A GIS-based DRASTIC approach to assessing aquifer vulnerability adapted for intrinsic risks posed by differing land uses (Rustenburg Municipality)

by

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DECLARATION

I, Samuel Jakobus Mostert (26029287), declare that the thesis/dissertation, which I hereby submit for the degree Magister Sciencia Geography at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

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ABSTRACT

Groundwater resources play a vital role in the sustainability of a vast majority of communities world-wide. Various anthropogenic activities (particularly related to agriculture, mining, and other diffuse and point sources of contamination), however, pose a significant threat to the quality of groundwater resources. Once contaminants reach the aquifer, the mitigation thereof becomes expensive and often not readily possible. A proactive approach to the assessment of aquifer vulnerability to contamination, rather than a reactive approach, is thus of utmost importance for the future sustainability of our groundwater resources.

This dissertation deals with the assessment of aquifer vulnerability in the Rustenburg Municipality, South Africa. The assessment of aquifer vulnerability is conducted using a well-known vulnerability index called DRASTIC within a geographical information system (GIS) environment. DRASTIC is an acronym for a set of parameters that characterize the hydrogeological setting and combined evaluated aquifer vulnerability; viz.: **D**epth to water level, Nett **R**echarge, **A**quifer media, **S**oil media, **T**opography, **I**mpact of the vadose zone, and Hydraulic **C**onductivity.

An additional objective is to adapt the current DRASTIC model to account for the potential influence of land surface uses on groundwater resources through the incorporation of land use as a vulnerability factor.

The final vulnerability map shows that the highest vulnerability aquifer rating fell within the range of moderately high vulnerable (7-8) and the addition of the land use variable did not change the highest vulnerability rating. The spatial distribution of the moderately high vulnerable areas, however, was found to vary significantly with incorporation of the land use parameter. GIS proved great compatibility with an aquifer vulnerability model such as DRASTIC.

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CHAPTER 1: INTRODUCTION

1.1 Introduction

The water quality of South Africa is rapidly deteriorating, while the lack of scientific and engineering capacity to counter and mitigate this deterioration is of great concern. Mining activities are one of the known contributors to polluting South Africa's water sources and has recently been brought to light with the public awareness of acid mine drainage.

Groundwater has long been considered a very important, yet fragile, source of potable fresh water on earth. Groundwater can be seen to play a major role not only in maintaining life, but also in directing social development. The South African government has also acknowledged the importance of protecting groundwater resources from contamination and in response, the project "Protocols for assessing groundwater pollution impacts – formulation of a research study" was funded and implemented by the Water Research Commission (Saayman et al., 2007).

Groundwater is considered to form part of the earth's hydrological cycle. It constitutes the part of water in the hydrological cycle that occurs in permeable geological structures defined as aquifers. Aquifer refers to the portion of the subsurface that is completely soaked or saturated with water.

Groundwater is an important and valuable natural resource in South Africa which is rapidly deteriorating as a result of constant anthropogenic pressure. The main anthropogenic activities considered in this study include mining and agricultural practices.

The incorporation of GIS with a well-established vulnerability assessment model such as DRASTIC is seen to offer a powerful, useful and cost effective tool in the initial steps of assigning resources to manage groundwater resources. Aquifer vulnerability assessment

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models such as DRASTIC, however, are limited to the main hydrogeological factors controlling aquifer vulnerability without consideration for any land surface contaminant source (or load). This study seeks to identify the capacity of the application of spatial analyses software, such as GIS, and a known vulnerability assessment model, DRASTIC, and adapt the DRASTIC model through incorporating various land use activities to consider not only the main hydrogeological factors controlling aquifer vulnerability, but to include land surface contaminant sources (or loads). The study further seeks to apply both the DRASTIC and adapted DRASTIC model to the study area (greater Rustenburg Municipality) to provide a visual interpretation of vulnerable aquifer areas.

This study seeks to identify the capacity of the application of spatial analyses software, such as GIS, and a known vulnerability assessment model, DRASTIC. The study further seeks to adapt the DRASTIC model to include intrinsic risks posed by varying land uses to potentially identify various areas of varying vulnerability of aquifers to contamination to best manage or mitigate potential devastating effects on the groundwater supply.

This dissertation contains:

- A brief overview on the earth’s hydrological cycle and potential contamination sources to groundwater (sections 2 and 3)
- A background of water monitoring in South Africa with focus on the 2006 Department of Water Affairs and Forestry’s best practice guidelines (section 4)
- A summary of the global and South African approaches to aquifer vulnerability assessments (sections 5 and 6)
- A summary of various applicable land use impacts on groundwater (Section 7)

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- A detailed description of the methodology used for the compilation of aquifer vulnerability maps using the DRASTIL (adapted DRASTIC approach)approach for the greater Rustenburg municipality (section 8)
- The results from the DRASTIL method applied for the greater Rustenburg municipality (section 9) and a discussion based on the results from this study (section 10)
- A final conclusion based on the findings of this study (section11).

1.2 Problem Statement

Once groundwater is contaminated it becomes very costly to remediate and may take a long time to recover. Consequentially, proactive management of groundwater, where possible, is essential, as contamination from diffuse sources is not only seen as an environmental issue but also as an economic and health concern (Yang et al., 2010).

The constant increase in awareness and understanding of groundwater monitoring management problems has led to a need for information on groundwater quality, quantity and vulnerability, as well as effective monitoring so that remedial action can take place to rectify these problems and prevent their reoccurrence. A pressing need thus presents itself (in regions dominated by large scale anthropogenic activities, such as mining and agriculture) for research into identifying vulnerable aquifer locations and a method to design or potentially optimize a monitoring program. This will aid in better management and the potential mitigation of the contamination of groundwater sources before it reaches a state of non-repair. The use of GIS (Geographical Information Systems) for designing groundwater monitoring programs on a regional scale in South Africa is fairly limited.

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1.3 Aim

The aim of this research is to assess the potential of the DRASTIC approach for aquifer vulnerability mapping for the greater Rustenburg Municipality. Additionally, intrinsic impact ratings of several land use practices will be incorporated in an attempt to identify areas of varying vulnerability of aquifers to contamination.

1.4 Objectives

Research contained within this study seeks to provide insight into the integration of the DRASTIC model, as well as its possible adaptation to incorporate various land use factors, within the Geographical Information System (GIS) environment and its application for assessing the vulnerability of various aquifers to contamination. The DRASTIC and adapted DRASTIC model methodology will be used to produce aquifer vulnerability maps on a regional scale in South Africa (Rustenburg Municipality). Furthermore it is hoped that this research will create awareness of the use of the DRASTIC model and its adaption as a useful, powerful and cost-effective decision making tool, that incorporates not only the main hydrogeological factors controlling aquifer vulnerability, but also includes the consideration for land surface contamination sources (or loads), for the initial steps of assigning resources toward the management of groundwater reserves in the Rustenburg Municipality.

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CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter will cover the hydrological cycle of the earth in order to establish how groundwater links in to the movement and storage of water on earth and provide some detail on two concepts that affect aquifer vulnerability namely: saturated zone vulnerability and unsaturated zone vulnerability. General contamination sources as well as contamination sources identified within the study area is also discussed.

A background of water monitoring in South Africa with specific focus on the 2006 Department of Water Affairs and Forestry's (now the Department of Water and Sanitation, here forth referred to as DWS) best practise guidelines are outlined in section 2.3 and provides an indication of minimum and recommended sampling frequencies and discusses two main sampling methods used in groundwater monitoring.

The concept of aquifer vulnerability mapping is a concept that is being applied world-wide and section 2.4 discusses global approaches to vulnerability mapping as well as a variety of vulnerability mapping methods that exists. Section 2.5 covers the work done on aquifer vulnerability in South Africa with specific reference to the DRASTIC model and the work of Lynch et al. (1994).

Various land use activities as pertaining to the study and their potential impacts are discussed in section 2.6 and attempts to highlight the importance of the consideration of land use activities as an important factor in aquifer vulnerability mapping.

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2.2. Hydrological Cycle and Pollution

2.2.1Hydrological cycle

The hydrological cycle is a conceptual model that relates to the movement and storage of water in the atmosphere, lithosphere, biosphere, and hydrosphere. Water on earth is stored in various areas or "reservoirs" which includes the atmosphere, oceans, lakes, rivers, soils, glaciers, snowfields, and groundwater. Water is transported from one reservoir to the next by means of the following processes: condensation, evaporation, runoff, precipitation, deposition, infiltration, sublimation, melting, transpiration, and groundwater flow (Pidwirny, 2006).

Figure 1 provides an overview of the earth's hydrological cycle. Water, and subsequently contamination, enters the groundwater reservoir largely through the infiltration of surface water into the unsaturated zone of the earth's crust. From here, the water percolates into the saturated zone of the earth's crust. Aquifer vulnerability to contamination can thus be divided into two categories, namely unsaturated zone vulnerability and saturated zone vulnerability (Saayman et al., 2007). Figure 2 provides a detailed overview of the saturated and unsaturated zones and possible means with which water enters and travels within each zone.

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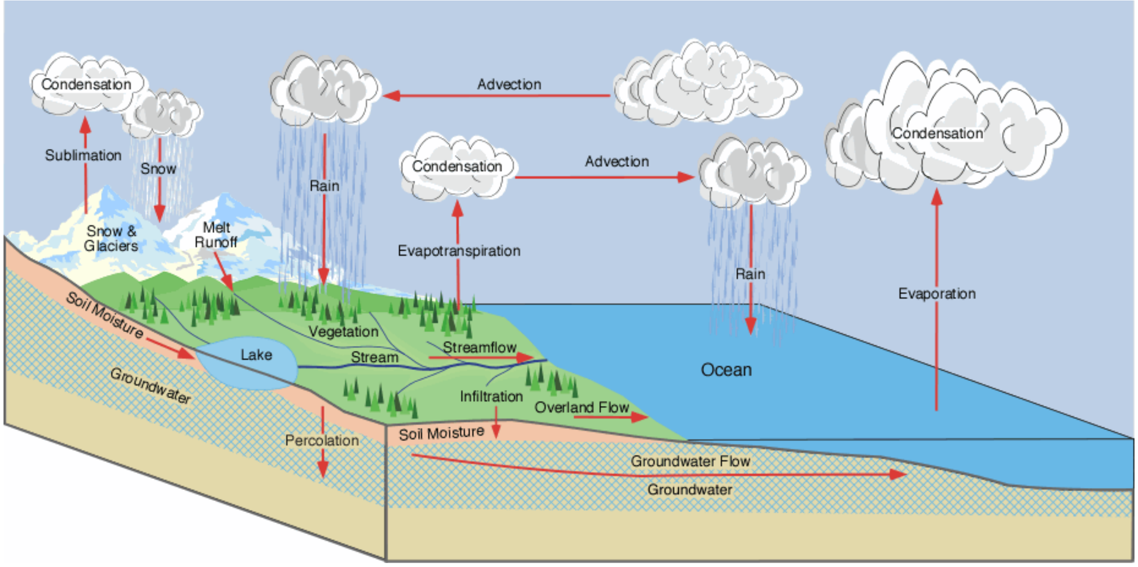

Figure 1: The hydrological cycle (Sourced from Pidwirny, 2006).

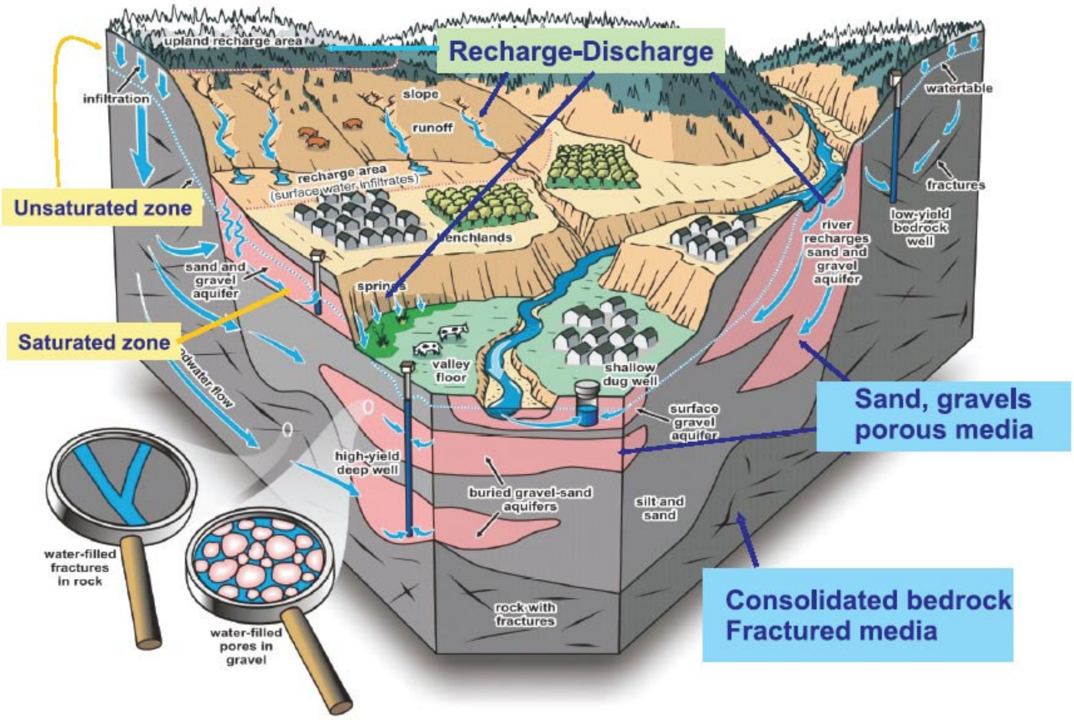

Figure 2: Saturated and unsaturated zones (Sourced from Rivera, 2008).

2.2.1.1Unsaturated (or Vadose) zone vulnerability

Unsaturated zone, also referred to as vadose zone, vulnerability is defined by Saayman et al. (2007) as the ease with which groundwater (at the water table) may become contaminated by a contaminant source at the surface or in the unsaturated zone. The susceptibility of the unsaturated zone to contamination is controlled by various factors such as the nature of the strata overlying the saturated zone and the nature of the contaminant and its mixing properties.

Other properties of the unsaturated zone that play a role in the vulnerability of the unsaturated zone to contamination include (Chilton, 2006):

- The physical and chemical properties of the parent material of the weathered material (soil)
- Past and present climatic conditions
- Relief and hydrology
- Presence and type of surface cover
- Artificial surface disturbances.

Various processes occur within the saturated zone that can potentially have an impact on percolating contamination sources. These processes all vary with differing textures, structures, clay content, organic matter and pH values. Processes that have an impact on the percolating contamination sources within the saturated zone include (but are not limited to) (Yang et al. 2010):

- Biodegradation
- Neutralization
- Mechanical filtration

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- Chemical reaction
- Volatilization
- Dispersion.

2.2.1.2 Saturated zone vulnerability

The vulnerability of the saturated zone to contamination can be described as the period of time after the contaminating activity has stopped, to when the contaminant is first detected in the groundwater (Saayman et al., 2007).

Various factors, as with the unsaturated zone vulnerability, control the vulnerability of the saturate zone to contamination (Chilton, 2006):

- Effective field capacity
- Percolation rate factor
- Rock type and thickness.

2.2.2 Pollution

Groundwater pollution is a global phenomenon which threatens the earth's water resources, resulting in potentially detrimental economic and health effects. Groundwater pollution is often considered to be of a more serious nature in comparison to surface water pollution due to the longer residency in groundwater (Tredoux et al., 2004). Groundwater pollution can source from a variety of common anthropogenic sources.

Point sources of pollution include:

- Waste disposal facilities
- Industrial pollution
- Wastewater treatment works
- On-site sanitation

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- Cemeteries.

Diffuse sources of pollution include:

- Agricultural practices
- Atmospheric fallout.

Land use practices which result in the alteration of terrain, such as the clearing of vegetation, over-abstraction of groundwater, or excavation below the water table, are also known to significantly contribute to groundwater pollution (Tredoux et al., 2004).

Chemical, organic and bacteriological constituents present in groundwater as a result of polluting activities can lead to both chemical and hydrological changes. These changes can result in the mobilization of constituents originally present in the aquifer (Tredoux et al., 2004).

To identify each and every source of pollution within a study area, however, becomes extremely difficult, and to some extent impossible, as the sources of pollution is vast and can often not be seen by the naked eye. A SEA (Strategic Environmental Assessment) of the study area (Rustenburg) was able to identify various sources of groundwater pollution. These included (Ecological and Environmental Consultants, 2003):

- Slag and tailings dams to the north
- Leach plants
- Process water storage- and rain collecting dams
- Various smelter plants
- Discontinued and active dumps (slag, ash & waste)
- Sewage works
- Leaking pipelines, run-off from industrial plant areas
- Agricultural practices.

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According to a press release by the Water Research Commission (WRC), nearly two thirds of the population of South Africa is reliant on groundwater for domestic use (Adams, 2011). This includes using groundwater for activities such as drinking, bathing, cooking and laundry. The pollution of groundwater due to industrial, municipal, and subsistence- and commercial farming practices is of rising worldwide concern (Jasorita et al., 2005).

The South African landscape, with the primary exporting commodities being gold, diamonds, platinum and other minerals and metals, is scattered with mining industries which utilize precious groundwater resources on a daily basis for various mining processes. The agricultural landscape makes extensive use of fertilizer and other natural resources, especially water to irrigate their crop which, if not controlled, leaches into and contaminate our groundwater. Industrial activities, such as mining, are often accompanied by a population influx as a result of employment opportunities. The population influx often leads to the expansion of urbanized areas and the forming of informal settlements, all of which require "basic needs" services from municipal areas. The primary sources of pollution attributable to municipal "basic needs" services include the leakage from sewage systems, septic tanks and probable release of waste water from water disposal sites (Ahmed, 2007). Once groundwater is contaminated, it becomes very costly to remediate and may take a long time to recover (Babikeret al., 2005).Water monitoring is thus of utmost importance in the protection of both surface water and groundwater supply.

2.3. Monitoring Background

The South African Constitution (Act 108, 1996) states that everyone has a right to an environment that is not harmful to his or her well-being. This Act, especially over the past few years, has led to a paradigm shift and a radical change of views of water management

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and protection in South Africa. Such a shift is apparent when considering the National Water Act (Act No 36, 1998), which focuses on the following principals:

1. The basic human needs of present and future generations
2. The need to protect water resources
3. The need to share water resources with countries
4. The need to promote social and economic development through the use of water
5. The need to protect aquatic ecosystems.

The management of water resources, especially groundwater resources, should be based on proactive principles rather than reactive principles. This may reduce costs associated with remediation as groundwater takes a long time to recover.

The freshwater component of the Global Environmental Programme (GEMS/Water) has been operating as the resource water quality monitoring and assessment division of the United Nations Environmental Programme (UNEP). The GEMS/Water achieved its international status through direct interactions with key agencies and individuals worldwide and has built a global water quality database known as GLOWDAT. Since 1998, the number of participating countries has increased (Van Niekerk, 2004).

The Department of Water and Sanitation, was approached by the United Nations Environmental Programme to take part in the GEMS/Water programme. South Africa thus formed a part of the GEMS/Water programme shortly after the World Summit held in 2001 (Van Niekerk, 2004).

The general fresh water quality of various countries, including South Africa, has been objectively rated by comparisons to global water quality assessments. South Africa has been ranked 47th out of a possible 122 countries based on general water quality. The water quality of each country was based on a single indicator value and the validity of the data remains

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questionable. This ranking process is thus questionable as the water quality results were based on the data of samples for which the collection method remains unknown, and the selected sites were considered as unrepresentative of the countries' water supply (Van Niekerk, 2004).

Thus, it can be seen that there is a pressing need to standardise the method used to obtain samples as well as the selection of sampling sites to be able to produce correct, representative samples that could be compared on a global scale.

The framework on which South Africa's current water protection, use, development, conservation, management and control is based on, is the National Water Act 1998 (Act 36 of 1998) (Department of Water Affairs and Forestry, 2000).

Monitoring of groundwater has become a national priority as the population of South Africa has become increasingly reliant on ground- and surface water as a source of fresh water supply (Department of Water Affairs and Forestry, 2000). According to the DWAF best practice guidelines, the current minimum (but not recommended), sampling frequency of various water sources is as per Table 1 (Department of Water Affairs and Forestry, 2006 (a)).

Table 1: DWAF minimum sampling frequency

Minimum Sampling Frequency	
Source/Locality	**Frequency (Sample Every)**
Rivers/Fountains/Springs	3 Months
Dams	6 Months
Boreholes	12 Months
Treatment Works	3 Months
Point of Use (e.g. Tap)	3 Months

The optimum sampling frequency according to the DWAF best practice guidelines, and recommended frequency, is more costly but also provides a better "bird's eye view" of

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the condition of water sources. This allows for early detection of potential contamination. The optimum sampling frequency according to the DWAF best practice guidelines is as per Table 2 (Department of Water Affairs and Forestry, 2000).

Table 2: DWAF optimal sampling frequency

Optimum Sampling Frequency	
Source/Locality	**Frequency (Sample Every)**
Rivers/Fountains/Springs	2 Weeks
Dams	2 Months
Boreholes	6 Months
Treatment Works	1 Month
Point of Use (e.g. Tap)	1 Month

The basic fundamentals of any water monitoring programme can be defined as a repetitive process of continuous checks and balances. A monitoring programme, in short can be summarised as shown in Figure 3 (Department of Water Affairs and Forestry, 2006 (a)).

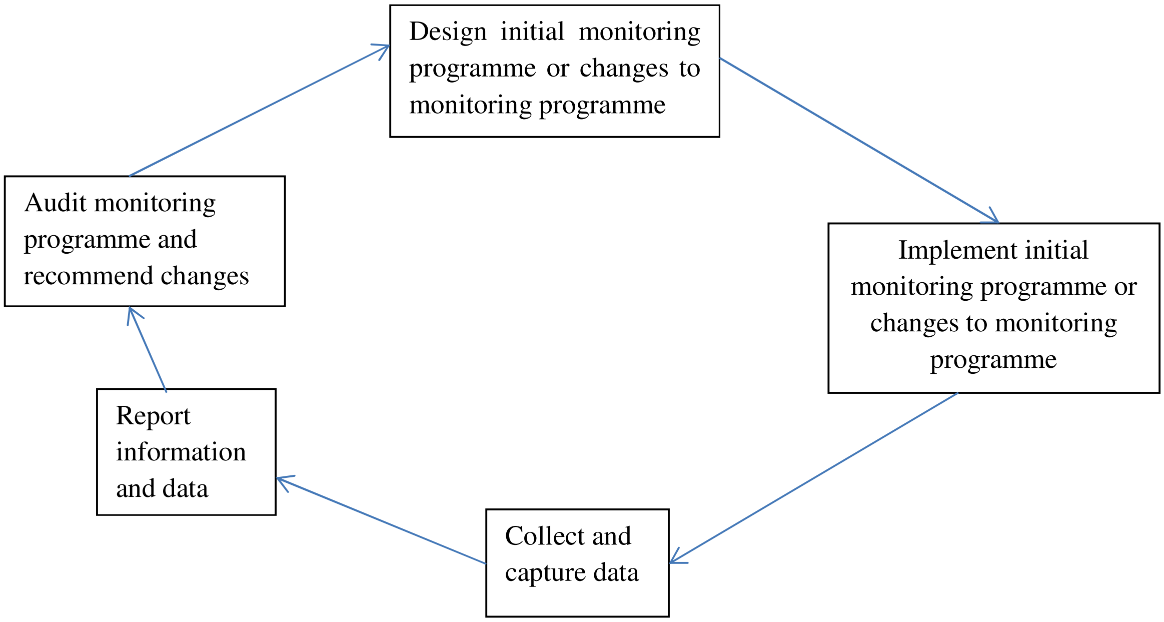

Figure 3: Monitoring program flow diagram

The chemical composition of groundwater is considered to remain fairly stable and changes occur more slowly than what would be observed in surface water (e.g. dams,

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streams, etc.) (Department of Water Affairs and Forestry, 2006 (a)). The slow changes in groundwater therefore lead to a decreased sampling frequency (Table 2).Groundwater is suggested to be sampled once every six months in relation to once every two weeks for surface water. The six month period is so set to account for seasonal variability.

Ground is normally sampled using a grab sample technique. A grab sample can be described as a sample that represents the water quality for a locality for a specific point in time only.

Two other main methods for sampling groundwater exists namely stratified sampling method and composite sampling method. Stratified sampling with depth involves the sampling of a small volume of water from specific depths of the borehole's water column. The concept behind stratified sampling of a borehole is to determine the vertical distribution of water quality within a borehole and to identify the entry level of contamination (Department of Water Affairs and Forestry, 2006 (a)). A major drawback of this sampling method is that the water column should not be disturbed in order to minimize the mixing of water. The current methods of borehole sampling all rely on the lowering of a sampling device into the water column which to some degree automatically disturbs/mixes the upper layers of water of the water column with the lower layers of the water column.

Composite sampling involves the slow removal of water form a borehole. An equivalent of three volumes of water should be purged from high yielding boreholes to remove the stagnant water potentially altered by the environment. Newly accumulated water should be sampled after recovery or partial recovery of the water level (Department of Water Affairs and Forestry, 2006 (a)).

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2.4. Global Approach to Vulnerability Mapping

The use of vulnerability-based decision tools for the managing and protection of groundwater resources plays an important role in identifying specific areas requiring water quality monitoring in order to protect our water resources. Throughout time various methods have been proposed in an attempt to determine the vulnerability of aquifers. Although merit is found in most methods, applying a variety of methods in any one study site tends to yield varied results.

2.4.1 European Approach

In 1997, an objective methodology for "intrinsic" and "specific" vulnerability assessment and mapping of karst environments was proposed under a scientific programme sponsored by the European Commission, European COST Action 620. The COST Action also set out to propose a European standard of consistency in the establishment of vulnerability and risk mapping, accounting for specific regional and environmental variations as well as the different stages of economic development and scientific investigation of karst environments. The developmental centre is focused on karsts while the method itself is considered to have the potential to be applied to all aquifer types (Malik et al., ND).

2.4.2 COST Action 620 vulnerability mapping

Special protection for karst aquifers, due to their exceptional properties, involves a multifactorial approach and the use of vulnerability mapping.

2.4.2.1 Approach 1

The locating of contaminant sites and the assisting of decision makers and planners has been greatly forwarded by the incorporation of **vulnerability mapping**. Vulnerability mapping requires the input of several factors generally obtained through field studies. Under the COST Action 65 guideline, these factors can be grouped into

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the following general categories: soil, type of recharge as well as saturated and non-saturated zones which include the degree of development of the karst network which must be in accordance with the conceptual model of a karst aquifer describing the actual behaviour of the karst (Zwahlen, 2003).

2.4.2.2 Approach 2

Identifying **specific contaminants** that are affecting the water quality on a large scale has made the development of specific vulnerability a necessity in the management of groundwater. Specific contaminants of concern include nitrates, organic fertilizers, and chlorinated solvents (Zwahlen, 2003).

2.4.2.3 Approach 3

The incorporation of both intrinsic and specific vulnerability maps as tools in water quality management. The term intrinsic vulnerability here was defined as a function of the hydrogeological factors. The term specific vulnerability in this case refers to the potential anthropogenic impacts of the risk or hazard to the system (Zwahlen, 2003).

The COST Action 620 is seen to follow a conventional source-pathway-target model as a backbone for both environmental management as well as assessing risk and vulnerability concepts. The source is considered as the point at which contamination is released. This is generally considered to be at the land surface, although subsurface contamination is also possible. The pathway is the path of flow a contaminant follows to the target area while the target is considered as the area or receiving environment that needs to be protected (Zwahlen, 2003).

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2.4.3 Intrinsic vulnerability

Intrinsic vulnerability of groundwater in context with the European Approach considers three aspects:

1. Adaptive transport time from the source to the target
2. Physical attenuation
3. Relative quantity of contaminants that can reach the target.

Adaptive transport time is influenced by the permeability, hydraulic gradient, effective porosity, and the distance between the source and the target. Physical attenuation is influenced by dispersion, dilution and dual porosity effect usually resulting in a decrease in the concentration of the contaminant. The final aspect, relative quantity of contaminants that can reach the target, is influenced by the effective or relative recharge (Daly et al., 2002 in Zwahlan, 2003:17).

The COST Action 620 approach makes use of a COP method (Figure 4), assessing three factors that have an impact on intrinsic vulnerability (Vias, 2010):

- Concentration of flow (C)
- Overlying layers (O)
- Precipitation regime (P).

The factor C is represented by areas of varying infiltration conditions, particularly in areas where infiltrating water bypasses protective layers (Daly et al., 2002). The factor O represents the protection provided by layers above the saturated zone to the groundwater. Various factors of the unsaturated zone are also considered and include: thickness, porosity, permeability of the soil and each of the lithological layers. The P factor represents the amount of precipitation and its intensity for a particular area (Vias, 2010).

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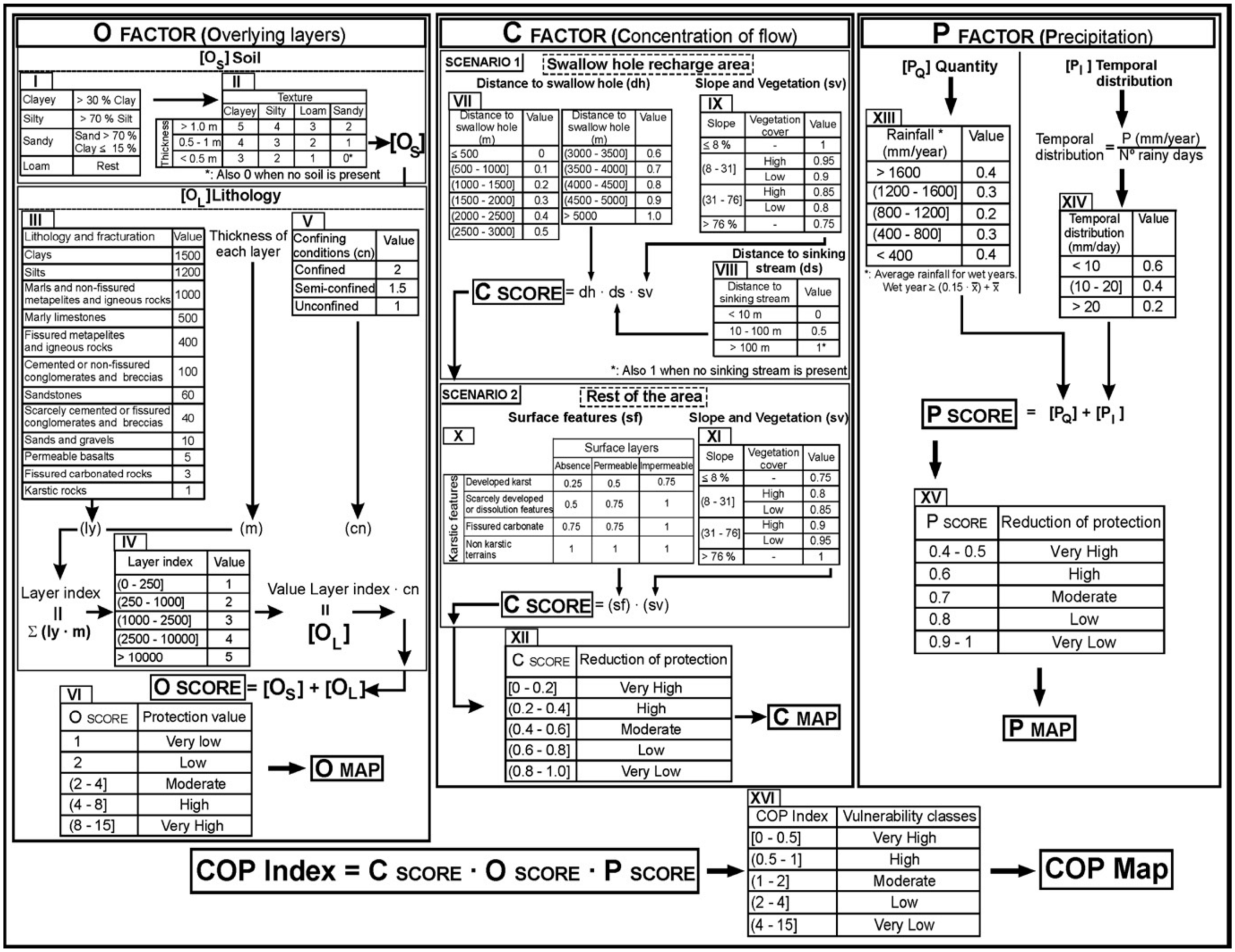

Figure 4: General outline of the COP method (Sourced from Vías et al., 2010)

A fourth additional factor, karst network development (K), is considered for source vulnerability mapping in karst areas (Andreo et al., 2006). The factor K combines both the "vertical pathway" with the most horizontal pathway through the saturated karstic bedrock to the source (Daly et al., 2002).

2.4.4 Specific vulnerability

Intrinsic vulnerability alone does not consider the large variety of specific contaminants and contamination scenarios. Specific vulnerability is based on the assessment

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of a given contaminant and its particular properties. Specific vulnerability enhances the findings from intrinsic vulnerability by making provision for the assessment of positive attenuation effects related to specific contaminant properties such as its retardation and degradation over time and distance (Andreo et al., 2006) COST Action 620 recognised the benefits of GIS tools to provide digitized and easily updatable vulnerability maps.

2.4.5 Groundwater risk assessment

Risk is defined by the COST Action 620 as "the likelihood or expected frequency of a specified adverse consequence." The calculation of risk is not intended as an absolute measure but rather a means of relative measure or comparison.

The potential risk of contamination is determined through a combination of the relatively static intrinsic characteristics of an aquifer and the dynamic factors of potential polluting activities (Saidi et al., 2011). The risk intensity of a polluting activity can be calculated using equation 1 of Hotzl et al. (2004) and Werz and Hotzl 2007; where R_I represents the risk intensity, H_I represents the hazard indices and V_I represents the vulnerability factor.

$$R_I = (1/H_I)*V_I \qquad [Eq.1]$$

Groundwater risk assessment, with the combination of the associated vulnerability assessment, can thus be used to establish the consequences of a contamination event (Saidi et al., 2011).

2.4.6 Vulnerability mapping methods

The complexity of groundwater flow, contaminant transport and interactions between pollutants and the subsurface makes creating a single absolute integrated vulnerability index a great challenge. Vulnerability to contamination is believed to be scientifically more accurately evaluated through the assessment of each pollutant, class of pollutant (nutrients,

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pathogens, micro-organics, heavy metals, etc.), or group of polluting activity (industrial effluent disposal, agricultural cultivation, etc.) separately. Using this technique, however, may result in the generation of numerous maps for a given area, making its use in numerous applications difficult (Carter et al., 1987).

Various checks should be put in place to validate a specific outcome. This can often be done through comparison with other methods. Various models over time have been created to try and map vulnerability with no single model found to be suitable for all environments (Saayman et al., 2007). Four models have however been identified to be commonly used to determine aquifer vulnerability.

2.4.6.1 AVI (Aquifer Vulnerability Index) method

The Aquifer Vulnerability Index (AVI) method can be seen as a groundwater vulnerability assessment method that focuses on two physical parameters (Stempvoort et al., 1993):

- Thickness of each sedimentary layer above the uppermost, saturated aquifer surface (d)
- Estimated hydraulic conductivity of each of the concerned sedimentary layers (K).

The above two physical parameters together allow for the estimation of an approximate hydraulic resistance ‘c’ value which is calculated using equation 2 for layers 1 to i (Stempvoort et al., 1993).

$$c = \sum d_i/K_i \qquad \text{[Eq.2]}$$

Hydraulic resistance (c) is a theoretical value used to describe the aquifers ability to “resist” vertical flow.

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Table 3: Relationship of aquifer vulnerability index to hydraulic resistance (Sourced from Stempvoort et al., 1993)

Relationship of Aquifer Vulnerability Index to Hydraulic Resistace		
Hydraulic Resistance 'c'	Log c	Vulnerability (AVI)
0 to 100 y	<1	Extremely high
10 to 100 y	1 to 2	High
100 to 1000 y	2 to 3	Moderate
1000 to 10000 y	3 to 4	Low
> 10000 y	>4	Extremely low

Limitations to the AVI Method (Stempvoort et al., 1993) include:

- Certain parameters which may be contaminant-specific are ignored
- AVI method considers only nearest to surface aquifers and considers each aquifer to be of equal value
- The estimates of K for various sediment types used in the AVI method are approximations
- AVI method does not consider lateral continuity or discontinuity of aquifer rigorously.

2.4.6.2 SINTACS

SINTACS is a modification of the US Environmental Protection Agency model, DRASTIC (Napolitano et al., 1996). The acronym SINTACS sources from Italian words used to describe the various factors used: Soggicenza (Depth to groundwater); Infiltrazione (effective infiltration); Non saturo (unsaturated zone attenuation capacity); Tipologiadellacopertura (Soil/overburden attenuation capacity); Acquifero (saturated zone characteristics); Conducibilità (Hydraulic conductivity); Superficatopografica (Topographic surface slope) (Cavita, 2010). The SINTACS method differs from the DRASTIC model by allowing one to use, at the same time and in different subareas, different weight classes corresponding to different situations (Napolitano et al., 1996).

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The vulnerability index for SINTACS is calculated using equation 3; where $P_{(1,7)}$ relates to the rating of each of the seven SINTACS parameters and $W_{(1,n)}$ is the corresponding weight in each class, which can range from 1 to n (Napolitano et al., 1996) :

$$I_v = \sum P_{(1,7)} W_{(1,n)} \qquad [Eq.3]$$

2.4.6.3 GOD vulnerability index model

During the 1990's, extensive trials on the GOD vulnerability index (GOD VI) model were conducted in Latin America and the Caribbean. This model is based on a simplistic concept and is easily applied. The GOD VI model considers two basic factors to determine aquifer pollution vulnerability (Foster et al., 2007):

- The level of hydraulic inaccessibility of the saturated zone of the aquifer.
- The pollutant attenuation capacity of the strata overlaying the saturated zone of the aquifer.

The GOD VI model makes use of three parameters to calculate an aquifer's vulnerability to pollution (Foster et al., 2007):

- Groundwater hydraulic confinement in the concerned aquifer
- Overlaying strata (vadose zone or confining beds)
- Depth to groundwater table.

Various criticisms were made in regard to the GOD VI model primarily relating to the simplicity of it structure. Some criticisms include (Foster et al., 2007):

- Concern that, with regard to the classification of the overlaying strata, too much weight was placed on dynamic porosity (recharge time lag) rather than pollutant attenuation
- The original GOD VI model was considered to not include explicit consideration of soils in an agricultural sense.

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2.4.6.4 DRASTIC

DRASTIC is a model developed in the United States through a combined effort between the National Water Well Association (NWWA) and the USA Environmental Protection Agency (EPA) whereby several factors relating to aquifer vulnerability is assigned a "vulnerability" weight to determine vulnerability (USEPA, 1985). The vulnerability of an area as determined by the DRASTIC model represents the sensitivity of an aquifer to being undesirably impacted at any point by an imposed contaminant pressure from the land surface.

The DRASTIC vulnerability mapping model is based on a composition of seven hydrogeological factors that play a role in the movement of groundwater. Due to the DRASTIC model being limited to considering only hydrogeological factors that play a role in the movement of groundwater without consideration for the presence of a land surface contaminant source (or load) that may exert pressure on the surrounding groundwater resource, one may find areas characterised as high vulnerability areas but have no contamination hazard (given that there are no land surface contaminant sources present) (Ruopu et al., 2013).

The DRASTIC model, as with most vulnerability models, can also be considered to walk a fine line between being an essential indicator for the protection of groundwater resources and an over-simplification on which expensive resources and decisions are made. Models such as the DRASTIC model intend to assess the natural buffering capacity of an area through the representation of various hydrogeological factors such as the impact of the vadose zone (I). Many users of vulnerability models do not account for vadose zone variations when assessing the aquifer vulnerability for an area and input generic "vulnerability" values for specific vulnerability variables. At any scale of vulnerability and in any model used for vulnerability mapping there will always exist a form of simplification of complex interactive geological and hydrological processes. Vulnerability models such as the

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DRASTIC and GOD models do not compensate for any anthropogenic land surface alterations such as infrastructures or terrain alterations.

Vulnerability mapping however is not without merit, not as a definitive decision making tool but as a screening tool. The screening tool gives valuable feedback in identifying where detailed hydrological studies need to be implemented and where priority to effective monitoring of water quality needs to be ensued. In an ideal world, it would be highly preferable to perform a detailed geological and hydrological study of every development that may potentially contaminate groundwater. It is however not feasible as the economic costs involved would be astronomical. This then presents a great opportunity for the development and use of reliable screening tools, such as vulnerability models, to determine and prioritise areas in need of further detailed study and monitoring (Rahman, 2008).

The DRASTIC model is found to be a simple model that integrates well with geographic information systems (GIS). The ease of integration of the DRASTIC model with GIS makes the model a well suited model for vulnerability mapping of groundwater on a regional scale (Javadi et al., 2011). The constant development advances and application in the business world of GIS has driven the consolidation and representation of relevant global spatial data. Much of the data needed for the DRASTIC model is readily available to the public from the Department of Water and Sanitation. The compatibility of the DRASTIC model and GIS greatly improves the flexibility of the model to be adapted and incorporate additional factors.

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The seven parameters of the DRASTIC model are described in detail below.

(1) Depth to water (D)

Depth to water level refers to the distance surface pollutants have to travel before reaching the aquifer (Hasiniaina, 2010). Various factors affect the rate at which surface pollutants seep through the soil substrate and the quantity of pollutant seepage within an area. Rate and quantity are mainly affected by slope and soil properties.

(2) Net recharge (R)

Net recharge is related to the environment's ability to naturally recharge its groundwater through the process of infiltration (Sililo et al., 2001). Recharge data will be obtained from the Department of Water and Sanitation's Groundwater Resource Directed Measures (GRDM) 4.0.0.0 (2010).

(3) Aquifer media (A)

Aquifer media refers to the composition or material of an aquifer (saturated zone beneath the water table). Aquifer media is generally determined through the investigation of geological maps.

(4) Soil media (S)

Soil plays a particularly important role in the infiltration capacity of surface water and pollutants and subsequent net recharge of an aquifer. The soil media will be determined from soil classification maps. The most predominant soil types can be described as (Voudouris et al., 2010):

- Fine textured
- Medium textured

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- Coarse textured
- Thin layer of soil
- No soil.

(5) Topography (T)

Topography plays an integral role in both the infiltration rate as well as runoff direction of surface water and pollutants. Typically, steeper sloped areas increase surface runoff and subsequent washing away of pollutants (Yang et al., 2010). Flat areas in general are considered to slow the velocity of surface runoff and potentially pool water which increases both the potential for infiltration and the concentration of contamination. Slope topography can be calculated using a Digital Elevation Model (DEM) (Al-Adamat, 2003). Steeper slopes are assigned a low rating value and flat areas a high rating value (Yang et al., 2010).

(6) Impact of the vadose zone (I)

The vadose zone refers to the unsaturated zone between the soil and the water table. The composition of the vadose zone may have an effect on the retention capacity, travel time and percolation of water to the aquifer after infiltration. Various processes occur within the vadose zone that can potentially have an impact on percolating contamination sources (Yang et al., 2010).

(7) Hydraulic Conductivity (C)

Hydraulic conductivity is the ability of the aquifer to transmit water and may reflect on the permeability of the aquifer media. Therefore, hydraulic conductivity presents an

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indication of the potential migration and dispersion of contamination within the saturated zone (Rahman, 2008).

2.4.6.5 Motivation for DRASTIC modelling and its incorporation with GIS

The DRASTIC model is considered to be the most recognised and widely used aquifer vulnerability modelling process (Armengol et al., 2014). Its popularity is driven by the fact that it is a relatively inexpensive, easy to use model that makes use of data that is easily available to the public or can be estimated. The popularity of the DRASTIC model is also further increase by the fact that it produces an end product that is easily interpreted and incorporated into the decision making process (Abdullahi, 2009). The DRASTIC model is considered to be better suited for land use management when compared to other aquifer vulnerability indexes such as EPIK and GOD (Shirazi et al., 2012). Shirazi et al. (2012) also found that the DRASTIC model was able to evaluate an extensive amount of complex databases and proved to be a good model for the assessment of aquifer vulnerability in agricultural, arid, semi-arid and basaltic regions.

The use of Geographical Information Systems (GIS), with its strength lying in multiple criteria decision analyses, has proven to be promising as a tool to visually analyse and interpret spatial variations of different parameters (Dutta et al., 1998). Many studies have thus far been conducted exploring the DRASTIC model and GIS with relation to aquifer vulnerability assessments. Many of these studies focus either on urban catchments, as the greatest variety and highest concentrations of contamination sources are considered to be found in these areas, or on the assessment of regional basins to assess the health and economic impacts of contaminated groundwater.

Dutta et al. (1998) further extended the uses of the DRASTIC model in GIS from only assessing aquifer vulnerability, to designing and optimizing groundwater monitoring systems.

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Although this extended application of the DRASTIC model and GIS was a relatively new approach at the time, the authors found it more efficient than existing methodologies in that it considers more of the possible aspects of groundwater contamination.

A study done by Rahman (2008) was able, to a large extent, to identify that Aligarh in India is comprised of areas of moderate to high pollution vulnerability zones.

A more recent study by Hasiniania et al. (2010) suggested and identified the capacity of GIS to facilitate the implementation of the sensitivity analysis applied on the DRASTIC vulnerability index which otherwise according to the authors would have been impractical. This study thus supports the findings of Rahman (2008) that the implementation of the DRASTIC model through the use of GIS provides an efficient tool for assessing and analysing the vulnerability of groundwater to pollution.

The DRASTIC model is thus a popular aquifer vulnerability assessment model worldwide used that not only integrates effectively with a spatial assessment program such as GIS but is also easily modified to include various other factors. The DRASTIC model is also seen to be a good aquifer vulnerability assessment model for the use in semi-arid areas, such as South Africa, which end product is easily interpreted and incorporated into the decision making process. Although other aquifer vulnerability methods exist, the DRASTIC model is considered the best suited model for the assessment of aquifer vulnerability in this study.

2.5. Aquifer Vulnerability in South Africa

South Africa is currently experiencing a population growth rate of around 1.4% per year. The pressure placed on the South African groundwater resources to accommodate the increasing population coupled with the immense mining activities of this country have led to

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an increase in the amount of groundwater potential investigations. Investigations stretch as far back as the late 1960's seen in the work of Enslin et al. (1976).

Lynch et al. (1994) believed that the DRASTIC model was a well suited model for investigating groundwater vulnerability in Southern Africa. The DRASTIC model was specifically designed to be used as a screening tool and not for site specific assessment by requiring a study area to be larger than 0.4 km^2. As with most models, certain assumptions on the behaviour of variables or environmental conditions are made. The DRASTIC model is considered to be based on four major assumptions (Lynch et al. 1994):

- The contaminant is introduced at the surface of the earth.
- The contaminant is flushed into the groundwater through precipitation.
- The contaminant has the mobility of water.
- The evaluated area has to be 0.4 km^2 or larger.

Although flawed, the strength of DRASTIC as a model is mainly due to the fact that it considers most of the major groundwater controlling factors when modelling. Lynch et al. (1994) set out to create a national-scale groundwater vulnerability map of Southern Africa. One limitation encountered during their study was that they did not believe that the data on hydraulic conductivity for Southern Africa was sufficient and did not include it in their study (Lynch et al., 1994). Table 4 depicts the six factors then taken into consideration along with their associated vulnerability rankings used by Lynch and co-authors to produce a groundwater vulnerability map of Southern Africa.

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Table 4: Ratings values used in the DRASTIC concept by Lynch (Sourced from Lynch et al., 1994)

RATING VALUES FOR THE USE IN THE DRASTIC CONCEPT			
Depth to groundwater (D_r)		**Net recharge (R_r)**	
Range (m)	**Rating**	**Range (mm)**	**Rating**
0-5	10	0-5	1
5-15	7	5-10	3
15-30	3	10-50	6
>30	1	50-100	8
		>100	9
Aquifer Media (A_r)		**Soil Media (S_r)**	
Range	**Rating**	**Range**	**Rating**
Dolomite	10	Sand	8-10
Intergranular	8	Shrinking and/or Aggregated clay	7-8
Fractured	6	Loamy Sand	6-7
Fractued and Weathered	3	Sandy Loam	5-6
Topography		Sandy clay loam and loam	4-5
Range (% slope)	**Rating**	Silty clay loam, sandy clay and silty loam	3-4
0-2	10	Clay loam and silty clay	2-3
2-6	9		
6-12	5		
12-18	3		
>18	1		
Impact of the Vadose Zone (I_r)			
Range			Rating
Gneiss, Namaqua metamorphic rocks			3
Ventersdorp, Pretoria, Griqualand West, Malmesbury, Van Rhynsdorp, Uitenhage, Bokkeveld, Basalt, Waterberg, Soutpansberg, Karoo (Northern), Bushveld, Olifantshoek			4
Karo (southern)			5
Table Mountain, Witteberg, Granite, Natal, Witwatersrand, Rooiberg, Greenstone, Dominion, Jozini			6
Dolomite			9
Beach sands and Kalahari			10
Parameter weightings			
D_w			5
R_w			4
A_w			3
S_w			2
T_w			1
I_w			5
C_w			3

Although the study conducted by Lynch et al. (1994) included a few shortcomings and assumptions, they believed that the approach used to map groundwater vulnerability and the tools (GIS) used to achieve it remain valid. Some of the assumptions included in the study are noted below.

In terms of the DRASTIC model (Lynch et al., 1994):

- The effect of anthropogenic activities on groundwater is not considered.
- Water quality problems, whether from natural or man-induced circumstances, are not included in the model.
- Neglected physical factors affecting groundwater contamination include:
  - Fracturing and faulting
  - Duration and intensity of precipitation events
  - Soil reactivity
  - Specific contaminant mobility
  - Anisotropy
  - Heterogeneity of soil
  - Dilution.

In terms of the study (Lynch et al., 1994):

- Many datasets used in the production of the vulnerability map are not yet available for Southern Africa.

2.6. Land Use Impacts on Groundwater

Land cover and land use practices are considered to be an extremely important factor in the assessment of groundwater vulnerability to contamination. The factor of land cover and land use practices introduce possible points of land surface contamination sources (or loads) that may threaten groundwater quality.

The improper planning of land use activities often results in the contamination of groundwater resources (Sililo et al., 2001). The pressures exerted on the natural environment as a result of land use changes are however poorly understood (Scanlon, 2005).Land use

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activities are believed to affect water sources in terms of both availability of water and the quality thereof (Kiersch, 2000). A wide range of groundwater pollutants have been identified and include bacteria and other micro-organisms, major inorganic ions such as NO_3, Cl and SO_4, heavy metals and organic chemicals (Sililo et al., 2001). Correct management of, and the adequate treatment of water can result in improved water quality for downstream users.

2.6.1 Hydrological regime

The impacts associated with groundwater, in terms of the hydrological regime, as a result of varying land use practices can be attributed to recharge. Land use changes are considered to have both positive (increase) and negative (decrease) effects on groundwater recharge (Kiersch, 2000). Land use changes from grassland to urbanized areas may increase run off of water and drastically decrease infiltration resulting in a lowered recharge rate. Following land use activities such as logging or deforestation it is likely that the water table may rise as a result of decreased evapotranspiration. Recharge is also likely to increase as a result of increased infiltration (Tejwani, 1993).

2.6.2 Groundwater quality

The effects of land use activities or changes in land use on water quality can also be chemical in nature. Groundwater is considered to be potentially susceptible to contamination wherever there is a source releasing contaminants to the environment. Potential contamination sources, as a result of land use activities, have been identified and include (Sililo et al., 2001):

- Municipal Sources
    - Sewer leakage, sewage effluent, sewage sludge, urban runoff, landfill, latrines and septic tanks.
- Agricultural Sources

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    - Leached salts, fertilisers, pesticides and animal wastes.
- Industrial Sources
    - Process water, water treatment, plant effluent, hydrocarbons, tank and pipeline leakage.
- Mining Sources
    - Solid wastes and liquid wastes.

2.6.2.1 Municipal sources

The design of sewage networks and solid waste collection and disposal facilities were incorporated out of necessity to cope with the generation of large quantities of waste produced by concentrated human activity in settlements (Sililo et al., 2001). Urban areas are often considered to have well designed and, idealistically, well maintained sewage networks. The resultant potential for contamination from leaking sewers in urban areas is thus considered as potentially small.

Eishwith et al. (2010) estimated that 12% of effluent transported through sewer systems is lost due to leakages from joints in the sewer system. Leaking sewage networks, based on a study of urban areas in Germany, were found to potentially contribute to groundwater contamination through increasing concentrations of sodium, chloride and nitrogen sulphate compounds (Eishwith et al., 2010).

Informal settlements are generally associated with poor, if any, sanitation services and practices. Informal settlements where use of pit latrines is made, usually quite closely clustered, or where there is a lack sanitation facilities often have a large cumulative impact on groundwater quality (Wright, 1999). Numerous South African informal settlements have a number of potential polluting activities which vary from on-site sanitation systems to storm water drainage systems (Wright, 1999). Significant groundwater pollutants in the form of nutrients, pathogenic micro-organisms (helminths, protozoa, bacteria and viruses) and

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biodegradable organics (proteins, carbohydrates and fats) have been identified to source from South African informal settlements. Nutrient concentrations of water are generally described in terms of nitrogen (N) and phosphorus (P) (Kiersch, 2000).

Waste disposal of solid wastes and their impact on groundwater in South Africa has been well documented (Tredoux, 1984; Weaver and Tworeck, 1988; Saayman, 1998). Landfills are most commonly used in the disposal of waste products with organic and inorganic substances often found in high concentrations in the leachate from domestic landfills (Sililo et al., 2001).

Contaminants of most concern introduced into groundwater from a domestic landfill source include nitrogen compounds, sodium, potassium, chloride, calcium, magnesium and dissolved oxygen (Engelbrecht 1993). Additionally, studies of the landfill-site in Gazipur, India yielded microbiological parameters in the form of total coliforms and faecal coliforms in groundwater and leachate (Mor et al., 2006).

The standards for the disposal of industrial wastes have become more stringent resulting in a decrease in the number of potential landfill sites that comply with these standards. The cost of disposing of industrial wastes has also increased in order to comply with new standards. This makes the "legal" disposal of waste materials, due to costs, ineffective to many industries (Sililo et al., 2001). The groundwater qualities at waste disposal facilities, which have been charged with the storage of industrial waste material in South Africa, have been recorded and contamination detected (Sililo et al., 1999). The main pollutants of concern in groundwater contamination at these sites include organic compounds, most notably volatile aromatics (Sililo et al., 2001).

Urbanization often results in an increase in the human population of an area which may lead to an increase in the mortality rate of that area. Burial of humans are common

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practice in all countries and remain the most popular method of disposing of the dead in South Africa (Sililo et al., 2001). A study conducted by Engelbrecht in 1998 found that the decomposition of human bodies led to the introduction of microbes into groundwater at a cemetery study site. However, the impact of cemeteries on South African groundwater remains unclear as very few studies have been conducted in this area (Sililo et al., 2001).

2.6.2.2 Industrial sources

Impacts on groundwater resources from industrial activities vary in relation to the type of industry present. Industrial effluent generally contains high concentrations of contaminants which include chloride, nitrate, hydrocarbons or heavy metals (Sililo et al., 2001). Industrial waste may be dumped on the land surface or disposed of in excavations at or near the site of a plant (Zaporozec et al., 2002). Severe environmental strain is found to occur below industrial solids waste dumps which might endanger domestic or agricultural water supplies (Zaporozec et al., 2002).

Liquid industrial wastes are generally in the form of industrial by-product, process water, cleaning water, and waste water effluent. Liquid wastes often infiltrate into underlying aquifers from the discharge into open land surfaces or open streams and the leakage from basins (Zaporozec et al., 2002).

It is also common practice to store hydrocarbon liquids such as fuel in underground storage facilities. These facilities, such as fuel stations, often consist of underground transport pipelines where leakages of fuel into the groundwater may occur through spills from these underground storage facilities and transport pipelines.

2.6.2.3 Mining Sources

Mining activities are prevalent within the Greater Rustenburg Municipality. Some of the most common mineral resources mined within the Greater Rustenburg Municipality include chromium (Cr) and platinum.

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Dewatering in order to commence or continue with mining activities is common and may impact on groundwater chemical quality. Dewatering results in the lowering of the surrounding water table exposing deeper seated rocks and mineral to oxidation. Groundwater exposed to the processes of dewatering is often found to change in chemical quality in relation to increased sulphates, phosphates, metals, fluoride and trace elements (Zaporozec et al., 2002).

Mines also commonly make use of tailings storage facilities in order to store excess residues from mining and milling processes. These tailings facilities are commonly exposed to environmental elements, most particularly air and precipitation. The exposure of sulphide minerals in rock stockpiles such as mine tailings to oxygen and precipitation results in the oxidation of sulphur in the mineral to a higher oxidation state. The higher oxidised state of sulphur results in the lowering of water pH to a more acidic level. Acidic water containing a low pH, when interacting with bases in rock formations or residue deposits, such as tailings, result in the mobilization of heavy metals and dissolving of salts. This phenomenon is commonly referred to as Acid Rock Drainage (ARD) or Acid Mine Drainage (AMD) (Sililoet al., 2001).

Iron pyrite (FeS_2) is the most important source of AMD that results in water pollution. This is due to the fact that acid can form if there is an abundance of FeS_2 and an inefficient amount of neutralizing minerals to counteract the acid formation. The exposure to oxygen needed for the oxidation of FeS_2 is generally the limiting factor of acid generation. The exposure to oxygen as well as the exposed surface area of FeS_2 increases with the breaking of FeS_2-bearing rock. Sub-surface FeS_2 obtains access to oxygen through molecular diffusion via air-filled pores of the stock pile or mining residue, or by air flow through pores as a result of temperature or pressure gradients (Usher, 2003).

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The important interactions involved in AMD are as follows (Usher, 2003):

(1) $FeS_2 + 7/2\ O_2 + H_2O \Rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+$

(2) $Fe^{2+} + ¼\ O_2 + H^+ \Rightarrow Fe^{3+} + ½\ H_2O$ (rate limiting step)

(3) $Fe^{3+} + 3H_2O \Rightarrow Fe(OH)_3$ (Yellow boy) $+ 3H^+$

(4) $FeS_2 + 14Fe^{3+} + 8H_2O \Rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+$

It should be noted AMD however is not limited to tailings facilities but can also occur as a result of underground mining shafts, ore stockpiles and open pit discharge or runoff (Manders et al., 2009).

Nitrate pollution of groundwater is also common as a result of mining activities. This is due to the fact that a vast majority of modern commercial explosives contain ammonium nitrate (also sodium nitrate and calcium nitrate) as an oxidising agent. The loading and blasting practices as well as the presence of water all have an impact on the amount of nitrates entering the water system (Forsyth, 1995).

Nitrates can enter the water system either at the mining area or alternatively at the waste rock disposal sites. Nitrates entering the water system can be as a result of spillage during explosive transportation or charging, leaching of explosives in wet blast holes or from remaining undetonated explosives left after blasting (Forsyth, 1995).

2.6.2.4 Agricultural sources

Agriculture (subsistence and commercial) is considered to be one of the most common human land use practices. Many agricultural activities take place on the land surface but the associated impacts carry great risks to groundwater (Zaporozec et al., 2002).

A lack of knowledge and poor understanding of nitrates in soil and crop nutrient needs can ultimately result in significant deterioration of groundwater quality. The risk of

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groundwater contamination from nitrate leaching increases under the following conditions (Stevens et al., 1993):

- Nitrogen application exceeds crop needs
- Timing of nitrogen application does not coincide with crop needs
- Nitrogen application exceeds bacteria and micro-organism needs
- Soils are well-drained
- Soil thickness and distance between root zone and groundwater
- Excess rainfall or irrigation increases leaching.

Nitrogen-rich fertilizers are of particular concern due to the relative ease with which nitrate anions are leached from soils towards groundwater. Nitrate anions in soil are easily leached as they show negligible interaction with the negatively charged matrix present in the top soil.

Nitrogen fertilizers are commonly used by farmers in aid of crop growth. The nitrogen applied through fertilizers interacts with bacteria present in soil, converting the nitrogen to plant-available-nitrates. The plant-available-nitrates get consumed by plants as a nutrient aiding in the growth process. Bacteria present in the soil also consume nitrate-nitrogen when sufficient organic matter is present in the soil. The uptake of nitrates by bacteria and other micro-organisms is known as immobilization. Nitrate-nitrogen is also known to be used by specific bacteria as a substitute for oxygen in an oxygen deprived environment. These bacteria convert nitrate-nitrogen to various gases such as nitrogen, nitrous oxide, and nitrogen-oxide. The process of the conversion of nitrate-nitrogen into gasses is known as denitrification. When the input of nitrogen through nitrogen fertilizers exceeds the needed amount that can be taken up by crop for growth, immobilization by bacteria and other micro-organisms, and the conversion of nitrates to atmospheric gasses

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through denitrification of the excess nitrate-nitrogen can leach out of the root zone and potentially enter groundwater.

Soil texture is also considered to have a profound impact on nitrate-nitrogen contamination of groundwater. Soil texture affects the percolation or permeability of a soil. The texture of a soil gives an indication of the portions of various particles, which differ in size, present in a given soil. Larger grained, coarser soil textures increase the hydraulic conductivity of a soil which encourages movement of water downward through the soil toward the groundwater table. Finer grained soils decrease the hydraulic conductivity rate of soils resulting in water moving less freely through a soil toward the groundwater table. The presence of continuous vertical macro-pores in bulk dry soils can also potentially increase the leaching of nutrients through the promotion of macro-pore or bypass flow (Powel, 1994).

Well drained soil consisting of more course grained soils thus promotes the leaching of nitrate-nitrogen through the soil toward the groundwater. This ultimately results in a decreased uptake time of nitrogen-nitrates for plants, for immobilization and denitrification by micro-organisms (Powel, 1994).

The leaching of nitrate-nitrogen into groundwater is further exaggerated in areas where the input of water into a soil through natural means (e.g. precipitation) and/or artificial means (e.g. irrigation) exceeds the rate of evapotranspiration. When the input of water within a particular area exceeds the evapotranspiration rate, water transport below the rooting zone occurs, which promotes the nutrient losses through leaching (Lahmann et al., 2003).

Surface and groundwater resources are also at risk of pollution from pesticides. The leaching of pesticides into groundwater depends on the specific chemical’s persistence and mobility, as well as the soil structure. The monitoring and detection of pesticides and other persistent organic material’s impacts are often difficult to quantify. This is mainly due to the

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very low concentrations present in water sources as well as the specialist sampling and analysis instruments which are required. Incomplete results of pesticide pollution in surface and groundwater may be found when testing for pollution as pesticides are transported in association with suspended matter (Kiersch, 2000).

The application of inorganic fertiliser is common in agricultural land use activities as well as in urban gardens. Phosphate (PO_4) compounds are a common constituent of fertilizers (Zaporozec et al., 2002) while phosphate is also less soluble than nitrate. In general, phosphate does not infiltrate unless under abnormal circumstances (Harry et al., 1985). The leaching of phosphate into water is inhibited by sorption processes to clay particles. The intensive runoff from livestock farms have also been identified as a possible contributor of phosphorus levels in water (Kiersch, 2000).

Irrigation water often contains high concentrations of dissolved salts. Through various absorption processes of plants and soil as well as water losses through evaporation, the salt concentration that was dissolved in the water gets left behind and accumulates in the soil. Good irrigational practices make provisions for the accumulation of salts in the soil and through the use of additional water, leach these salts from the soil. Through the continuous use of this method, the excess water, which now contains a very high dissolved salt concentration, percolates into the groundwater system increasing the dissolved salt concentration of the groundwater (Zaporozec et al., 2002).

Stigter et al. (2006) attempted to calculate specific vulnerability of groundwater by incorporating intrinsic risks for various agricultural activities. Within the study they also attempted to assign intrinsic risks to non-agricultural land use activities. Table 5 indicates the various land use activities identified in their study and their associated risk rating.

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Table 5: Rating of land cover according to IGP Map (Stigter et al., 2006)

Land use	Rating
Agricultural areas	
Irrigation perimeters (annual crops), paddy fields	90
Permanent crops (orchards, vine yards)	70
Heterogeneous agricultural areas	50
Pastures and agro-forested areas	50
Artificial areas	
Industrial waste discharges, landfills	100
Quarries, shipyards, open-air mines	80
Continuous urban areas, airports, harbours, (rail)roads, areas with industrial or commercial activity, laid out green spaces	75
Discontinuous urban areas	70
Natural areas	
Aquatic environments (salt marshes, salinas, intertidal zones)	50
Forests and semi-natural zones	0
Water bodies	0

2.7 Conclusion

Groundwater forms a part of the larger earth's hydrological cycle that is influenced through various sources of contamination, both natural and anthropogenic (Pidwirny, 2006). It is seen that groundwater is recharged through surface water that infiltrates into the unsaturated zone and further into the saturated zone (Saayman et al., 2007). The vulnerability of each of these zones to contamination is controlled by various factors such as the physical and chemical constituent of the parent material of the weathered material, relief and hydrology, percolation rate factor, rock type and thickness (Chilton, 2006).

Various anthropogenic sources of contamination are of concern within the study area as indicated in a strategic environmental assessment (SEA) of the Rustenburg area conducted by Ecological and Environmental Consultants in 2003. Among the study site specific possible sources of contamination are: slag and tailings dams to the north, discontinued and active dumps, sewage works, leaking pipelines, run-off from industrial plant areas and agricultural practices (Ecological and Environmental Consultants, 2003).

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The South African Constitution (Act 108, 1996) regarding the right of an individual to an environment that is not harmful to his or her well-being has led to a paradigm shift in the protection of South African water resources, specifically in the past few years and is evident when viewing the National Water Act (Act No 36, 1998). The National Water Act 1998 (Act 36 of 1998) provides the framework on which South Africa's current water protection, use, development, conservation, management and control is based on. DWS compiled a document which highlights the best practised guideline pertaining to water monitoring. According to the DWS best practised guidelines, a minimum frequency of once every 12 months has been set for the monitoring of groundwater resources (Department of Water Affairs and Forestry, 2006 (a)). However, the DWS best practised guidelines recommend that the optimum sampling frequency of once every 6 months should be maintained for efficient quality monitoring(Department of Water Affairs and Forestry, 2006 (a)).

The concept of aquifer vulnerability modelling is not a new concept and over time various methods and models have been proposed in an attempt to determine the vulnerability of aquifers. A scientific programme sponsored by the European Commission, European COST Action 620, in 1997 proposed an objective methodology for the assessment and mapping of "intrinsic and "specific" vulnerability of karst environments (Malik et al., ND). The methodology proposed by the COST Action 620 consisted of a multifactorial approach to vulnerability mapping and follows a conventional source-pathway-target model as a backbone for environmental management and assessing the risk and vulnerability concepts (Zwahlen, 2003). To assess intrinsic vulnerability, the COST Action 620 makes use of the COP method whist specific vulnerability assessment focuses on a particular contaminant and its particular properties (Vias, 2010). The benefit of GIS tools to provide digitised and easily updatable vulnerability maps is recognised by the COST Action 620.

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The complexity of groundwater flow, contaminant transport and interactions between pollutants and the subsurface makes creating a single absolute integrated vulnerability index a great challenge (Carter et al., 1987). Various models over time have been created to try and map vulnerability with no single model found to be suitable for all environments. Commonly used models however are identifiable and include the AVI (Aquifer Vulnerability Index) method, SINTACS, GOD Vulnerability Index model and DRASTIC. Each model has its merits, not as a definitive decision making tool but as a screening tool. The DRASTIC model specifically was found to be a simple model that integrates well with geographic information systems (GIS). The ease of integration of the DRASTIC model with GIS makes the model a well suited platform for vulnerability mapping of groundwater on a regional scale (Javadi et al. 2011). The compatibility of the DRASTIC model and GIS greatly improves the flexibility of the model to be adapted and incorporate additional factors. Additionally, the DRASTIC model has been used in various studies with good success.

Lynch et al. (1994), applied the DRASTIC method on a national scale in 1994 in an attempt to create a groundwater vulnerability map of Southern Africa. During their study, they found that certain limitations existed in terms of the DRASTIC model, specifically relating to a lack of available hydraulic conductivity data. Hydraulic conductivity data was excluded from the study in an attempt to not impact on results. They also noted that certain assumptions were made during the study, both in terms of the DRASTIC model itself and in terms of the availability of datasets.

The pressures exerted on the natural environment as a result of land use and land use change is considered to be an extremely important factor in the assessment of groundwater vulnerability. Land use activities are seen to affect groundwater, in terms of the hydrological regime as well as the quality. Various sources of potential contamination of groundwater in

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terms of a chemical nature have been identified and include various municipal sources, agricultural sources, industrial sources and mining sources.

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CHAPTER 3: BACKGROUND ON STUDY AREA

3.1. Study Area

The study area is situated between 25° 17’ 01.6” and 26° 07’ 38.5” latitudes and 26° 59’ 22.5” and 27° 39’ 29.4” longitudes in the North West Province, South Africa (Figure 5). The study area includes the southern part of the Pilansburg National Park, the Rustenburg Nature Reserve and the Magaliesburg Nature Reserve. Included in the study area, especially in the north and east, are various platinum, chrome and silica mines. Various land use activities such as small scale agricultural, industrial, and commercial activities, residential areas and tourism activities are included in the Rustenburg town areas. Major residential nodes within close proximity of the study area include Brits to the east, Krugersdorp to the south and Randfontein to the south-east.

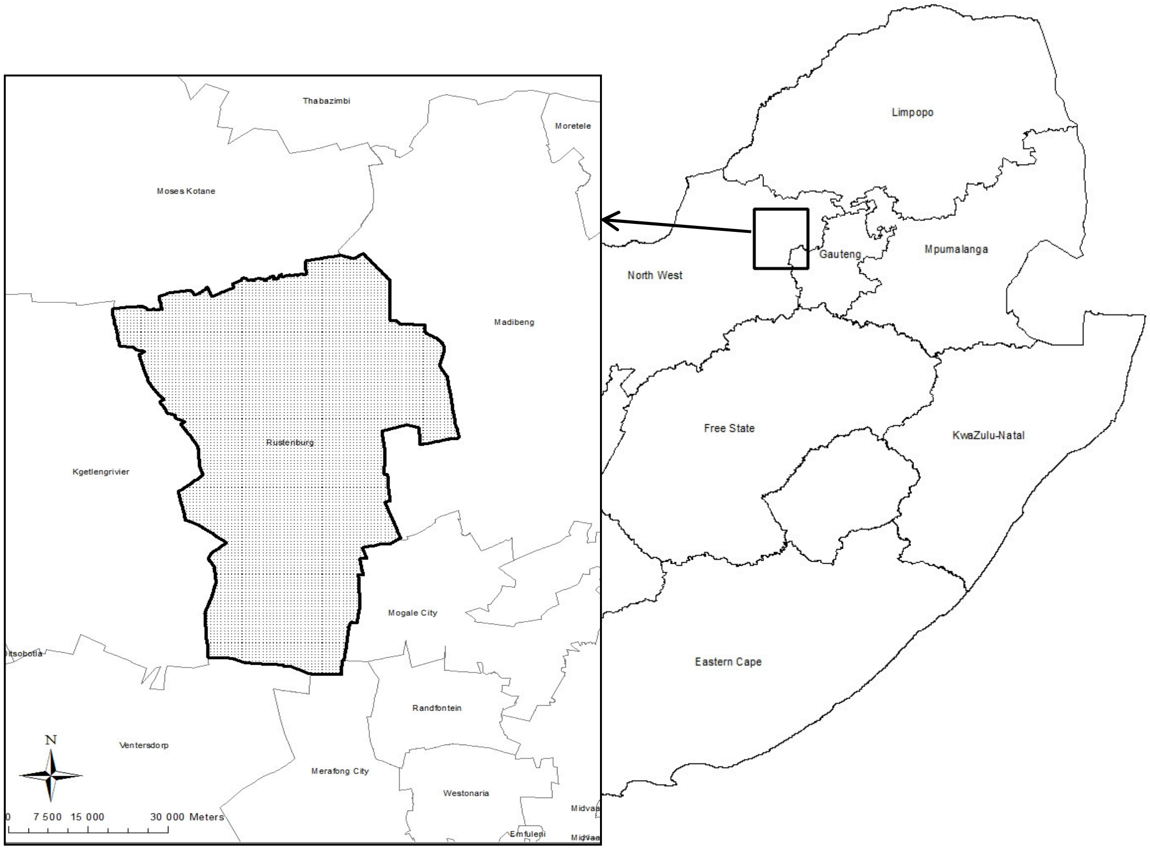

Figure 5: Visual representation of the study area

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3.3 Major industrial and economic activities within the North West Province

Six forms of major industrial and economic activities have been identified within the North West Province. They consist of (Visser et al., ND):

- Agriculture
- Mining
- Industry and manufacturing
- Wholesale and retail distribution
- Infrastructure
- Tourism and leisure.

3.3.1 Agriculture

Agricultural in the North West Province is considered second only to mining in terms of economic activities. Mixed crop and livestock farming are the primary agricultural practices found in the east of the North West Province and moves to almost exclusively livestock farming in the west. The shift in agricultural practices from east to west could be attributed to the change in rainfall experienced within the province ranging from 700mm in the east to less than 300mm in the west (Visser et al., ND).

3.3.2 Mining

Mining is considered one of South Africa's primary economic activities and one of the key sectors of economic activity of the North West Province. The platinum mines situated in the Rustenburg Municipality are recorded as having produced nearly 70% of the world's total platinum. The mining sector in the North West Province also provides important raw materials for local mineral based industries (Visser et al., ND).

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3.3.3 Industry and manufacturing

Industry and manufacturing are seen to greatly contribute to employment creation within the economic sector of the North West Province. Industrial and manufacturing sectors within the North West Province can be separated into three forms of economic activities. The first is primary economic activities which relates to the mining and agricultural industries. Secondary economic activities are more related to the manufacturing and processing sectors while the final form of economic activity, tertiary economic activities, relates to activities such as banking and insurance (Visser et al., ND).

3.3.4 Wholesale and retail distribution

Wholesale and retailing can be seen as the selling of items in bulk or large quantities to mainly retailers or the selling of small quantities of items to mainly the public, respectively. Wholesaling and retail distribution is recognised as the third most important economic sector within the North West Province (Visser et al., ND).

3.3.5 Infrastructure

Infrastructure is important in the development and expansion of a province. Infrastructure provides a network that opens important linkages to trade and investment of a country or province. A good infrastructure network is especially important to land locked countries and provinces. The North West Province has a very good infrastructure network and includes road and railway infrastructure, air transport, post and telecommunication, electricity and water supply (Visser et al., ND).

3.3.6 Tourism and leisure

Ideally situated in a high eco-tourism potential area with close access to the main cities of Gauteng, the North West Province is one of South Africa's most visited attractions.

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The Rustenburg Municipality sports two major tourism attractions which include the Pilansberg nature reserve as well as the leisure resort Sun City (Visser et al., ND).

3.4 Climate

Rustenburg falls within the summer rainfall climatic zone. Rustenburg is classified as warm to hot with temperatures ranging from -6.0°C to 40°C and an average temperature of 19°C. Rainfall is considered to be erratic and variable receiving 450 – 750 mm rainfall per year. The majority of the rainfall occurs during the months of October to February (Ecological and Environmental Consultants, 2003).

Seasonal variations occur with regard to rainfall, wind and temperature. Summer months are dominated by rainfall and temperatures ranging between 16°C and 31°C with daily averages around 23°C. The winter months are dominated with low rainfall and temperatures ranging between 3°C and 24°C with daily averages of 12°C (Ecological and Environmental Consultants, 2003).

3.5 Geology

The study area falls mainly within the Bushveld Igneous Complex, a nearly two billion year old saucer-shaped layered igneous intrusion which occurs throughout the northern parts of South Africa (Cousins, 1959). The Bushveld Igneous Complex is host to a wide range of igneous rocks ranging in composition from ultramafic to felsic.

Several historical events gave rise to the current geomorphological structure found in the Rustenburg area. These historical events in a Strategic Environmental Assessment of Rustenburg, were grouped together into four phases and are described as follows (Ecological and Environmental Consultants, 2003):

- Deposition of the quartzite and shale from which the mountains are constructed

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- Tilting of the range
- Burial of the range under ice and till
- Re-emergence of the range and subsequent erosion to its present form.

The study area is comprised of several geological types as depicted in Table 6 and Figure 6.

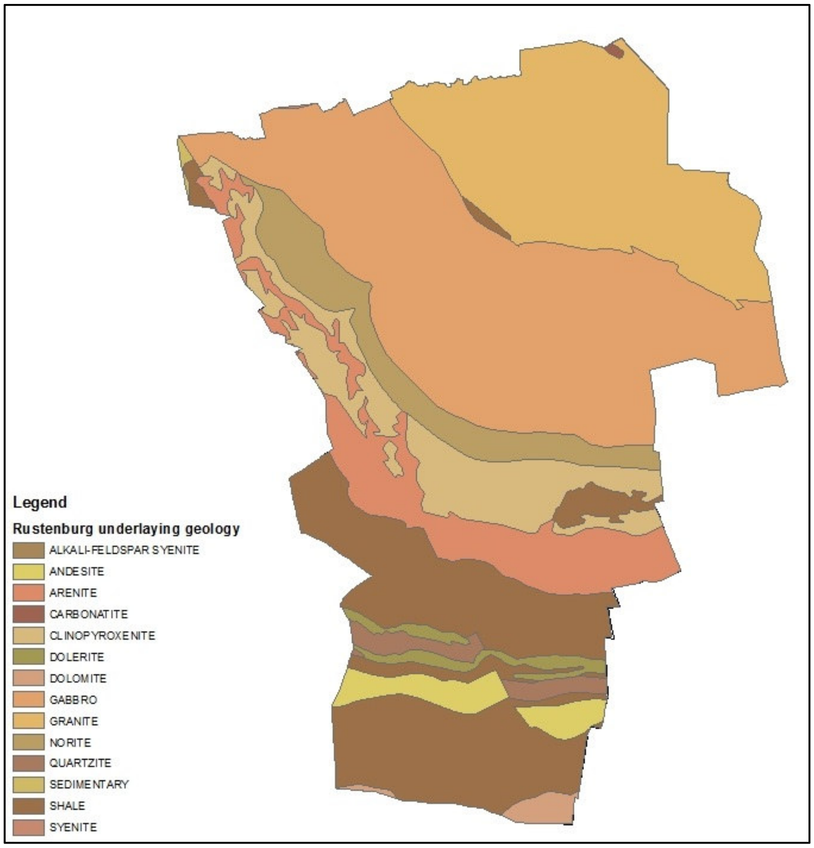

Figure 6: Visual representation of underlying geology of the study area

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Table 6: List of underlying geology of study area

List of study area underlying geology	
Gabbro	Sedimentary
Norite	Arenite
Andesite	Quartzite
Alkali- Feldspar Syenite	Iron Formation
Clynopyroxinite	Granite
Carbonatite	Rhyolite
Shale	Dolomite
Syenite	Dolerite

3.6 Conclusion

The North West Province is situated in an ideal geographical location which boasts a host of favourable economic activities. The two main economic driving forces in the North West province could be attributed to mining and agriculture. Mining activities are seen to be most concentrated in the Rustenburg municipality.

The annual average precipitation of the North West Province is seen to vary from around 700mm in the east to less than 300mm in the west. The study area is situated towards the east of the North West Province where a more favourable climate for livestock and mixed crop farming exists due to a higher annual average precipitation as opposed to western parts of the North West Province where agricultural activities are mostly focused on livestock farming due to the lower annual average precipitation (Visser et al., ND).

The geology of the study area falls mainly within the Bushveld Igneous Complex, a nearly two billion year old saucer shaped layer igneous intrusion which comprises of a wide range of igneous rocks (Cousins, 1959). Several types of geological types are identified within the study are and is depicted in Table 6 and Figure 6.

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CHAPTER 4: METHODS

4.1 Introduction

Chapter 4 provides detailed information on the steps followed using ArcMap 10.0 (ESRI (Environmental Systems Resource Institute). 2010. ArcMap 10.0. ESRI, Redlands, California) to create the individual DRASTIC parameter maps needed to produce an aquifer vulnerability map of the study area. The DRASTIC model is a standardised principal level, meaning that the model focuses on criteria rather than specific or unique situations in each area (Kalinskiet et al., 1994). This chapter also provides the steps followed to create a vulnerability map based on land use activities that occur in the study area.

4.2 Data

Several types of data were used to construct the thematic layers of the individual DRASTIC model parameters. A summary of the data used can be seen in Table 7.

Table 7: Data Used in constructing the DRASTIC Model parameters

Data type	Source	Format	Used to produce
Borehole Data (Water Level Data)	Department of Water and Sanitation, National Groundwater Archive (https://www3.dwa.gov.za)	Table	**D**
Annual Recharge	Author: Vegter 1995 in the Department of Water and Sanitation, Groundwater Resource Directed Measures (GRDM)	Digital	**R**
Geology	Data processed by GEOSS in the Department of Water and Sanitation, Groundwater Resource Directed Measures (GRDM)	Digital	**A, I**
Soil	Source: Surface Water Resources of South Africa 1990: WR90 in the Department of Water and Sanitation, Groundwater Resource Directed Measures (GRDM)	Digital	**S**
Topography	Digital Elevation Model (DEM). University of Pretoria	Digital	**T**
Land use	Source: CSIR Consortiun and data processed by GEOSS in the Department of Water and Sanitation, Groundwater Resource Directed Measures (GRDM)	Digital	**L**

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4.3 GIS Tools

Various tools within the GIS processing environment was used in this study. Blow follows a list and description of the individual tools used to create the final DRASTIC and DRASTL maps.

4.3.1 Inverse Distance Weighted

Inverse Distance Weighted (IDW) is an interpolation tool that forms part of the Geostatistical extensions of ArcGIS. IDW works on the assumption that object/things that are situated close to one another are considered to be more alike than those situated further away. This interpolation tool allows you to predict a value for any unmeasured location within a study area using the values measured form nearby surrounding locations. The closest measured value will be considered to have the most influence, with the influence diminishing as a function of distance (ESRI (Environmental Systems Resource Institute). 2010. ArcMap 10.0. ESRI, Redlands, California). The IDW interpolation tool will be used to interpolate water level values within the study area.

4.3.2 Feature to raster

The Feature to raster tool is a conversion tool to convert feature class which contains points, lines, or polygons features to a raster dataset. The input field type selected to be rasterised determine the output raster dataset created. The Feature to Raster conversion tool always uses the centre of the cell to determine the value of a raster pixel. This tool allows the user to select the output size of each individual cell that comprises the target feature layer (ESRI (Environmental Systems Resource Institute). 2010. ArcMap 10.0. ESRI, Redlands, California). This feature will be used to rasterise all feature layers used in this study to produce the DRASTIC and DRASTIL maps.

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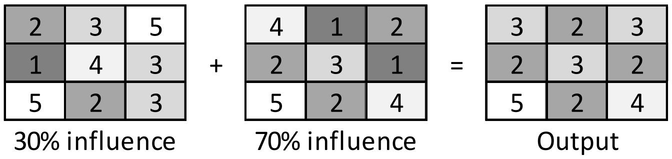
4.3.3 Reclassify

The reclassify tool forms part of the ArcGIS spatial analyst extensions. This tool allow for the reclassification (or change) of values in a raster dataset. The reclassify tool allows for the user to select a target cell attribute (entry) and assign a new value in its place (ESRI (Environmental Systems Resource Institute). 2010. ArcMap 10.0. ESRI, Redlands, California). This tool will be used in this study to reclassify each individual rasterised thematic map used to produce the DRASTIC and DRASTIL output maps.

4.3.4 Weighted Overlay

The weighted overlay tool allows for the union of multiple rasterised thematic layers (criteria) that may not all have equal influence on a specific outcome. This tool is one of the most used approaches to solve multicriteria problems such as site selection. Each individual criteria is assigned an influence percentage rating based on its importance to the desired outcome. The collective influence percentage of each individual criteria needs to add up to 100 %. The criteria of that form part of the weighted overlay is multiplied by its influence percentage and then added together. An illustration of how the weighted overlay process works can be seen in Figure 7. Weighted overlay is a raster dataset output and is in integer format, thus the final output map is rounded off to the nearest whole number (ESRI (Environmental Systems Resource Institute). 2010. ArcMap 10.0. ESRI, Redlands, California). The weighted overlay tool will be used to assign a percentage influence to each individual parameter of the DRASTIC model to produce a final aquifer vulnerability map.



2	3	5
1	4	3
5	2	3

30% influence

+

4	1	2
2	3	1
5	2	4

70% influence

=

3	2	3
2	3	2
5	2	4

Output

Figure 7: Illustration of weighted overlay process

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4.4 Steps in the Composition of Individual Parameter Maps (DRASTIC)

4.4.1 Depth to water level

The following process was followed for the D-parameter (Table 8):

1. Create a Microsoft Excel (2010) data table of applicable borehole localities and associated water levels.
2. Add Microsoft Excel (2010) table including borehole localities to ArcMap 10.0.
3. Export Microsoft Excel (2010) data table to shape file based on geographic projection and coordinates of each borehole.
4. Create a raster file of the depth to water using a Spatial Analysis Tool– Inverse Distance Weighting.
5. Extract the depth to water level raster by using the Rustenburg municipal boundary as a mask.
6. Reclassify the resultant extracted mask according to the predetermined ranges and its associated rating for each range.

Table 8: Range, rating and weight of the study area Depth to groundwater (Lynch et al., 1994)

Depth to groundwater (D_r)	
Range (m)	**Rating**
0-5	10
5-15	7
15-30	3
>30	1
Weight = 5	

4.4.2 Net recharge

The following process was followed for the R-parameter (Table 9):

1. Add the shape file based on net recharge to ArcMap 10.0.

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2. Extract the net recharge raster by using the Rustenburg municipal boundary as a mask.
3. Create a raster file of "net recharge" using a Spatial Analyst Tool– Raster Calculator™.
4. Reclassify the resultant extracted mask according to the predetermined ranges and its associated rating for each range.

Table 9: Range, Rating and weight of the study area net recharge (Lynch et al., 1994)

Net recharge (R_r)	
Range (mm)	**Rating**
0-5	1
5-10	3
10-50	6
50-100	8
>100	9
Weight = 4	

4.4.3 Aquifer media

The following process was followed for the A-parameter (Table 10):

1. Add Shape file based on geology of South Africa to ArcMap 10.0.
2. Extract the geology from the geology feature file by using the Rustenburg municipal boundary as a mask.
3. Create a raster file of the geological types using a Spatial Analyst Tool – Feature to Raster™.
4. Reclassify the resultant extracted mask according to the predetermined ranges and its associated rating for each range.

Table 10: Aquifer type, rating and weight of the study area aquifer media (Lynch et al., 1994)

Aquifer Media (A_r)	
Range	**Rating**
Dolomite	10
Intergranular	8
Fractured	6
Fractured and Weathered	3
Weight = 3	

4.4.4 Soil Media

The following process was followed for the S-parameter (Table 11):

1. Add the shape file containing soil media data to ArcMap 10.0.
2. Extract the soil media from the added soil media feature file by using the Rustenburg municipal boundary as a mask.
3. Create a raster file of the soil types using a Spatial Analyst Tool – Feature to Raster™.
4. Reclassify the resultant extracted mask according to the predetermined ranges and its associated rating for each range.

Table 11: Soil type, rating and weight of study area soil media (Lynch et al., 1994)

Soil Media (S_r)	
Soil Type	**Rating**
Sand	8-10
Shrinking and/or aggregated clay	7-8
Loamy sand	6-7
Sandy Loam	5-6
Sandy clay loam and loam	4-5
Silty clay loam, sandy clay and silty loam	3-4
clay loam and silty clay	2-3
Weight = 2	

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4.4.5 Topography

The following process was followed for the T-parameter (Table 12):

1. Add the digital elevation model (DEM) of South Africa to ArcMap10.0.
2. Extract the DEM for the study area by using the Rustenburg municipal boundary as a mask.
3. Create a surface percentage slope raster file using Spatial Analysis – Surface Analysis – Slope™.
4. Reclassify the resultant percentage slope map according to the predetermined ranges and its associated rating for each range.

Table 12: Range, Rating and weight of the study area topography (Lynch et al., 1994)

Topography (T_r)	
Range (%)	**Rating**
0 - 2	10
2-6	9
6-12	5
12-18	3
18+	1
Weight = 1	

4.4.6 Impact of the vadoze zone

The following process was followed for the I-parameter (Table 13):

1. Add Shape file based on geology (governing rock type) of South Africa to ArcMap 10.0.
2. Extract the geology from the geology feature file by using the Rustenburg municipal boundary as a mask.
3. Create a raster file of the geological types using a Spatial Analyst Tool – Feature to Raster™.

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4. Reclassify the resultant extracted mask according to the predetermined ranges and its associated rating for each range.

Table 13: Governing rock type, rating and weight of the study area vadoze zone

Vadoze zone	
Governing Rock Type	**Rating**
Arenaceous sediments	
Sedimentary	5
Arenite	5
Hard and recrystalised or metomorphised arenaceous sediments	
Quartzite	5
Iron Formation	5
Biochemical and Igneous Carbonate	
Dolomite	9
Carbonatite	9
Felsics	
Granite	6
Rhyolite	6
Mafics	
Gabbro	4
Norite	4
Andesite	4
Argillaceous Sediments	
Shale	4
Weight = 5	

4.4.7 Hydraulic Conductivity

Due to the lack of publicly available data concerning hydraulic conductivity for the study area and in an attempt to not skew the data and final outcome, hydraulic conductivity will not be considered in this study.

4.5 DRASTI

Each criteria of the DRASTI model is given a weight based on the work of Babiker et al. (2005) and Lynch et al. (1994). The weights are as per Table 14:

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Table 14: List of DRASTIC model's factors and associated weights (Lynch et al., 1994 and Babiker et al., 2005)

DRASTC Model factors and weights	
Factor	**Weight**
Depth to water	5
Net **R**echarge	4
Aquifer Media	3
Soil Media	2
Topography	1
Impact of the Vadoze zone	5

The final DRASTI Index is then computed using a linear equation (Equation 3), where D, R, A, S, T and I are the six criteria and the subscript $_r$ and $_w$ are the respective rating and weight.

$$\text{DRASTI Index} = D_rD_w + R_rR_w + A_rA_w + S_rS_w + T_rT_w + I_rI_w \qquad \text{[Eq. 3]}$$

The final aquifer vulnerability map will be expressed as a value per 25mx25m grid. The process of calculating aquifer vulnerability is described by Figure 8.

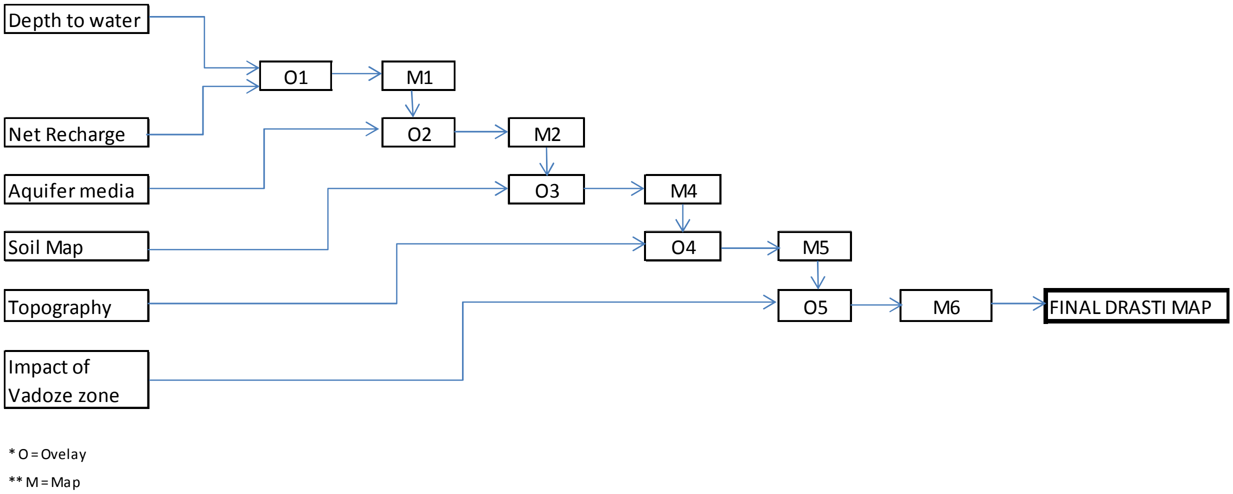

Figure 8: Flow diagram of the DRASTIC model used to evaluate aquifer vulnerability.

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4.6 Land Use

The following process was followed for the L-parameter (Table 15):

1. Add Shape file based on land cover of South Africa to ArcMap10.0.
2. Extract the land cover from the land use cover feature file by using the Rustenburg municipal boundary as a mask.
3. Create a raster file of the land cover types using a Spatial Analyst Tool – Feature to Raster™.
4. Reclassify the resultant extracted mask according to the predetermined ranges and its associated rating for each range.

Table 15: List of study area's land use activities and associated weights (Department of Water Affairs and Forestry 2006 (b)).

LAND USE ACTIVITIES	RATING
Natural Areas	
Barren rock	2
Dongas & sheet erosion scars	2
Forest	2
Forest and Woodland	2
Thicket &bushland (etc)	2
Unimproved grassland	2
Waterbodies	2
Wetlands	2
Degraded: forest and woodland	4
Degraded: thicket &bushland (etc)	4
Agricultural Areas	
Cultivated: permanent - commercial irrigated	8
Cultivated: temporary - commercial dryland	4
Cultivated: temporary - commercial irrigated	6
Cultivated: temporary - semi-commercial/subsistence dryland	4
Forest plantations	4
Artificial areas	
Mines & quarries	10
Urban / built-up land: commercial	8
Urban / built-up land: industrial / transport	10
Urban / built-up land: residential	6
Urban / built-up land: residential (small holdings: bushland)	6

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The final Risk Map is then computed using the linear equation in equation 4.

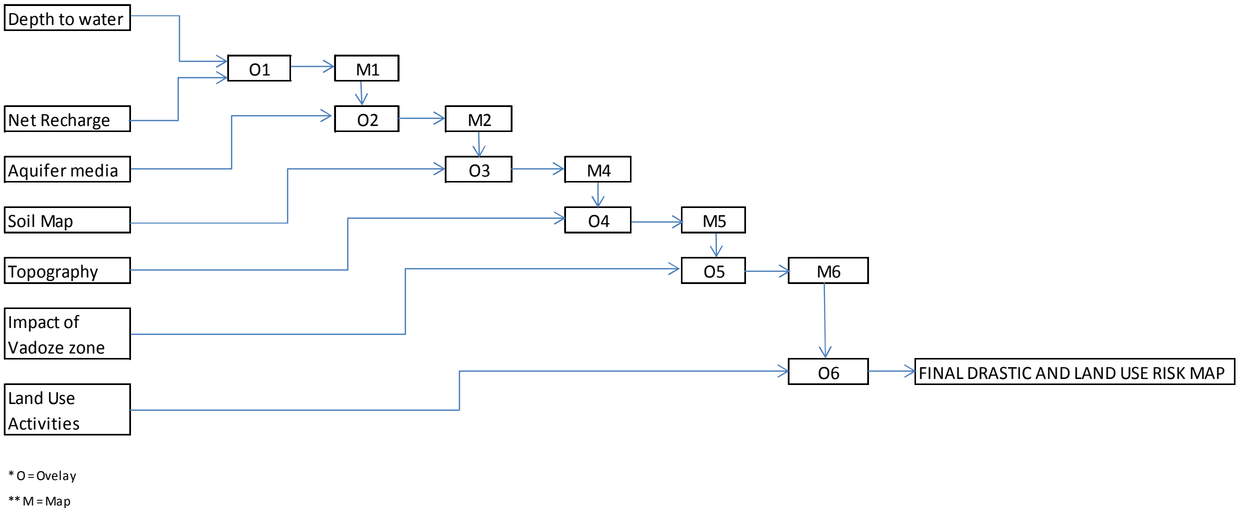

Figure 9: Flow diagram of the DRASTI and land use activities combined to evaluate aquifer vulnerability

Vulnerability map = DRASTI index + Land Use activities [Eq. 4]

4.7 Conclusion

The methods followed in this study incorporate the use of GIS and a known and flexible aquifer vulnerability mapping method, DRASTIC, that is adapted to make provision for the potential pressures exerted on groundwater resources through varying land use. The method followed includes the addition of spatial data for the various individual DRASTIC and land use parameters in the form of shape files to ArcMap 10.0. The spatial data for each individual parameter for the study area is extracted through masking. The extracted spatial data is then converted to a raster file through the use of a spatial analyses tool called feature to raster. The resultant raster maps are reclassified according to their respective vulnerability indexes and finally overlaid with each other using a weighted overlay procedure to produce a singular aquifer vulnerability map of the study area.

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Limitations were experienced in terms of the study which related to a lack of data for some parameters of the DRASTIC model. No data in terms of hydraulic conductivity (C) was publically available for the study area at the time. In an attempt to not impact on the results, the author decided to exclude this parameter from the modelling process until such a time that the data became available. The geology of the study was use to derive both the impact of the vadose zone and the aquifer media parameters of the study area.

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CHAPTER 5: RESULTS

5.1 Introduction

Chapter 5 seeks to provide a visual representation and discussion of each of the individual parameter's results as well as the final aquifer vulnerability map. The findings from these results are further discussed in Chapter 6. The results found in this study seek to fulfil the aims and objectives set out in the study in Chapter 1.

5.2 Depth to Water Level

The data for the depth to groundwater for the study area was obtained from the Department of Water and Sanitation's National Groundwater Archive. 610 (six hundred and ten) monitoring localities data entries were used to calculate the depth to water level for the study area. Average values for monitoring localities with multiple depth values were used. The single water level recorded for the remaining monitoring localities within the study area was used in the Inverse Distance Weighted (IDW) procedure to produce an interpolated Depth to water level map (Figure 10). Based on the IDW depth to groundwater map, the maximum value calculated was 97.33m whilst the minimum was calculated at 0.001m. The average depth to water level based on the IDW map for the Rustenburg municipality was relatively shallow with an average water level calculated at 19.21 meters with a standard deviation of 9.78 metres. According to Figure 10, the vulnerability associated with the depth to water level appears to increase from the periphery to the centre of the study area.

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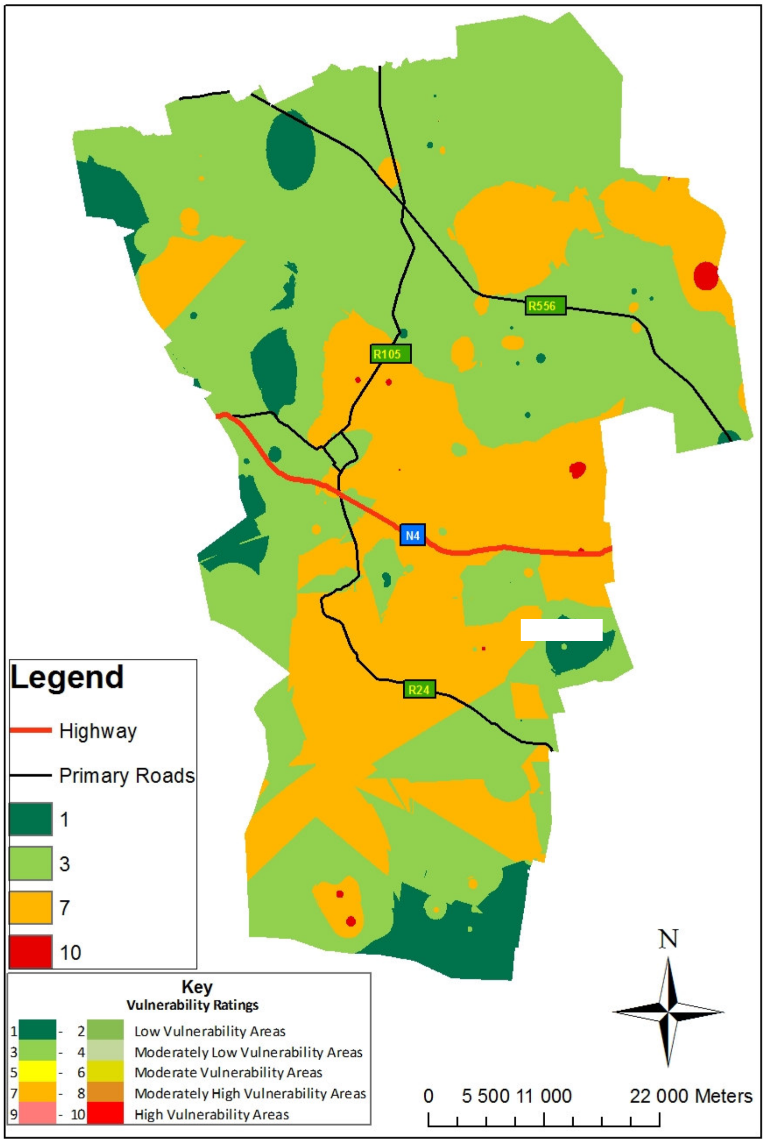

Figure 10: Reclassified depth to groundwater map with associated weights for the study area

The pie chart (Figure 11) indicates the percentage composition (chart values rounded to the nearest percentage) of the individual vulnerability rank for the study area. 7.1% of the study area consists of low (1-2) vulnerable areas. Over half of the study area (58.9%) consists of moderately low (3-4) vulnerable areas. Roughly a third of the study area (33.7%) comprises of moderately high (7-8) vulnerable areas. The remaining 0.3% can be categorised as high (9-10) vulnerable areas.

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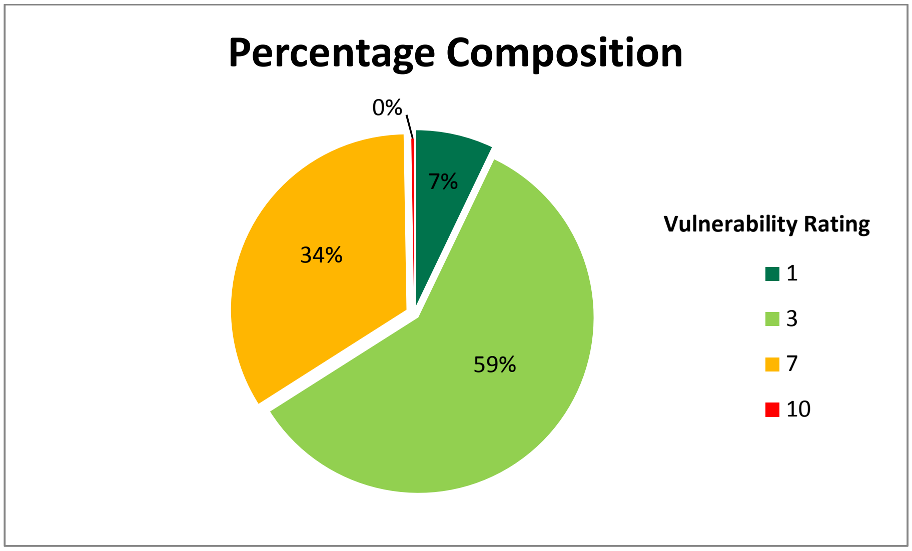

Figure 11: Cell counts per rating of the reclassified depth to groundwater study area map.

5.3 Net Recharge

Rustenburg receives very sporadic and variable rainfall ranging from 450 to 750 mm per year. Although characterised by a fairly high annual rainfall, the net recharge of the groundwater for the study area is considered to carry a low to medium vulnerability risk. Various properties of an area, such as soil properties and land use, are considered to have an influence on the recharge of groundwater and could possibly explain the relatively low groundwater recharge rate in relation to the mean annual rainfall seen in the study area.

The data used to determine the net recharge of the study area was obtained from the Groundwater Resource Directed Measures (GRDM) 4.0.0.0 (Department of Water Affairs and Forestry, 2006 (b)). The recharge map (Figure 12) indicates that the study area can be broken up into three distinct recharge areas. The northern region of the study area has a recharge value of 6 mm/a, while much of the central and southern regions have a recharge value of 14 mm/a. The last region situated in the southeast of the study area has a recharge value of 15 mm/a. The resultant risk recharge map indicates that 55% of the study area is

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comprised of moderately low (3-4) vulnerable areas and the remaining 45% of medium (5-6) vulnerable areas.

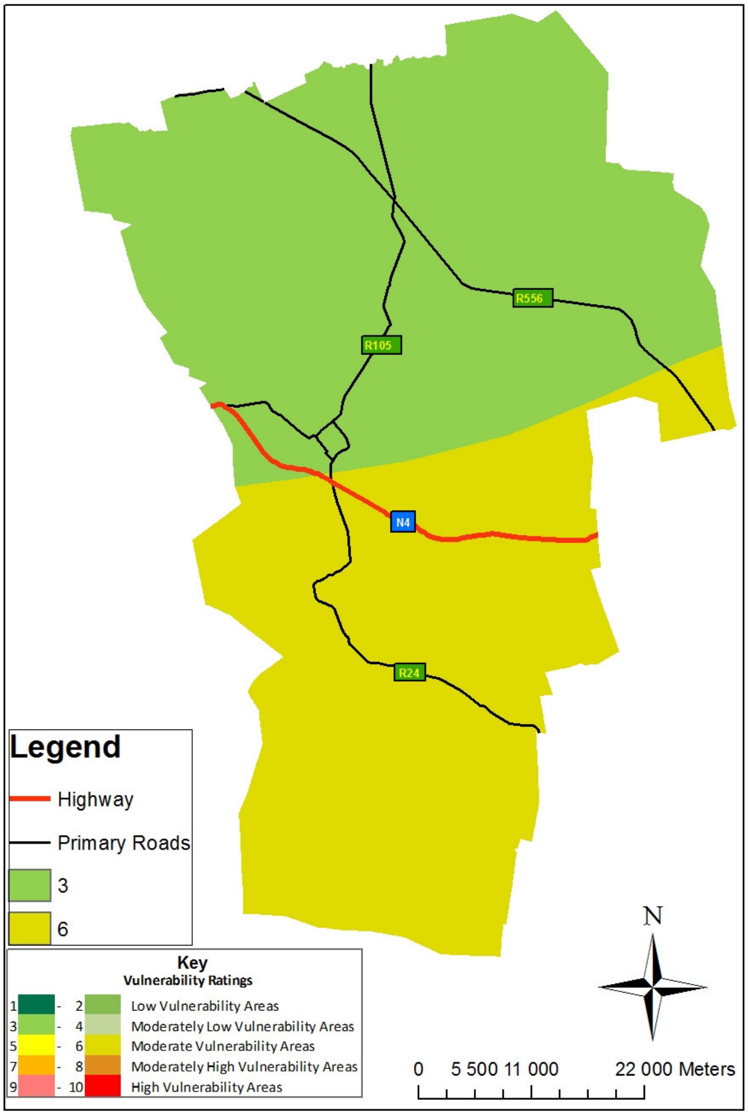

Figure 12: Groundwater (mm/a) recharge map of the study area and the vulnerability recharge map with associated weights for the study area.

5.4 Soil Media

The data used to determine the Soil Media of the study area was sourced from the Groundwater Resource Directed Measures (GRDM) 4.0.0.0 (Department of Water Affairs and Forestry, 2006 (b)). Figure 12 indicates that the soil media of the study area can be identified as sandy, sandy clay loam and sandy loam soils. The north-eastern section of the study area is defined as sandy soils which have a very high permeability rate, resulting in the high vulnerability ranking.

Much of the central and northern regions of the study area are dominated by sandy clay loam soils, whilst the southern region is dominated by sandy loam soils. Both sandy clay loam soils and sandy loam soils are considered to be medium textured soils allowing for intermediate permeability rates. A small section in the north eastern section of the study area is dominated by sandy soils which are considered to have a fairly coarse texture allowing for moderately high permeability rates. This is represented on the reclassified soil media map (Figure 13) with moderately low (3-4), medium (5-6) and moderately high (7-8) vulnerable areas dominating the upper, central and lower regions of the study area.

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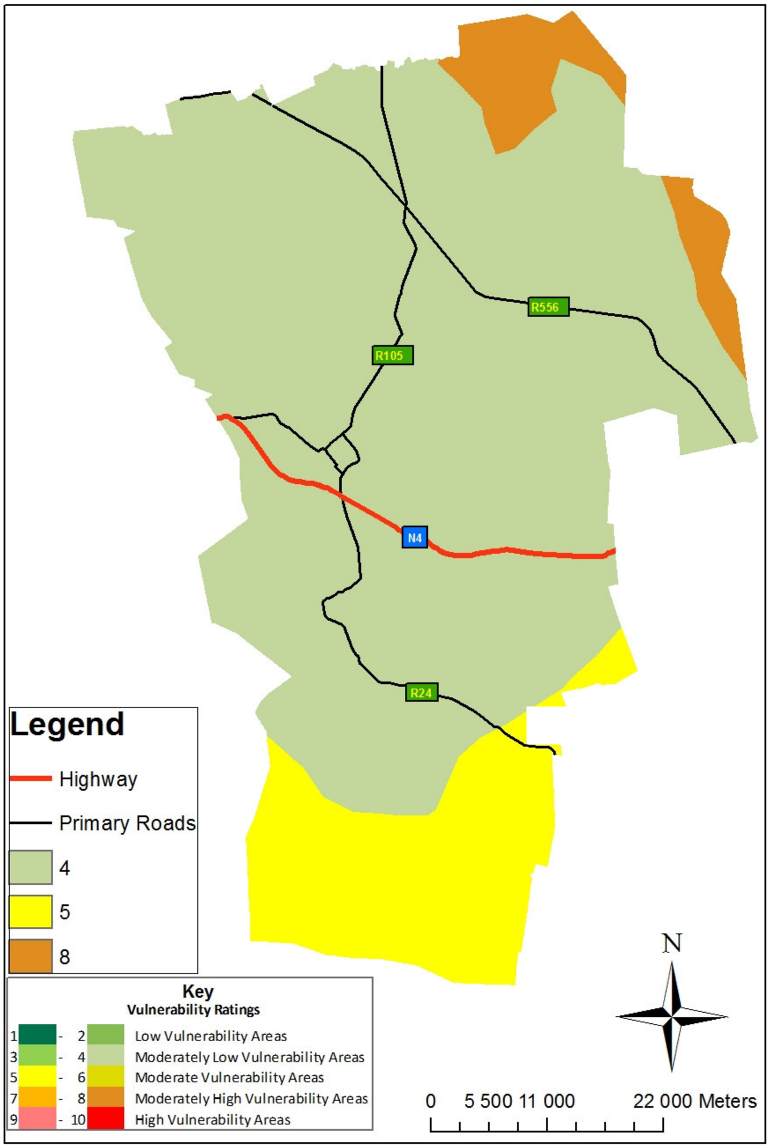

Figure 13: Soil map of the study area.

The pie chart (Figure14) indicates the percentage composition (rounded to the nearest percentage) of the individual vulnerability rank for the study area. 80% of the study area is made up of moderately low (3-4) vulnerability areas. The study area is further categorised by 15% medium (5-6) vulnerable areas, whist the remaining 5% of the study area can be categorised as being moderately high (7-8) vulnerable.

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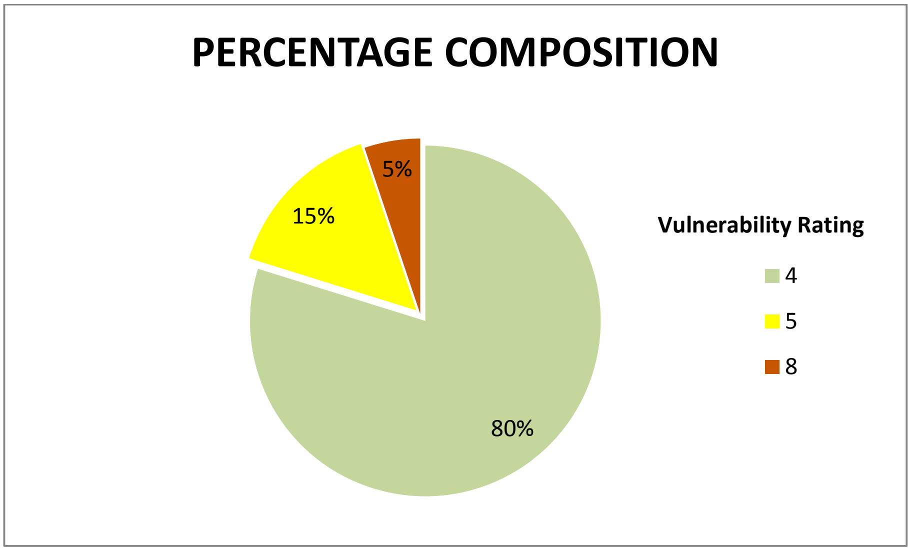

Figure 14: Cell counts per rating of the reclassified soil media study area map.

5.5 Topography

The topography of the study area was calculated from a 25m Digital Elevation Model (DEM) of South Africa. Topography as expressed in Figure 15 is an indication of slope percentage. A strip of steep sloped areas can be seen stretching from the east to the west of the study area. This strip of steep sloped areas is as a result of the Magaliesberg mountain range which stretches for an estimated 120km from Bronkhorstspruit Dam, east of Pretoria, to Rustenburg. The Magaliesberg mountain range is estimated to rise around three hundred and thirty meters above the surrounding plains. A large proportion of the remaining study area appears to be dominated by slopes of less than 12% ranging in vulnerability values of medium (5-6) and high (9-10).

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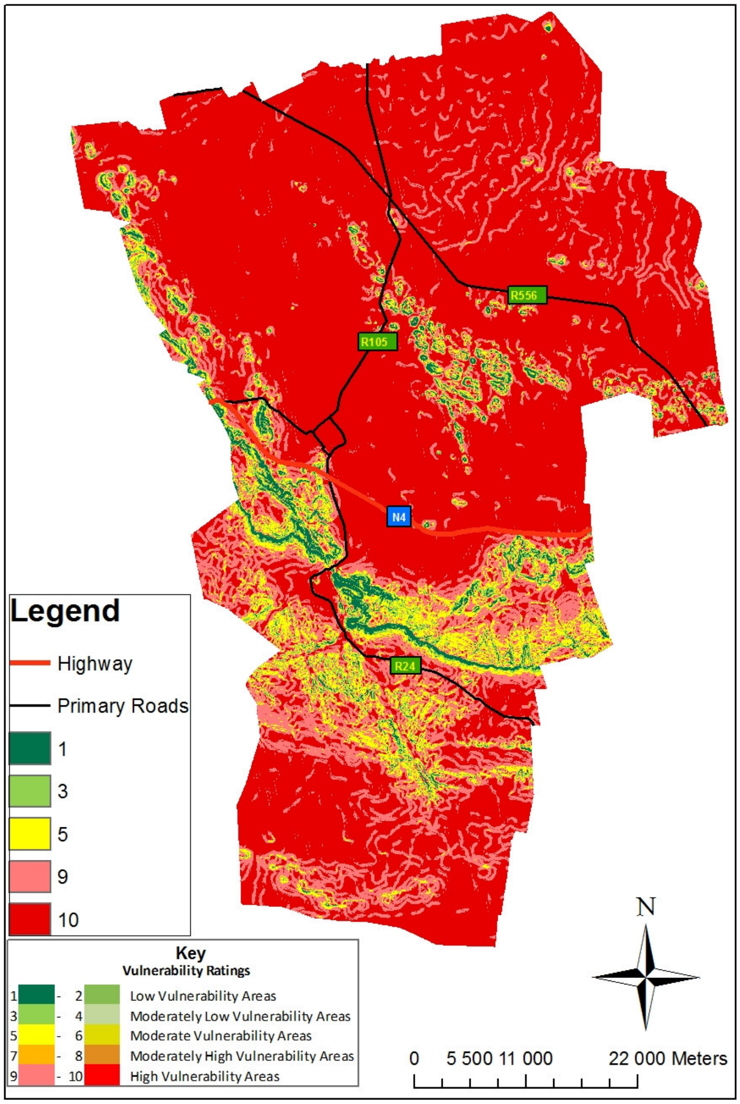

Figure 15: Reclassified topography (slope) map with associated weights of the study area.

The pie chart (Figure 16) indicates the percentage composition (rounded to the nearest percentage) of the individual vulnerability rating for topography for the study area. It can be seen that the study area is dominated by low slope areas resulting in large areas being susceptible to "pooling." 68% of the study area can be attributed to low slope percentage, high vulnerable (9-10) areas. 18% of the study area comprise of medium slope areas carrying a medium (5-6) vulnerability rating. The remaining 14% of the study area can be attributed to steep slope areas with a low (1-2) and moderately low (3-4) vulnerability ratings.

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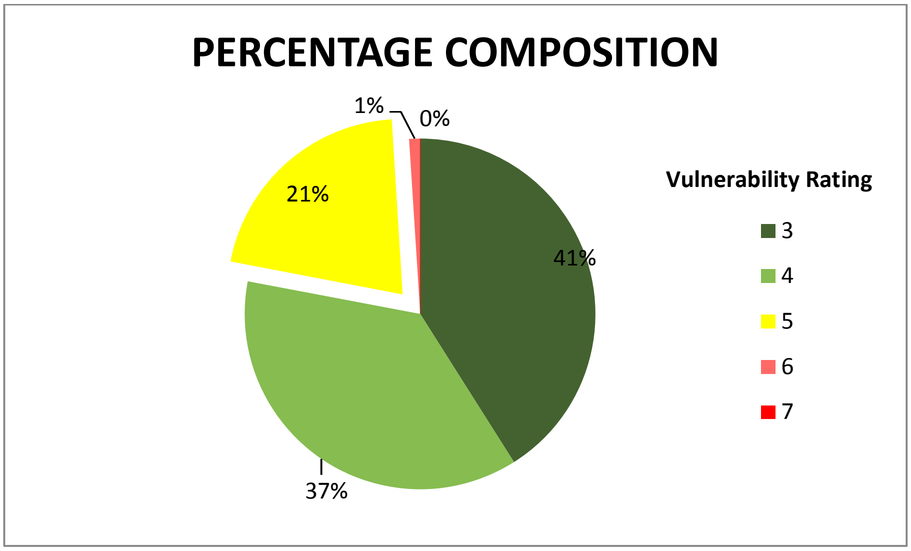

Figure 16: Cell counts per rating of the reclassified topography (% slope) study area map.

5.6 Impact of the Vadose Zone

The vadose zone parameter (Figure 17) was determined from the geological profile of South Africa as portrayed in the Groundwater Resource Directed Measures (GRDM) 4.0.0.0 (Department of Water Affairs and Forestry, 2006 (b)).

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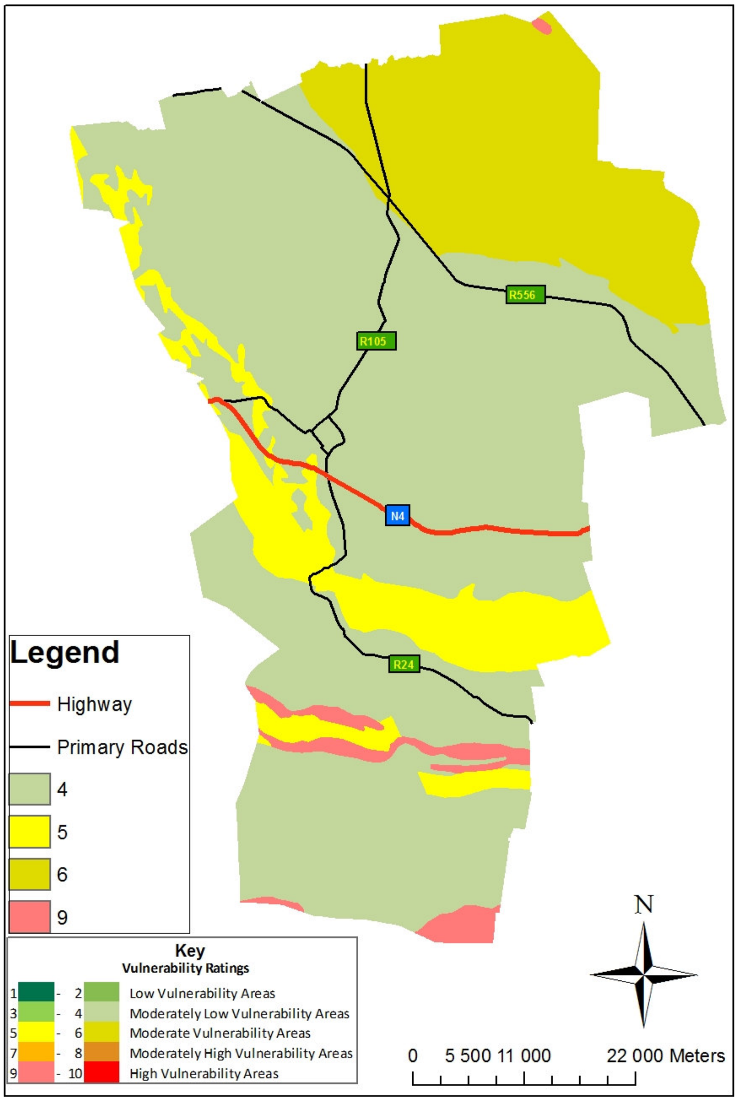

Figure 17: Reclassified impact of the vadoze zone with associated weights of the study area

The pie chart (Figure 18) indicates the percentage composition (rounded to the nearest percentage) of the individual vulnerability rank of the Impact of the vadose zone for the study area. 68% of the study area is dominated by moderately low (3-4) vulnerable areas. Medium (5-6) vulnerable areas occupy 30% of the study area, whilst the final 2% of the study area is comprised of high (9-10) vulnerable areas.

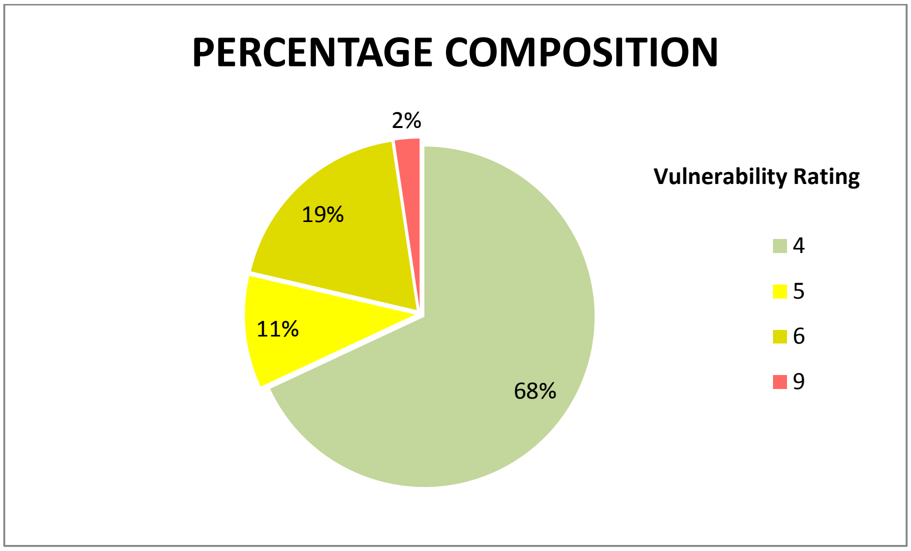

Figure 18: Cell counts per rating of the reclassified Impact of the Vadose Zone study area map

5.7 Aquifer Media

The aquifer media (Figure 19) of this study is determined from geological maps of South Africa as portrayed in the Groundwater Resource Directed Measures (GRDM) 4.0.0.0 (Department of Water Affairs and Forestry, 2006 (b)). Each geological feature was grouped into one of four groups as outlined in Table 9. Its associated vulnerability was sourced from the work done by SD Lynch in 1994.

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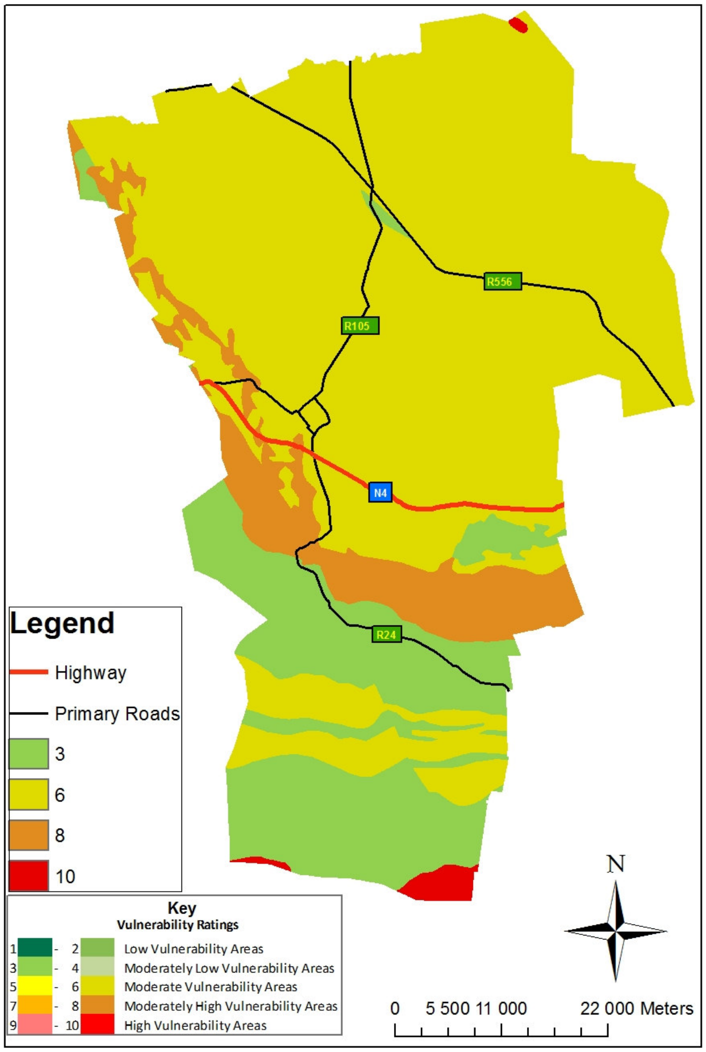

Figure 19: Reclassified map of the Aquifer media with associated weights of the study area

The pie chart (Figure 20) indicates the percentage composition (chart values rounded to the nearest percentage) of the individual vulnerability rank of the aquifer media for the study area. A large portion (71%) of the study area is dominated by medium (5-6) vulnerable areas. 19% of the study area can be categorised in to moderately low vulnerable areas (3-4), whist the remaining 10% of the study area is split as 9% moderately high vulnerable (7-8) and 1% high vulnerable (9-10) areas.

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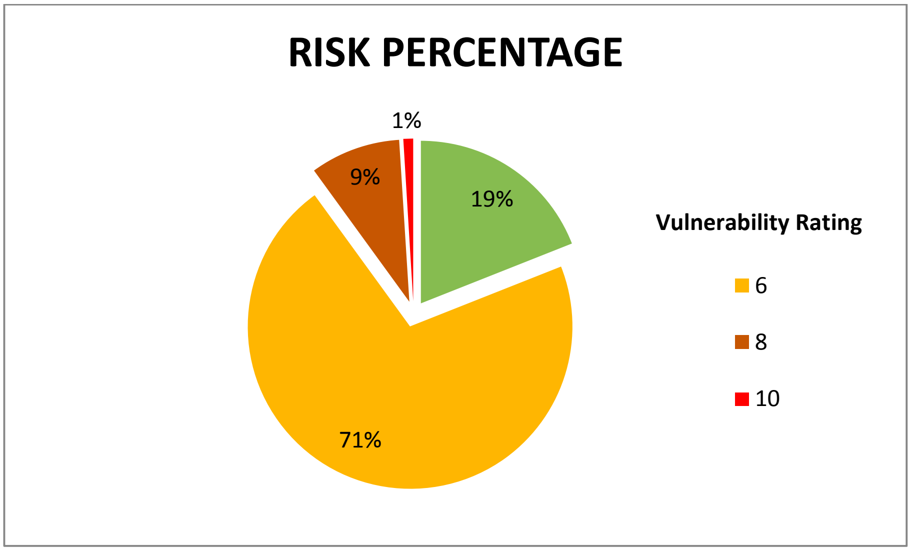

Figure 20: Cell counts per rating of the reclassified Aquifer media study area map.

5.8 Land Use

The land use of this study (Figure 21) is determined from a Land cover map of South Africa as portrayed in the Groundwater Resource Directed Measures (GRDM) 4.0.0.0 (Department of Water Affairs and Forestry, 2006 (b)). Each land cover type was identified and carries various vulnerability ratings as outlined in Table 14. The vulnerability rating is based on the hazard classification rating assigned to each individual land use activity in the Groundwater Resource Directed Measures (GRDM) 4.0.0.0 (Department of Water Affairs and Forestry, 2006 (b)).

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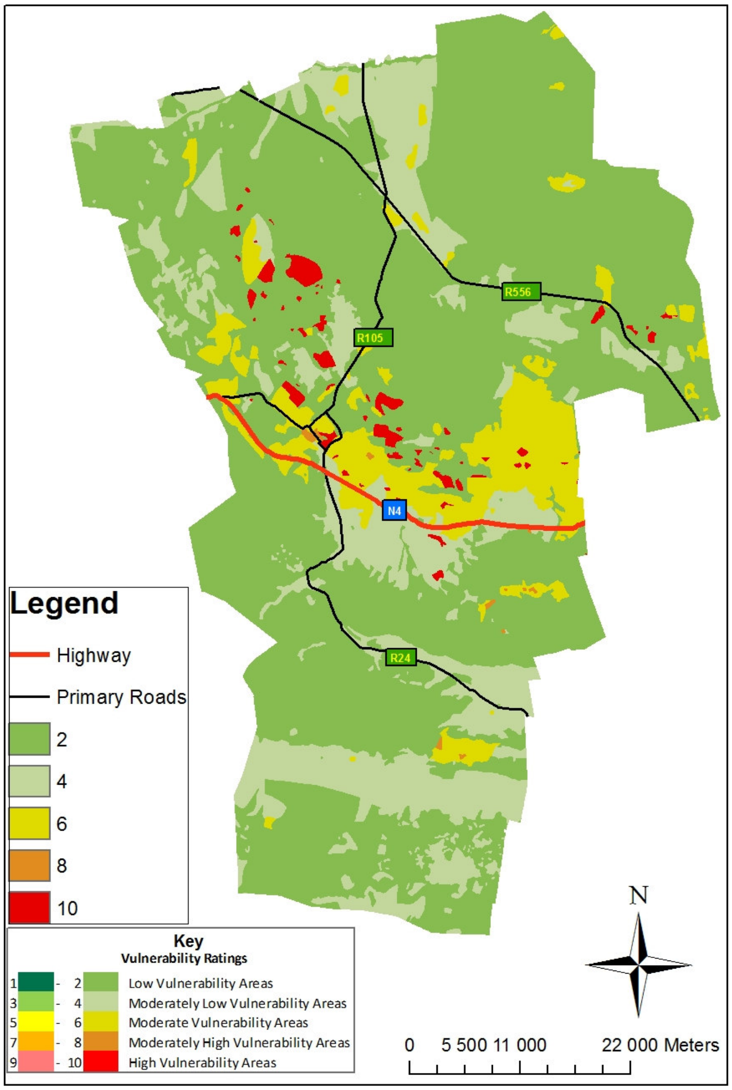

Figure 21: Reclassified impact of the land use with associated weights of the study area.

The pie chart (Figure 22) indicates the percentage composition (chart values rounded to the nearest percentage) of the individual vulnerability rank of the land use for the study area. A large majority (70.1%) of the study area is dominated by low (1-2) vulnerable areas. Moderately (3-4) low vulnerable areas makes up 19.6% of the study area, whilst medium vulnerable (5-6) areas make up another 9%.The remaining 1.3% of the study area can be broken up into 0.1% moderately high (7-8) and 1.2% high (9-10) vulnerable areas.

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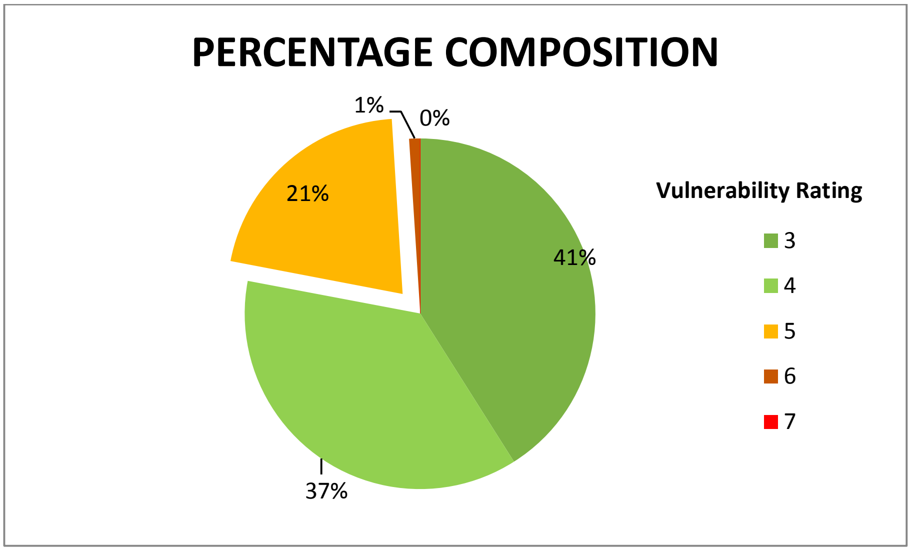

Figure 22: Cell counts per rating of the reclassified Land Use study area map

5.9 DRASTI Aquifer Vulnerability Map

The combined DRASTI map was produced from a weighted overlay procedure in ARC GIS. Each individual DRASTI variable had a predefined percentage influence adding up to 100% which was the used to formulate the final DRASTI map. The percentage influence assigned to each of the DRASTI variables are as per **Error! Reference source not found.**Table 16 and Figure 23. The percentage influence as per Table 16 is based on the work of Lynch et al. (1994).

Table 16: Percentage influence of each individual DRASTI variable (Lynch et al., 1994).

Variable	Percentage Influence
D	25%
R	20%
A	15%
S	10%
T	5%

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I	25%
DRASTI	100%

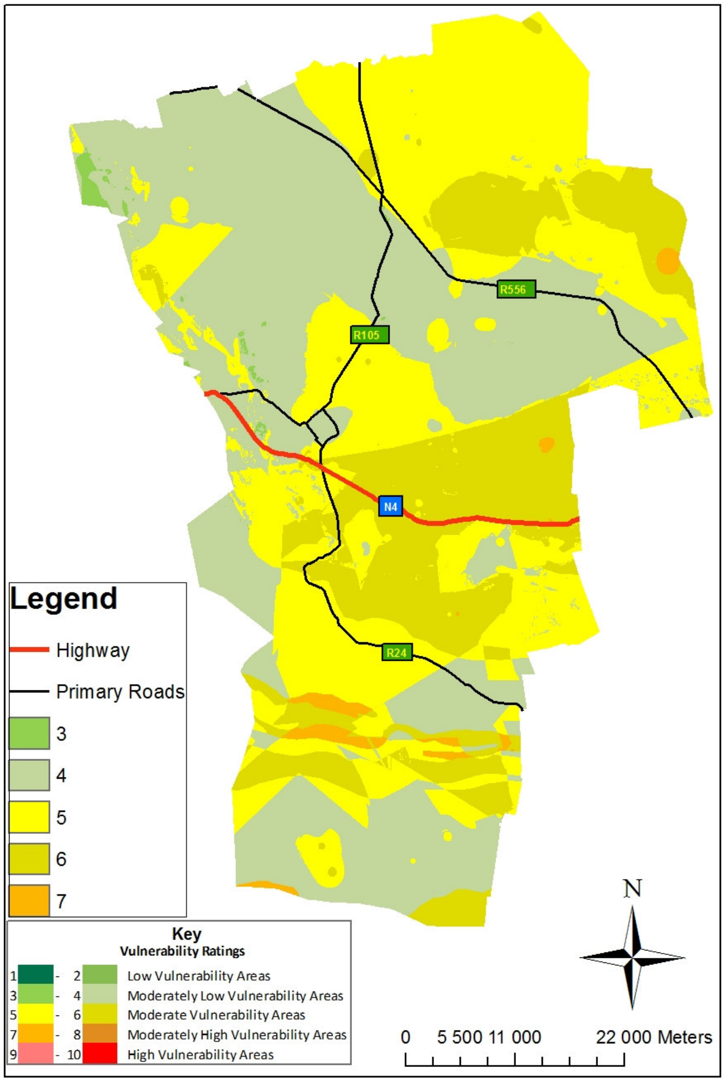

Figure 23: DRASTI vulnerability map.

The pie chart (Figure 24) indicates the percentage composition (chart values rounded to the nearest percentage) of the individual vulnerability rank of the DRASTI vulnerability map. From Figure 24 it can be seen that 41.2% of the study area is dominated by moderately

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low (3-4) vulnerable areas. 57.6 % of the study area is comprised of medium vulnerable areas (5-6) and the remaining 1.2% of moderately high (7-8) vulnerable areas.

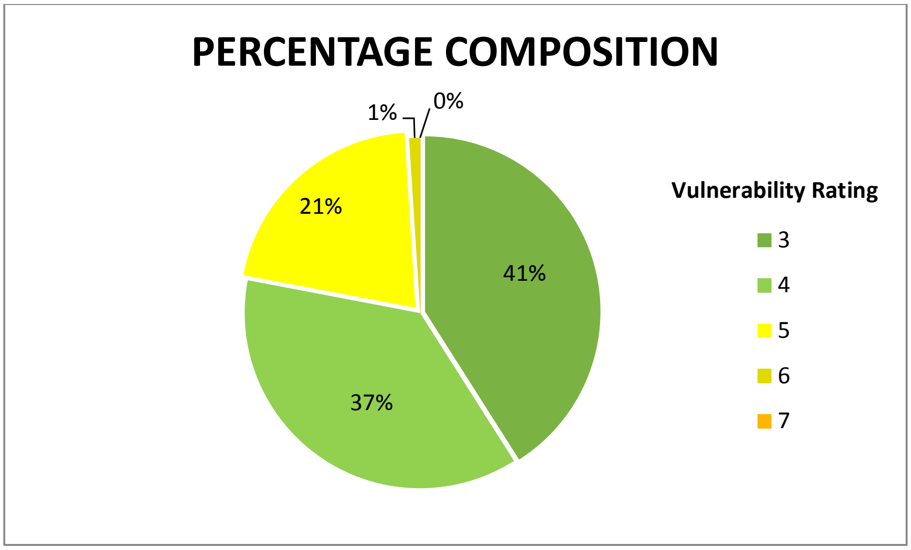

Figure 24: percentage composition per rating of the DRASTI vulnerability map

5.10 DRASTIL Aquifer Vulnerability Map

Land use is considered to be an important variable of concern when determining aquifer vulnerability. This is due to the fact that without any land use activities occurring on the land surface there will be very little potential contamination pressure exerted on the underlying aquifer. As a result, the land use factor being assigned a high percentage influence (20%) to aquifer vulnerability. The remaining DRASTI variables have been proportionally adjusted by a ratio of 1.25:1 in terms of their respective percentage influence as in Table 15 to accommodate the inclusion of the land use factor (L). The adjustment by a ratio of 1.25:1 for each of the DRASTI variables was used in order to keep the proportion of influence similar to that of the work of Lynch et al. (1994) in Table 16.

The combined DRASTI map, overlaid with the reclassified land use map using a weighted overlay procedure in ARC GIS, was used to produce a final DRASTIL vulnerability map. Each individual DRASTIL variable had a predefined percentage influence adding up to

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100% which formulated the final DRASTIL map. The percentage influence assigned to each of the DRASTIL variables is as per **Error! Reference source not found.** Table 17 and was used to compile Figure 25.

Table 17: Percentage influence of each individual DRASTIL variables.

Variable	Percentage Influence
D	20%
R	16%
A	12%
S	8%
T	4%
I	20%
L	20%
DRASTIL	100%

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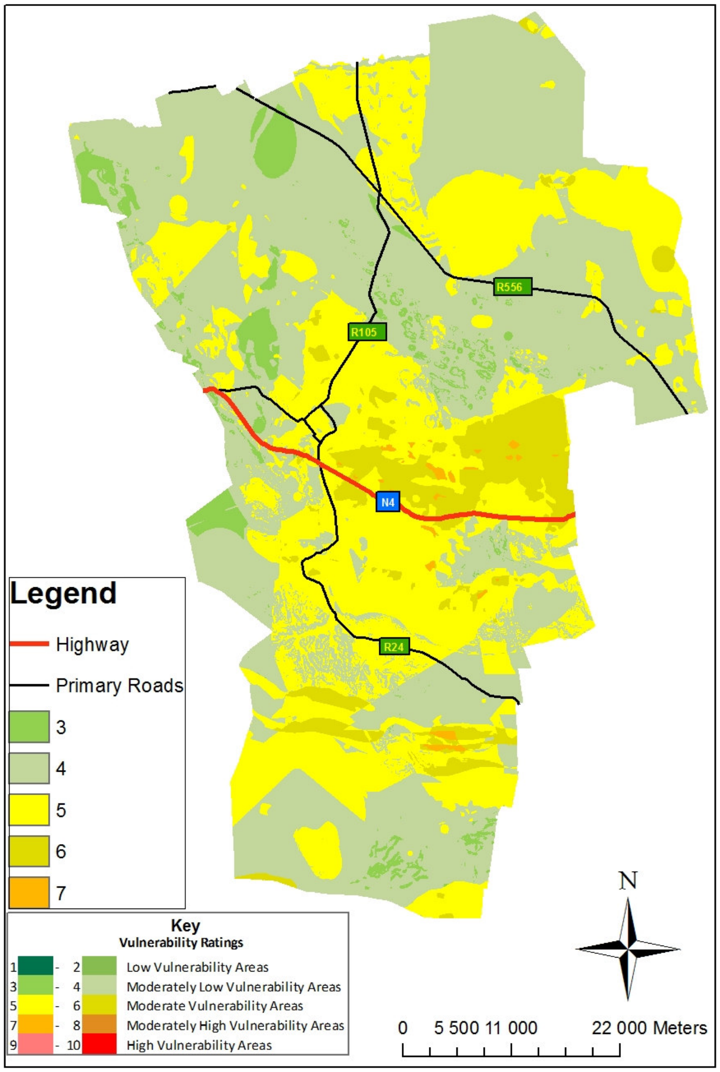

Figure 25: DRASTIL vulnerability map.

The pie chart (Figure 26) indicates the percentage composition (chart values rounded to the nearest decimal percentage) of the individual vulnerability rank of the DRASTIL vulnerability map. Figure 26 shows that 42.8% of the study area is dominated by medium vulnerable areas (5-6). 56.9% of the study area consists of moderately low vulnerable areas (3-4) and the remaining 0.3% of the study area comprise of moderately high vulnerable areas (7-8) areas.

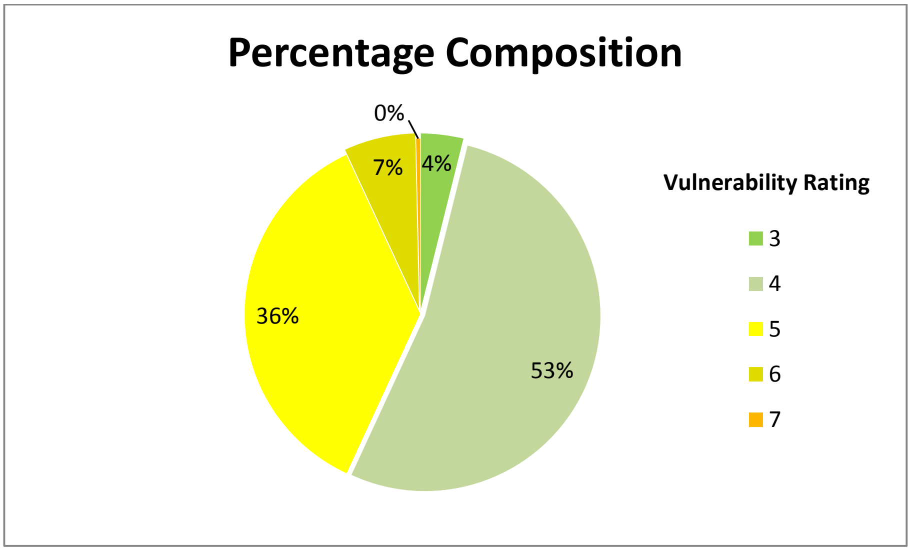

Figure 26: Percentage composition per rating of the DRASTIL vulnerability map

5.11 Conclusion

In total, six individual parameter D,R,A,S,T and I were combined using a weighted overlay method in ArcGIS to produce a final aquifer vulnerability map based on the main hydrogeological factors controlling aquifer vulnerability. A seventh parameter, land use (L), was incorporated to the DRASTI model in order to account for potential pressures exerted on groundwater through land surface contaminant sources (or loads). The purpose of this study was to compare the impact of adaptation of a vulnerability assessment method to incorporate land use as a potential contributing factor rather than to evaluate different vulnerability assessment methods or the potential influence of factors. Although the results of the two aquifer vulnerability maps did not differ in terms of the severity of vulnerability it was found that the distribution of vulnerability had changed with the incorporation of land use activities as a parameter influencing aquifer vulnerability.

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CHAPTER 6: FINDINGS

6.1 Discussion

The aim of this study was to assess the groundwater vulnerability of the greater Rustenburg Municipality through the application of the DRASTIC approach and further incorporate intrinsic impact ratings of varying land use practices to potentially identify areas of varying vulnerability of aquifers to contamination.

For the purposes of the groundwater vulnerability mapping for the greater Rustenburg Municipality, hydraulic conductivity was removed as a factor of the DRASTIC model due to the absence of publicly available spatial data for this component. The groundwater vulnerability modelling thus consisted of a modified DRASTIC model approach to incorporate only the DRASTI factors. The resultant DRASTI model was further adapted by incorporating varying land use activities and land cover to form the DRASTIL model.

Table 18 gives a quick reference to the weights of each individual parameter used in this study as well as the weight of each individual variable within each parameter.

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Table 18: DRASTIL Parameter and variable weights used in the study

RATING VALUES FOR THE USE IN THE DRASTIL CONCEPT			
Depth to groundwater (D_r)		**Net recharge (R_r)**	
Range (m)	**Rating**	**Range (mm)**	**Rating**
0-5	10	0-5	1
5-15	7	5-10	3
15-30	3	10-50	6
>30	1	50-100	8
		>100	9
Aquifer Media (A_r)		**Soil Media (S_r)**	
Range	**Rating**	**Range**	**Rating**
Dolomite	10	Sand	8-10
Intergranular	8	Shrinking and/or Aggregated clay	7-8
Fractured	6	Loamy Sand	6-7
Fractured and Weathered	3	Sandy Loam	5-6
Topography		Sandy clay loam and loam	4-5
Range (% slope)	**Rating**	Silty clay loam, sandy clay and silty loam	3-4
0-2	10	Clay loam and silty clay	2-3
2-6	9		
6-12	5		
12-18	3		
>18	1		
Impact of the Vadose Zone (I_r)			
Range			**Rating**
Gabbro			4
Norite			4
Andesite			4
Alkali- Feldspar Syenite			4
Clynopyroxinite			4
Shale			4
Syenite			4
Sedimentary			5
Arenite			5
Quartzite			5
Iron Formation			5
Granite			6
Rhyolite			6
Dolomite			9
Dolerite			9
Carbonatite			9
Land Use/Cover (I_L)			
Range			**Rating**

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Natural Areas	
Barren rock	2
Dongas & sheet erosion scars	2
Forest	2
Forest and Woodland	2
Thicket & bushland (etc)	2
Unimproved grassland	2
Waterbodies	2
Wetlands	2
Degraded: forest and woodland	4
Degraded: thicket & bushland (etc)	4
Agricultural Areas	
Cultivated: permanent - commercial irrigated	8
Cultivated: temporary - commercial dryland	4
Cultivated: temporary - commercial irrigated	6
Cultivated: temporary - semi-commercial/subsistence dryland	4
Forest plantations	4
Artificial areas	
Mines & quarries	10
Urban / built-up land: commercial	8
Urban / built-up land: industrial / transport	10
Urban / built-up land: residential	6
Urban / built-up land: residential (small holdings: bushland)	6
Parameter weightings	
D_w	5
R_w	4
A_w	3
S_w	2
T_w	1
I_w	5
L_w	5

Figure 27 represents both the DRASTI (left) and DRASTIL (right) vulnerability maps overlaid with major roads to allow for a quick reference of the differences in vulnerability/risk maps produced by the DRASTI model and the adaptation of the DRASTI model through inclusion of land use (DRASTIL).

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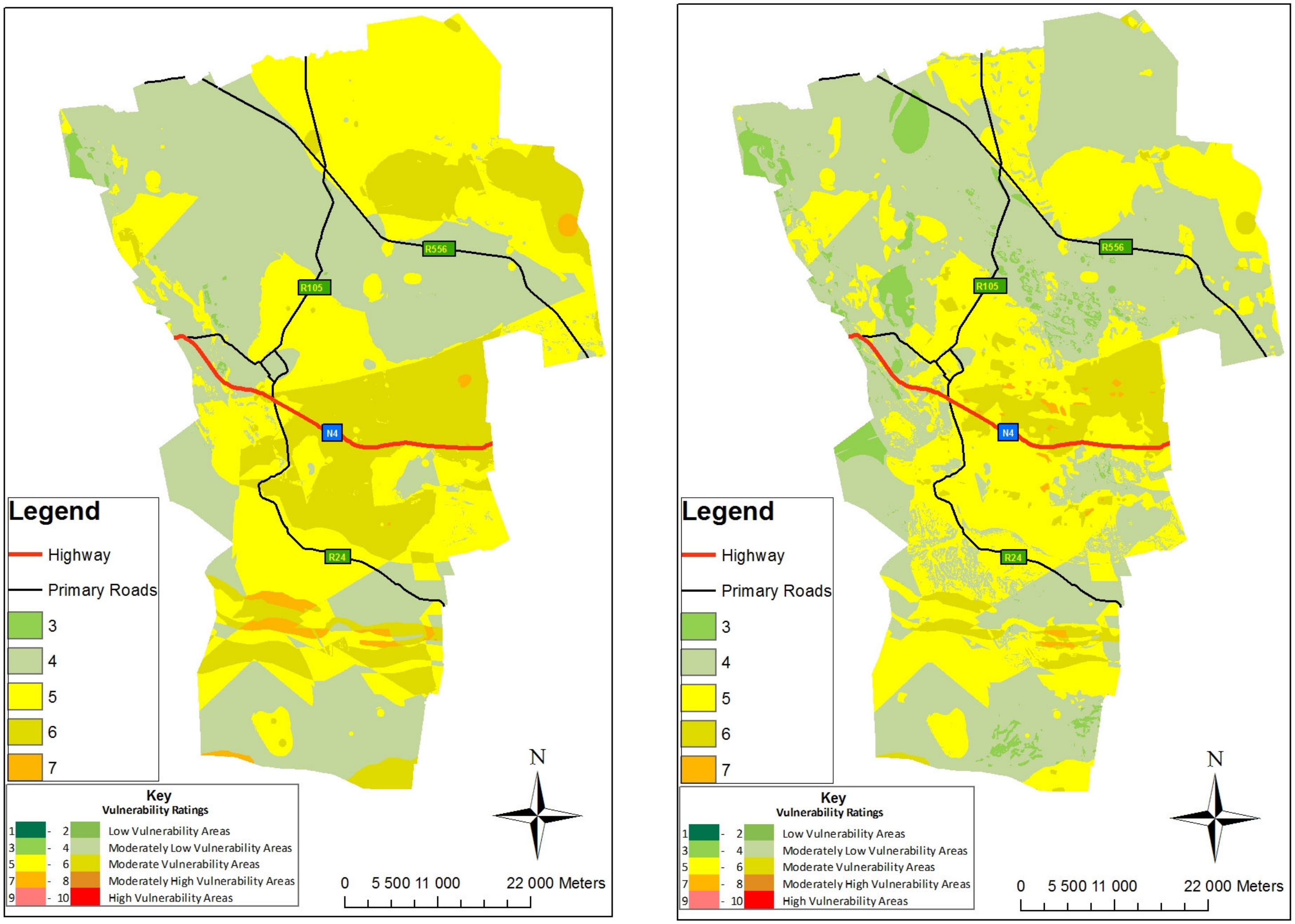

Figure 27: DRASTI (left) vulnerability map and DRASTIL (right) risk map overlaid with major roads

The DRASTI vulnerability map (Figure 27) identified that 1.1% of the study area consists of moderately high vulnerable (vulnerability ratings 7 and 8) areas. 1.1% of this moderately high vulnerable areas fall under the vulnerability rating of 7, whist 0% fall under the vulnerability rating of 8). Ten distinct areas with a vulnerability rating of 7 were identified within the study area (Figure 28). The first area (area 1) of moderately high vulnerability (vulnerability rating of 7) is situated roughly 3.3 km north of the town Bethanie. The second area is situated 2 km north of Marikana. The third area (area 3) identified as having a moderately high vulnerability rating (vulnerability rating of 7) covers a small area next to the N4 highway, approximately 6.5 km west of the town Mooinooi. The fourth area (area 4) covers a small area (roughly 0.12 km^2) approximately 9.82 km southeast of Wigwam. The fifth (area 5) and sixth areas (area 6) with a vulnerability rating of 7 is situated in close proximity to one another. Area 6 is situated 2 km south of area 5. Area 5 and area 6 is situated roughly 28 km south of the city of Rustenburg and roughly 19.6 km east of Derby. The seventh (area 7) and eighth areas (area 8), much the same as area 5 and area 6, is situated in close proximity to one another. Area 8 is situated roughly 1.3 km south of area 7. Area 7 and area 8 is situated along cultivated land approximately 7.7 km southeast of Maanhaarrand. The ninth identified area (area 9) with a vulnerability rating of 7 is also situated along cultivated land approximately 3.1 km to the south of Maanhaarrand. The final area with a vulnerability rating of 7, area 10, is situated on the south western border of the Rustenburg Municipality. Area 10 is situated approximately 6.6 km south of Mathopestad and 5.2 km southeast of Molote.

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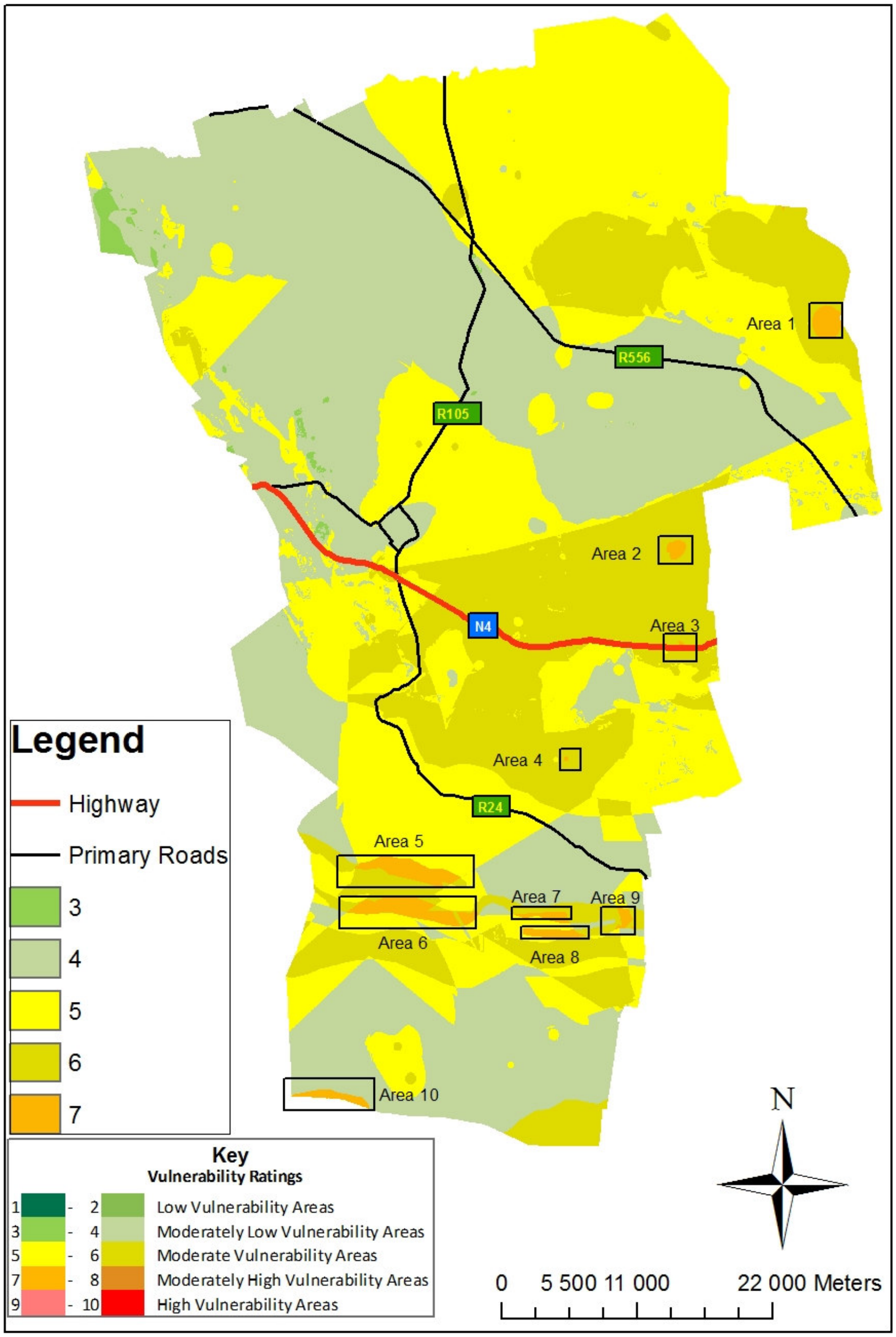

Figure 28: Identified DRASTI vulnerability rating of 7 identified areas

When looking at the DRASTI composition of area 1, it can be seen that three factors out of the possible six DRASTI factors mainly contributed to its medium vulnerability classification. The three factors have been identified as D (depth to water level), S (soil media) and T (Topography). Area 1 is situated in an area where the depth to groundwater is interpreted as between 0m to 5m. Groundwater levels ranging between 0m to 5m has a very high associated vulnerability rating of 10. The soil media of the area is considered to be Sa-Salm (Sandy-Sandy loam) while the topography of the area is also considered to be fairly flat with the slope percentage of the area ranging from 0% to 6%.

Four factors of the DRASTI composition had been identified to be the main contributors to the vulnerability rating of 7 recorded at area 2 and area 3. The four individual factors are D (depth to water level), R (nett recharge), A (Aquifer media), and T (Topography). Area 2 and area 3 are both situated in areas where the depth to groundwater is interpreted as ranging between 0m to 5m which has an associated vulnerability rating of 10. The nett recharge of the areas 2 and 3 fall within the range of 10mm/a to 50mm/a. Nett recharge range of 10mm/a to 50mm/a has an associated medium vulnerability rating of 6. A fractured aquifer media is seen within both area 2 and area 3 which also has an associated medium vulnerability rating of 6. Area 2 and area 3 are located in a fairly flat area with the slope percentage of the area ranging from 0% to 2%. Flat areas with slopes ranging from 0% to 2% are considered to "pool" surface water easily, resulting in a high associated vulnerability rating of 10 for these areas.

When looking at the DRASTI composition of the area 4, it can be seen that four factors out of the possible six DRASTI factors mainly contributed to its moderately high vulnerability classification of 7. The four factors have been identified as D (depth to water level), R (nett recharge), A (Aquifer media), and T (Topography). Similarly to that of area 2 and 3 the depth to groundwater is interpreted as ranging between 0m to 5m which has an associated vulnerability rating of 10. Area 4 also falls within a nett recharge range of 10mm/a

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to 50mm/a which has an associated vulnerability rating of 6. An intergranular aquifer media is seen within area 4 which has an associated moderately high vulnerability rating of 8. The topography of the area is also considered to be fairly variant with the slope percentage of the area ranging from moderately sloped (vulnerability rating of 5) to steep sloped (vulnerability rating of 10).

Five factors of the DRASTI composition had been identified to be the main contributors to the vulnerability rating of 7 recorded at area 5, area 6, area 7, area 8, and area 9. The five individual factors are D (depth to water level), R (nett recharge), A (Aquifer media), T (Topography), and I (Impact of the vadose zone). Areas 5, 6, 7, 8, and 9 are all situated in areas where the depth to groundwater is interpreted as ranging between 5m to 15m which has an associated vulnerability rating of 7. The nett recharge of the areas 5, 6, 7, 8, and 9 fall within the range of 10mm/a to 50mm/a. Nett recharge range of 10mm/a to 50mm/a has an associated medium vulnerability rating of 6. A fractured aquifer media is seen within areas 5, 6, 7, 8, and 9 which also have an associated medium vulnerability rating of 6. The topography of areas 5, 6, 7, 8, and 9 are also considered to be fairly variant with the slope percentage of the area ranging from fairly flat (vulnerability rating of 3) to steep sloped (vulnerability rating of 10). The vadose zone of areas 5, 6, 7, 8, and 9 are derived from an underlying dolerite geological structure. The impact of the vadose zone derived from a dolerite geological structure has a high associated vulnerability rating of 9.

Four main factors out of the possible six DRASTI factors have been identified that contributed to the moderately high vulnerability of 7 recorded at area 10. The four factors have been identified as R (nett recharge), A (Aquifer media), T (Topography), and I (Impact of the vadose zone). The nett recharge of the area 10 fall within the range of 10mm/a to 50mm/a. Nett recharge range of 10mm/a to 50mm/a has an associated medium vulnerability rating of 6. A dolomitic aquifer media is seen within area 10 which has an associated high

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vulnerability rating of 10.The topography of area 10 is also considered to be flat with the slope percentage of the area ranging from 0% to 2% and 2% to 6% which has a high associated vulnerability rating of 10 and 9 respectively. The vadose zone of area 10 is derived from an underlying dolomitic geological structure. The impact of the vadose zone derived from a dolomitic geological structure has a high associated vulnerability rating of 9.

The remainder of the DRASTI map comprised of medium (vulnerability rating of 5 to 6) to moderately low vulnerable (vulnerability rating of 3 to 4) areas.

The second part of the study incorporated the various land use practices of the greater Rustenburg Municipality with the DRASTI model (DRASTIL). The incorporation of the land use factor to the DRASTI model was seen to adapt the current DRASTI model to better relate to actual risk of areas to contamination rather than its vulnerability.

The term aquifer vulnerability is a difficult term to define with a single standardised definition still to be formulated. The general concept of aquifer vulnerability however relates to the ease with which the groundwater resource could be contaminated. Aquifer vulnerability assessments as such are generally conducted following a source, pathway, and receptor model of contamination. The DRASTIC model as used in this study follows a similar procedure and is conducted with the assumption that contaminants released at the surface which moves downwards through the unsaturated zone toward the water table or laterally through the saturated zone (Liggett et al., 2009).

The assessment of the risk of an aquifer to contamination is made by the incorporation of a hazard (or hazard), the consequence of losing the resource at the receptor with aquifer vulnerability (Liggett et al., 2009). The incorporation land use in this study to the DRASTI model is seen to introduce a hazard that has been assigned a risk rating, based on its consequence of losing its resource, to an aquifer vulnerability assessment. Based on the

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adaptation of the current aquifer vulnerability assessment model (DRASTI) to include a hazard, with an associated consequence, (Land use (L)) it can be considered that the outcome produced by the DRASTIL model relates better to the actual risk of contamination of aquifers than simply to its vulnerability.

It is clear when comparing the DRASTI vulnerability map to the DRASTIL risk map (Figure 23 and Figure 25) as well as the percentage composition pie chart of each of the models (Figure 24 and Figure 26) that the incorporation of land use practices and land use cover had an effect on the final DRASTI aquifer vulnerability map, especially in the spatial distribution of vulnerability areas. Although the highest vulnerability and risk rating recorded in both DRASTI and DRASTIL maps remains unchanged at medium vulnerability/risk, it can be seen that the percentage composition and the distribution of the various vulnerability/risk areas changed. When referring to Figure 24 (percentage composition of the DRASTI vulnerability map) it can be seen that 1.1% of the study area comprised of moderately high vulnerability (7-8) areas. Within the moderately high vulnerability of the DRASTI vulnerability map it was found that 1.1% of the study areas pertain to the vulnerability rating of 7 and 0% pertain to the higher moderately high vulnerability rating of 8. When referring to Figure 26 (percentage composition of the DRASTIL risk map) which incorporated land use as a parameter it can be seen that 0.4% of the study area comprised of moderately high risk (7-8) areas. Within the medium risk areas, 0.4% pertained to the risk rating of 7 and 0% falls under the higher end of the moderately high risk rating (risk of 8). It can thus be seen that the percentage composition of the vulnerability/risk rating 7 within the DRASTI and DRASTIL maps remained fairly similar (difference of 0.7%).

Vulnerability assessment methods such as the DRASTIC model focus on providing visual insight, through maps, into the intrinsic aquifer vulnerability of areas and is generally criticised for it oversimplification. Intrinsic vulnerability is used to describe the relative

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degree of natural protection of groundwater form land surface introduced contaminants. The conventional DRASTIC model makes no provision for the incorporation of the contamination potential and the associated consequences of various land use activities.

Land use and land cover play an integral part in the determination of aquifer vulnerability as it modifies the DRASTIC model from a model solely focused on several hydrogeological factors controlling aquifer vulnerability to include the consideration for land surface contaminant sources (or loads). The product of a conventional DRASTIC model can potentially be misleading as it may indicate areas that are highly vulnerable to contamination but do not contain any land surface sources of contamination. The risk thus of that vulnerable aquifer being contaminated is considered to be low. The importance of the incorporation of land use into an existing aquifer vulnerability method lies in the ability to provide decision makers with a method for groundwater risk assessment that accounts for other factors that influence the potential contamination of an area as well as the underlying aquifer's vulnerability to contamination.

As discussed above, a clear difference can be seen in the spatial distribution between the DRASTI vulnerability map and that of the DRASTIL risk map (Figure 27). The implications of the change in the distribution of the vulnerable areas will greatly impact the user's decision for the allocation of initial resources, such as where to perform detailed hydrogeological studies.

6.2 Limitations of the study

Various limitations were experienced during the conducting of the study and were contained within this study of the aquifer vulnerability of the greater Rustenburg Municipality.

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6.2.1 Lack of hydraulic conductivity spatial data

The DRASTIC model is based on several individual geological and hydrogeological parameters. As was found in the study conducted by Lynch et al.(1994), there is a lack of publically available hydraulic conductivity spatial data for South Africa. The hydraulic conductivity of aquifers, particularly in hard rock aquifers can vary greatly over short distances and in order not to skew the final aquifer vulnerability/risk map through the use of generic hydraulic conductivity rates for various aquifer media types, especially at a regional scale; the author did not incorporate the parameter in this study. It was, therefore, decided to focus this assessment on the vadose zone and to exclude the phreatic zone. It is suggested that when the assessment is placed on a more localised and focused scale that resources be allocated to determine actual hydraulic conductivity values.

6.2.2 Land use spatial data integrity

Land use practices and urban and rural development is constantly changing, expanding or retracting. Land use practices or land use cover at the time of the capturing and creating of the land use spatial data may have changed slightly. The integrity of the spatially represented land use/ land cover used for the current study may vary slightly to that of the actual current land use/ land cover of the area.

6.2.3 Duplication of Impact of the vadoze zone (I) and Aquifer media (A)

No publically available spatial data with reference to the impact of the vadoze zone could be obtained by the author. The vadoze zone was however derived from geological maps of South Africa. The aquifer media for the study area was also derived from geological maps of South Africa. This resulted in a replication of spatial data used in the study for both aquifer media as well as for the impact of the vadose zone. However, in doing this, the duplication of geology has different implications in that the A-factor considers the saturated media and the I-factor the protection offered by different media from contaminants entering

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the aquifer. For this reason, it may be argued that – in this instance – the C-factor becomes redundant as it is included intrinsically in the geological media.

6.2.4 Neglecting of certain physical parameters

Although impossible to include all parameters that may have an impact on groundwater vulnerability, certain physical parameters that may potentially have a significant impact of the contamination of groundwater resources are not considered in the DRASTIC method. Some of these parameters include: precipitation intensity and duration, the reactivity of pollution variables within specific soils, fracturing and faulting, underground flow directions and the presence of aquatards.

6.2.5 Qualitative versus quantitative assessment

It should once again be emphasised that vulnerability assessments such as this relate relative vulnerability within a given study area and supply no quantitative results, nor do they imply low risk in given areas. Cognisance of this will ensure that such assessments can be used in better management but should not result in considering given areas as low risk despite lower vulnerability with respect to other higher areas.

Although various limitations, as listed above, are encapsulated within this study and the creation of certain layers, such as the impact of the vadose zone, was based on assumptions and could with good reason be contested, the approach used to map aquifer vulnerability and the application thereof in GIS still carries merit.

To date no attempt has been made to actually validate the findings of this study and should thus be considered as a draft of the aquifer vulnerability/risk of the greater Rustenburg Municipality. Further research and validation of this study, through the undertaking of detailed hydrogeological studies of the area as well as the employment of a standardised method for water quality monitoring as detailed in Section 2.3, is thus necessary before the

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results found in this study can be presented as a valuable decision making tool for various planners.

6.3 Conclusion

A distinct difference in the spatial distribution of vulnerability/risk rating could be seen between the produced DRASTI and DRASTIL maps. The changes in the spatial distribution of vulnerability/risk was attributed to three main land use activities namely, agriculture, mining, and urban areas. The incorporation land use in this study to the DRASTI model is seen to change the focus of the final product from predicting an aquifer's vulnerability to contamination to identifying the risk of groundwater to contamination. The importance of the incorporation of land use into an existing aquifer vulnerability method lies in the ability to provide decision makers with a method for groundwater risk assessment that accounts for other factors that influence the potential contamination of an area as well as the underlying aquifer's vulnerability to contamination.

Various limitations were experienced during this study and included: a lack of spatial data for hydraulic conductivity of the study area, land use spatial integrity, the duplication of impact of the vadoze zone (I) and aquifer media (A) parameters and neglecting of certain physical parameters. Despite the limitations and assumptions contained in this study, the approach used to map aquifer vulnerability and the application thereof in GIS still carries merit.

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CHAPTER 7: CONCLUSION

Groundwater quality is very rarely adversely affected without the input of anthropogenic activities. Anthropogenic impacts in the form of land use can adversely negatively affect the groundwater quality of its immediate surroundings and in the case of resilient contamination variables; groundwater contamination can spread vast distances.

The aim of this study was to assess the potential of the DRASTIC approach for aquifer vulnerability mapping for the greater Rustenburg Municipality. Additionally, intrinsic impact ratings of several land use practices will be incorporated in an attempt to identify areas of varying vulnerability of aquifers to contamination.

The aim of the study was address through three main objectives. The first objective was to review various literature to determine if the viability of the incorporation of the DRASTIC model within the Geographic Information System (GIS) environment. The literature revealed that the development of the ArcGIS software has allowed for an easy to use user interface for the simulation of aquifer vulnerability models. The ease of archiving, retrieving and display of spatial data has also improved greatly. Additionally, it also provided a platform for the assignment of numerical ratings to specific spatial attribute data. This thus makes ArcGIS a very useful tool for this study and adaptation of simulation models. The use of the DRASTIC model has been documented in the works of various authors (Dutta et al., 1998, Rahman, 2008, Hasiniania et al., 2010, Lynch et al., 1994, Babiker et al., 2005) The authors found that the DRASTIC model was easily incorporated into the ArcGIS environment and that it greatly facilitated the assessment and analysis of aquifer vulnerability.

The second main objective was to assess if the adaption of the DRASTIC model to include land use as a factor as part of aquifer vulnerability assessment was possible in the

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ArcGIS environment, as well as its application in for assessing the vulnerability of various aquifers to contamination. It was found that ArcGIS provided a sufficient environment for the adaptation of the DRASTIC model to incorporate land use as a factor as part of aquifer vulnerability assessment. The incorporation land use in this study to the DRASTI model is seen to introduce a hazard that has been assigned a risk rating, based on its consequence of losing its resource, to an aquifer vulnerability assessment. Based on the adaptation of the current aquifer vulnerability assessment model (DRASTI) to include a hazard (Land use (L)), with an associated consequence, it can be considered that the outcome produced by the DRASTIL model relates better to the actual risk of contamination of aquifers than simply to its vulnerability. It was found that the importance of the incorporation of land use into an existing aquifer vulnerability method lies in the ability to provide decision makers with a method for groundwater risk assessment that accounts for other factors that influence the potential contamination of an area as well as the underlying aquifer's vulnerability to contamination.

The final objective of the study was to produce an aquifer vulnerability map, using the DRASTIC model, and an aquifer risk, using the adapted DRASTIC model, in ArcGIS of the study area (greater Rustenburg Municipality). The two final vulnerability/risk maps was to be compared in order to see the effect the incorporation of the land use factor had on the final outcomes. It was found that within the greater Rustenburg Municipality, the highest aquifer vulnerability/risk rating remained to be moderately high (vulnerability/risk rating of 7-8) in both the conventional DRASTI aquifer vulnerability map and the DRASTIL aquifer risk map which incorporated land use as a parameter. It was also found that the percentage composition of medium vulnerable/risk areas remained fairly similar with 1.1% of the study area being covered by moderately high vulnerable areas in the DRASTI aquifer vulnerability map and 0.4% in the DRASTIL aquifer risk map.

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A significant change in the spatial distribution of the medium vulnerability/risk areas however occurred between the DRASTI and DRASTIL maps. The main cause of the change in the spatial distribution of medium vulnerable/risk areas between the DRASTI and DRASTL map can be attributed to the presence of agricultural, urban and mining land use activities and the high risk rating assigned to them.

Although various limitations were experienced throughout the study and various assumptions were made, the study should be viewed as a comparative study and the approach used to map aquifer vulnerability and the application thereof in GIS still carries merit. Validation is however still required for both the aquifer vulnerability maps (DRASTI and DRASTIL) before the results of this study can be presented as a decision making tool for various planners.

It should be noted that vulnerability/risk assessments are not quantitative and serve to relate anticipated aquifer susceptibility relative to approximate areas. Incorporation of land use is seen to influence the spatial distribution of vulnerability/risk and validation of the findings through water monitoring may be sensible.

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