinking and agricultural standards in accordance with international groundwater quality guidelines. The vulnerability map of DRASTIC produced a beneficial tool to provide an indication of vulnerability to pollution. The highly vulnerable zones that dominate most of the study area make it crucial for an introduction of sustainable methods to manage the groundwater resources, facilitate and implement routine monitoring. In terms of the highly vulnerable areas it can be said that these zones are challenging to monitor, based on the fact that it is dependent on many resources to constantly monitor it. By prioritizing zone of vulnerability, routine monitoring avoids further pollution to the already more polluted areas.

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# **Chapter 1: Introduction**

## **1.1 Overview of the study**

The present study shows the vulnerability of the aquifer to potential contaminants. The integrated hydrogeological conceptual model, DRASTIC, GIS and risk assessment methods were used for vulnerability assessment of the Table Mountain Group aquifer (TMG). The assessment was carried out to i) explain the potential vulnerability of the aquifer to contaminants, ii) investigate the vulnerability status of the study aquifer and iii) to determine the suitability of groundwater for agricultural and drinking purposes. The information produced by the studied aquifer can be used as a guideline for groundwater suitability for agricultural purposes or for potable use.

## **1.2 Background**

Aquifer vulnerability studies are the significant work for the sustainability and protection of groundwater resources. It has become a key issue in the field of hydrogeological research in recent years. The general concept of aquifer vulnerability is based on the assumption that the physical environment may provide some degree of protection to groundwater from natural impacts, particularly with regards to contaminants entering the subsurface environment. The degree of protection of groundwater leads to land areas becoming vulnerable to potential contamination than others. Furthermore, aquifer vulnerability studies provide preliminary information and criteria for decision making in areas of delineation of monitoring networks and management of water resources in the context of regional planning as related to protection of groundwater quality.

Aquifer vulnerability assessment provides a basis for initiating protective measures and will normally be the first step in an aquifer pollution hazard assessment and quality. Moreover, the vulnerability assessment serves primarily as a direct protection for groundwater. Also, the aquifer vulnerability assessment is important in defining critical zones of non-point source potential contaminants that assists in establishing an effective monitoring network for groundwater resource management.

Information about aquifer vulnerability to potential contamination is crucial to facilitate groundwater planning and management. Additionally, this information can assist in the choice of proper locations for certain activities so that the adverse effects on groundwater are minimized and thus protection of groundwater is achieved. Therefore, in this study, a GIS based zone mapping groundwater vulnerability assessment method is used to facilitate designing and implementing routine monitoring.

Methods to estimate aquifer vulnerability can be broadly classified into three: Process-based simulation methods, Statistical methods and Overlay and index methods. Process-based methods utilize simulation models to predict contaminant transport in both space and time. These methods require analytical or numerical solutions to mathematical equations that represent coupled processes governing contaminant transport. The data required is rarely available and requires to be estimated by indirect means. An example of a process based model is MODFLOW, where the computer model simulates the flow of groundwater through aquifers. Although process-based methods are more sophisticated, the results are not necessarily more accurate. Process based simulation models are not continually used for vulnerability assessments. This is due to the fact that running these simulations require a tremendous amount of data and expertise to execute them, making running costs high.

Statistical methods are designed for assessing groundwater vulnerability relative to the occurrence of constituents in ground water to explanatory variables. These variables describe either potential sources of these constituents or the relative ease with which it may migrate to the position in the flow system where the ground water sample is taken. Several statistical methods have been used to relate water quality data to explanatory variables (Tesoriero et al., 1998). The California Vulnerability Approach (CALVUL) is an example of statistical methods. It is used to determine whether the groundwater in the agricultural land is vulnerability to potential threats. If it is vulnerable the land becomes part of a groundwater protection area. CALVUL is developed by the Department of Pesticide Regulations to determine the specific vulnerability of groundwater to pesticide residues. Process-based methods and statistical methods are not commonly used for vulnerability assessment because they are constrained by data shortage and non-availability of the technicality for implementation.

Overlay and index methods is a simple aquifer vulnerability assessment method. It requires less data and gives a clear description of the vulnerability. It is capable of combining maps of subsurface attributes such as depth to the water table, groundwater recharge rate as well as soil and aquifer material properties. The extent of vulnerability is qualitative and relatively assessed by considering the measured parameter. Each attribute is rated by using expert opinion of detailed knowledge of the study area in question to provide an accurate result of the groundwater's vulnerability (Abdelmadjid & Omar, 2013). The common examples of overlay and index methods are GOD, AVI, SINTACS and DRASTIC. The previously mentioned methods study areas are typically large in scale and their data is readily available. GOD is designed to map groundwater vulnerability over large regions based on the parameters such as: Groundwater Occurrence, Overall lithology, Depth to groundwater table. It is used in regions where most groundwater resources were in hard rock aquifers. The method was developed in Great Britain and it was known to be used in consideration to the likelihood of fractures or fracture systems to develop in the soils, overburden and/or overlying geologic units of the aquifer. It had been applied alongside DRASTIC in the Cabril river basin, Portugal to determine groundwater vulnerability to pollution (Fernandes et al., 2014).

The Aquifer Vulnerability Index (AVI) quantifies vulnerability by hydraulic resistance to vertical flow of water through the protective layers. The AVI method was used to map a 3100 km<sup>2</sup> area along the Saskatchewan-Alberta boundary (Stempvoort et al., 2013). AVI maps can be used to define groundwater protection zones, or for screening sites for land use selection. Within GIS, AVI maps can be compared or merged with other GIS-referenced information, such as land use and water quality. The SINTACS model is a modification of DRASTIC that Italian nationals have adopted with a score ranging from 1-10. SINTACS uses seven environmental parameters (groundwater table depth from surface actual infiltration, self-depuration effect unsaturated zone, overburden type, hydrogeological characteristic of the aquifer, hydraulic conductivity and topographical; surface slope) to identify area where groundwater sources are vulnerable to potential contamination. Furthermore, the method uses different weight coefficient multipliers for every impact situation examined, so as to increase the score proportionately to the importance of the parameter in determining the degree of vulnerability to potential threats (Arpa et al., 2001). These parameters are prescribed by the Italian environmental regulations for assessing intrinsic vulnerability.

Generally, a comprehensive aquifer vulnerability assessment method requires further composite and detailed knowledge of the system being assessed. Simpler methods that incorporates more approximations and are less precise, but require less detailed information about the system being assessed. Although complex methods may describe transport mechanisms more precisely, the data required are often unavailable and must be approximated from limited existing information.

However, DRASTIC is the most widely used indexing method. It is universally applicable and incorporates parameters that are generally available. DRASTIC is extensively utilized across the globe as the inputs it requires for the application is commonly available or easy to obtain. This method is a valuable tool for identifying groundwater sources that are vulnerable to potential contamination using elementary hydrogeological variables that are capable of influencing the potential contamination transport from surface sources to groundwater. Thus making it suitable for regional scale assessment. Furthermore, the high number of inputs that DRASTIC requires for its input layers, limits the impact of potential errors of the individual parameters on the final result. The GOD method is one of the more modern methods of aquifer vulnerability assessment. Despite the fact that GOD was developed approximately 20 years after DRASTIC. But DRASTIC remains the most popular choice of vulnerability assessment globally and is the chosen method for the vulnerability assessment in this present study.

Aquifer vulnerability assessment for various nations is controlled by the groundwater circumstances in that specific nation. An aquifer vulnerability assessment was conducted by (Rahman, 2008) in India. His study used DRASTIC to assess the groundwater vulnerability alongside GIS tools and software to determine the groundwater vulnerability zones in shallow aquifers. It was revealed that the groundwater in and around Aligarh, India are that in a larger part under moderate to high pollution vulnerability zones. His study of the region suggests that the DRASTIC method can be used for prioritization of vulnerable areas.

In South Africa, the previous studies on aquifer vulnerability had been carried out by (Makonto & Dippenaar, 2014). The authors utilized the DRASTIC to determine the influence of the vadose zone on the groundwater regime in the Limpopo Province. The authors used a section of DRASTIC method to evaluate the vadose zone as a pathway for pollutants to travel. The certain parameters of the method were overlaid to produce a vulnerability map. The different weightings were

attributed in the methods and the results obtained indicated a high vulnerability in the upper parts of the Molototsi catchment.

In the province of the Western Cape, DRASTIC is carried out in the Cape Agulhas town. Cape Agulhas is used as the study area to perform the aquifer vulnerability assessment. This region is composed mainly of farmland and natural vegetation. There are many agricultural activities in this region that have a great potential threat to groundwater. Pesticides is a significant link to agriculture, where it is utilized to combat pests and disease in areas where crops are being planted. The resultant agricultural produce is very likely to be threatened if routine monitoring of the aquifer is not conducted in order to sustain the aquifer. Agriculture is primarily the main economic sector within the economy of Cape Agulhas of which wheat, barley and canola farming as well as livestock farming are the predominant economic activities within this sector. The competitive nature of agriculture on the export market as well as mechanisation, processing, value adding and input supply production and marketing offer opportunities for viable investment and business development. Agriculture employs the most people and is the most important sector in the region (Chand, 2016).

The concentrated agricultural practices potentially contributed to the current deteriorating quality of the Cape Agulhas region. The efforts put-forth to escalate the agricultural production and the associated revenue had led to the excessive application of fertilizers, pesticides, herbicides, and soil fumigants. This in turn did elevate the contamination occurrences in the study area. In addition, the infiltration of untreated leaking wastewater and the overloaded malfunctioning treatment plants and the corresponding effluent contribute to the on-going contamination of Cape Agulhas (Clever & Brown, 2005).

The protection of groundwater source is selected in order to evaluate groundwater pollution potential of Cape Agulhas. With a number of towns relying on groundwater as their major or only source of water, illustrates that the increasingly important role that groundwater plays in ensuring an adequate water supply to these towns (Toens, 1991). With Cape Agulhas being one of these towns it required to sustain this groundwater supply for future use.



### **1.3 Statement of research problem**

The lack of applying comprehensive assessment may lead to aquifer contamination if it remains unattended to. The aquifer vulnerability assessments form an important input to managing the risk of water resource degradation. The study argues that the assessment of aquifer vulnerability and protection of aquifers for future use is required to deal with the situation at present, by using the DRASTIC method. It can be utilized on numerous scales and platforms across the globe. Aquifer vulnerability needs to be given immense consideration as the quality and resources of groundwater in South Africa is being disregarded.

Additionally, South Africa as a country needs to protect its water resources as its groundwater sources potentially being under threat is hazardous for the environment. As a result this may well affect agricultural dominant regions such as Cape Agulhas that is recognized for one of the highest quality of groundwater bearing aquifers in South Africa. Furthermore, this water source is important to many neighbouring regions that rely on it. If routine monitoring of the groundwater quality is not implemented, grievous consequences may result as the implications for neglect of groundwater resources and aquifers will degrade the groundwater quality.

### **1.4 Research question and thesis statement**

The main research question of the current study is that, is the groundwater in the study area at risk of potential threats or not? Subsequently, the use of this information will sustain the quality of the groundwater in the study area. The other three sub-questions intended to be addressed are: i) Is the TMG aquifer under potential threat to contamination? ii) To what extent is DRASTIC method appropriate tool to assess threats to aquifer contamination in rural settings? iii) How can the contamination of the TMG aquifer be prevented?

The current study uses the DRASTIC method in the assessment, quantification and interpretation of the aquifer in the study area. The result can be used to speculate the vulnerability of the aquifer to potential threats and protection it for future use.

## 1.5 Research objectives

The study aim was to determine if the groundwater in the study area is at risk of potential threats or not and consequently uses this information to increase sustainability on groundwater use.

This is done by analysing the groundwater content by subjecting it to the DRASTIC method parameters and interpreting the results of this method.

The detailed objectives of the present study are to:

- Explain the vulnerability of the aquifer to contaminants using integrated hydrological conceptual model, DRASTIC and risk assessment methods
- Determine groundwater suitability for agricultural and drinking using risk assessment
- Establish groundwater levels using geostatistical, geospatial and risk assessment tools

## 1.6 Significance of the study

The significance of the study links to the vulnerability assessment of groundwater aquifers. As it provides a foundation to initiate a preventative measure for imperative groundwater resources. It will consistently be the initial phase in a groundwater contamination quality assessment. Demarcation of contamination vulnerability zones is a very necessary step to protect and efficiently manage aquifer system within the study area. Cape Agulhas is acknowledged to constitute one of the highest quality of groundwater bearing aquifers in South Africa. Critically, the water source is important to many neighbouring regions that rely on it for an adequate water supply. Thus, the information gained from this study is crucial for its effective management because it will influence, prevent and control groundwater contamination.

## 1.7 Conceptualization of the study

Within the whole scope of aquifer vulnerability, the present study focused on the combination of methods to evaluate aquifer vulnerability to potential contaminants. Moreover, literature on the appropriate methodological approaches used in such areas was reviewed and a selection of an applicable method chosen. Figure 1 shows illustrates the research framework followed in the current study. This study examined the potential contamination of the aquifer in terms of the several parameters of the DRASTIC method. In addition, the vulnerability map, which will be obtained in this study, is expected as to inform public and government while preparing land use plans with considering groundwater protection zones. As a result of this study, the prepared vulnerability map could be an informative tool for the education of public.

Sustainable Development Goals (SDG) also known as global goals, is a prevalent call to end poverty, protection of the planet and ensure that all people enjoy peace and prosperity. The SDG succeeded the Millennium Development Goals (MDG) which had expired in 2015. Unlike the MDG, the SDG is a framework of seventeen goals and 169 targets across social, economic and environmental areas. The seventeen goals build on the success of the MDG and includes new areas such as climate change and sustainable consumption.

Clean water and sanitation form part of SDG's key to success on tackling issues more commonly associated with another. Water scarcity affects more than 40 percent of people around the world. Although a large volume of people have gained access to improved water sanitation since 1990, diminishing sources of potable water is a major problem impacting every continent. The SDG set to meet their goals by 2030, thus requiring adequate infrastructure, providing sanitation facilities and encouraging basic hygiene at every level. Finally, protecting and restoring water-related ecosystems are essential if the mitigation of water scarcity is a priority.

## 1.8 Research framework

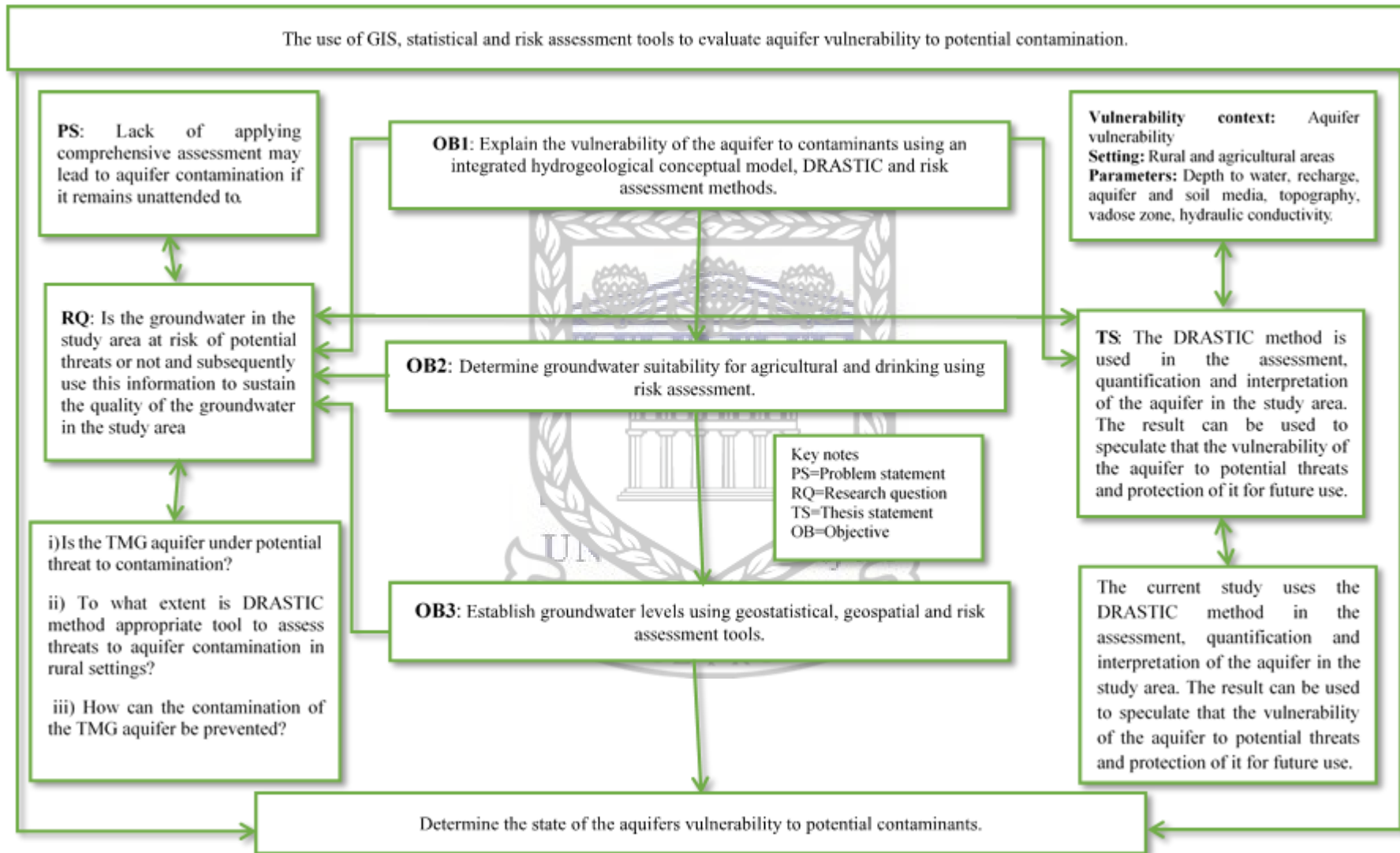


Figure 1: Research framework of the study

## 1.9 Outline of thesis

The current study aims to cover seven individual chapters. Chapter one introduces and gives the general introduction of the study providing additional background information and previous studies for the research and explaining the nature of the topic and rationale as well as the outline of the project. Theoretical and the conceptual framework is introduced in this chapter as well. Chapter two presents the literature on aquifer vulnerability and the framework to the proposed research topic in question. It also contains several writings on previous studies and previous thesis publications on the same study area as well as an in depth description on the DRASTIC method. Chapter three incorporates the research design and the methodology in which the study had been carried out, how the data had been obtained, where it had been obtained and how the data samples had been analysed. It includes the location of the site selection, where drilling of wells and boreholes have taken place on the study sites with descriptions of study populations and unit of analysis for each aim and objective. Additionally the chapter gives the geographic of the case study area where the location of the area of interest is illustrated. Chapter four provides the presentation and discussion of the results for the experiments conducted based on the procedures outlined for the first objective discussed in the first chapter. Chapters five and six entails the interpretation of the vulnerability map and involves the validation of the conceptual model. Chapter seven concludes the study providing a conclusion based on the findings of this study and suggests some recommendations on conducting further studies in aquifer vulnerability in the Heuningnes catchment

## **Chapter 2: Literature review**

### **2.1 Introduction**

Chapter 2 presents the work by previous scholars to show the existing gap in knowledge and practise regarding risk assessment of groundwater. The review has been presented as follows: Firstly to explain the vulnerability of the aquifer to contamination using integrated hydrological conceptual model, DRASTIC and risk assessment methods. Secondly to determine groundwater suitability for agricultural and drinking using risk assessment. Finally to establish groundwater levels using geostatistical, geospatial and risk assessment tools. Furthermore discussed are the evaluation of typical groundwater vulnerability issues and processes occurring in the vadose zone. This chapter is based on the importance of determining how the DRASTIC method and GIS systems are applied to assess groundwater vulnerability to potential contaminants. The literature reviewed has a significant contribution towards understanding and assessing groundwater vulnerability to pollution.

### **2.2 Conceptual and theoretical framework for aquifer vulnerability**

The concept of aquifer vulnerability assessment is not characterized by direct field measurements, as many other methods available. The vulnerability is founded on the fundamental concept, by Vrba & Zaporozec (1994) idea which states that “some land areas are more vulnerable to groundwater contamination than others”. Mapping the degree of aquifer vulnerability to potential contaminants illustrates the effective protection administered by the natural environment may vary considerably from one place to another. Vulnerability perceived areas can be categorized into naturally vulnerable areas, well protected zones and potentially problematic areas. Thus overlaying maps of the most vulnerable areas generates the map of potentially vulnerable areas i.e. vulnerability map.

Furthermore, the aquifer vulnerability concept entails two particular views: intrinsic and specific vulnerability. Intrinsic vulnerability of groundwater to contamination is understood as natural property of the hydro geological system, determining the risk of migration of impure substances from the surface of the territory to groundwater. Whereas specific vulnerability takes into account the type of polluting substance, its load, time of impact, as well as the spatial character of the focus of contamination connected with it. However, intrinsic vulnerability takes into account of the inherent geological, hydro- logical and hydrogeological characteristics of an area, but being independent of the nature of contaminants (Aller et al., 1987).

Overlay and index methods rely mainly on the quantitative compilation and interpretation of mapped data as the aquifer vulnerability is a relative, non-measurable, dimensionless property (Krishna et al., 2015). The main aspects used for the intrinsic vulnerability are depth to water, recharge, aquifer media, soil media, topography, vadose zone and hydraulic conductivity. These aspects aid in the environmental decision making processes. Nonetheless, vulnerability assessment is a meaningful management concept for guiding decisions on groundwater protection tasks at hand.

The theoretical framework on which the current study follows is the infiltration process. It is defined by which water on the ground surface enters the soil. Infiltration is administered by two main forces, gravity and capillary action. It is stated that smaller pores bid a greater resistance to gravity; very small pores pull water through capillary action in addition to and even against the force of gravity (Aller et al., 1987). Infiltration rate is the speed at which water enters the soil. It is usually measured in depth over time. The subsurface is a reservoir that stores water essential for many uses. If the infiltration rate is restricted, the water will not readily enter the subsurface as it will move downslope as run off where it eventually evaporates. Thus less water is stored in reservoirs.

The progression of infiltration has been broadly studied together by hydrologists as well as soil physicists. Specified by Horton (1933) when water reaches the ground surface, it infiltrates the soil surface at a rate that decreases with time. He also mentions that for any given soil there is a limiting curve that defines the maximum possible rates of infiltration versus time. This curve is known as the curve of infiltration capacity of the soil. The capacity decrease with time and consequently reaches an approximately constant rate. The reduction in the capacity is a result of the soil pores being filled by water. Past studies have revealed that the decline is more rapid and the final constant rate is lower for clay soils with fine pores than for open texture sandy soils (Cherry & Freeze, 1979).

The infiltration capacity is the maximum rate at which water can be absorbed by a given soil per unit area under given conditions (Abdullahi & Garba, 2015). The infiltration capacity is reliant on the observations at the ground surface. Multiple analysis of infiltration have considered a one dimensional approach. A one dimensional approach has the vertical flow system as an entry of inflow boundary at the top. Horton (1933), states that if the parameters of rainfall intensity, initial soil moisture content and a set of unsaturated characteristics curve are given, the initial curves of the infiltration versus time can theoretically be predicted.

Moreover, if the rainfall rates, infiltration rates and hydraulic conductivities are all expressed in units of L/T, the final constant infiltration rate in the Horton (1933) curves is numerically equivalent to the saturated hydraulic conductivity of the soil.

Subsequent to the soil becoming saturated at the surface, the infiltration rate will be equal to the rainfall rate. Thereafter, it decreases gradually toward a value equal to the saturated hydraulic conductivity of the soil. Amid the period as the soil pores are filling up with water, the moisture contents, pressure heads and hydraulic heads are increasing with time and the downward hydraulic gradient is decreasing. The outcome of this decrease is balanced by an increase in the hydraulic conductivity values under the influence of the rising pressure heads. Consequently the decrease in infiltration rate occurs at the point when the arrangement of gradients and conductivities in the soil can no longer accept all the water supplied by recharge. Following that the soils no longer accept rainfall, the water is then available for surface run off. With run off, the result is the rise of the water table. This rise in the water table provides the source of replenishment that allows the prevailing rate of recharge to continue (Cherry & Freeze, 1979).

When recharge intensity is less than the infiltration capacity, the entire water source reaching the ground can infiltrate. However, if the rainfall intensity surpasses infiltration capacity, infiltration will then only occur at the infiltration capacity rate. The water in excess of that capacity will be stored in depressions, become surface run off or eventually evaporate. The mechanism of infiltration and groundwater recharge are not always one dimensional. In regions with altering elevations, certain portions of groundwater recharge areas may not receive direct infiltration to the water table. Besides, recharge favours concentrations in depressions where temporary pools develop during high rainfall periods. Under these circumstances, the water table still rises. This is owed to the vertical infiltration beneath the points of recharge and subsequent horizontal flow toward the water table depression (Cherry & Freeze, 1979).

The significance of infiltration lies within the hydrological processes. Factors that affect this process include the soil type, degree of saturation as well as the land use of the specific region. Natural recharge of aquifers can be a slow process as groundwater moves slowly through the unsaturated zone. The rate of recharge is also an important consideration. However, an aquifer in a region of substantial rainfall renders enough recharge to replenish the aquifer almost immediately. The prevailing mechanism of potential contaminants transport to the unsaturated zone is by advection along wetting front edges during the infiltration process. Furthermore,



surface run off can cause erosion. These sediments consequently reduce the capacity of the reservoirs to store water, most studies appear to show that infiltration is the main mechanism for reducing potential contaminant loads. For its importance in the hydrological cycle as an interfacing process linking surface and subsurface waters (Weaver, 1998), infiltration is one of the most intensively investigated topics in hydrology and soil physics.

### **2.3 Application of the DRASTIC method**

Internationally the DRASTIC method was used in Aligarh, India by Rahman (2008). His findings disclose that the groundwater in Aligarh, India are that more than half are under moderate to high pollution vulnerability zones. This is a result of the topography of the region and its surrounding areas of Aligarh, India. His study suggests that the DRASTIC method can be used for prioritizing of vulnerable areas in order to prevent the further pollution to already more polluted areas. Furthermore, in America South-western Idaho, Dorsey-spitz (2015) implemented DRASTIC. She utilized a groundwater model to spatially delineate areas by vulnerability to groundwater contamination risk. Two Geographical Information System-based groundwater vulnerability models were used and the DRASTIC method was created using generic, available data and site-specific data. Neither set of model predictions seemed good enough to inspire confidence and it was clear that the results produced with the two model runs are not interchangeable. As a result of the small sample size it limited the opportunities to conduct statistical analysis to validate the model outcomes. Additional studies would need to be performed using the same approach, but with larger sample sizes so that it would not negatively affect the results (Dorsey-spitz, 2015).

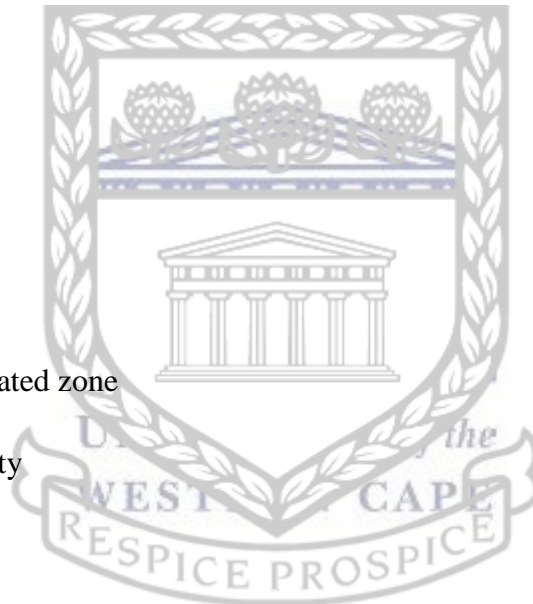
In Europe, Breaban & Paiu (2012) used DRASTIC to determinate the aquifer vulnerability and nitrate level present in the Barlad city of Romania. Additionally to determine the susceptible zone for groundwater pollution by integrating hydrogeological layers in GIS environments. The DRASTIC method had found that within the region of the Barlad city, the vulnerabilities had varied from being predominant with moderately high values. It had also stated that high concentration is present in high pollution areas as well as in moderate polluted areas.

DRASTIC has been used on a local scale in South Africa in the Pietermaritzburg region. It had been used to calculate the groundwater vulnerability of a region close to the city of Pietermaritzburg. The objective of DRASTIC in the Pietermaritzburg region was to generate a regional scale vulnerability map of the groundwater. The results of this method informed local decision makers and enabled proactive prevention of groundwater pollution, in accordance

with section 13 of the 1998 National Water Act (Demile & Zwiers, 2003). At present DRASTIC will be applied in the Western Cape region in Cape Agulhas to determine the state of groundwater to vulnerability in the Heuningnes catchment area. Heuningnes catchment, named as the catchment area of Cape Agulhas, contains several sub-catchments. They are labelled as follows: G50B, G50C, G50D, G50E, and G50F. This study will be concentrating on sub-catchment G50C (Clever & Brown, 2005).

The DRASTIC method has hydrogeological parameters to characterize or analyse aquifers. The parameters are listed as:

- (D) Depth to water table
- (R) Recharge rate
- (A) Aquifer media
- (S) Soil permeability
- (T) Topography
- (I) Impact of the unsaturated zone
- (C) Hydraulic conductivity



These parameters are used in the GIS techniques to produce vulnerability maps. The DRASTIC method is a valued tool for identifying groundwater supplies that are vulnerable to potential threats. It uses basic hydro-geologic variables believed to influence potential pollutants transported from the surface sources to groundwater. DRASTIC is an overlay and index method where upon each of the parameters of the DRASTIC method are combined using overlay operations in ArcGIS software. Overlaying these parameters involve combining spatial and attribute data from two or more spatial data layers and are among the most common and powerful spatial data operations. The overlaying of each parameter are accomplished using weighted sum, weighted overlay and raster calculator to produce a vulnerability map. DRASTIC has key assumptions that are defaulted with each parameter, in order to maintain the accuracy of the study. The assumptions are that:

- Contamination occurs at the land surface
- The contaminant must enter the water table when the rain falls on the land surface and percolates into the saturated zone
- The contaminant travels with water, at the same rate as one another
- DRASTIC will be applied to an area 100 acres or larger (Aller et al., 1987)
- The aquifer must be unconfined
- The dominant pollutants are not pesticide

An aquifer is rock formation which yields sufficient water quantities for use. An aquifer's primary porosity is described as the pores in the rock that is occupied by water whereas secondary porosity refers to the fractures in the rock that are occupied by water (Aller et al., 1987). Aquifer media is described as the characteristics of the aquifer and is vital in groundwater vulnerability assessments in addition to determining the flow of water. The aquifer media also determines the permeability and the porosity of the medium which the pollutant is in contact with the aquifer. These affect the route and path length the potential threats will follow. The path of groundwater flow is also affected by the fractures in the aquifer. The more fractures present in the rock formation, the greater the aquifer's susceptibility to pollution (Hasiniaina et al., 2010).

On a basis, the aquifer must be protected and this protection is essential for sustainability. The vulnerability of an aquifer is defined as the sensitivity of groundwater quality to an imposed contaminant load, which is determined by the natural characteristics of the aquifer. Aquifer vulnerability solely indicates whether the physical and biochemical characteristics of the subsurface prevent or favour the transport of pollutants into it. The vulnerability is the sensitivity of an aquifer to potential threats and the capacity of it becoming polluted over time. The vulnerability of an aquifer is to a large extent controlled by factors such as: the permeability of the unsaturated zone, the depth to the water table, the groundwater recharge rate, the topography of the area, the dominant soil types, underlying geology. The vulnerability of a groundwater body can be assessed by physical measurements and groundwater modelling. An aquifer can be classified into a well-protected aquifer if the percolation time through the unsaturated zone covering layers exceed 10 years.

The manner of aquifer vulnerability to contaminants from external pollution was first introduced in the late 1960's in France by Albinet & Margat, (1975). These authors had the original concept of aquifer vulnerability and were developed by them. Several other methods of aquifer vulnerability assessment followed consecutively in the following years by Aller et al., (1987), Arpa et al., (2001) and Vrba & Zaporozec, (1994). It was then that the term aquifer pollution to vulnerability surfaced for the integration capacity of the area to the pollution from external sources (Buyukdemirci, 2012). The concept is derived from the notion that the physical environment may offer some sort of preservation of groundwater against anthropological occurrences, with due note taken to potential pollutants entering the subsurface zone (Ersoy & Gültekin, 2013).

Furthermore, some land regions in a study area are more prone to groundwater contamination than others, thus an aquifer vulnerability map portrays areas of vulnerability classifying direct areas into several levels of vulnerability. The levels of vulnerability are important to understand. Foster et al., (2004) defines areas that are more vulnerable to potential pollution than others on the basis of hydrogeological and anthropogenic factors.

Aquifer vulnerability is determined according to the nature of the overlying soil cover. According to the Department of Water Affairs, vulnerability of aquifers in the study area are significantly high, as it is vulnerable to many pollutants except those strongly absorbed or readily transformed in many pollution scenarios. There is a clear distinction between aquifer vulnerability and pollution risk. Pollution risk depends on both the aquifer vulnerability and the existence of significant pollutants.

The important matter of the fact is the selection of the methods to estimate aquifer vulnerability. There are several methods that can be broadly classified into three approaches. These methods are:

- Process-based simulation methods
- Statistical methods
- Overlay and index methods

Process-based methods attempt to predict contaminant transport in both space and time. These methods require analytical or numerical solutions to mathematical equations that represent coupled processes governing contaminant transport. Although process-based methods are more sophisticated than the overlay and index methods, the results are not necessarily more accurate.

Statistical methods for assessing groundwater vulnerability relate the occurrence of constituents in ground water to explanatory variables. These variables describe either potential sources of these constituents or the relative ease with which it may migrate to the position in the flow system where the ground water sample is taken. Several statistical methods have been used to relate water quality data to explanatory variables, including logistic regression (Tesoriero et al., 1998).

Overlay and index methods combine maps of subsurface attributes such as depth to the water table, groundwater recharge rate as well as soil and aquifer material properties. Each attribute is weighted using expert opinion of the relative importance of that attribute to groundwater vulnerability in that area. Study areas for overlay and index methods are typically large in scale. Although these methods are simple and use readily available data, they rely heavily on qualitative judgment for both the parameters chosen and their relative weights.

Aquifer vulnerability determination is an important tool to protect groundwater resources. The vulnerability of an aquifer to pollution is directly related to the hydraulic characteristics of the aquifer overburden and to a significant degree by the characteristics of contamination. The vulnerability of groundwater to pollution depends on the travel time of infiltrating water, the relative quality of the contaminants that can reach groundwater and the contaminants attenuation capacity of the soil materials through which the water and contaminants travel. In addition the vulnerability of an aquifer to pollution is determined by the extent of the interactions between soil or aquifer characteristics and the pollutants.

The principles for vulnerability assessment include intrinsic vulnerability of a site. Contaminant attenuation characteristics are essential in aquifer vulnerability assessment studies. Aquifer vulnerability to pollution is directly linked to the hydraulic characteristics of the aquifer overburden and to a large extent determined by the characteristics of contamination depletion. Vulnerability may or may not include an assessment of whether pollutants are present or absent in the region of interest. Vulnerability that is independent of whether or not contaminants are present and which focuses primarily on a description of natural environmental conditions is often referred to as intrinsic vulnerability.

Coastal aquifers embody the subsurface transition between terrestrial and marine systems, and form the almost invisible pathway for tremendous volumes of freshwater that flow to the ocean. Changing conditions of the earth's landscapes and oceans can disrupt the fragile natural equilibrium between fresh and saltwater that exists in coastal zones. Among these, over-abstraction of groundwater is considered the leading man-made cause of seawater intrusion. Moreover, many of the world's largest urban settings, where sources of contamination are profuse, have been built over the freshwater in coastal aquifers. Thus, coastal aquifers are important receptors of human impacts to water on Earth.

Levanon et al. (2017) measured the fluctuation of salinity and groundwater level in a coastal aquifer in Israel. They find that the time lag of groundwater salinity with respect to the tide in the open sea is on the same order as the time lag of the water table, but much larger than of the hydraulic head at the same depth. They link the change in salinity to the displacement of water in the capillary fringe, which causes a vertical shift of the water column in the saturated zone.

A significant number of the submissions present new field data that show how coastal aquifers respond to forcing's, such as recharge events and tides. Such studies are invaluable, because while our understanding of the groundwater processes has advanced considerably, the interplay of multiple processes operating at the same time under the influence of natural heterogeneity remains challenging to unravel. Yet, scientific understanding of aquifer systems at the field scale and forecasting changes at a decadal timescale is what is required to support water management. And this is perhaps where some of the most significant future challenges lie.

## **2.4 DRASTIC parameters for aquifer vulnerability**

As mentioned in the previous chapter, the study scale of this study is assessing aquifer vulnerability to potential contamination. In this thesis assessing aquifer vulnerability was carried out using the DRASTIC method and GIS techniques combined with hydrogeological data layer i.e. depth of water, net recharge, aquifer media, soil media, topography, impact of vadose zone and hydraulic conductivity. It is these parameters that are most relevant with regards to factors that control groundwater pollution potential. The several DRASTIC parameters concluding output is a vulnerability map, illustrating low to high vulnerability areas of the catchment. Additionally, this research attempted to demonstrate the effective method for groundwater pollution risk assessment and water resource management.

As it is stated, DRASTIC has seven parameters; there are three significant parts 1) Weight 2) Ranges 3) Ratings. Each parameter feature is classed into ranges or significant media types that have an adverse impact on pollution potential. Weight multipliers are then used for each factor to balance and enhance their importance. Each parameter feature has a weight relative to each other in order of importance from 1 to 5, with the least significant being 1 and the most significant being 5. Each feature has been subdivided into ranges or media types based on its impact on pollution potential. The ranges then receive a rating from 1 – 10, with 10 having the highest pollution potential. Ratings are typically between 1 – 10 and is the assigned value providing a relative assessment between ranges in the feature (Ersoy & Gültekin, 2013).

When individual DRASTIC parameters are assigned weights it is evaluated with respect to each parameter to determine the relative importance of each factor. The higher the weighting numbers the more significant the factor (Al-abadi et al., 2014). Each DRASTIC factor is assigned a range or significant media type's dependant on the impact on pollution potential. These ranges were depicted in (Aller et al., 1987). Every range for the individual DRASTIC parameters is assessed with regards to each other for the determination of the relative significance of each range to the impact in potential pollution (Aller et al., 1987). Following the three significant variables, the DRASTIC Vulnerability Index (DVI) is derived or calculated from it. The DVI is a weighted sum of the seven parameters and is calculated using the following equation:

$$DVI = Dr * Dw + Rr * Rw + Ar * Aw + Sr * Sw + Tr * Tw + Ir * Iw + Cr * Cw$$

Where “r” is the rating for each parameter and “w” is the weighting factor for each parameter respectively. The DVI is a representation of the extent of the aquifer vulnerability in a specific region and can be used with GIS to produce the Aquifer vulnerability map, see Figure 2. (Dorsey-spitz, 2015).

Hydrogeological factors help to evaluate the relative groundwater pollution potential of any hydrogeological setting. Hydrogeological setting is a composite description of all the geological and hydrological factors controlling groundwater flow into, through, and out of an area (Kim and Hamm 1999). Depth to water, net recharge, aquifer media, soil media, topography, impact of the vadose zone and hydraulic conductivity are the hydrogeological factors that constitute the DRASTIC method. Additional parameters is possible to add to the DRASTIC method to modify it to make it more suitable for specific regions. In this study, the

standardized DRASTIC method is used to determine the aquifer vulnerability of the Heuningnes catchment.

## **2.5 Data for DRASTIC parameters**

Hamza et al., (2015) carried out a GIS-based DRASTIC method impact on groundwater vulnerability assessment and its subjectivity in a view to finding a common stand for standardization. It is revealed that all the DRASTIC parameters are equally significant irrespective of their assigned weights. It was established that 46 % of 977 million km<sup>2</sup> of land assessed globally fell within moderate to high vulnerability category. The significant proportion of land area cover around the world is vulnerable; hence, mapping groundwater vulnerability is inevitable for a sustainable land-use planning

Gupta, (2014) in her study assessed the groundwater vulnerability using as overlay index method, DRASTIC, which is used to prepare a vulnerability map using GIS, of the study area, Jabalpur District, India. It was deduced that approximately 15%, 76% and 9% of the area lies in low, medium and high vulnerability zones. Further the study of population growth water demand by various sectors are also assessed to find the overall vulnerability in terms of groundwater development which shows that if the current trend of growth in population industrial and agricultural sector continues, soon the district will fall into exploited zone. The main data used was groundwater exploration data, CGWB report, population data, hydro-meteorological data, Aster DEM, with resolution 30 m. The method used to assess the groundwater vulnerability is DRASTIC method which is proposed by Aller et al (1987) can be applied on the regional scale and intrinsic vulnerability of the aquifer under study can easily be obtained.

Sener et al., (2009) utilized Aquifer vulnerability has been assessed in the Senirkent-Uluborlu Basin within the Egirdir Lake catchment (Turkey) using the DRASTIC method, based on a geographic information system (GIS). There is widespread agriculture in the basin, and fertilizer (nitrate) and pesticide applications have caused groundwater contamination as a result of leaching. It is concluded that 20.8% of the basin area is highly vulnerable and urgent pollution preventions measures should be taken for every kind of relevant activity within the whole basin.

Vulnerability analysis, data obtained from hydrogeological field investigations should be used for weighting of DRASTIC parameters. Data layers were digitized and were converted to raster



data sets using ArcGIS. Then, the DVI was computed and the vulnerability map of the basin was prepared taken into consideration hydrogeological field observations and investigations.

Victorine et al., (2015) conducted their study in the aquiferous formations in Douala by evaluating the aquifer vulnerability. It was evaluated using the DRASTIC method. ArcGIS quantile classification subdivided the area into four groups; very low, low, moderate and high ground water vulnerability risk zones covering about 30%, 30%, 20% and 20% of the study area respectively. This region that reflects high category is more vulnerable to pollution and consequently, needs to be managed more efficiently.

The water levels of 94 wells with at least five wells per location were measured. The primary sources of recharge in Douala are runoff from the draining Wouri/Dibamba Rivers and precipitation which infiltrates through the ground surface to the water table. The Aquifer media was obtained using field mapping (borehole cuttings sampling), the geologic map of Douala and the available geologic logs from borehole data. The soil media were obtained using sieve analysis. The surface elevation map was plotted using a 90m resolution Digital Elevation Map (DEM) of the area using ArcGIS. Impact of vadose zone was prepared from subsurface lithostratigraphic map from borehole drilling profiles of Douala. The value of hydraulic conductivity is controlled by the properties of the aquifer and determines the rate of groundwater.

Demile & Zwiers, (2003) compiled a regional scale vulnerability map of the ground-water in Pietermaritzburg, South Africa. The intrinsic vulnerability of the Pietermaritzburg region was found to range from low to very high. The area found to be highly vulnerable is the region northeast of Springbank which requires investigation at a local scale. The output DRASTIC map has the ability to easily communicate information pertaining to groundwater vulnerability of the region, to the required end users. This is of critical importance if chapters 3 and 4 of the National Water Act are to be fully realized.

Figure 2 illustrates the DRASTIC vulnerability index which range from extremely low to extremely high. The input parameters, in the form of GIS layers are overlaid to generate the final vulnerability map. The vulnerability map is used to illustrate the extent of vulnerability across the study area.

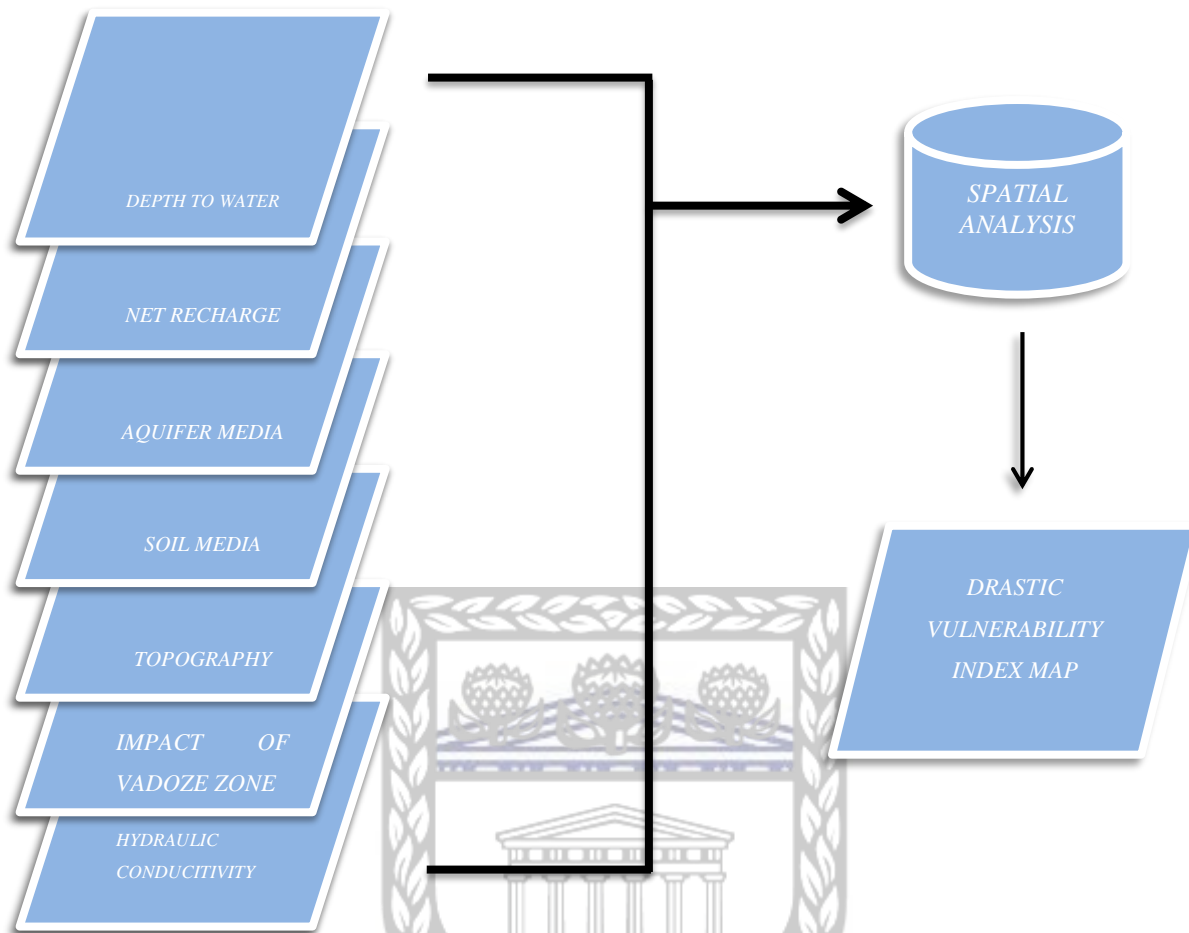


Figure 2: DRASTIC vulnerability index (DVI) map flowchart

## 2.6 Hydrogeological model for aquifer vulnerability

### 2.6.1 Application of the integrated hydrogeological conceptual model

The hydrogeological conceptual model was developed to develop an enhanced understanding of the groundwater system in the Heuningnes catchment. The model is based on depth to water, recharge, geology and hydraulic conductivity. The groundwater of the TMG aquifer in Cape Agulhas is said to be the purist form of groundwater in the entire aquifer. The model development begins with the geologic field observations such as bore logs, geophysics and geologic maps. Thereafter, hydrogeological field observations such as groundwater hydrographs, pumping tests and groundwater physicochemistry take place. There upon the geologic and hydrogeological framework is created to develop the full hydrogeological conceptual model.

The data required includes that of several well points in the area, water levels and water quality for the development of the conceptual model. This affects the time available for a potential threat to undergo chemical and biological reactions such as dispersion. A low depth to water parameter will lead to a higher vulnerability rating. Depth to water can be estimated based on well log data. Depth to water is used to delineate the depth to the top of a confined aquifer. The shallower the water depth the more vulnerable the groundwater is to pollution. The depth to water table is measured by subtracting the value of the water table from the surface elevation of the well. Depth to water is an important source because it determines the depth of the material through which a contaminant travels before reaching the aquifer (Aller et al., 1987). It is defined as the distance from the ground surface to the water table. With regards to the depth to water, the water table generally follows the topography, where in certain regions there is an influence from the river systems (Rasmussen et al., 1998).

The amount of water which enters the aquifer is the net recharge. This value can be calculated on an annual or monthly basis with data available. It can be said that recharge is also the largest pathway for contaminant transport. Therefore, the amount of recharge is positively correlated with the vulnerability rating. The net recharge can be calculated using climate data by applying a mass balance on the water. Hence net recharge = precipitation, evaporation and run off. The recharge water therefore is a significant vehicle for percolating and transporting contaminants within the vadose zone to the saturated zone.

The net recharge is the total quantity of water which infiltrates from the ground surface to the aquifer on an annual basis. Net recharge includes the average annual amount of infiltration and does not take into consideration the distribution, intensity and not duration of these events. Rainfall data is needed for this parameter (Krishna et al., 2015). Also the water level on the wetlands on the large coastal plain has an elevation of less than 10mamsl until it reaches De Mond. The gradient too is extremely flat which suggests slow movement of groundwater with maximum recharge rates (Rasmussen et al., 1998).

A high permeability allows more water and therefore more contaminants to enter the aquifer. Therefore a high permeability will yield a high vulnerability rating. Aquifer media refers to aquifer material. Aquifer media can be obtained using field mapping such as borehole cuttings and sampling. The contaminant attenuation is dependent on the amount and sorting of fine grains. In general the perspective of the larger grain size the more fractures or openings within the aquifer, the higher the permeability and the lower attenuation capacity, consequently the

greater the pollution potential (Victorine Akenji et al., 2015). Aquifer media refers to the consolidated/unconsolidated rock which serves as an aquifer.

Soil media affects the transport of the potential threat and water from the soil surface to the aquifer. The soil media can affect the types of reactions which can take place. Additionally, different soils will provide better habitats for micro-organisms which can potentially biodegrade the contaminant. The soil media is referred to as the uppermost portion of the vadose zone, characterized by significant biological activity. Soil happens to play a major role in the amount of recharge which can infiltrate into the ground and hence on a potential threat to move vertically into the vadose zone (Gupta, 2014). Soils pollution potential is largely affected by the type of clay present, such clays shrink or swell potential as well as soil grain size. Water abstracted is of good quality as Napier straddles the contact between the Bokkeveld Group shale and the quartzite of the TMG that essentially form the Soetmuisberg range to the North of the study area.

Topography of the land affects groundwater vulnerability because the slope of the land is an important factor in determining whether the contaminant released will become run-off or infiltrate the aquifer. With a low slope, the contaminant is more likely to infiltrate the aquifer. So digital elevation data may be used to calculate and project the slope using GIS. The slope degree will determine the extent of pollutant run-off and settling long enough to infiltrate. The topography refers here to the slope variability of the land surface. The degree of slope will determine the extent of runoff of the pollutant and settling long enough to infiltrate slope grades one needed (Buyukdemirci, 2012). The study area constitutes the southernmost extension of the Overberg known as the Strandveld. In this region the only noteworthy topographical features are the Soetanyberge in the west of the area which rise 249m above masml and the Sandberg west of Struisbaai that reaches a maximum altitude of 156 mamsl (Rasmussen et al., 1998).

Fractures, bedding planes and inter-granular voids in the aquifer relates to the Hydraulic conductivity. These components become the pathways for fluid movement and hence a pathway for contaminant movement once a contaminant enters the aquifer. The hydraulic conductivity will then be positively correlated with the vulnerability rating. The hydraulic conductivity is of importance as it controls the rate of groundwater movement in the saturated zone, thereby controlling the degree and fate of contaminants. Hydraulic conductivity is data derived from pumping tests or bailer tests. The hydraulic conductivity is of importance as it

controls the rate of groundwater movement in the saturated zone, thereby controlling the degree and fate of the contaminants (Domenico & Schwartz, 1990). A bailer test determined the Hydraulic conductivity of the study area.

Heuningnes has two major tributaries, that of the Karsriver and Nuwejaarsriver. These major tributaries flow into the Soetendalsvlei. The length of the river from the mouth of the Heuningnes to the confluence of the Karsriver and from Soetendalsvlei is 15km. The Kars river rises via many tributaries in the north facing slope of the Bredasdorpberge. In the lower reaches of the Nuwejaars the topography is very flat and low lying and several pans and vleis drain into the river. Further downstream the Nuwejaars flows into Soetendalsvlei. It is clear that the major aquifer is present below or within the layer of young sediments which constitute the Strandveld (Rasmussen et al., 1998).

## **2.7 Groundwater validation for aquifer vulnerability**

### **2.7.1 Groundwater suitability for agricultural and drinking using risk assessment**

The main purpose of this objective is to determine groundwater suitability for agricultural and drinking using risk assessment by comparing it to several international drinking water standards. The data required for this step will come from the data that had been collected and analysed accordingly from the DRASTIC method. The research question that needs to be answered here is if the aquifer in the study area under potential threat to contaminants? If it is, what are the solutions to contain the threatened aquifer and what are the causes of the aquifer becoming under threat? The results and/or findings of this study will be measured to look at how the groundwater can be sustained for future use. Furthermore to uplift the standards of potable water if deemed necessary.

A comparison of water quality to international guidelines is a means way of determining the quality of the groundwater in the catchment. Whether it is for potable or agricultural purposes. The Department of Water Affairs and Forestry (DWAF, 1996a); (DWAF, 1996b) is South Africa's water quality standards and guidelines. The procedure of deriving quality and appropriate management guidelines for freshwater is lacking in South Africa (DWAF, 1996b). DWAF, (1996a) is aimed to develop protocols and derive a set of water quality criteria for the conservation of freshwater ecosystems in South Africa. These water quality standards have been developed in conjunction with a large number of water quality specialists, stimulated and

improved the understanding of criteria development among aquatic scientists and resource managers. Therefore this process founds the baseline for the development of water quality guidelines contained in (DWAF, 1996a) and (DWAF, 1996b) for potable and agricultural use,.

The second water guidelines used for comparison is World Health Organization. The sole purpose of the Guidelines for Drinking-water Quality is the protection of public health. Potable water does not represent any significant risk to health over a lifetime of use, including that of various sensitivities that may occur. WHO, (2006) guidelines are applicable to water intended for human consumption. Although, certain uses of water require high quality standards such as pharmaceutical purposes. For the current study, WHO,(2006) will be used for human water quality consumption.

The WHO, (2006) guidelines are intended to support the development and implementation of risk management strategies that will ensure the safety of drinking-water supplies through the control of hazardous constituents of water. These guidelines describe reasonable minimum requirements of safe practice to protect the health of consumers and/or derive numerical “guideline values” for constituents of water or indicators of water quality. In order to define mandatory limits, it is preferable to consider the guidelines in the context of local or national environmental, social, economic and cultural conditions. The approach followed in these Guidelines is intended to lead to national standards and regulations that can be readily implemented and enforced and are protective of public health.

## **2.8 Aquifer Risk assessment review**

### **2.8.1 Groundwater levels using geostatistical, geospatial and risk assessment tools**

The purpose of the second objective is to establish groundwater levels using geostatistical, geospatial and risk assessment tools. This objective is carried out in order to determine if the aquifer in the study area is under potential threat or not by means of a vulnerability map derived from DRASTIC. Furthermore, to sustain the quality of the groundwater the aquifer holds. This is started off by the geospatial analysis with the data set collected in the field. The data that is required for this step are all the data types collected for each parameter of the DRASTIC method. The research question that needs to be answered in this objective states that, spatially analysing the data to provide a vulnerability map in order to view how vulnerable the

groundwater is in the study area. The data analyses and model implementation were performed using statistical and ArcGIS software.

Aquifer vulnerability maps have become a standard tool for protection of groundwater sources from potential threats. These maps are invaluable step for taking an attention of risk of groundwater getting polluted in some areas. The development of vulnerability maps is beneficial in many parts of water management, concentrating on prioritizing areas for monitoring. The maps are an effective tool in helping authorities understands the potential pollution activities in future. Vulnerability maps created within DRASTIC contain information on the physical aspects of the study area used for analysis.

The generation of the vulnerability maps derive itself from GIS analysis. GIS techniques have been widely used in aquifer vulnerability mapping. The major advantage of GIS based mapping is the combination of data layers and rapid change in the data parameters used in the vulnerability classification. The maps using aquifer vulnerability assessment with DRASTIC method were prepared using hydrogeological data based on ArcGIS software. Therefore to assess groundwater vulnerability to potential threats, several attribute layers were assembled as intermediate steps. Attribute layers include hydrogeological setting, hydraulic conductivity of soil and depth to water table readings. Data from these attribute layers were used to produce the vulnerability map using ArcGIS. GIS allows spatial data gathering at the same time gives a means for data processing such as Geo-referencing, integration or spatial analysis. ArcGIS appears to be the major GIS software usage in the journals and research in this field.

There are many ways of defining geospatial analysis, but all in one way or another express the fundamental idea that information on locations are essential. The geospatial analysing system incorporates the use of multi-criteria mechanisms in GIS for the suitability evaluation of urban expansion land. A geospatial analysis technique was used to analyse several factors, including flow, scale, terrain, population, urban form and land use that play a dominant role in potential natural hazard occurrences. The overlay operation in GIS is mostly used in this research for potential natural hazards area maps. A framework integrated with the land use plan and spatial analysis techniques provides a possible way for knowledge acquisition from GIS database to support urban planners in decision-making processes (Strassberg, 2004).

## **Chapter 3: Research design and methodology**

### **3.1 Introduction**

Chapter 1 introduced and discussed this thesis' statement and constitutes the research question as well as stipulates the main aim coupled with the detailed objectives identified to give answer to the research question posed. Chapter 2 then highlights the literature review on aquifer vulnerability and the various methodological approaches to assessing its risk to potential contaminants. Additionally, it describes various other risk assessment methods to assess the vulnerability and the significance of DRASTIC compared to the several described methods.

This chapter describes the measurement of the unsaturated zone at the Heuningnes catchment of Cape Agulhas in the Western Cape. It includes site selection, drilling, drilling methods, measuring equipment as well as methods for determining hydraulic properties and methods for constructing the conceptual model. The conceptual model provides detailed information on sub surface properties in the study area and hydraulic conductivity relationships. The data for this particular study is collected and analysed during the course of one year with a combination of field work as well as desktop work had been applied to this research. The data were collected from boreholes and well points located across the Heuningnes catchment area of the Cape Agulhas region.

### **3.2 Description of study area and sampling sites**

The lower Water Resource Commission (WRC) catchment, G50C, is a relatively uniform terrain, sub-catchment of the WRC catchments in the Western Cape of South Africa (Figure 8). Geographically, the study area is located in the region of S 34.67164° and E 19.87789° (WGS1984). The G50C sub-catchment size is approximately 421 km<sup>2</sup>, with the average elevation mainly sea level. However the entire catchment has its higher elevations in the north towards the small town of Napier. The lower laying elevations directed toward the southerly region bordering the towns of Suiderstrand, Cape Agulhas and Struisbaai at sea level. Figure 8 demonstrates the sub-catchment boundaries (G50C) comprising of the Soetmuisberg mountains in the north and the south bordered by the coastal regions of the most southern tip of Africa. The groundwater flow in the study area is in response to gravitational forces, where the groundwater flow gradient is towards the tributaries and discharges into the river (Rasmussen et al., 1998). The data samples are collected across the study area to get a broad



overview of the study area which is followed by analyses of the data in order to better understand the state of the study area and compare it to its natural state.

Groundwater relief transpires during the winter months in the Western Cape, when the most rainfall occurs. The high rise of precipitation leads to the elevation of the water table and it is at this time that the groundwaters levels are in certain regions exceed the land surface. The mountainous area of the Bredasdorp mountain range, has elevations reaching approximately 645m and stretching east to west below Elim (Norman et al., 1999). These mountainous areas are natural groundwater recharge sites with direct infiltration of rainfall being another component of recharge. In the study area the discharge occurs proportionally as the northerly mountain range drops away to the undulating lowlands in the Nuwejaars River which then flows to the valley where it opens to the east of the Zoetendalsvlei as the ground flattens to a plain.

The WRC catchment is characterized by a Mediterranean climate, with hot dry summers from November to April and cool wet winters from May to October. The temperatures tend to be cooler near the coast as a result of the cooler ocean currents flowing on the southern coast off the shores of South Africa. High rainfall periods occur between the months of May through to October. During this period few clear days pass with mostly overcast and rain predicted weather.

The average rainfall along the coast is less on the east coast than west coast as the rainfall is 445mm and 540mm respectively (Toens, 1991). However, toward the northern boundary of Cape Agulhas in the region of the lower mountain range the rainfall is higher than both the east and west coast at 650mm average annually. This is indicative of groundwater recharge to be in high lying areas with least evaporation of water being lost. High temperature periods occur between the months of November through to April. In the course of these warmer periods the summer temperatures exceeds an average of 26 °C in January. As a result the potential evaporation surpasses rainfall. Cape Agulhas is a relatively windy area year-round with the prevailing winds being dominantly westerly in winter and southwest, southeast in summer.

The catchment has two major tributaries the Nuwejaars and Kars river, both rivers flows into one of the six main permanent lacustrine wetlands; Soetendalsvlei. In the Heuningnes catchment the Nuwejaars River originates north of Elim and flows into Soetendalsvlei (Norman et al., 1999). The Kars River rises via tributaries in the north facing slopes of the Bredasdorp Mountains where it also forms a flood plain northeast of Soetendalsvlei, thereafter flows into

the Heuningnes River. The drainage forms and estuary as they drain directly into the sea. Soetendalsvlei surface area is approximately 20 km<sup>2</sup> with the average water depth reaching around 8m deep. Soetendalsvlei is moderately saline with electrical resistivity's reaching between 300 and 700 mS/m, whereas the groundwater that enters Soetendalsvlei has an average electrical resistivity of between 400 and 1000 mS/m. Voelvlei is another permanent lacustrine wetland in the catchment and is situated towards the west of Soetendalsvlei along the Elim/Struisbaai gravel road. It is characterised by its unique hydrology as the Nuwejaars river feeds this vlei and onwards to Soetendalsvlei.

Water entering the wetland are predominantly alkaline and brackish as a result of its passage through limestone bearing Strandveld sands and Bokkeveld shale's affecting the water increasing its pH as well as Total Dissolved solids (TDS). Waters in the upper Bredasdorp mountain range tend to have low pH of 4.5 to 5.0 in comparison to the flood plain of 7.0 in the Heuningnes River.

The base geology of the area consists of a complex succession of fracture and folded rocks ranging from the Malmesbury group to the Bokkeveld group. In previous millions of years ago, the southernmost part of the African continent was subjected to extreme forces of structural integrity, responsible for complex faulted and folded features of the Cape fold belt (Toens, 1991). The Table Mountain Group (TMG) outcrops extensively as a narrow strip along the coast from Struisbaai. This Table Mountain Group (TMG) forms part of the Soetnysberge as well as the higher ground to the North. Its composition consists predominantly of shale, groundwater in this group is usually saline and of a poor quality unfit for human consumption. The Bokkeveld group is the only member of the Karoo Super group present in the area (Toens, 1991). It consists majorly of shale with groundwater bearing through this group having an exceptionally poor quality with electrical conductivities ranging between 500 and 1000 ms/m.

The Malmesbury group is only situated mainly in the western parts of the study area. This group consist mainly of shales. Groundwater in this group is usually saline and of poor quality (Rasmussen et al., 1998). Inland of the mountains are the undulating plains, comprising largely of the Bokkeveld shale and Cape fold belt. The age of the rocks is characterized by the Palaeozoic era. It falls under the Cape system, within the Bokkeveld group. The rock types are classified into quartzite, shale, sandstone and also limestone.

The coastal plain of the Cape Agulhas has remnants of an ancient wave cut platform. The coastal plain is covered primarily by calcareous sands of tertiary age. The surrounding coastal mountains are the Cape fold belt sandstone, capped by sections of limestone. The more inland mountains are the undulating plains comprised mainly of the Bokkeveld shale's, which together with Cape fold belt sandstones are part of the Cape Super group system. The soils derived from these rocks are acidic and highly infertile. The vegetation covering the surface of the Cape Agulhas region is mainly fynbos and contains calcareous sands of the tertiary age (Toens, 1991).

The sites that have been selected for groundwater monitoring include aspects of groundwater physicochemistry, pump tests and bailer tests as well as weather station locations. Figure 3 portrays the boreholes, piezometers and weather stations in the catchment. The catchments boreholes and well points strategically placed, where all 3 boreholes are located West and East of the Soetendalsvlei. There are 7 well points located around the perimeter of Soetendalsvlei and 6 well points are located around Voelvlei. At SanParks, Elim, 2 well points are located there. Along the Nuwejaar strip between Wiesdriff and Elandsdrift are 8 well points. These piezometers and boreholes are used for investigation of the quality of the water in the catchment with in situ techniques.

Figure 4 illustrates the locations of each of the weather stations used for the determination of the rainfall averages across the catchment over the period of study. It is known that the catchment is well known for its agricultural activities the water quality will be compared and analysed according to the standard of it being potable for agricultural use as well as human consumption. The entire catchment site is on the property of private ownership, where in Figure 3 also illustrates the locations of each piezometer and borehole are shown accordingly. Agriculture being the dominant land uses in the catchment as previously mentioned the main land use will affect the groundwater accordingly.

### G50C well point sampling sites

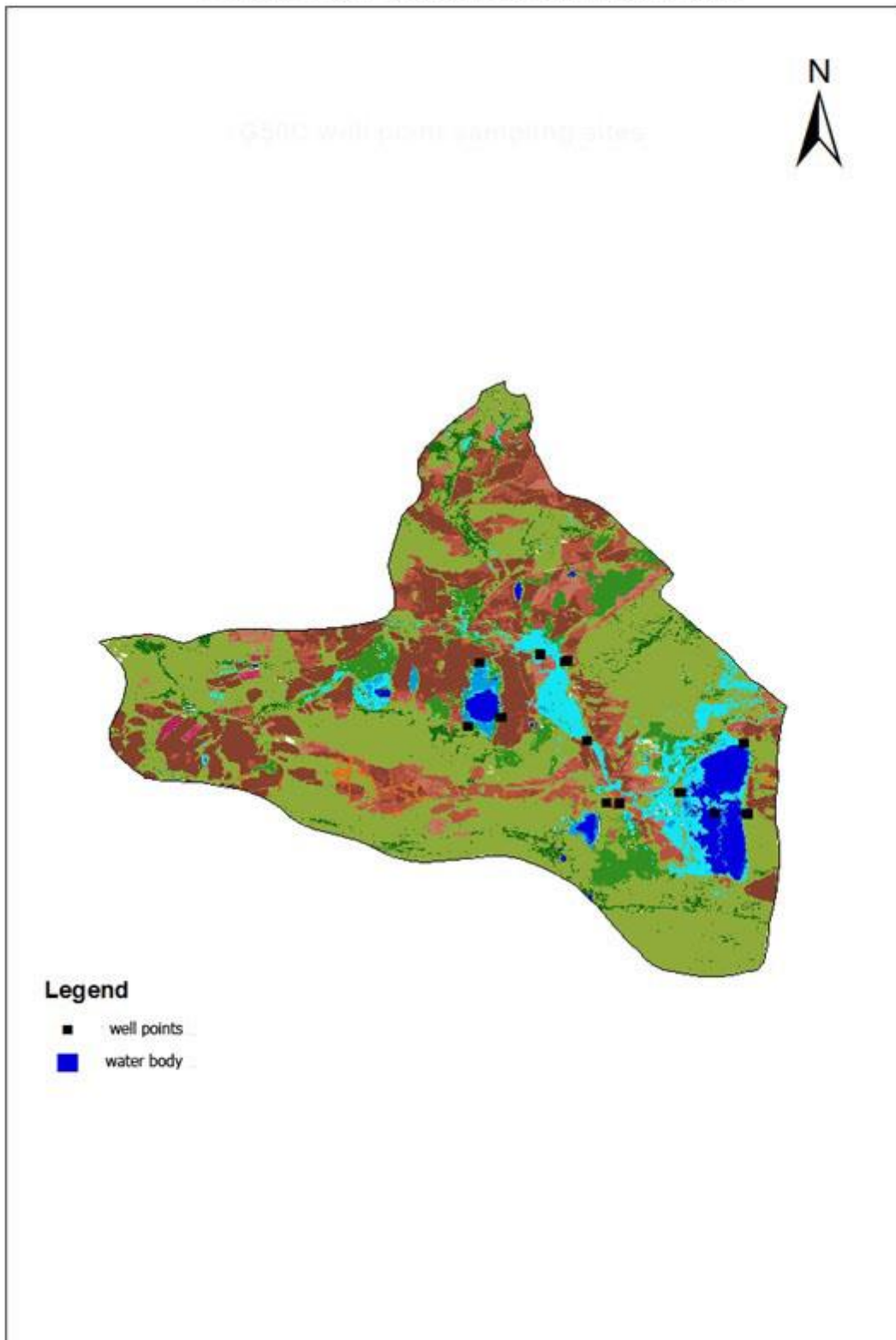


Figure 3: Illustrating the borehole and piezometer locations in the catchment

## G50B and G50C weather station locations

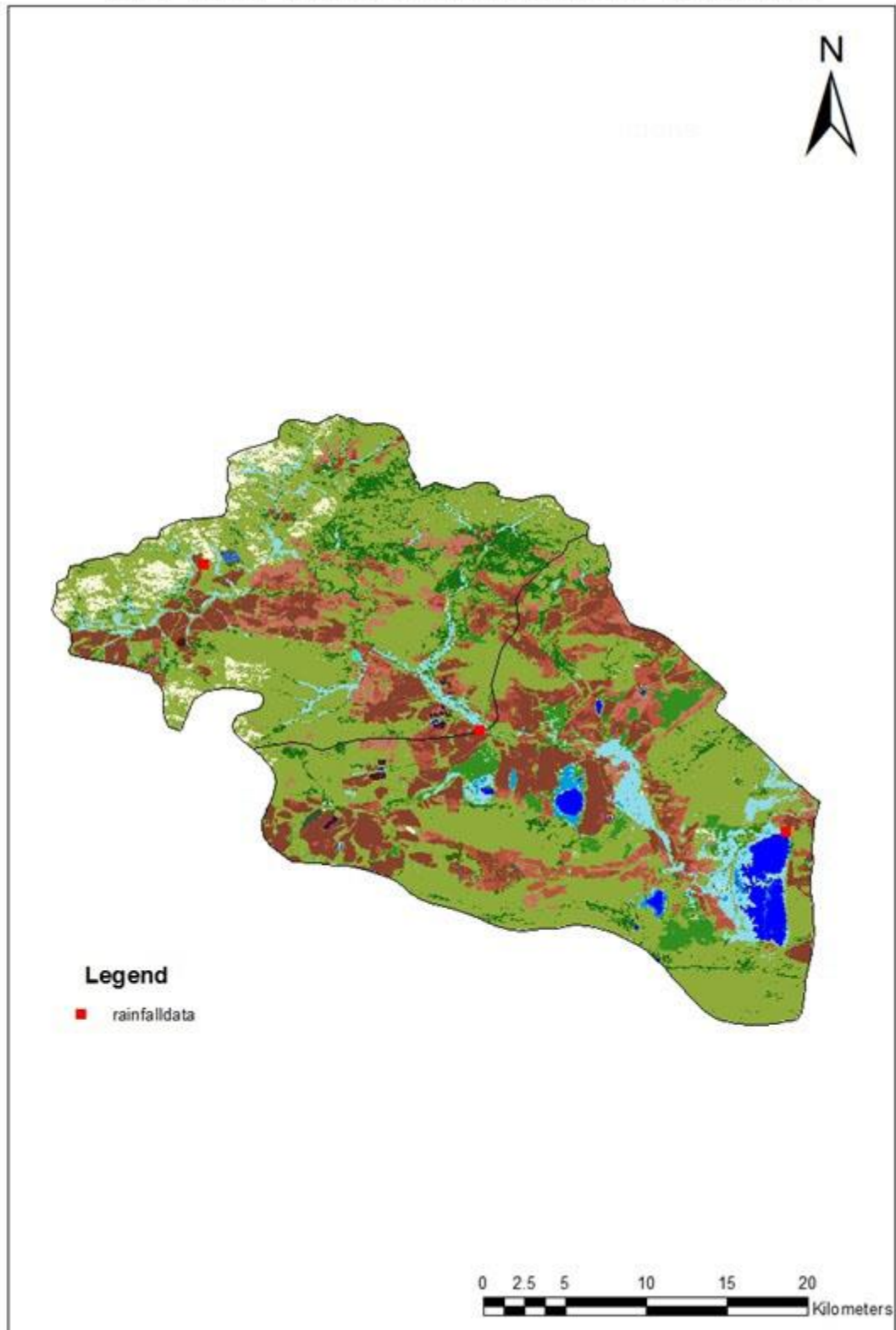


Figure 4: Displaying the locations of weather stations in the catchment G50B and G50C

### **3.3 Research design description**

The investigation of groundwater risk assessment involves measurement of in situ groundwater physicochemistry, pumping and bailer tests for determining hydraulic conductivity, groundwater depth to water between wet and dry seasons as well as rainfall data across seasons. These data parameters were acquired using in situ techniques, which involved continuous measurement of depth to water, in situ water chemistry upon fieldwork excursions.

Sampling needs to be taken with precision to not hinder accuracy of the samples collected. The main challenge with collecting groundwater samples is to collect samples without running the water through a large storage tank and plumbing system. Schwartz & Zhang (2002) procedure of collecting water samples was followed in the steps of water sampling.

At first, a field investigation was undertaken in 2015, with its main outcome being identifying possible drilling sites for the piezometers and boreholes. It was during this period that confirmation for drilling of well points was confirmed, in the catchment on the perimeter of Voelvllei as well as Soetendalsvei. All well points lie within the borders of G50C. Thereafter, the well points locations were confirmed, a contract with Borehole man© was drawn up and the drilling commenced after negotiations with land owners had been done to obtain permission to drill well points on their land. Over a period of approximately one month, all well points in the catchment had been erected according to the specifications by UWC.

As part of this research a total of 26 points (boreholes and piezometers), as part of the aforementioned network, were sampled over the course of one year. This was done to analyse data in accordance with DRASTIC parameters and water quality guidelines the sampling runs were conducted on a monthly basis throughout the course of one year. The purpose of which to acquire sufficient data for a comprehensive understanding of the groundwater system. Some limitations were experienced during field sampling that prevented some points from not being able to be sampled.

The current study has a main aspect of risk assessment, where the main outcome is a vulnerability map that determines its state of vulnerability and the likelihood of the groundwater being susceptible to potential contamination. The approach to the application of risk assessment is the monitoring of certain aspects of groundwater and decipher the surrounding areas and ground surface as all the parameter; depth to water, net recharge, aquifer media, soil media, topography, impact of the vadose zone and hydraulic conductivity are put together to understand the vulnerability state of the groundwater in the catchment.

### **3.4 Research methods**

The generation and collection of field data on groundwater is an important step in understanding and evaluating the groundwater's state of vulnerability in the Heuningnes catchment. Data collection samples were completed over the course of one year. With the data collection methods discussed, it portrays which methods are used for the collection of different sets of data for different parameters of DRASTIC. The drilling of several borehole locations in the Cape Agulhas study area was made to monitor the groundwater vulnerability to pollution and to obtain hydraulic properties of the unsaturated zone at these sites. In total 3 boreholes were drilled and 23 well points were placed. These well points and boreholes were placed on a specific geophysics line to obtain an accurate description of the subsurface lithology. The water samples will be collected at each borehole and well point situated in the study area. The fundamental part at this stage is planning in order to identify appropriate sample sites that allow for representative sampling of the study area. Field work will include collecting water samples to determine water quality, depth to water levels in each borehole, rainfall readings, soil composition, subsurface composition as well as topographic readings. The boreholes need to be purged before any sort of sampling can be taken with accuracy (Weaver, 1998). The main risk involved in data collection methods is that there could be human error when data recordings are done and equipment could run low on battery power or fuel in the field.

The purpose of analysing data is to obtain usable and useful information. The analysis, regardless of whether the data is qualitative or quantitative, may be to describe and summarize the data, identify relationships between variables, compare variables, identify the difference between variables and to forecast outcomes. Analysing of the collected data's primary requirement is that sorting and labelling of the data should be done in order to prevent misinterpretation or confusion of the data.

### **3.4.1 Description of the groundwater system using the integrated hydrogeological conceptual model**

Initial methods for the boreholes start with the drilling of each borehole and the drilling of the several well points using the mud drilling method. The mud drilling process is the direct mud rotary drilling technique using a rotating drill pipe with a hard-tooled drill bit attached at the bottom (Sundaram et al., 2009). Fluid is forced down through the drill pipe and then back up the borehole. It is then discharged at the surface through a pipe or ditch into a sedimentation tank, pond, or pit. As the cuttings settle in the pond, the fluid overflows into a suction pit, where a pump recirculates the fluid back through the drill rods.

The drilling fluid serves to: (1) cool and lubricate the bit, (2) stabilize the borehole wall and lastly (3) prevent the inflow of formation fluids, thus minimizing cross contamination of aquifers. Casing is not required during drilling. When unconsolidated materials overlie a bedrock aquifer, mud rotary can be used to drill the bedrock, the hole can be cased, and a less intrusive drilling method (such as air rotary) can be used to complete the well.

A jetting method was attempted for the fabricating of the well points. This method makes use of a high velocity stream of water to excavate the hole and to carry the excavated material out of the hole. It therefore requires some type of pump, either motor or hand-powered, of reasonable capacity, as well as a supply of water. It is possible to separate the water and the excavated material in a settling pool or tank and to reuse the water, thus minimizing the quantity required. Since this method depends on the erosive action of water, it is obvious that extremely hard materials cannot be penetrated. However, semi-hard materials may be penetrated by a combination of hydraulic and percussion effects. This is accomplished by raising and dropping a chisel-edged jetting bit. Coarse materials such as gravel require a greater water velocity to move them vertically out of the hole than do finer materials. However, very fine, hard packed materials such as clays require a high water velocity to dislodge them.



Two basic schemes are used:

(1) Water is pumped down a jetting tube or pipe which is used inside a temporary or permanent casing. The excavation of material by the stream of water allows the casing to descend and the excavated material is carried upward out of the well via the annular space between the jetting tube and the casing. Rotating the casing and cutting teeth on its bottom edge increases the rate of descent. If the casing sunk during the jetting operation is temporary, the final casing with screen attached is lowered inside the temporary casing, which is then jacked out of the hole. Alternatively, the permanent casing may be sunk during the jetting operation. In this case, the well screen is lowered inside the casing and the casing is then jacked up far enough to expose the well screen to the aquifer (Poehls & Smith, 2009).

(2) Jetting may be done by pumping the water down through the casing itself with the excavated material being carried up through an annular space around the outside of the casing. If jetting is interrupted before the casing is sunk to the full desired depth, so that the suspended material settles around it, difficulty may be experienced in re-starting the jetting process. When an open-ended casing is used, a well screen is subsequently lowered and the casing rose slightly to expose the well screen. Alternatively a string of casing with a special self-jetting point on the end of a well screen may be used. The jetting orifice at the end of the well screen is closed by a check valve which is held against its seat either by buoyancy or by a spring when not held open by the pressure of the jetting water. In some cases a smaller string of pipe passes down through the inside of the casing and screen and is screwed into the top of the jetting point. The pipe is used to transmit the jetting water from the pump to the point, without leakage out through the screen. After the jetting operation, this pipe is unscrewed and removed (Richards, 1954).

The jetting was not successful as it could not penetrate the bedrock of the underlying formation. Geophysical methods are also used in the field and are based on the physical properties of materials below the earth's surface. Borehole geophysics provides useful stratigraphic and hydrogeological data. Borehole geophysical techniques have been developed to help solve exploration and production problems in the petroleum industry and have become virtually indispensable tools. Many of these same advantages are available in groundwater applications. But unfortunately, the economics of the groundwater industry are such the most sophisticated tools are unaffordable in most studies. There are probably ten to fifteen types of logs that could be used to provide useful information about different aspects of the subsurface.

There are at least four types of logs that can be used. These logs give off information regarding the subsurface lithology to help correlate between boreholes (Schwartz & Zhang, 2002). The data of water samples were collected to draw upon monitoring of water quality in the study area.

The methods available for addressing the first objective include the development of the hydrologic conceptual model, where the model is derived from aspects of groundwater recharge sources and groundwater flow across the catchment through various lithology's that affect the quality and chemistry of the groundwater to where it discharges as well the groundwater table in the dry and wet seasons. Anthropogenic activities, topography, weather station data are analysed across the catchment and field observations are conducted as all forming part of the risk assessment of the catchment.

Various tools and equipment are used in this study as a way to gather all different aspects of data needed to be analysed. Each piece of equipment or tool has a separate task at hand for collecting a specific amount or part of the dataset required. For the major events such as the drilling of boreholes and well points, a mud rotary driller rig was used and attached to a trailer in order to reach most accessible places for drilling. This was successfully completed by Borehole man© (Figure 5).

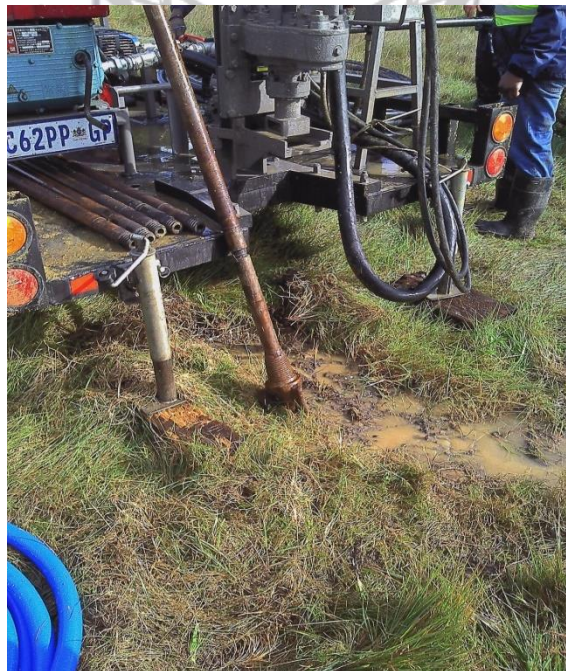


Figure 5: Illustration of the drilling setup containing drilling rig and drill bit

Objectives one procedure is to explain the vulnerability of the aquifer to contaminants using integrated hydrological conceptual model by noting the land use and other aspects of the study area including historical data sources. This is done in order to establish how these circumstances affect the groundwater quality over a period of time. The second and third objectives have similar procedures where the map of the study area demands to be drawn and display all the necessary aspects of the study area that are taken into consideration. The third objectives procedure is to establish groundwater levels, awarding the results and outcomes of the DRASTIC method.

### **3.4.2 Groundwater suitability for agricultural and drinking uses**

The second objective of this study entails determining the groundwater suitability for agricultural and potable usage. To achieve this, in situ groundwater physicochemistry was determined in the entire G50C catchment as a guide to the determination of the groundwater quality of the water in the catchment. Parameters of the quality include that of; Temperature, pH, EC (electrical conductivity), TDS (total dissolved solids), DO (dissolved oxygen), salinity as well as SPC (specific conductance) were measured on site with a multi parameter probe as each parameter had stabilized readings were measured.

With regards to the procedure for groundwater sampling in the field, there are several steps to follow before one proceeds with the sampling. Before visiting the field, observation permission needs to be granted in order to gain access to the site, as a result of it being private property. If pumping is going to take place, information such as hours of pumping, pumping rates, water levels should be taken. During the site visit the measurement of the water level before anything else is taken, as well as the measurements of any water level fluctuations in comparison to a previous visit (Sundaram et al., 2009).

Observing for a well verification number should be considered and making sure that it is clearly labelled. Taking note of the type of pump being used, the well diameter is noted. Thereafter establish an optimum pumping rate for purging and sample collection and decide where to route excess discharge. Purging is defined by the process of removing stagnant water from a monitoring well, prior to sampling, causing its replacement by groundwater from the adjacent formation, which is representative of actual aquifer conditions. At most times purging is done immediately prior to sampling. An aquifer test should also be conducted, such as a slug test that is used to check hydraulic connection between the well and the aquifer. The sample

collection points need to be at a near distance to the well head. Water levels should then be taken once again, after pumping the monitoring well (Sundaram et al., 2009).

Several steps are taken for sampling at boreholes and well points. The measuring of the water level is one of the very first steps. A well tape is used with a float on the end to get the water level measurement. Purging of the well follows and monitoring field measurements. Enough water must be withdrawn from the well to rinse sampling equipment and to conduct measurements of field properties. Withdrawing of the sample, as a general rule of thumb, pumping is the preferred method of groundwater sampling. Field measurements are monitored during purging with sample collection following immediately after final field measurements have been recorded. Processing the sample follows where it involves in part sample filtration, sample collection into appropriate containers and sample preservation. The final step towards completion is cleaning of equipment. Quality control is a very important aspect of groundwater sampling. Its goal is to identify, quantify as well as document bias and variability in the data that result from the collection, processing and handling of samples (Sanders, 1998).

With the measurements of Hydraulic conductivity, it begins with grain size analysis. From the grain size distribution of a sediment sample, an estimation of hydraulic conductivity can be derived and employing speculative similarity between hydraulic conductivity and some statistical grain size parameters such as geometric mean, median and diameter. With grain size analysis, however, it delivers information about the sub-surface material and the hydraulic values can be used as a first estimation for the design of further applications (Kalbus et al., 2006).

The hydraulic conductivity can be calculated following Darcy's law:

$$\frac{Q}{A} = K \left( \frac{h_1 - h_2}{\Delta L} \right)$$

The equation above basically states that the velocity of flow is proportional to the hydraulic gradient. Darcy's law basically calculates the flow rate of water through a medium (Schwartz & Zhang, 2002).

The hydraulic conductivity is calculated from the head difference, the time and the tube sample geometry. Performance and analysis are quick and easy, so that it can be useful for a detailed survey of the heterogeneity of stream beds (Kalbus et al., 2006). The hydraulic conductivity is a constant of proportionality relating the specific discharge to the hydraulic gradient.

Technically, hydraulic conductivity is a parameter describing the ease with which flow takes place through a porous medium. It has relatively large values for permeable units like sand and gravel and vice versa for poorly permeable materials like clay or shales.

This test is based on removing a known volume of water from a well or piezometer, and then as the water level recovers, the head is measured as a function of time. Slug tests are quick and easy to perform with in-expensive equipment. In contrast to pumping tests, only one piezometer is needed to perform a slug test. This method provides point of hydraulic conductivity (Kalbus et al., 2006).

Pumping tests are also used to determine hydraulic conductivity, requiring the existence of a pumping well and at least one observation well in the capture zone. The well is pumped at a constant rate and drawdown in the piezometer is measured as a function of time. A pumping test provides hydraulic conductivity values that are averaged over a large sub-surface volume, these values are more representative for the entire sub-surface body than conductivities obtained by point measurements. A smaller grain means smaller pores and more frictional resistance hence a low hydraulic conductivity (Kalbus et al., 2006).

The hydraulic conductivity works in conjunction with Darcy's Law and states that the amount of water flowing through porous media depends on the energy driving the water flow and the hydraulic conductivity of the porous media. It is a measure of the soils ability to transmit water when submitted to a hydraulic gradient. Hydraulic conductivity is dependent on the soil grain size, structure of the soil matrix, type of soil fluid and the relative amount of soil fluid present in the soil matrix. The crucial elements relevant to the solid matrix of the soil include pore size distribution, pore shape, tortuosity, specific surface and porosity. In relation to the soil fluid, the important properties include fluid density and fluid viscosity.

The saturated hydraulic conductivity of the water in soil can be measured by both field and lab experiments. Either way, the experimental measurements of Permeability (K) consists in determining the numerical value of the coefficient on Darcy's equation. The methodology used for the experimental determination of (K) in either lab or field experiments. Obtaining realistic values of hydraulic conductivity is difficult, but is still worth doing and should be a key part of geotechnical investigations. Several different approaches can be taken to estimating hydraulic conductivity. A visual assessment is one of them, by assessing the soil type and estimating an approximate range of hydraulic conductivity. Laboratory tests, as well as borehole tests, which

are the in situ tests being carried out in boreholes during drilling or later in monitoring (Louden, 1952).

Measuring groundwater recharge is defined as the amount of water that enters the aquifers. Effective rainfall is the amount of water that percolates downward in the unsaturated zone toward the water table, after subtracting the portions of water that are subject to run-off.

The amount of recharge received by an aquifer is by far the most important figure required. Yet this figure is usually the least well-known quantity in hydrogeology, especially in arid and semi-arid environments. Unfortunately it cannot be measured directly on any reasonable spatial scale. So many years of effort have failed to find a single, reliable method for measuring groundwater recharge due to the complexity of this phenomenon and the large variety of situations encountered. Recharge estimates are made particularly difficult in arid and semi-arid environments as a result of the vast variability of hydrological events in time and space. Several natural processes may also influence recharge on different scales, such as an infiltration front, preferential flow in soil structures, localised enhanced seepage in topographic depressions, rivers and irrigated fields (Izuka et al., 2010).

There are several methods to estimate groundwater recharge. A direct measurement of groundwater recharge begins with lysimeters. This is a device consisting of an in situ weighable soil column of a 1m<sup>2</sup> or greater cross-sectional area. The flux by rainfall into the column, the outflow by seepage in 1-2m depth and the weight are continuously measurable by modern lysimeters. Recharge is then directly measured if it can be assumed that the lower end of the lysimeter is below the zero flux plane. The water table rise method is the clearest indication of recharge if all abstractions remain unchanged and atmospheric pressure effects can be ruled out. If the storage coefficient of an aquifer is known, the spatially interpolated water table can rise and be converted into a volume of water. If a closed basin is considered, the water volume corresponding to a complete cycle of water table variation will allow the researcher to obtain recharge directly if the discharge is known, as both quantities are then equal.

Cumulative rainfall departure is another method, which uses some simple assumptions; it can be shown in a closed spring catchment. The cumulative rainfall departure curve is proportional to the water level response. This can be converted to a volume if the storage coefficient is known. It is common practise to express recharge as a percentage of better known rainfall. However it is unclear where the relationship comes from. This method is not a standalone method and must be verified by other methods. The method can be upgraded by starting the

linear relationship only after some threshold value of a minimum rainfall is required to be observed.

The Darcy method for groundwater estimation; these methods estimate the flux from a head gradient and a hydraulic conductivity. This method therefore requires an accurate determination of these two quantities representative of the scale on which the flux is to be determined (Domenico & Schwartz, 1990).

Spatial variability in recharge and preferential flow through the unsaturated zone are critical issues for contaminant transport and for assessing aquifer vulnerability to contamination. Quantifying recharge in areas subjected to preferential flow should be based on saturated zone data as a result of the saturated zone generally integrates contributions from preferred pathways.

Recharge is defined as any water that moves from land surface to the water table. A common recommendation is that recharge should be estimated by the use of multiple methods and the results compared. Water table fluctuations (WTF) were used to estimate recharge from the water level rise in a well multiplied by specific yield of the aquifer. This method actually measures the effect of recharge at the water table, which should provide estimates that correspond most closely to our definition of recharge; however, the appropriate value of specific yield must be known to translate the measured water level fluctuations into estimates of recharge.

Water table fluctuations in wells have been used by hydrologists for many years to estimate recharge. The water table fluctuation method assumes that a water level rise is caused by recharge arriving at the water table and that the specific yield is constant (Izuka et al., 2010). The method provides a point value of recharge computed from the water level rise on a well multiplied by the specific yield of aquifer as  $R(t_j) = Sy^* \Delta H(t_j)$

A few drawbacks of the water table fluctuation method, is that it requires an estimate of specific yield and assumes this value is constant with time. This method should best work for wells that show a relatively rapid water level rise in relation to the rate that water moves away from the water table. The amount of groundwater recharge, storage and discharge as well as the extent of groundwater contamination all depends on the soil media characteristics; the texture, porosity, specific yield, permeability and the attenuation capacity. Soil is a mixture of 3 soil separates. Soil properties such as depth, texture and permeability help determine the rate of

groundwater recharge as well as protection from groundwater contamination. Land surface factors such as topography, geology and vegetation along with soil properties determine the potential for groundwater threats.

The soil acts as a natural filter, in this context filtering means more than capturing solid particles. Filtering also means retaining chemicals or dissolved substances on the soil particle surface, transforming chemicals through microbial biological processes and retarding movement of substances. The soil's ability to lessen the amount of or reduce the severity of groundwater threats is called soil attenuation. During the attenuation, soil holds essential plant nutrients for uptake by agronomic crops, immobilizes metals that might be contained in municipal sewage sludge, or removes bacteria contained in animal or human waste.

Depth to water measurements are used for a variety of purposes including constructing water table contour maps and hydrographs, determining groundwater flow directions and gradients or defining seasonal water table fluctuations. The depth to water is measured by means of a dip meter, where it is lowered into the borehole or piezometer to obtain an accurate reading of the water level. Data collected from well points and boreholes, depth to water readings and groundwater physicochemistry; are used with an interpolation method, being Inverse Distance Weighting (IDW). IDW will produce interpolation layers to analyse the spatial distribution of the groundwater quality and the water table levels. Inverse distance weighting is an interpolation method e.g. it was used in comparison with kriging on the depth to groundwater of observation wells. The outcome is stated that kriging brings out the best result because as it has the lowest standard deviation. The water levels collected from each borehole and well point are taken to compare it with rainfall data, correlating and displaying it graphically. This aids in determining the recharge of the study area (Lyon, 2003).

The rainfall vs water levels are spread over long term as loggers aren't used to achieve constant data across a certain time period as funding doesn't allow. The water levels are spread across long term to then correlate with seasonal rainfall patterns. Bailer tests are carried out as a method of determining the Hydraulic conductivity of the study area. Following water levels are the collection and analysis of rainfall data across the catchment. This is achieved by using the weather stations in the catchment the data had been downloaded and analysed to obtain the rainfall readings for each month in the catchment, thus calculating the monthly average rainfall over the catchment.



These bailer tests are easily performed in comparison to pump tests. Hydraulic properties determined by bailer tests are representative only of the material in the immediate vicinity of the well. Bailer tests should be conducted in properly designed and developed wells or piezometers. When conducted in large numbers, bailer tests are valuable for determining subsurface heterogeneity. A bailer tests advantages are based on its ability that involves removal of little to no water from the aquifer, it's a relatively low cost test and requires little time to actually carry out this test. There is a method to calculate the hydraulic conductivity from raw bailer test data, usually the method of Bouwer & Rice, (1976). Also, computer programs are used for aquifer evaluation by bailer test to interpret the raw slug test data, namely AQtesolv that is utilized in this study.

### **3.4.3 Establishing groundwater levels using geostatistical, geospatial and risk assessment tool**

In relation to the third objective of the current study, the available methods are in situ, where groundwater physicochemistry is carried out alongside depth to water levels of all the well points in the catchment. These depth to water levels undergo geospatial assessment using Inverse Distance Weighting (IDW) to produce a map of the distribution of the various depth to water levels across the catchment in the dry and wet season.

For the measurement of water levels in each well point and borehole, a water level meter is used to give accurate water level readings. With regards to soil media and aquifer media, soil descriptions were logged as each well point or borehole had been drilled. A soil classification triangle was used for the description of soils. There are two ways to measure hydraulic conductivity, either in the laboratory, where samples are collected in the field and transported to the lab where it is then analysed. Secondly, field work is done to determine hydraulic conductivity, by means of Piezometers or a pumping test. The pumping test is a reliable method to obtain the hydraulic properties of an aquifer, as well as information on the water quality and its variability with time. With regards to in situ water quality measurements an YSI Professional plus 20™ Multi-parameter was used down each well point in the catchment. Rainfall from weather stations in the catchment was downloaded to obtain rainfall data in the catchment and plotted accordingly in dry and wet seasons. A GPS was used to obtain the coordinates in decimal degrees of all the well points in the catchment. In the field a 5l can of distilled water was always brought along with measurements of depth to water as the water level meter needed to be cleaned after every measurement as the salinity is very high, the measurements needed to be kept extremely accurate at all times.

Microsoft Excel was the initial step in computing the collected water levels, field parameters, groundwater physicochemistry, pump test and bailer test data. The use of Microsoft excel is for the generating of the graphs, thus requiring analytical skills. The data analysis consists of statistical analysis and GIS analysis. Once the data had been computed it had then been exposed to analytical methods to groundwater vulnerability to potential pollution. Analytical methods include that of geostatistical analysis using Arcmap, Aqtesolv using Horslev method, HOBOWare Pro for logging water level rise after bailing for determining aquifer characteristics and IBM SPSS© for statistical analysis.

For compiling the data obtained through the various methods, it was firstly hand written in a field notebook and integrated to Microsoft excel spreadsheets. Data had been strategically labelled according to the various parameters of DRASTIC it pertained to. Data in Microsoft excel had been screened and checked over to avoid incorrect inserts with regarding units of measurements and maintaining consistency.

Firstly each borehole and well point location was digitally marked with a GPS such that each borehole and well point could be pin pointed on a map using GIS software's such as Arcmap. Arcmap can be used to obtain a general consensus on the locations of the drilling across the study area. A tape meter is used to obtain the depths of each borehole and well point. A multi meter is used to obtain the characteristics of the groundwater determining its pH levels, temperature as well as Total Dissolved Solids (TDS).

The boreholes and piezometers depth to water readings are then logged on field excursions to develop water table fluctuations as well as identifying areas of low water tables and shallow water tables (Sundaram et al., 2009). There after the aquifer media is studied in the catchment by analysing borehole logs that have been drilled and noting the drillers logs as the driller drilled the consecutive well points in the catchment using mud rotary drilling, the highest accuracy had been used to log the lithology as the well points were logged as each length of drill bit descended.

Thirdly soil media and topography data had been collect via datasets available on line [www.usgs.com](http://www.usgs.com) USGS is the United States Geological Site that holds a vast amount of up to date data on the lithology's of the world. Lastly hydraulic conductivity measurements are collect via the means of a pump test or bailer test. All these data points undergo analytical methods to correctly format them for the generation of the vulnerability map that constitutes the result of the catchments groundwater vulnerability to pollution.

## **3.5 Quality control/Assurance of data**

### **3.5.1 Validity of data**

It is important to notice that the materials and methods used in this study is an integral part in measuring the water retention of undisturbed soil samples (Konig & Weiss, 2009). Therefore, this methodology is a crucial part of the study as it provides the basis for most accurate estimates of hydraulic conductivity. The methodology is quite labour-intensive and time-consuming as it requires a high level of care and concentration for the prevention of flawed measurements from occurring, by disturbing or over-or-under saturating the samples.

### **3.5.2 Reliability of data**

Primarily, the Standard Operating Procedure (SOP) was followed forming reliability. A number of alternative quality control measures had been included in analytical routines. These include; (1) Routine analysis of duplicate samples, (2) Collecting, handling and storing samples properly and document the entire sampling event. (3) Using appropriate purging, sampling equipment, procedures, decontaminate and storing equipment properly, (4) Occasional analysis of blanks such as distilled water which have been subjected to the same range of field and laboratory preparation steps as the real sample. These can assist in determining the entry of contamination where contamination is entering into the analytical process and resulting in false positive measurements. Sampling procedures were efficiently documented and attained successfully (Sundaram et al., 2009).

The final step towards completion is cleaning of equipment. Quality control is a very important aspect of groundwater sampling. Its goal is to identify, quantify as well as document bias and variability in the data that result from the collection, processing and handling of samples. All of the data composed was checked for errors by a statistical approach. The data was cleaned of inaccurate values. Consequently all outlying or abnormal data points were highlighted and cleaned.

## **3.6 Research integrity**

### **3.5.1 Ethical consideration**

Autonomy is the “personal rule of the self that is free from both controlling interferences by others and from personal limitations that prevent meaningful choice” (Novitzky & Cooper, 2013). Autonomous individuals act intentionally, with understanding, and without controlling influences. In the proposed study permission will be required to access data or study sites, such as the boreholes, on account of the sites that may be private property.

### **3.5.2 Technical consideration**

The idea that the burdens and benefits of new or experimental treatments must be distributed equally among all groups in society. It requires that procedure uphold the spirit of existing laws and are fair to all players involved. The farmers and community members will be informed about the study that is being undertaken.

### **3.5.3 Legal consideration**

This is the action that is done for the benefit of others. Beneficent actions can be taken to help prevent or remove harms or to simply improve the situation of others. This study will seek to benefit all parties associated.

## **3.7 Study limitations**

Water quality is affected by a variety of contaminants from various sources. This particular study does not cover these aspects. The method lacks information on the specific sources of chemical contamination from the environment. This can be minimized through modifications of the methods with addition of these parameters and environmental conditions. During periods of groundwater recharge the concentration of salt content is altered in the aquifers, therefore time will be an issue when gathering water samples from the boreholes because of seasonal change in salinity. Therefore, doing the assessment of the boreholes should be in dry seasons. Historical data can assist to derive a pattern of precipitation. There are numerous ships commuting with harmful elements, of which are not considered in terms of leakages and spillages, potentially being a source of water contamination.

## **Chapter 4: Integrated hydrogeological conceptual model of the groundwater in the catchment**

### **4.1 Introduction**

This chapter provides an integrated approach to the understanding of the groundwater system in the Heuningnes catchment. The conceptual model generated is based on the evaluation of available data on groundwater levels, rainfall, aquifer and soil media, topography, impacts of the vadose zone and the hydraulic conductivity. The conceptual model is a description of reality in terms of verbal description, equations, governing relationships or natural laws that purport to describe reality. The hydrogeological model was developed with Surfer to elucidate the groundwater system including that of the aquifer characteristics that store the groundwater. The model begins with illustrating the seven parameters of DRASTIC: depth to water, net recharge, aquifer media, soil media, topography, impact of the vadose zone and hydraulic conductivity.

### **4.2 Methods used**

Groundwater systems are mainly hidden from plain sight. The use of groundwater simulation models are used to infer the properties of groundwater systems. Furthermore, to simulate the flow and storage of water within the subsurface under variable conditions, including natural conditions and human-made influences such as pumping. The most widely used groundwater simulation model is Surfer. It is a fully fledged contouring and surface modelling software developed to run under Microsoft Windows. It also interpolates irregularly spaced xyz data into a regularly spaced grid and is used in this current study to generate a conceptual model.

### **4.3 Key results on integrated hydrogeologic conceptual model**

Figure 7 is the conceptual model illustrating all seven parameters of DRASTIC. The conceptual model subdivides each of these parameters illustrating how each parameter influences the other. The following subsections provide comprehensive descriptions of the physical characteristics of the catchment in terms of DRASTIC parameters.

The shallower the water depth the more vulnerable the groundwater is to potential pollution and vice versa (Aller et al., 1987). In contrast, vicinities in the study area with a higher depth to water reading are indicative of groundwater recharge. It is important to understand that depth to water readings over time can prove areas of higher depth to waters over a period of time as

well as classify areas of low depth to water over time. Respectively the average of the depth to water readings over time will be indicative of areas of high vulnerability as opposed to areas of lower vulnerability states. Figure 7 illustrates the general groundwater flow in the catchment using the depth to water readings over contours of water levels as well as showing areas of higher water levels and lower water levels.

The Heuningnes catchment receives its recharge from precipitation and rivers during high rainfall (Toens, 1991). The rainfall is moderate, with the rain falling mainly in the winter months. The temperatures are equable, varying on average between a maximum of 25°C in the summer and a low 6.6°C average in the winter. The average rainfall varies between 20.71mm in December and April 51.55mm. The source of the recharge is denounced from high laying areas to the flood plain of the mountain ranges of the Soentanyberge as well as the Bredasdorp mountain range. This is the initial point of recharge for groundwater in the catchment (Toens, 1991). The study aimed at determining the groundwater recharge using available data where the mean annual precipitation values are investigated. Toens, (1991), states that during the winter season where precipitation average is at its highest the water table exceeds the land surface, giving certain areas water logged and inaccessible (Figure 6).

Precipitation infiltrating through the younger laying lithology's percolates into the older strata beneath, in a geological aspect. As a result, the permeability of the overlying Bredasdorp formation is much higher than that of the underlying lithology. The product of this phenomenon is two superimposed water tables with contrasting water chemistry qualities (Toens, 1991). In the catchment, springs develop where the water table intersects the land surface, hence the depth to water will be taken as zero at these points. Groundwater flow directions in the catchment flow towards the coast (Figure 7), the same as the flow of the major tributaries of the catchment, but at a slower movement relative to the surface flow (Toens, 1991). The catchments water table largely follows the topography, moving to the lower levels of wetlands, where the elevations run fairly flat with levels less than 10m. This shallow gradient is exceptionally flat in these low lying areas which characteristically suggest slow movement of groundwater with maximum recharge (Toens, 1991).

## G50C winter water logged regions

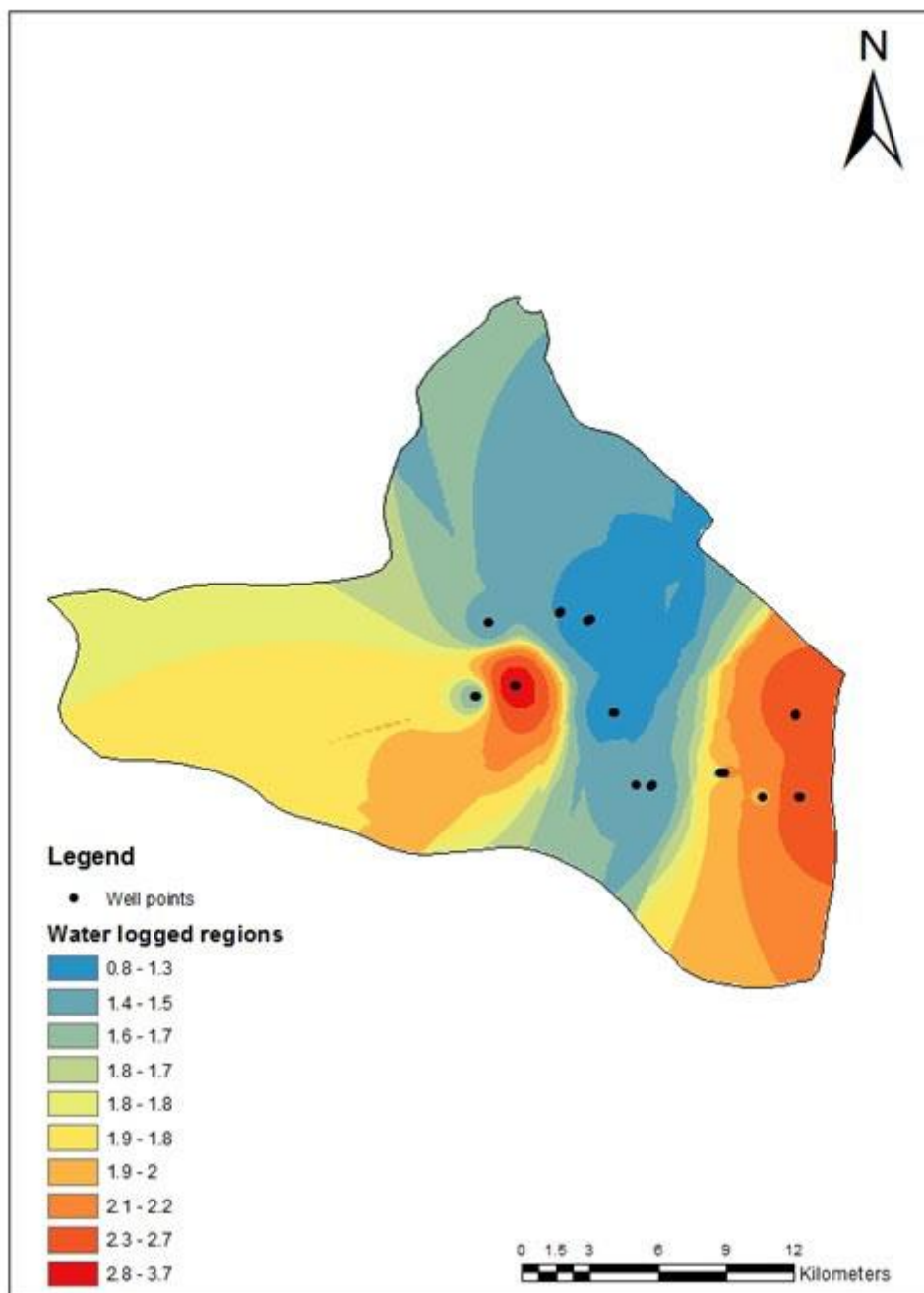


Figure 6: Water logged regions G50C

The aquifer consisting in the study area is the Table Mountain Group (TMG) aquifer. The TMG is the lowest part of the two groups of which the Cape Supergroup is comprised, the other group consisting of Bokkeveld. It is composed of quartzite sandstone which erodes to give rise to the nutrient poor soils characteristic of Fynbos. The sandstones making up the TMG are brittle and do tend to fracture readily as it is composed of deep seated fractured aquifers belonging to the Cape Supergroup. The outcrops are largely placed as a definite strip along the coast of Struisbaai (Visser, 2001). The Bokkeveld group is the only member of the Cape Supergroup present in the area which comprises predominantly of shale and yields a rather poor quality of groundwater in the catchment with EC values ranging between 500 to 1000 mS/m.

The Malmesbury group is situated predominantly in the western parts of the study area and encompasses mainly shale deposits, with groundwater in this group typically saline and of a poorer quality (Toens, 1991). The age of the rocks are characterized by the Palaeozoic era, with most of the rock types being classified into quartzite, shale, sandstone as well as limestone. Another formation present in the catchment is the Bredasdorp group, which consists mainly of calcarenite, lenticular conglomerate beds are well developed at modest locations. Groundwater in this formation similarly yields poor quality with the EC values ranging at approximately 300 mS/m.

Carr et al., (2006) study was undertaken in the Agulhas plain with their main objective being the Chronological, Sedimentological and Palynological evidence derived from a programme of coring in pan floors and wetlands. He attempted to shed more insight on the environmental and ecological dynamics of the winter rainfall zone of the late quaternary. His sampling sites concentrated on the perimeter of Voelvllei, as Voelvllei is situated in the Bokkeveld geological setting. Cores VV3 and VV5 of Carr et al., (2006) were extracted using the Vibracorer technique on the eastern borders of the vle. The core depths reached lengths of between 2 and 2.5m deep. Similarly all cores displayed compositions that were very alike. The upper regions composed of moderately to poorly sorted medium or medium-fine sands, with a progressive downwards-fining trend, culminating in relatively organic rich silt-clays between the middle to lower regions of the cores depths (Carr et al., 2006).

The TMG comprises mostly of quartzite sandstones which erodes generating poor nutritional soils that are brittle and tend to fracture readily. The soils are also acidic and highly infertile. Soil characteristics can be described in the Elandsdrif region as starting off with the top soil,



moving along further into the subsurface as clay followed by sand deposits. Clay and sand are very dominant in the lithology of the study area. Clay soils are characteristically known for having a very high water-holding capacity, but most of the water is tightly bound and not available to plants.

These soils are very favourable aggregated structure in the top soil layer. Sandy soils are often dry and fast draining; these soils usually have little to no ability to transport water from deeper layers through capillary transport (Aller et al., 1987). The soil data that is described is taken mainly between Voelvlei and the Soetendalsvlei. The wetland where the soil is sampled is situated between the two vlei's. In the wetland 7 to 9 transects were used to obtain soil data as a cross section of the wetland. Transects cut across the Nuwejaars River, with three sample points taken on each side of the river.

Table 1 describes the sampling points and depths as well as the type of soil obtained from each sampling location and depths. (.1) ending is an indication of a surface sample and (.2/.3) is an indication of a deeper depth sample respectively and so forth. Parameter readings of each sample were taken as follows: Bulk density, volumetric moisture content, organic content, Clay %, Silt % and Sand %. The soil type in the area ranges from Sandy loam, loam, loamy sand, silt loam, clay loam, loam and sand.

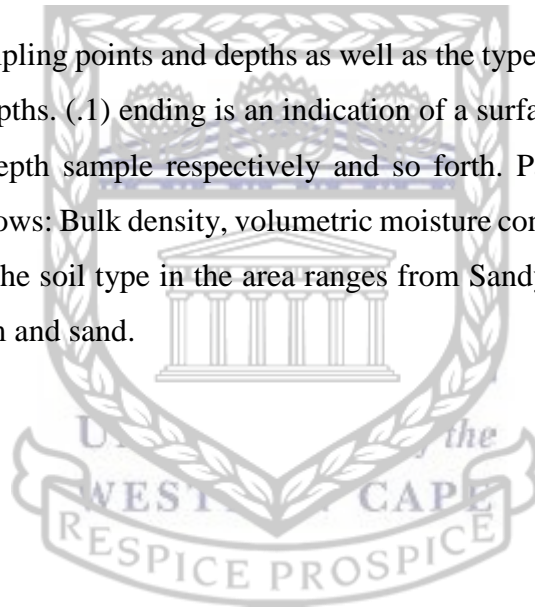
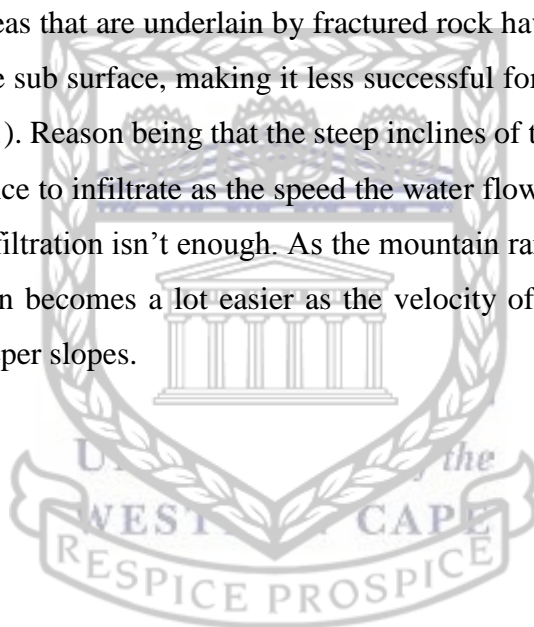


Table 1: Describing soil samples collected and their physical parameters

ID	BD	Vol. Moisture Cont.	Organic Content	Clay (%)	Silt (%)	Sand (%)	Soil Type
1.1.1	1.28	0.16	10.63	7.4	22.4	70.2	Sandy Loam
1.2.1	1.07	0.21	17.51	3	40.4	56.6	Sandy Loam
1.3.1	1.20	0.16	7.68	14.2	26.6	59.2	Sandy Loam
1.3.2	2.16	0.30	1.78	10	21.2	68.8	Sandy Loam
1.3.3	1.45	0.23	2.33	15.4	38.4	46.2	Loam
1.4.1	1.24	0.59	17.10	1.6	25.6	72.8	Sandy Loam
1.4.2	2.03	0.31	0.38	5.8	21.8	72.4	Sandy Loam
1.4.3	1.91	0.32	0.10	4.8	10.2	85	Loamy Sand
1.5.1	1.41	0.20	4.47	7.2	19.4	73.4	Sandy Loam
1.5.2	1.82	0.25	2.62	0.2	34.8	65	Sandy Loam
2.1.1	1.40	0.09	3.46	10.6	32.6	56.8	Sandy Loam
2.1.2	1.71	0.36	3.16	15.6	37.8	46.6	Loam
2.1.3	2.00	0.35	1.54	7.2	19.4	73.4	Sandy Loam
2.2.1	1.38	0.08	3.62	5.6	26.8	67.6	Sandy Loam
2.2.2	2.03	1.86	3.31	4.8	29	66.2	Sandy Loam
2.3.1	1.19	0.11	6.13	5.8	22.2	72	Sandy Loam
2.3.2	1.81	0.23	1.66	12	25.8	62.2	Sandy Loam
2.4.1	0.73	0.24	12.23	7.8	38.8	53.4	Sandy Loam
2.4.2	1.59	0.31	0.35	5.2	8.8	86	Loamy Sand
2.5.1	1.58	0.05	2.77	11	28	61	Sandy Loam
2.5.2	1.40	0.29	4.51	13.2	56.4	30.4	Silt Loam
2.6.1	1.34	0.07	5.34	12.6	34	53.4	Loam
2.6.2	1.67	0.32	4.47	7.2	55.2	37.6	Silt Loam

The catchment includes the dividing line between the Atlantic and Indian oceans. The most noticeable topographic features of the region start off with the Soetanyberge in the south. It stands at a maximum altitude of 249m above sea level and is the highest peak in the study area (Rasmussen et al., 1998). The west of Struisbaai has the second highest peak, with a height of 156m above sea level. The underlying geology of the area comprises of a complex succession of fracture and folded rocks ranging from the Malmesbury group to the Bokkeveld group. In the past, millions of years ago, the southernmost part of the African continent was subjected to extreme forces of structural integrity, responsible for complex faulted and folded features of the Cape Fold Belt.

Topographically steep areas that are underlain by fractured rock have an adverse effect on the infiltration of water to the sub surface, making it less successful for the water to penetrate the land surface (Toens, 1991). Reason being that the steep inclines of the mountain ranges do not give precipitation as chance to infiltrate as the speed the water flows down these slopes are at a relative speed where infiltration isn't enough. As the mountain ranges flatten out toward the flood plain the infiltration becomes a lot easier as the velocity of the water is considerably lower than it is in the steeper slopes.



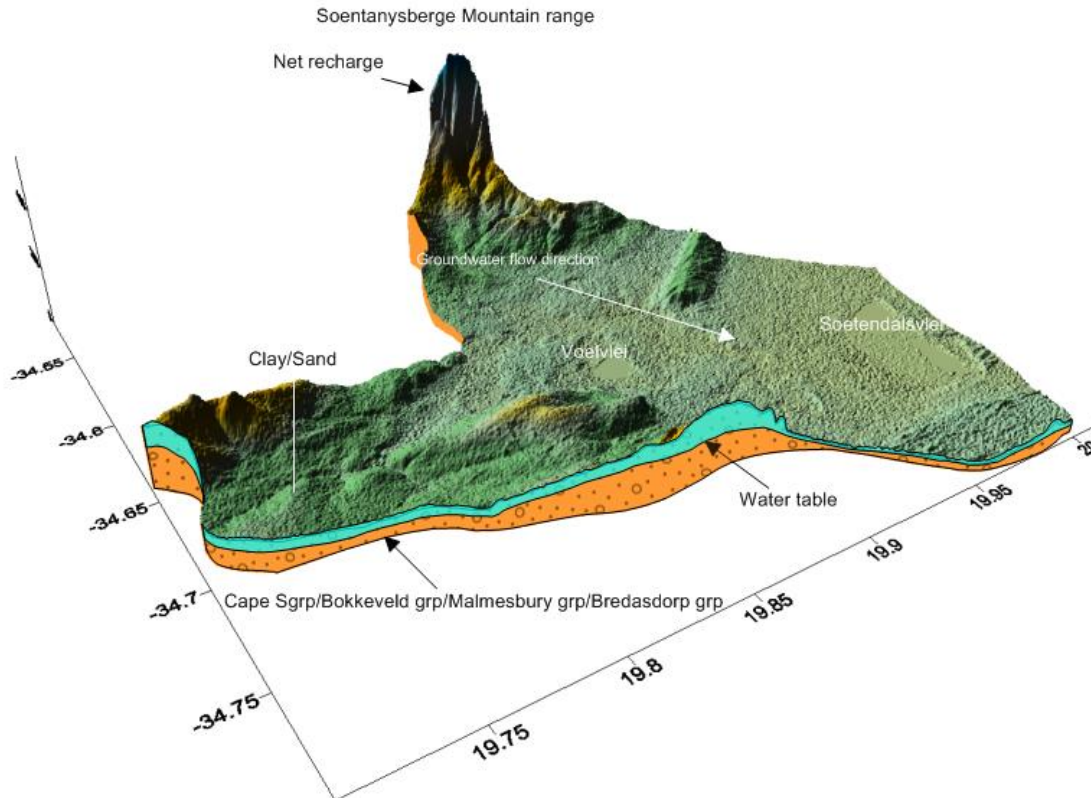


Figure 7: Conceptual model of G50C

#### 4.4 Discussion on Integrated hydrogeological conceptual model

The model presented in this chapter is used to help better understand the groundwater system in the Heuningnes catchment. The model illustrated a reasonable result by portraying each DRASTIC parameter and their individual influence to the aquifers vulnerability. The model showed that the depth to water parameter illustrated mostly shallow water levels. An implication of shallow water levels depicts a higher vulnerability to potential pollution. With winter months, having the water table rise above the land surface, creating water logged regions and making these areas more prone to potential pollution. The net recharge parameter illustrated in the model portrays recharge occurring in the higher laying areas of the catchment.

The higher laying areas are situated solely in the north of the catchment. However, the remaining land cover which consists of 90% of the catchment is low laying sea level height. This low lying characteristic is expected to have a higher vulnerability as percolation of recharge is favourable in a level setting as opposed to a mountainous high laying region of the Soetmysberge and Bredasdorp mountain range. The TMG deep seated fractured aquifer,

composed of quartzite sandstones, shale deposits as well as Limestone (Toens, 1991). These lithologies consummate nutrient poor soils, poor quality and saline groundwater.

Future detailed information will assist with regards to groundwater management of the catchment. The models main advantage was its ability to incorporate all parameters of DRASTIC, reflecting their interrelations and how each individual parameter affects the vulnerability of the TMG aquifer. Results compared to Adelena et al., (2010) reveal that the conceptual model for his concept of recharge was successful in elucidating the groundwater flow mechanisms and possibilities of recharge in Cape Flats (study area).

#### **4.5 Summary**

In summary, this chapter illustrated the integrated hydrogeological conceptual model. The model visually portrayed the seven parameters of DRASTIC and their individual characteristics that directly affect the aquifers vulnerability. Furthermore, the models result presented the general shallow water levels and recharge points in the north of the catchment. This shallow water level is indicative of a higher vulnerability region. However the net recharge occurring in the north of the catchment in high lying areas are expected to be lower vulnerability regions as run off catalysed by steeper inclines. Aquifer media of the TMG shown in the model is composed relatively of deep seated fractured system. It includes lithology of quartzite sandstones, shale deposits and limestone. These lithologies are indicative of nutrient poor soils and bearing low quality as well as saline groundwater. The model notably revealed the groundwater system in the Heuningnes catchment with predictions of vulnerability of the aquifer to potential pollution.

## **Chapter 5: Vulnerability of the aquifer to potential contaminants using risk assessment methods**

### **5.1 Introduction**

The current chapter presents and discusses the findings from hydrochemical analysis of the groundwater in the Heuningnes catchment. The chapter aims to analyse and relate the physical groundwater parameters in order to determine the state of the groundwater quality over time. The chapter describes that the water quality is highly saline as a result of the underlying lithology in the Heuningnes catchment and compares the groundwater quality to International drinking water standards as well as international and national agricultural water quality. The addressing of the second objective is carried out here, which states that the vulnerability of the aquifer to contaminants are analysed. This is utilized by DRASTIC and risk assessment methods incorporated with in situ statistical analyses methods.

In addition, the chapter is based on the assumption that by statistically assessing the physical groundwater parameters, dominant measurements that quantify the groundwater's quality can be determined. This objective was met by characterizing the groundwater hydrochemistry by correlating the physicochemical properties used by the Principal component analysis (PCA) as well as Cluster analysis. Following the Cluster and PCA analysis the major physicochemical characteristics are pointed out and classed regionally across the catchment to portray areas with their altering characteristics. These highlighted regions are classified by poor physicochemical properties to areas with favourable specified physicochemical properties.

### **5.2 Methods used**

The groundwater physicochemistry readings were obtained on site with multi-meters providing data inputs giving rise to in situ methods that are used across the entire catchments well points. The multi-meters provide measurements of Temperature ( $^{\circ}\text{C}$ ), Dissolved Oxygen (% and mg/l), Specific Conductance (SPC) ( $\mu\text{S}/\text{cm}$ ), Electrical Conductivity (EC) ( $\text{mS}/\text{cm}$ ), Total Dissolved Salts (TDS) (mg/l), Salinity (SAL) (ppt) and pH levels. These measurements were recorded using the YSI Professional<sup>©</sup> and/or Hach HQ40d<sup>©</sup> portable multi-parameter meters. The onsite measurements were taken from all 26 well points in the catchment following the techniques prescribed by Arthur et al., (2007). Numerous chemical reactions occur as the groundwater flows through the subsurface lithology and anthropogenic activities allow for

alteration of groundwater quality as seepage occurs to the water table. Therefore the approach of statistical analysis of groundwater physicochemical aids in the identification of the state of the quality of the groundwater in the area, distinguishing areas of poor groundwater quality as opposed to areas of higher groundwater quality. The standards used for the classification and comparison of the groundwater in the study area includes:

- Domestic use by (DWAF, 1996a)
- Agricultural use by (DWAF, 1996b)
- Potable water by (WHO, 2006)

These guidelines are the basis for comparison of groundwater quality in the catchment as it quantifies the quality of the groundwater suitable for use agriculturally or for domestic use. Groundwater in situ measurements were analysed using IBM ® SPSS® statistics 21. This statistical software is a reliable program used for statistical analysis of the groundwater physicochemical parameters to produce easy to understand results of the quality of the water in the catchment using various analytical techniques. These techniques include:

- Descriptive statistical summary of groundwater such as minimum, maximum, mean, standard deviation
- Descriptive statistics utilized to depict groundwater quality in the catchment on their physicochemical parameters in comparison to (WHO, 2006), (DWAF, 1996a) and (DWAF, 1996b).
- Pairwise association of a set of variables displaying them as a matrix, Correlation analysis

Physicochemistry, the physical and chemical properties of water determines its fitness for a variety of uses and for protecting health and integrity of aquatic ecosystems. Many of these properties are controlled or influenced by constituents who are either dissolved or suspended in water DWAF, (1996b), where this study focuses on the quality of water compared to potable water standards for human consumption and agricultural use.

The correlation analysis is a means of statistical assessment by studying the relationship between various variables. A correlation is used in this study to establish connections between groundwater physicochemical parameters in the Heuningnes catchment. When a relationship is found between physicochemical parameters, it means that when one variable alters, there

will be a systematic change in the other variable. The correlation between the variables can be either positive or negative. A positive correlation depicts that if one variable increases or decreases the other variable will increase. On the other hand, a negative correlation exists if one variable decreases where the other increases and vice versa.

The  $r$  value which is derived from the Pearson's correlation is a measure of the strength and direction of the correlation between variables and ranges from +1 to -1. An  $r$  value of +1 is indicative of a very strong positive correlation whereas -1 indicates a very strong negative correlation. However if the  $r$  value lies close to zero or on 0, there is reason to state that there is little to no relationship between two variables.





### 5.3 Key results on the vulnerability of the aquifer to contaminants

Table 2 illustrates the minimum, maximum, mean and standard deviation values generated from the 26 well points in the catchment. In order to obtain a significant understanding of the quality of the groundwater in the catchment, the physicochemical properties were compared with multiple standards. Afore mentioned physicochemical properties were analysed for the purpose of association with different standards.

Table 2: Statistical summary of the Heuningnes catchment groundwater physicochemistry for 2016/2017

	Minimum	Maximum	Mean	Standard Deviation
<b>Temp</b>	14.6000	23.2000	18.903883	1.8407118
<b>DO (%)</b>	.1000	69.9000	2.783554	8.7351480
<b>DO (mg/l)</b>	.0100	6.7300	.253008	.8173668
<b>SPC (µS/cm)</b>	7.8600	100849.3307	30621.139683	22546.1436445
<b>EC (mS/cm)</b>	.0067	85.7000	26.749669	19.5577322
<b>TDS (mg/l)</b>	325.0000	66643.1199	19891.262026	14310.0478650
<b>Salinity (ppt)</b>	.2400	68.6771	19.928129	15.1185388
<b>pH</b>	6.3800	9.1400	7.409358	0.4288405

The descriptive statistics table summary shows the distribution of all the measured physicochemical parameters the parameter pH is considered as an important ecological factor and provides a significant piece factor of information in many type of geochemical equilibriums. The pH values range between 6.38 and 9.14, indicative of a neutral to alkaline setting. Acidic pH levels in the Western Cape region are generally found in groundwater as a result of organic acids and the lithology's the groundwater flows through. In the Heuningnes catchment the main lithology's that the groundwater flows through is limestone bearing rock, thus the reasoning behind the groundwater being alkaline. The mean and standard deviation of the pH is 7.40 and 0.42 respectively. These values meet the drinking requirements and agricultural use of groundwater with DWAF, (1996a) and WHO, (2006).

As a result of these values being permissible with these standards, it has no significant effect on health if consumed. TDS is an important parameter which conveys a very peculiar taste to water and reduces its potability. The TDS values in Table 8 illustrate values ranging from 325 to 66643.11 mg/l. The mean and standard deviation values of TDS are 19891.26 and 14310.04 mg/l respectively.

The TDS concentration is directly proportional to the electrical conductivity of water. The EC, measured in MicroSiemens per centimetre, is a measure of the water's ability to conduct an electrical current. The EC values of the groundwater samples vary between 0.0067 and 85.7 mS/cm, with the mean and standard deviation values of 26.7 and 19.655 mS/cm (Table 9). DWAF, (1996b) has a target water quality range for EC of 0 to 70 mS/cm, hence the groundwater salinity falls within the required limitations. No health effect is associated with the electrical conductivity of water in this range and is acceptable for potable use.

Table 4 displays the physicochemical results obtained from the analysis of different groundwater samples. TDS recorded an average reading of 20 197.8 mg/l, well over the permissible limit of the DWAF and WHO standards of 450 mg/l and 600 mg/l respectively. The Salinity mean value of 20.3 sits comfortably below the allowed indication of 400. Furthermore the average temperature of the groundwater succumbed to a mean value of 19°C where the required WHO, (2006) value of 28°C is stated. In this way pH, EC, Salinity and Temperature of the physicochemical properties of the groundwater in the Heuningnes catchment fall within the required limitations of DWAF, (1996b) and WHO, (2006) guidelines for potable water uses.

Table 3: Physicochemical parameters analysed from the groundwater sampling sites in the Heuningnes catchment

	<b>TEMP</b>	<b>DO*</b>	<b>DO</b>	<b>SPC</b>	<b>EC</b>	<b>TDS</b>	<b>SAL</b>	<b>PH</b>
<b>PZ1</b>	18.8	0.4	0	20615.7	17.7	13202.7	13.3	7.2
<b>PZ2</b>	18.7	1.2	0.1	29217.1	25.1	18905.5	16.8	7.3
<b>PZ3</b>	18.6	0.2	0	41670.1	35.7	27140.3	27.2	7.3
<b>PZ4</b>	18.4	0.2	0	2479.9	2.1	13128.7	6.1	7.4
<b>PZ5</b>	18.8	4.2	0.4	8106.9	7.1	4781.2	4.1	7.8
<b>PZ6</b>	19.1	1.5	0.1	34430	29.7	17730.2	16.5	7.6
<b>PZ7</b>	20.5	1.3	0.1	35713.1	32	23370.7	22.9	7
<b>PZ8</b>	19.6	1.5	0.1	39810.4	35.4	25714.2	25.9	7
<b>PZ10</b>	18.7	1	0.1	33201.9	27.3	21599.4	20.7	7.4
<b>PZ11</b>	18.8	1.2	0.1	48286.3	43.7	31447.2	32.4	7.4
<b>PZ12</b>	19.3	0.2	0	42490	37.9	27608.5	27.5	7.5
<b>PZ13</b>	17.4	1	0.1	64230.7	55.2	42084.1	43.2	7.2
<b>PZ14</b>	17.6	9.1	0.9	65856.6	56.8	43144.7	44.6	7.4
<b>PZ15</b>	18.6	5.2	0.5	15052.3	13.5	10673.2	9.8	7.5
<b>PZ16</b>	18.5	7.8	0.7	19674.3	17.6	15861	15	7.1
<b>PZ17</b>	20.1	0.2	0	30298.6	26.9	6892.7	17.8	7.5
<b>PZ18</b>	19.1	0.2	0	52276.5	45.4	34111.3	36.6	7.3
<b>PZ19</b>	19	4.3	0.4	3167.1	2.7	2083.4	1.7	8
<b>PZ20</b>	18.8	17.6	1.7	34176.9	29	22558.9	23.2	7.6
<b>PZ21</b>	19	0.2	0	20265	18.1	13171	12.1	7.5
<b>PZ22</b>	19.5	0.2	0	15245.3	13.6	9888.2	8.9	7.6
<b>PZ23</b>	19.2	0.2	0	20065.8	18	13053.5	12	7.5
<b>BH1</b>	18.9	5.1	0.5	32104.7	28	21217.9	20.9	7.1
<b>BH2</b>	19.1	0.2	0	47673.2	41.6	30657.2	33.7	7.7
<b>BH3</b>	20.2	0.2	0	22962.3	20.9	14919.1	13.9	7.7

Furthermore the percentage of TDS values (see Table 8) above the DWAF, (1996b) and WHO, (2006) is 53%, with the required maximum limit of potable use being between 1000 and 3000 mg/l. According to Cherry & Freeze, (1979) on groundwater classification, this value is of significance as it explains that the concentrations of TDS that are erratically high, with the resultant being very corrosive characteristically. No health effects are associated with high TDS values in water, with the high levels the water may give signs of reluctant taste and odour (WHO, 2006). The mean displayed in Table 4, is compared to International drinking standards and guidelines to the likes of DWAF, (1996b) and WHO, (2006) and as mentioned above, parameters pH and EC fall within the required standards.

Table 4: Average results of the physicochemical parameters compared to various drinking water standards and guidelines

	MEAN	(DWAF, 1996a)	(WHO, 2006)
<b>TEMP</b>	19.0	-	28
<b>DO*</b>	2.6	-	6
<b>DO</b>	0.2	-	-
<b>SPC</b>	31162.8	-	-
<b>EC</b>	27.2	0 - 70	1200
<b>TDS</b>	20197.8	0 - 450	<600
<b>SAL</b>	20.3	-	400
<b>PH</b>	7.4	6.0 - 9.0	7.0 – 9.2

PH values indicate that 92.7% of the sampled groundwater (see Table 6) in the Heuningnes catchment fall within the 6 – 8 group. Water with a low pH is said to be acidic. The groundwater in the catchment leans towards an alkaline characteristic, with only 7.3% of the groundwater samples being more alkaline. Generally speaking groundwater has a pH of 6 to 8.5, as a result the limestone bearing rock in the catchment neutralizes acid effectively. The pH values of the catchment sit comfortably between 6 and 8.

Table 5: Classification of groundwater based on temperature physicochemistry parameter

	MEAN	(DWAF, 1996a)	(WHO, 2006)
<b>TEMP</b>	19.0	-	28
<b>DO*</b>	2.6	-	6
<b>DO</b>	0.2	-	-
<b>SPC</b>	31162.8	-	-
<b>EC</b>	27.2	0 - 70	1200
<b>TDS</b>	20197.8	0 - 450	<600
<b>SAL</b>	20.3	-	400
<b>PH</b>	7.4	6.0 - 9.0	7.0 – 9.2

Table 6: Classification of groundwater based on pH physiochemistry parameter

pH	N	Percentage of samples
<2	0	0
2 – 4	0	0
4 – 6	0	0
6 – 8	101	92.7
8 - 10	8	7.3
10+	0	0
<b>Total</b>	109	100

The classification of salinity is given in Table 7, 48.5% of the groundwater samples sat below the 15 ppt class, this is indicative of Mesohaline waters where these waters are generally found in estuaries where fresh waters mix with salts. It is classed as brackish waters. Euhaline waters salinity vary between 30 and 35 ppt, 16.8% of the sampled groundwater in the catchment have a higher salinity, however the higher salinity is a result of the underlying lithology that the groundwater flows through as it increases its salinity on its flow path.

Table 7: Classification of groundwater on salinity physiochemistry parameter

Salinity	N	Percentage of samples
<15	49	48.5
15 – 29	27	26.7
30 – 45	17	16.8
46 – 59	7	6.9
60+	1	1.0
<b>Total</b>	<b>101</b>	<b>100</b>

Table 8: Classification of groundwater based on TDS physicochemistry parameter

TDS mg/l	N	Percentage of samples
<20 000	55	53.4
20 000 – 27 000	19	18.4
28 000 – 36 000	16	15.5
37 000 – 44 000	5	4.9
45 000 – 52 000	6	5.8
52 000 – 59 000	1	1.0
60 000+	1	1.0
<b>Total</b>	<b>103</b>	<b>100</b>

In accordance to Richards, (1954) the EC values stand majorly between 15 and 39 mS/cm at 37.9% of the groundwater samples concentrated in this area (see Table 9). EC values in this range are categorized as a very high salinity, whilst 35% tend to have lower salinity's but it is still considered to be of high value, resulting from the path the groundwater follows as it flows through the underling lithologies of the Heuningnes catchment.

Table 9: Classification of groundwater based on electrical conductivity physiochemical parameter

<b>EC mS/cm</b>	<b>N</b>	<b>Percentage of Samples</b>
<b>&lt;15</b>	36	35.0
<b>15 – 39</b>	39	37.9
<b>40 – 64</b>	22	21.4
<b>65 – 89</b>	6	5.8
<b>90+</b>	0	0.0
<b>Total</b>	103	100

Table 10: Classification of groundwater based on specific conductance physicochemistry parameter

<b>SPC</b>	<b>N</b>	<b>Percentage of Samples</b>
<b>&lt;30 000</b>	54	52.4
<b>30 000 – 47 000</b>	25	24.3
<b>48 000 – 65 000</b>	15	14.6
<b>66 000 – 83 000</b>	7	6.8
<b>84 000+</b>	2	1.9
<b>Total</b>	103	100

Table 11: Correlation matrix of the groundwater physicochemical parameters in the Heuningnes catchment 2016/2017

	Temperature	DO %	DO mg/l	SPC $\mu\text{s/cm}$	EC mS/cm	TDS mg/l	Salinity ppt	pH
<b>Temperature</b>	1							
<b>DO %</b>	-0.058	1						
<b>DO mg/l</b>	-0.061	<b>0.998**</b>	1					
<b>SPC <math>\mu\text{s/cm}</math></b>	-0.054	0.202*	0.220*	1				
<b>EC mS/cm</b>	-0.031	0.186	0.203*	<b>0.998**</b>	1			
<b>TDS mg/l</b>	-0.098	0.219*	0.236*	<b>0.947**</b>	<b>0.945**</b>	1		
<b>Salinity ppt</b>	-0.097	0.213*	0.232*	<b>0.967**</b>	<b>0.965**</b>	<b>0.975**</b>	1	
<b>pH</b>	-0.400**	0.036	0.040	<b>-0.299**</b>	<b>-0.305**</b>	<b>-0.348**</b>	<b>-0.321**</b>	1

**BOLD** Correlation is significant at the 0.01 level (2-tailed).

\* Correlation is significant at the 0.05 level (2-tailed)

#### 5.4 Discussion on the vulnerability of aquifer to potential pollution

Previous literature survey states TDS values flowing through the TMG aquifer are usually low in the catchment and pH levels of 6 to 8 in the higher lying areas of the catchment. The perimeter of the Soetendalsvlei portrays EC readings in the region of 300 to 700 mS/m. Readings of between 4000 mg/l and 5000 mg/l and 50 mS/cm and 60 mS/cm for TDS and EC respectively were expected in the F region of the catchment as it is situated very close to a river that suggests waste running into it. Furthermore the bad odour surrounding the area is a result of defecation from the livestock being used for fertilizer. Suspected fertilizer use causes alterations in the quality of the groundwater in this area. However upon measurements taken from the F region there was unusual spike in levels of pH, EC as well as TDS values. These values of the parameters are higher on average than other sampling sites across the catchments well points.



Preceding literature of the study area explains the physicochemical parameters of the Heuningnes catchment, giving a broad perspective of the groundwater quality in the study area. It had been estimated that the groundwater entering the Soetendalsvlei has an EC of between 400 and 1000 mS/cm, these readings dependent on seasonal rainfall and groundwater recharge. The water entering the wetland is also alkaline and brackish due to the limestone bearing Strandvelds and Bokkeveld shale's it flows through (Gordon, 2012).

The groundwater physicochemistry is focused primarily on characterizing in situ subsurface conditions of the water quality in the study area. As stated above, the main physicochemical properties measured in the field are **Temperature (°C)**, **Dissolved Oxygen (% , mg/l)**, **SPC (µS/cm)**, **EC (mS/cm)**, **TDS (mg/l)**, **SAL (ppt)** and **pH** levels. These parameters are explained in detail below, giving the description of them as well as how they play a role in determining the quality of water, with the outcome focused mainly on whether the groundwater in the area is fit for human consumption and agricultural use.

The highest conductivities were recorded during late autumn, early winter ranging from 2.75 to 4.2 mS/cm<sup>-1</sup>. In the north of the Soetendalsvlei, the readings of EC were around 2.64 mS/cm<sup>-1</sup> and in the south of Soetendalsvlei the readings of EC were around 2.1 mS/cm<sup>-1</sup>. In the Voelvrei region the lowest EC readings comprised of 2.2 mS/cm<sup>-1</sup> (Gordon, 2012). In the wetland the pH levels remained fairly alkaline from 8 to 9 throughout this particular study period. The highest recorded pH levels was in the wet season with a reading of 9.14, whereas the lowest recorded pH level in the catchment was at a reading of 6.38 in the dryer months.

The TDS values from the groundwater in the TMG group are usually low. The EC readings in this group are between 50 and 150 mS/m, with pH levels of between 5 and 6. In the Bokkeveld group the groundwater EC readings are between 500 and 1000mS/m, unfit for human consumption. The groundwater abstracted from the TMG aquifer between Koppie Alleen and Struisbaai yield poor quality of water with EC readings in excess of 300 mS/m (Cleaver & Brown, 2005).

Voelvrei and Soetendalsvlei are moderately saline with EC readings between 300 to 700mS/m whereas smaller pans to the likes of Soutpan, Melkbospan, Vispan are strongly saline with EC readings in the region of 2460 to 13230 mS/m. The water in the upper mountain region streams

has a relatively low pH of around 4.5 to 5 and the EC readings around 43 mS/m. The pH of the water in most of the lowland wetlands varies from 6 to 8 (Cleaver & Brown, 2005).

The electrical conductivity is a reliable indicator of salinity and can be rapidly accomplished at negligible cost. The salinity of the groundwater in the region of the Nuwejaars River had EC readings of around 40 mS/m in the wet season and around 400 mS/m in the drier periods. The quality of the groundwater is poor in the north of the Soetendalsvlei, with EC readings exceeding 1000 mS/m in the dry season and a decrease in the wet season to around 300 mS/m. It can be said that the recharge of the groundwater brings the salinity of the groundwater down (Norman et al., 1999). Groundwater abstracted from the aquifer in the higher lying areas of Napier have EC readings of 32 mS/m, of good quality (Rasmussen et al., 1998).

DO is a measure of how much gaseous oxygen is dissolved in the water. Dissolved-oxygen concentrations fluctuate with water temperature seasonally as well as diurnally (daily). Groundwater sources usually contain a low level of dissolved oxygen (DO) compared to surface waters. A DO level less than 1.0 mg/L is considered anaerobic (Castle & Nemeth-Harn, 2007). Dissolved oxygen readings in the catchment is relatively consistent throughout, with DO readings values between 0.01 and 0.02 mg/l. be that it is consistent throughout the wet and dry season.

The Specific conductance, which is also known as the specific conductivity, is the physicochemical parameter that measures the ability of water to conduct electricity, i.e. the amount of energy that can be transmitted through a material or substance. The specific conductivity is stated in  $\mu\text{S}/\text{cm}$  (micro Siemens per centimetre). Sanders, (1998) states that typical specific conductance of groundwater (freshwater) is in the region of 50 to 50 000  $\mu\text{S}/\text{cm}$  and as a result is temperature dependant.

Electrical conductivity is widely used as an indicator of the dissolved salts in groundwater. This property has significance as it has the advantage of being easy to measure in the field. It is said that the higher the EC becomes the characteristics of the groundwater portrays it being more dissolved salts in the groundwater (Davidson & Wilson, 2011). The EC readings in the catchment vary at different regions, past literature as well as (DWAF, 1996b) and (DWAF, 1996a) are used as a relative comparison for groundwater quality.

Total dissolved salts is indicative of the salinity behaviour of groundwater, the way groundwater obtains its TDS is as a result of its chemical weathering to sub surface lithology's (Ecjhao & Dandwate, 2012). The measurements of TDS are of significance as it conveys a peculiar taste to water and hence results in its potability being reduced. It is stated that the desirable limit for domestic and agricultural use is 300 mg/l and 585 mg/l respectively whereas the maximum allowed limit is 500 mg/l and 3000 mg/l respectively. Stated by DWAF, (1996b), the target value for TDS in water for potable use lies between the regions 0 – 450 mg/l. Simply speaking, is the salt content of the water, where TDS and EC values are proportional to salinity (Ecjhao & Dandwate, 2012).

Figure 8 shows the different classes of separated regions where classes generally have between 2 to 3 piezometers and or 1 borehole. The initial class, A, consists of Piezometers 1 and 2. This class is situated at the south of Voelvlei and surrounded by medium amounts of shrubbery and a fair amount of trees as well. The piezometers are on the premises of a holiday home, with water storage tanks on site for the use of the household. It is expected that the groundwater quality should be on par with target water quality.

Class B is located in the NNW banks of Voelvlei. In winter months the vlei nearly encapsulated the 2 piezometers (3 and 4) at this location as the water levels of the vlei rise. Towards the west of this class is higher lying ground which has a predominant use for agriculture, in a manner for livestock grazing (sheep) and crop yields.

Class C is situated on the south easterly banks of Voelvlei and also contains 2 piezometers (5 and 6) on a sloped region. This class region has had recently a holiday home built nearby, with the dominant land use here being agriculture, where it focuses mainly on crop yield in the vicinity.

Classes D and E is situated mainly towards the north of the G50C catchment. Class D and E contains 5 piezometers (7, 8, 10, 11, 12). Its land use is mainly focused on crop yield and livestock.

On accounts, piezometers can found to be vandalized by livestock and need on site repairs. In winter months this region is completely water logged and tends to be inaccessible as the water table surpasses the land surface. Class F, which is centrally located on the catchment, contains two piezometers (13 and 14). It is situated very close to the Nuwejaars River, where it seems to be having waste running into it. The odour of the region is very bad as a result of the livestock faeces being used for fertilizer production. The water quality in the area is expected to be on poor quality in this specific area.

Classes G and H are situated not too far from one another, both G and H have 2 piezometers and one borehole each. The Nuwejaars River also cuts through these classes and separates them. Class G is located on the premises of SAN Parks offices. The land use here is very similar to H where they both share areas dominated by shrubbery and scattered vegetation, which the vegetation cover is mainly that of Fynbos. Class H is located in the western borders of the Soetendalsvlei. It is based on agricultural land that is not in current use. As stated, shrubbery and vegetation dominate the area.

Class I contains just 2 two piezometer (19 and 20), located nearby a weather station at the highest tip of the Soetendalsvlei, surrounded by very white sands. It does lay on agricultural land with heavy articulated vehicles frequenting the area. Let it be known, this area is not far off from a dump site. Class J is the final class and is located on the eastern banks of the Soetendalsvlei. This land is occupied by a cottage where the dominant land use here is generally recreational, occasionally livestock graze the land.

## G50C classes areas

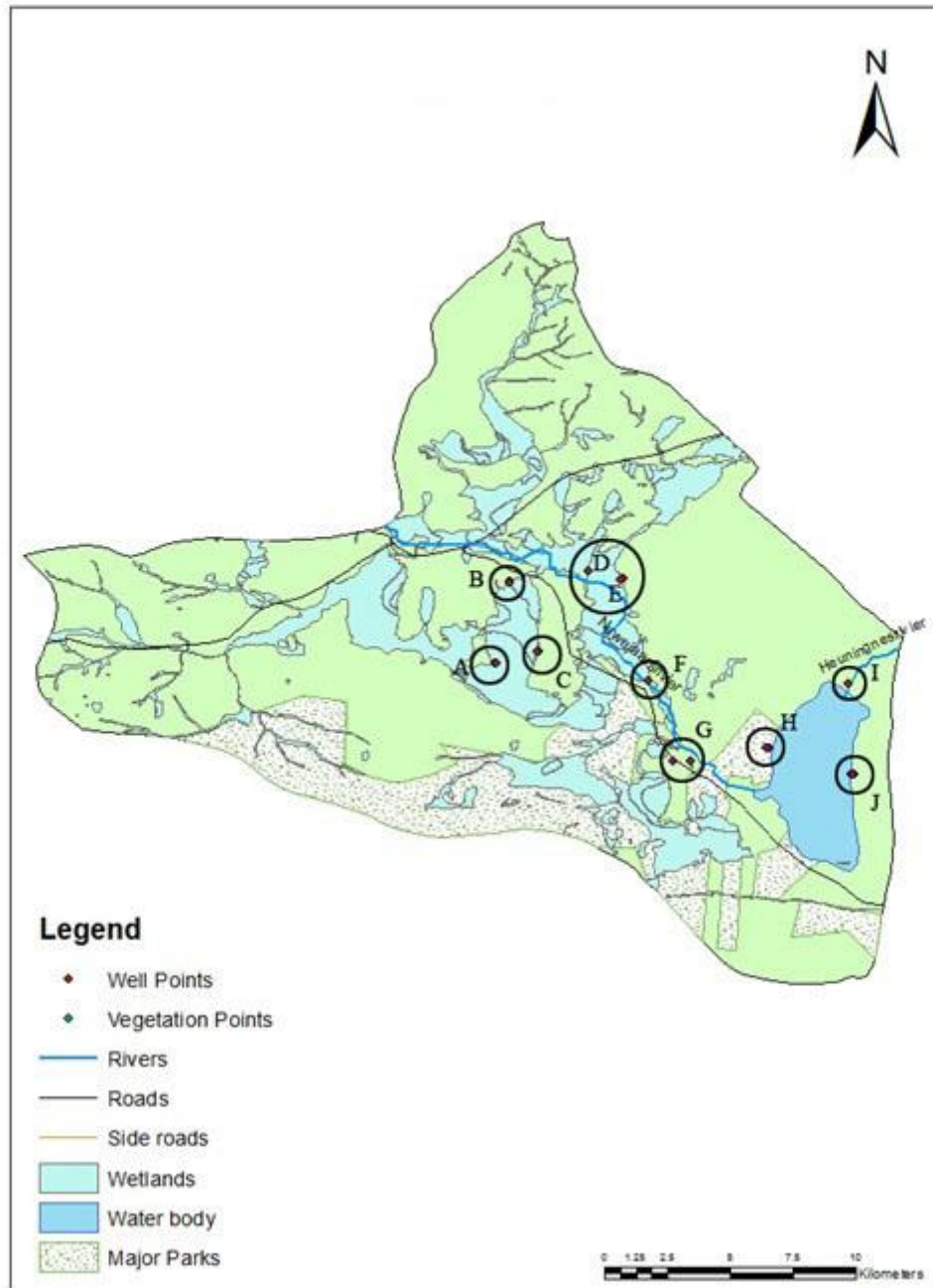


Figure 8: Illustrating all the well points in the area and the class distribution

It is clearly illustrated firstly that DO% and DO mg/l have a positive correlation, as one variable increases the other increases with their  $r$  value of 0.998 it is a very strong positive correlation. SPC's correlation with EC and TDS is of a very strong positive nature. The Pearson value of 0.998 and 0.947 states a positive correlation, hence when SPC increases in value, so does TDS and EC. The  $r$  value between EC and TDS is 0.945, this is indicative of a highly positive correlation with EC. Though there is a close relationship between TDS and Electrical Conductivity, they are not the same thing. The relationship between TDS and EC is often described by a constant and as a result the positive correlation indicates that if TDS values increase the EC values increase as well. Furthermore pH has a negative relationship with several parameters, that of Temperature, SPC, EC, TDS and Salinity. As these physicochemical parameters decrease or increase, the pH value will increase or decrease respectively. It can be said that most physicochemical properties have a linear relationship with one another.

## **5.5 Summary of chapter**

In summary, the chapter presented and discussed the findings from the hydrochemical analysis of the groundwater in the catchment in relation to the physicochemical properties. The characterization of groundwater hydrochemistry through correlation of the physicochemical properties was utilised by the Principal component analysis (PCA) as well as Cluster analysis. Following the Cluster and PCA analysis the major physicochemical characteristics were pointed out and classed regionally across the catchment to portray areas with their altering characteristics. The defining conclusion to the chapter states that most physicochemical properties have a linear relationship with one another.

## **Chapter 6: Determining the groundwater levels using geostatistical, geospatial and risk assessment tools**

### **6.1 Introduction**

This chapter was aimed at reviewing the findings of DRASTIC parameters through the analysis of the vulnerability index map. It refers to the third objective, which was to establish groundwater levels using geostatistical, geospatial and risk assessment tools to predict the risk of the groundwater's potential risk to pollution. It speculates that all seven parameters of DRASTIC will give an accurate estimation to the potential risk to contaminants in the Heuningnes catchment. The vulnerability index map is derived from the DRASTIC vulnerability index equation. The chapter uses geostatistical as well as geospatial analysis tools to determine the groundwater vulnerability's potential risk to pollution of the Heuningnes catchment.

All seven parameters of DRASTIC have vulnerability maps that are assessed and developed individually before being overlaid and combined to form the final vulnerability index map. In planning to achieve this objective each DRASTIC parameter had been subjected to ArcMap with their data manipulated using ArcMaps Spatial analyst tool to interpolate and portray the parameters data in a manner that is simpler to interpret i.e. the vulnerability layers. Consequently, the vulnerability maps illustrate initially the extent of the vulnerability by their assigned rating to the Heuningnes catchment. Furthermore the IDW method is used to prepare the vulnerability map to potential pollution.

## 6.2 Methods used

Geostatistical and geospatial analysis of DRASTIC parameters play a major role in the generation of the maps to be interpreted. In ArcMap the geostatistical analyst tool utilizes sample points taken at different locations, thus being the locations of the piezometers and boreholes in the Heuningnes catchment. The tool then interpolates the data attached to these locations to generate a continuous surface. The data attached to the locations are that of depth to water levels, topography, net recharge levels, aquifer media, soil media, impact of the vadose zone and as well as hydraulic conductivity. Hence the geostatistical analyst tool derives an accurate surface using the attached data from the locations of the wells to predict values for each location in the landscape.

Geospatial analysis is the subsequent tool used for the interpretation in ArcMap. Geospatial analysis is the ability to analyse, synthesize and draw conclusions from massive amounts of geographic data. The various data types used in the construction of the overlay maps are summarized in Table 12. The locations of each well in the catchment were digitized accompanying the dataset it consists of. Furthermore, the definitive goal of the vulnerability results generated from GIS is the subdivision of the catchment into several hydrogeological units with different levels of vulnerability. The groundwater's potential threat to pollution in the catchment is assessed by combining DRASTIC with the GIS analysis tools as discussed above. For the purpose of interpolation, the tool Inverse Distance Weighting (IDW) was used. IDW uses the measured values surrounding the locations of the wells in the catchment (Asadollahfardi et al., 2015), it predicts the measured values from the location of the wells that are closest to it and have more influence on the predicted value than those farther away. IDW technique is a useful tool to observe the over-all trend of the area as well as giving accurate estimations of absent data. Dorsey-spitz, (2015) and researchers concluded in their study that IDW is the suitable method of interpolation to estimate groundwater quality variables in Urmia, Iran, thus in the Heuningnes catchment, IDW is as well the most preferred method to interpolate data as opposed to kriging or co-kriging.



Table 12: DRASTIC index parameters weights and ratings for the G50C catchment, Heuningnes

DRASTIC Index Parameters	Rating	Weight
Depth to water		
0 – 1.5	10	5
1.5 – 4.6	9	
Net Recharge		
0 -50.8	1	4
Aquifer Media		
Metamorphic/Igneous	3	
Thin bedded Sandstone, Limestone, Shale sequence	6	
Massive Sandstone	6	3
Massive Limestone	7	
Sand and Gravel	8	
Soil Media		
Gravel	10	2
Sand	9	
Shrinking and/or Aggregated Clay	7	
Clay Loam	3	
Topography		
0 – 2	10	1
1 – 6	9	
6 – 12	5	
12 – 18	3	
18+	1	
Impact of the Vadose zone		
Shale	5	
Sandstone	7	
Bedded Limestone, Sandstone, Shale	6	5
Metamorphic/Igneous	4	
Sand and Gravel	8	
Hydraulic Conductivity		
$4.72 \times 10^{-7} - 4.71 \times 10^{-5}$	1	3

Furthermore, some land regions in a study area are more prone to groundwater contamination than others, thus an aquifer vulnerability map portrays areas of vulnerability classifying direct areas into several levels of vulnerability. The levels of vulnerability are important to understand. Foster et al., (2004) defines areas that are more vulnerable to potential pollution than others on the basis of hydrogeological and anthropogenic factors. *Table 13* tabulates the vulnerability class definition

developed by Foster et al., (2004). When individual DRASTIC parameters are assigned weights it is evaluated with respect to each parameter to determine the relative importance of each factor (Table 12). The higher the weighting numbers the more significant the factor (Al-abadi et al., 2014).

Table 13: Aquifer vulnerability class (Foster et al., 2004)

<b>Vulnerability class</b>	<b>Resultant definition</b>
Extreme	Vulnerable to most water pollutants with rapid impact in many pollution scenarios
High	Vulnerable to many pollutants (except those strongly absorbed or readily transformed) in many pollution scenarios
Moderate	Vulnerable to some pollutants but only when continuously discharged or leached
Low	Only vulnerable to conservative pollutants in the long term when continuously and widely discharged or leached
Minor	Confining beds present with no significant vertical groundwater flow leakage

Table 14: Description of weights in DRASTIC

<b>Weight</b>	<b>Significance</b>	<b>Description</b>
1	Least	Negligible contribution in factors that have an impact on an aquifer
2	Less	Little effect in enhancement or reduction of vulnerability due to the feature
3	Moderate	Medium effect
4	More	Consideration in the assessment process AND is crucial due to its properties in Relation to aquifer vulnerability.

## 6.3 Key results on groundwater levels

### 6.3.1 Depth to water level

The depth to water reading is the level of the water in the wells situated across the entire catchment. The depth to water readings were calculated by subtracting the level of the height of the well to the ground surface. The depth to water levels in the G50C catchment were classed into two ranges following Aller et al., (1987) system of classification, putting them in a shallow water level bracket. It can be stated that the shallower the water level is the more susceptible the groundwater will be to potential pollution (Aller et al., 1987). Within the G50C (Figure 8) catchment of Heuningnes, the groundwater depth to water readings vary from 0.5m to deeper readings of 3.4m. These readings displayed in Figure 8 were taken over a period of one year, with the measurements all taken from 23 piezometers and 3 boreholes giving a total well points of 26 in the catchment with data. In G50C the lowest readings of depth to water was taken at the northern section of the catchment at 0.5m shallow. The deepest depth to water reading point was taken at a more central point of the catchment and a reading of 3.4m.

Table 15: Range and ratings for the depth to water layer (meters)

<b>DRASTIC index rating</b>	
Range	Rating
0 -1.5	10
1.5 – 4.6	9

# G50C Depth to water

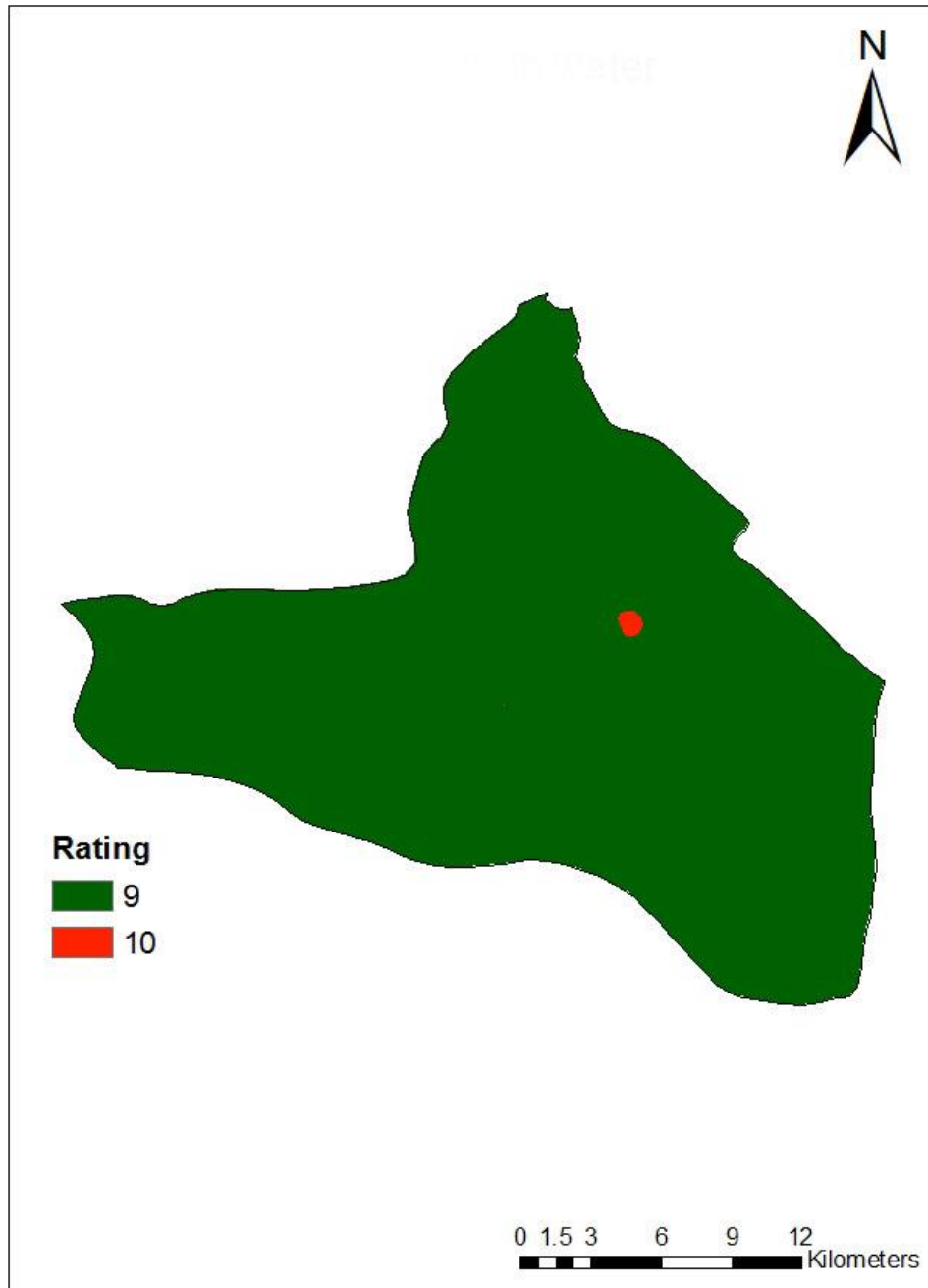


Figure 9: Depth to water rating map

### 6.3.2 Net recharge

The Net recharge is represented by precipitation which infiltrates through the surface of the ground and percolates to the water table (Aller et al., 1987). The local recharge of the study area was determined by rainfall averages over a significant period of one year. The rainfall readings in mm over the year ranged from 13.562 – 17.59 mm. Figure 10 displays the rainfall averages across the entire G50bc catchment with high readings of rainfall occurring to the north of the catchment in higher lying areas. The lower readings of rainfall occurred toward the centre of the catchment where the underlying terrain is relatively flat.

Table 16: Range and rating for net recharge

<b>DRASTIC index rating</b>		
Range		Rating
0 -50.8		1

G50C Net recharge

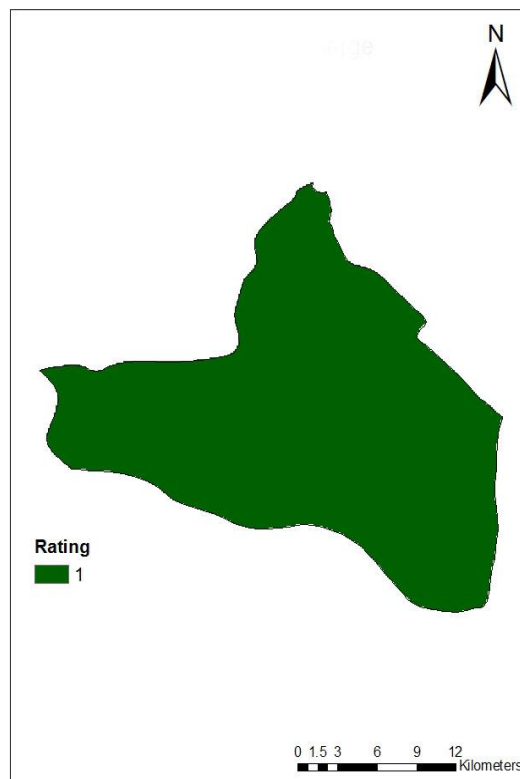


Figure 10: Net recharge rating map

### 6.3.3 Aquifer media

Aquifer media is the saturated permeable geologic formation. It contains and transmits water in economic amounts under ordinary hydraulic gradients for water supply and has generally sand and gravel media. Aquifer contamination potential depends on the amount and sorting of grain sizes. Generally, aquifer permeability increases with the grain size and fractures, thus the greater the pollution potential for the aquifer. Figure 11, prepared by the hydrogeology and lithology's of the Heuningnes catchment, illustrates rating factors. These ratings were assigned to the regions of high permeability with larger weightings as opposed to regions with low permeability that receives weights and ratings of lower values.

Table 17: Range and ratings for the aquifer media layer

<b>DRASTIC index rating</b>	
Range	Rating
Thin bedded Sandstone, Limestone, Shale sequence	6
Sand and Gravel	8
Weathered Metamorphic/Igneous	3
Massive Sandstone	6
Massive Limestone	7

## G50C Aquifer media

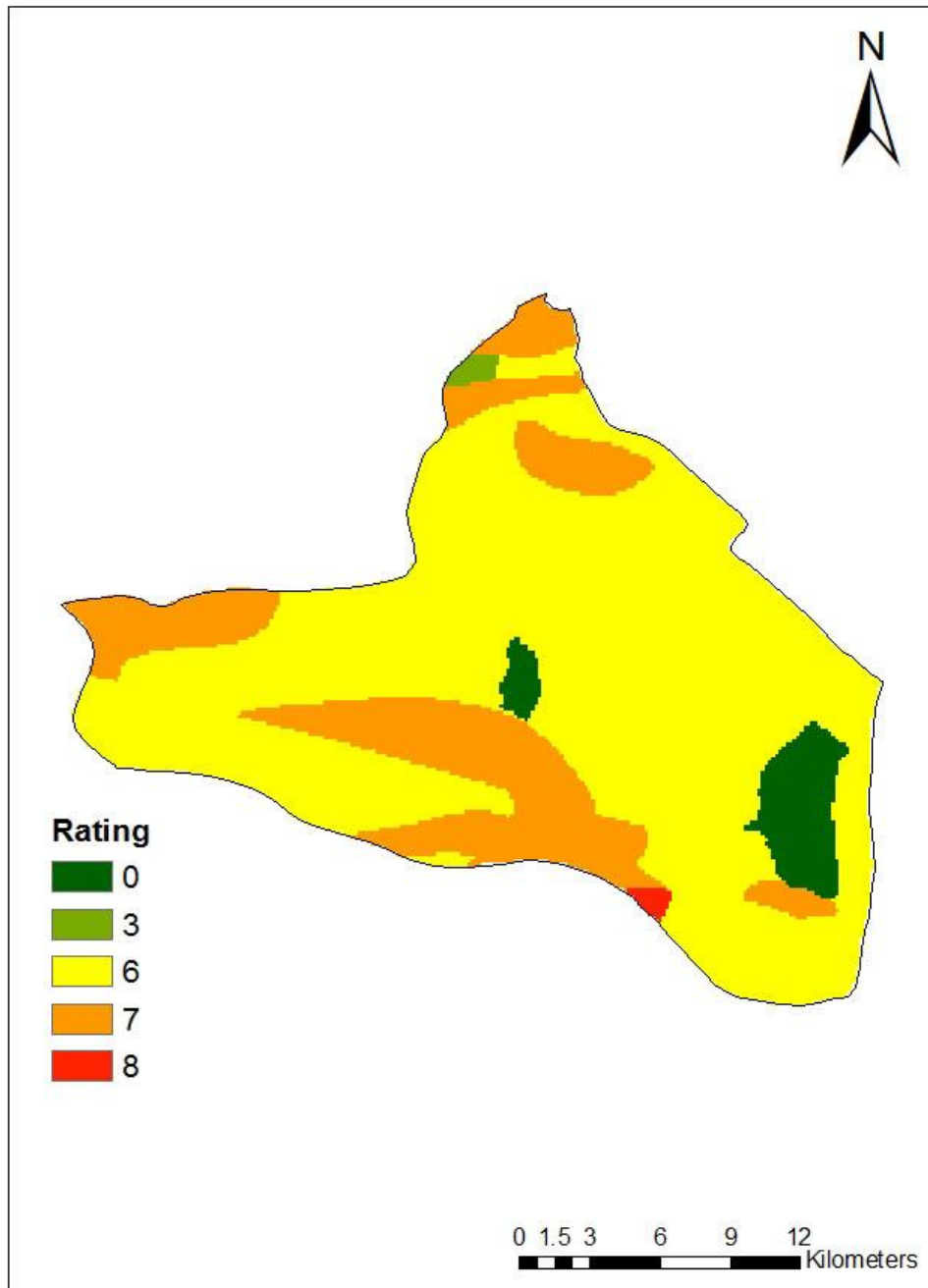


Figure 11: Aquifer media rating map

### 6.3.4 Soil media

The soil media refers to that uppermost section of the vadose zone characterized by the relevant biological activity (Aller et al., 1987). The soil data was determined from online soil data as well as field work assignments, auguring of the soil. Table 18 illustrates the sampling site with average depths of auguring to 3 meter increments. The soil types: Sandy Loam, Loam, Loamy sand and Silt loam (See Table 1). In Figure 12 it displays the soil type across the G50BC catchment. The GIS map (Figure 12) displays soil type of shallow gravelly material to clay material. In essence, the soil types are then classed into their independent characteristics according to their porosity. A soil type like clay loam will be given low ratings as it is very difficult for recharge to percolate through this media. An increase rating is awarded to media types with the likes of gravel and/or sand as recharge has a much easier path to travel with very little resistance as it makes its way to the water table.

Table 18: Range and ratings for the soil media layer

<b>DRASTIC index ratings</b>	
Range	Rating
Gravel	10
Sand	9
Shrinking and/or Aggregated Clay	7
Clay Loam	3



## G50C Soil media

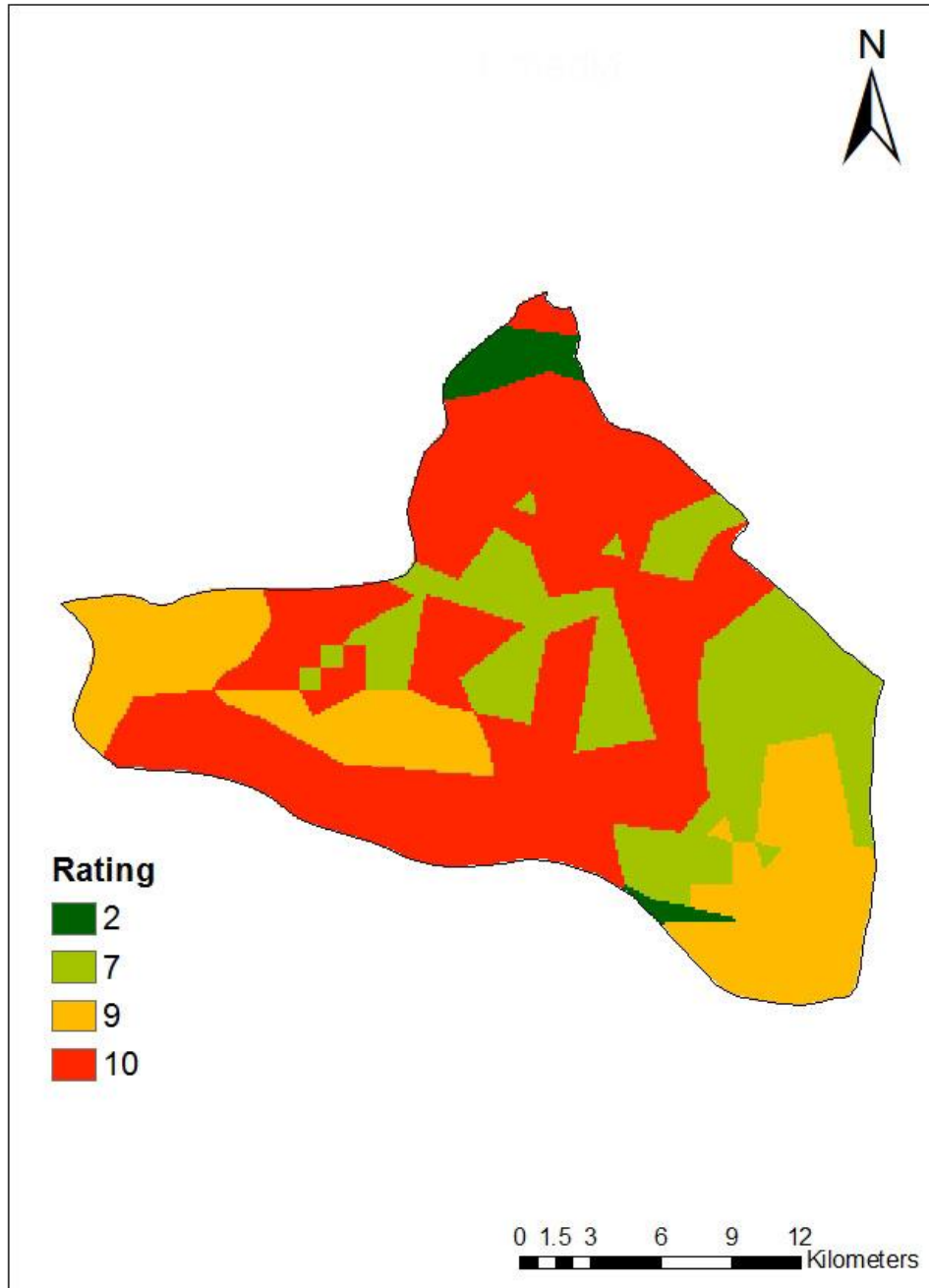


Figure 12: Soil media rating map

### 6.3.5 Topography

The topography of the Heuningnes catchment is of a relatively flat laying floodplain (see Figure 13). The topography is referred to as the slope of the catchment. It is indicative of whether the runoff in the catchment will remain in the surface, stagnantly to infiltrate or move at a pace towards lower laying areas. The main high lying areas in the catchment are the Soetanyberge in the north of the catchment, which peaks at a maximum altitude of 2000 mamsl. In the south of the catchment the mountain range of Bredasdorp is located with an altitude of 1800 mamsl. In-between these ranges the average altitude is near sea level, indicative of the floodplain.

The topographical data achieved to be analysed was obtained from the USGS Landsat imagery. A topographical layer in the form of a Digital Elevation Model (DEM) is acquired through them. The DEM is then analysed using ArcMaps geospatial analysis tools. With topography being analysed as part of this chapter, the slopes are categorized into the ranges with weights and ratings assigned to them.

Table 19: Range and ratings for the topography later (%)

<b>DRASTIC index rating</b>	
Range	Rating
0 – 2	10
2 – 6	9
6 – 12	5
12 – 18	3
>18	1

# G50C Topography

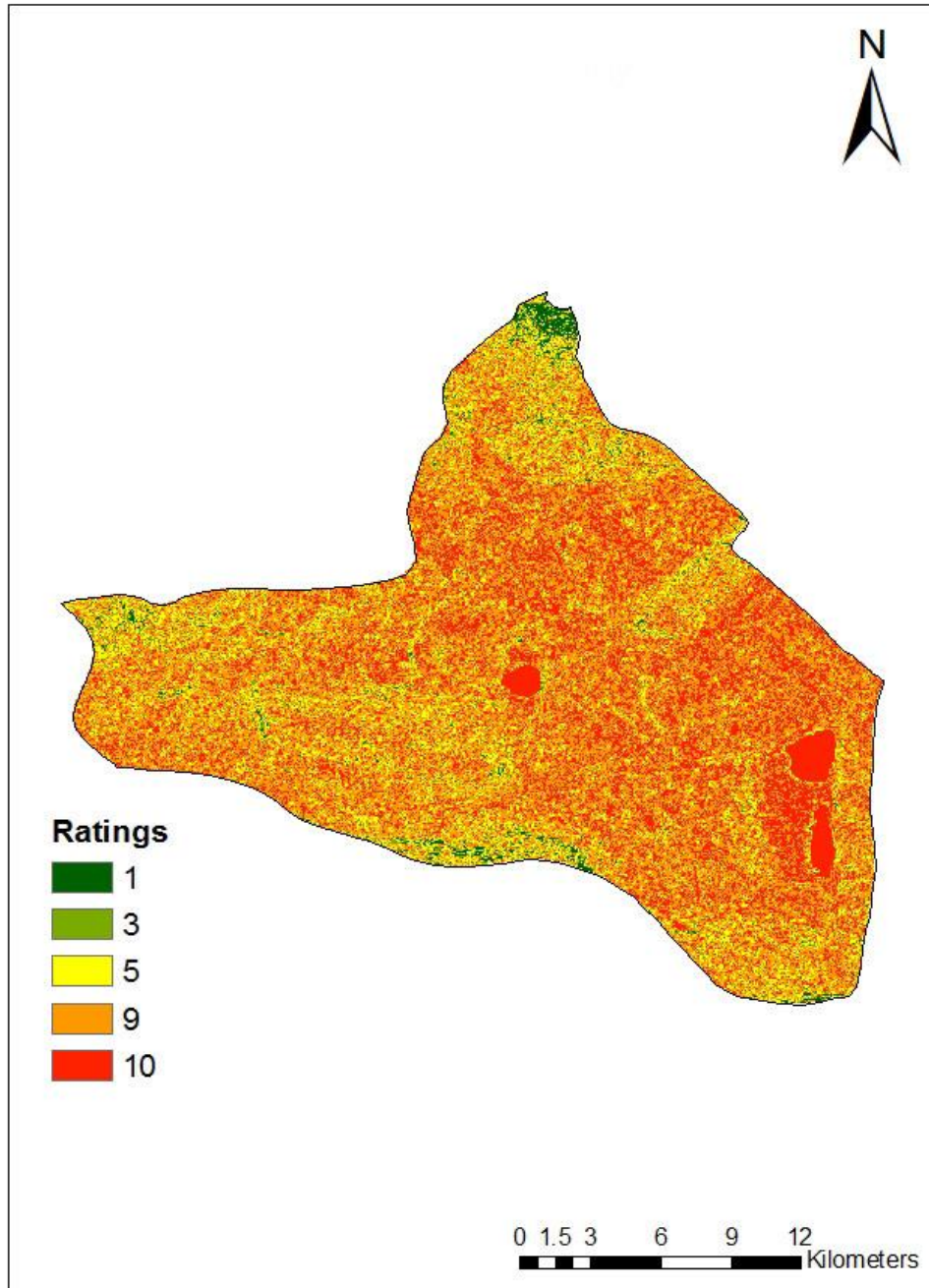


Figure 13: Topography rating map

### 6.3.6 Impact of the vadose zone

The vadose zone, defined as the zone above the water table that is unsaturated (Aller et al., 1987). Significance of the vadose zone lies within its type of media, which in essence determines the attenuation capacity of the materials between the soil horizon and the water table. The vadose zone media type laid mainly between sandstone, shale and limestone bearing lithology. Figure 14 illustrates the ratings attained to the impact of the vadose zone parameter. The ratings ranged from 0 for water bodies i.e. Soetendalsvlei and Voellevlei up to 8, indicative of sand dunes or gravel area. *Table 20* describes the ratings of each significant range in this parameter. A rating of 6 and 7 dominates most of the study area which is assigned to Limestone, Sandstone as well as shale, with the typical rating according to (Aller et al., 1987).

Table 20: Range and ratings for the impact of the vadose zone

<b>DRASTIC index ratings</b>	
Range	Rating
Bedded Limestone, Sandstone, Shale	6
Sand and Gravel	8
Sandstone	7
Shale	5
Metamorphic or Igneous	4

## G50C Impact of the vadose zone

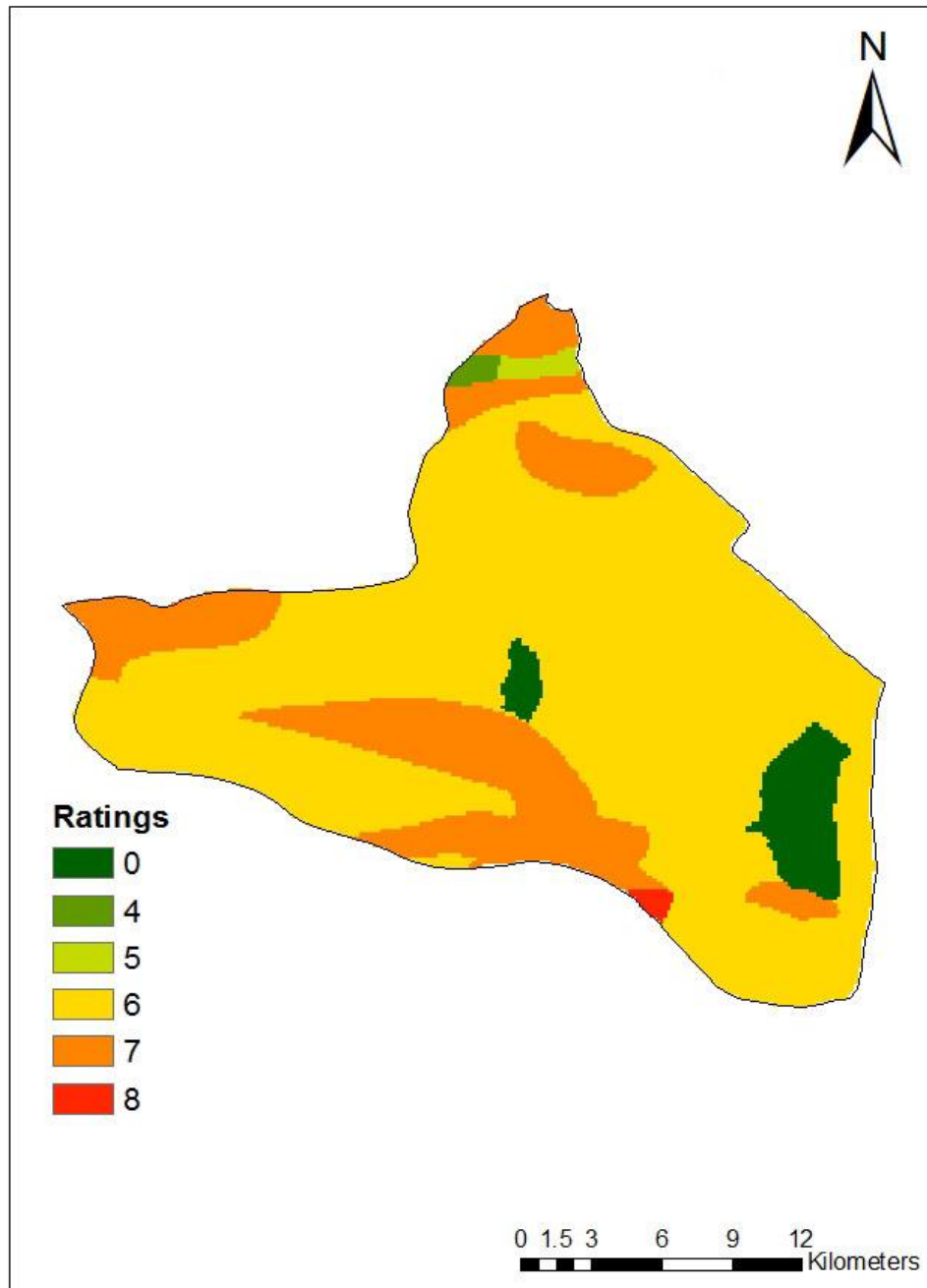


Figure 14: Impact of the vadose zone map

### 6.3.7 Hydraulic conductivity

This parameter refers to the ability of the aquifer materials to transmit water. It controls the rate at which groundwater will flow at a given gradient. Within the G50C catchment the hydraulic conductivity values varied between  $4.68 \times 10^{-7}$  to  $4.37 \times 10^{-5}$ . The hydraulic conductivity increases with the groundwater flow as well as potential pollution. The consequence of this is the raising aquifer vulnerability. The data obtained for the hydraulic conductivity came from field work in the form of pumping tests as well as slug tests. The in the westerly region of the G50C catchment (Figure 15) the hydraulic conductivity is higher compared to the easterly region of the catchment, but remains in the set first range of ratings, achieving a rating of 1 across the entire catchment. The westerly region is awarded a higher DRASTIC rating and the easterly region of the catchment awarded a lower DRASTIC rating.

Table 21: Range and ratings for the hydraulic conductivity layer (m/sec)

<b>DRASTIC index ratings</b>	
Range	Rating
$4.72 \times 10^{-7} - 4.71 \times 10^{-5}$	1

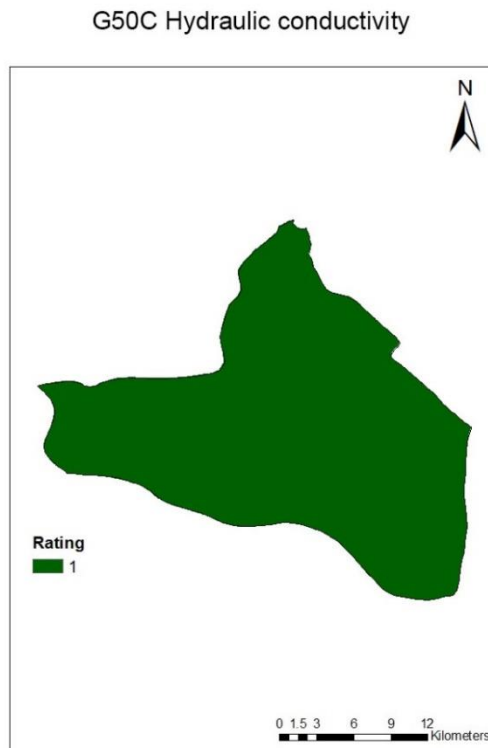


Figure 15: Hydraulic conductivity map

### 6.3.8 DRASTIC vulnerability map

The study has been implemented in the goal of the assessment of the groundwater vulnerability of the Heuningnes catchment. GIS played a major role in the methodology and data analysis of DRASTIC, where the vulnerability index map was created through this path. The added advantage of GIS is that it provides the user an opportunity to manage their data with minimum effort, simultaneously assisting in the data processing. DRASTIC prepares the vulnerability index map, which can be used as a screening tool to see whether a particular area is more or less vulnerable to potential pollution. The seven layers of DRASTIC were created in the ArcMap software, where it was assigned specific rating and weighting values that represents their contribution to vulnerability. The parameters data layers were obtained from different sources that are mentioned in the above subsequent chapters.

Following the creation of the seven parameters maps, the vulnerability index map was created by overlaying all seven maps by the rules of the DRASTIC equation carefully following the assigned weight of each parameter to give an accurate estimation. The depth to water table and impact of the vadose zone carry the highest weights of the seven parameters. Consequently these two parameters dominate the vulnerability map in terms of their individual calculated ratings. Shown in Table 22, the DRASTIC index scores range from 67 -140. Taking into account the range of the DRASTIC index, their classification was based on Natural breaks (Jenks) classification method in order to develop the desired patterns in the map producing 4 classes. Aller et al., (1987) did not propose a vulnerability index classification range, instead left the interpretation of the vulnerability index to the user allowing individuals field knowledge and hydro geological experience to assist their interpretation. For this study the Natural Breaks (jenks) classification was used as category ranges determined random distribution and output poor results which are in turn unreliable. Table 13 provides details of the 4 classes of vulnerability for the study area. The classes begin from Very Low (67 – 90), Low (91 – 110), Moderate (120 – 130) to High (140>) vulnerability.

Table 22: DRASTIC vulnerability map classification classes

<b>DRASTIC Vulnerability map classification (Natural Class, Jenks)</b>	
Range	Vulnerability
67 – 90	Very low
91 – 110	Low
120 – 130	Moderate
140>	High

G50C Vulnerability map

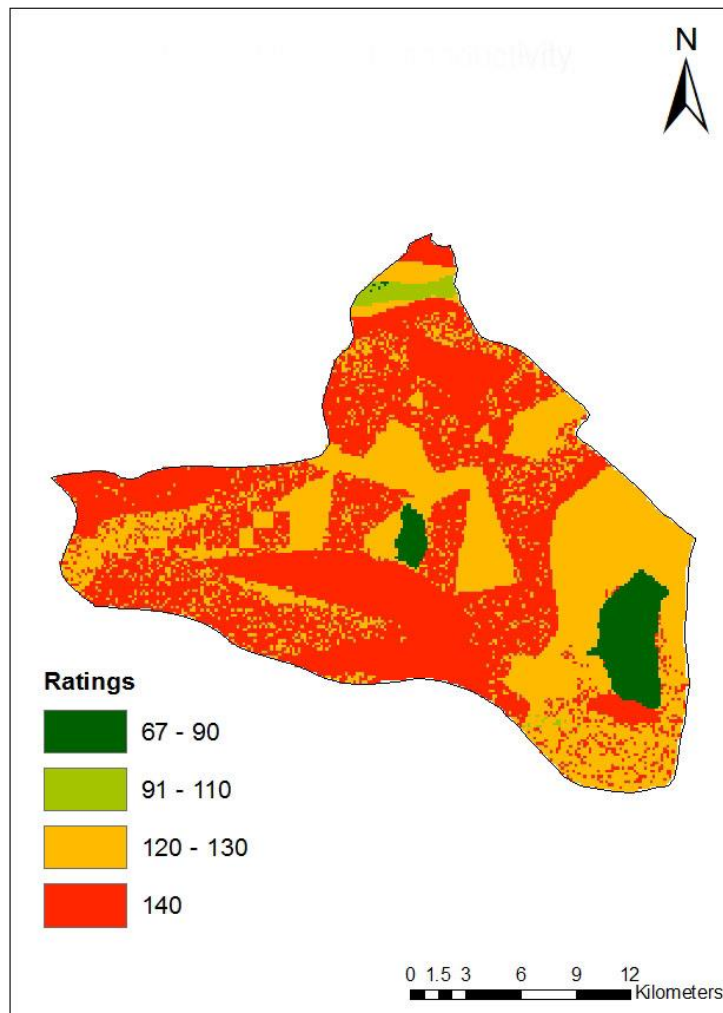


Figure 16: DRASTIC vulnerability index map



## 6.4 Discussion on groundwater levels

Furthermore, the shallower the depth to water readings the more susceptible it is to potential pollution as potential contaminants have a shorter distance to travel to the water table as opposed to a longer paths travelled through various lithology's if the depth to water readings were deeper (Aller et al., 1987). Figure 16 illustrates the vulnerability of the G50C catchment based on depth to water readings. As stated the shallower readings have a higher susceptibility to potential pollution, as indicated in red in Figure 16. The southern half of the catchment has a higher level of potential pollution as it has shallower readings of depth to water, whereas the northern half of the G50C catchment has a deeper depth to water indicated in a green shade (see Figure 16). The northern region of the catchment has a lower susceptibility to potential pollution, which consists of half of the catchment in the North, with average depth to water readings of 1.5m in the north of the catchment.

Areas with low rainfall receive low DRASTIC ratings whereas areas with high readings of rainfall receive high DRASTIC ratings. The higher ratings are as a result of groundwater recharge that is higher. It is a risk because of the permeable pathway from the surface to the water table for potential contaminants to travel.

Regions with higher permeability receive a higher rating as the groundwater percolating has an easier path to travel toward the water table as well as store in the underlying rock type. However, regions with lower permeability characteristics give rise to difficulty of groundwater to percolate through underlying lithology's as well as less storage for groundwater. *Table 17* describes the ratings attained by the aquifer media with it ranging from 3 – 8. The G50C catchment is dominated by ratings from 6 and 7 limestone, sandstone and shale, which have poor characteristics in terms of their permeability. Hence attaining their higher ratings.

In Figure 12 it displays the spread of the soil media. It is noticeable that the shade of red is most dominant across the catchment, evident in the centre and the north. It can be stated that the most dominant soil type is unconsolidated gravel material, which is a high rating media at 9 or 10. The second most dominant soil type is the darker shade of green (Figure 12), sandy soils. Sandy soils is rated nearly the same as above at 8 or 9 (Aller et al., 1987). Toward the north of the map (Figure 12) is a shade of orange, clay dominant soils. These soils achieve ratings of 3, a low rating for their characteristic of low porosity.

A slope with a steep gradient is stated to be of low vulnerability as the run-off is of a higher rate, these conditions allow potential contaminants less time to percolate or infiltrate, travelling to the water table. However, a shallower gradient is rated as a higher vulnerability as the rate of run-off is exceptionally slower than that of a steep slope, giving run-off an increased possibility to percolate or infiltrate, travelling to the water table, giving potential contaminants access to the water table more prone.

Furthermore in the higher lying areas of the catchment are the mountainous areas. These areas are located to the north and south of the catchment (see Figure 13). The higher lying areas have a lower rating of vulnerability. These regions are indicated by green shading on the map. Lower lying areas are indicated by a brighter red shade (Figure 13). This is indicative of shallower gradients and higher vulnerabilities.

To accurately manage and sustain the resources in the study area, this study produces an important tool for those in management of the area, as it contributes a complete indication of the groundwater's vulnerability to potential pollution. The higher the groundwater is to vulnerability makes it unquestionably necessary for local authorities to manage their resources sustainably. The DRASTIC vulnerability map of the G50C catchment in Heuningnes is given in Figure 16. Looking at Figure 16, shades of red are indicative of high vulnerability. The high vulnerability is situated across most of the study area dominating westerly and northerly by at least 87% (366.61km<sup>2</sup>) of the study area under high vulnerability. The shades of orange indicates moderate vulnerability, this moderate vulnerability is situated mainly on the east of the study area. It is said that more than 13% (54km<sup>2</sup>) of the study area falls under the moderately vulnerable zone. The lighter shades of green are indicative of areas under little or no vulnerability. Mainly as the greener shades represent the water bodies of the study area i.e. Soetendalsvlei and Voelvlei. Less than 1% of the study area is categorized as low vulnerability.

## 6.5 Summary of chapter

In summary, the chapter presents the results of the groundwater DRASTIC parameters by the analysis of the overlay maps created on ArcMap. All seven parameters have vulnerability maps that are assessed and developed individually before being overlaid and combined to form the final vulnerability index map. The Natural Breaks (jenks) classification was used as category ranges determined random distribution and output poor results which are in turn unreliable (Table 13) provides details of the 4 classes of vulnerability for the study area. The classes begin from Very Low (67 – 90), Low (91 – 110), Moderate (120 – 130) to High (140>) vulnerability. It is said that more than 13% (54km<sup>2</sup>) of the study area falls under the moderately vulnerable zone.



## **Chapter 7: Conclusion and recommendations**

The groundwater in the study area is at risk of potential threats. Consequently, the use of the information produced by this study will be treated as a guideline for the determination of action plans. It will be then possible to then increase sustainability on groundwater use for the future, as water is of utmost importance. The study encompassed the utilization of risk assessment methods and tools. These methods intend to explain the vulnerability of the aquifer to contaminants establish the groundwater levels and lastly stating the groundwater being at risk to potential threats.

The aquifer is vulnerable to contaminants as it can be said that, with all certainty, the catchment has a shallow water table. The shallow water table coupled with low lying terrain dominating the study area, receives influence of a greater risk to potential contaminants, as run off is minimal towards the centre of the study as opposed to the North of the study area, as recharge originates from the higher lying areas as groundwater flows towards the coast as confirmed by Toens, (1991). On the groundwater's path of flow it travels through geologic medium that renders typically saline and poorer quality of groundwater as a result of the underlying lithology (Toens, 1991). With the study area dominated by mainly agricultural activities, suitable crop production that is appropriately managed to sustain groundwater sources is recommended.

The groundwater levels in the catchment saw the water table being less than 5m, categorizing it as a shallow water table. This is evident throughout the study area. The multivariate statistical method saw the analysis of the physicochemical parameters of the in-situ measurements of the groundwater undergo analysis. Majority of the groundwater physicochemical parameters fall within the international guidelines for drinking as well as agricultural purposes (WHO, 2006). Furthermore, the cluster analysis of the physicochemistry of the groundwater illustrates characteristically linear relationships between majority of the physicochemical parameters. The geostatistical analysis of the study and findings conclude that the quality of the water in the catchment is up to international standards, thus necessary implementation of sustaining the well standard of the water in the catchment is of greater importance

The DRASTIC vulnerability map is the suitable method for regional scale assessment due to the availability of certain parameters, moreover, it may suffer from limitations as the weights and ratings are based on the expert opinion.

The highly vulnerable zones are proven to be 87% coverage of the total study area, which is mainly a result of the underlying lithology from the Impact of the vadose zone, also the shallower water levels from the depth to water parameters, as these two factors share the highest weight ratings. About 12% of the total study area is under moderate vulnerability due to the fact that moving in a more easterly direction of the study area (Figure 16) the depth to water becomes less shallow, soil media alters to a less permeable characteristic, although the topography remains fairly constant at a flat low lying terrain adding to the fact of a moderate vulnerability setting. The conductivity is constant across the entire catchment as the same can be said for the net recharge of the study area. Less than 1% of the total study area is under low vulnerability due to the fact that it contains both Soetendalsvlei and Voelvlei, which are classed as water bodies. Secondly, part of the low vulnerability is the lithology in the North (Figure 16) comprised of steep gradient slopes that assist with recharge and low infiltration giving less time for potential contamination to percolate.

Most of the study area is under high vulnerability, due to the fact that land surfaces and underlying geology of the total study area has poor characteristics in terms of its permeability and percolation of fluid through its medium. Additionally the cause of high vulnerability is the very shallow water levels across the entire catchment that aid in allowing a shorter travel time for potential pollutants to travel towards the groundwater.

This study produced a very beneficial tool to provide an indication of vulnerability to groundwater pollution. The high vulnerability zones that dominate most of the study area makes it absolutely necessary for an introduction of sustainable methods to manage the groundwater resources, monitoring and acting accordingly. It highlighted areas of high vulnerability to low vulnerability, as such high vulnerability zones are difficult to monitor, as it is dependent on many resources to constantly monitor it. The manner of mapping used in this analysis is one of qualitative, depicting the occurrence and distribution of the groundwater's potential to pollution. The assessment is based on the original DRASTIC index by (Aller et al., 1987). The findings suggest that based on the result, the aquifer is vulnerable to potential contamination. Sustainably, routine monitoring of the aquifer is recommended to avoid the further pollution to the already more polluted areas.

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