ASSESSING THE GROUNDWATER RESOURCES WITHIN THE TABLE MOUNTAIN GROUP USING REMOTE SENSING AND GEOGRAPHIC INFORMATION SYSTEM

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Thesis presented in partial fulfilment of the requirements for the degree of Master of Natural Science at the University of Stellenbosch.

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DECLARATION

I, the undersigned hereby declare that the work contained in this thesis in my own original work and has not previously in its entirety or in part been submitted at any university for a degree.

A. Matoti / Date

ABSTRACT

The Cape Town metropolitan area has limited water supply due to rapid population and urban growth. In many instances, surface water is the only source in water supply schemes. There is a need for additional water supplies to supplement the existing water sources. Groundwater systems can be used as primary or supplemental water supply sources especially in areas where there is high demand for water resources.

The aim of this study is to evaluate the groundwater potential within the Table Mountain Group (TMG) with the assistance of remote sensing and Geographical Information System (GIS). Previous hydrogeological studies have found the TMG to be the second largest hydrogeological unit in South Africa with extensively fractured and multi-porous rock. The study area is 5660 km^2 with TMG covering 1336 km^2.

In this study a Landsat Enhanced Thematic Mapper Plus (ETM+) image was used to identify lineaments. The identified lineaments were overlaid with vegetation, drainage patterns, faults and fractures digitized from 1:250 000 geological maps and borehole yields to show areas with promising groundwater resources.

The results did not show correlation between vegetation and lineaments. Most of the lineaments intersected drainage lines at some points, and a few were parallel to the drainage lines. Forty five percent of the digitized faults and fractures overlap with the Landsat lineament. The most dominating lineaments are oriented in a NW-SE direction. High yielding boreholes with average yield of about 12 l/s were found within the distance of 150m from the lineaments. The lineaments were further analysed to locate areas that could be suitable for groundwater exploration. These areas were identified using Landsat lineaments, boreholes and a Digital Elevation Model (DEM). The results showed that the most favourable lineaments and geological features were oriented in a 135-180° and 0-45° direction and areas with slopes of less than 40% were found to be suitable for drilling boreholes.

The amount of available groundwater within the TMG was also investigated by looking at both volume of recharge and amount that could be held in storage. Rainfall data was used to estimate recharge. Groundwater recharge was calculated to be 5% of

the total precipitation that falls on this area. Based on the average rainfall of 600mm per annum, the results show that TMG has an average recharge value of 30mm per annum. The total recharge for the area covered by TMG, which has an area of 1336km^2, is 160 million m^3. Geological profiles and cross sections were drawn to determine the storage capacity of the TMG, which was estimated to be 525 million m^3.

According to a study done by the Department of Water Affairs and Forestry (DWAF) in 1996, the anticipated water demand in the Cape Town metropolitan area will increase from 243 million m^3 in 1990 to 560 million m^3 in 2020. The estimated volume of water that can be stored within the TMG can meet the current demand for the next 10 years and supplement the existing surface water sources. Groundwater vulnerability of the TMG to contamination was assessed and mapped by using the DRASTIC index. The results demonstrate that the TMG area is at low risk to contamination.

OPSOMMING

‘n Vinnig groeiende bevolking en stedelike uitbreiding plaas toenemende druk op Kaapstad se water voorraad. Addisionele waterbronne sal benodig word om bestaande bronne aan te vul. Oppervlakwater is in die meeste gevalle die enigste waterbron, maar grondwater het die potensiaal om te dien as ‘n primêre of aanvullende voorsieningsbron, veral in areas waar groot water tekorte bestaan.

Die doel van hierdie studie is om die grondwaterpotensiaal van gesteentes van die Tafelberg Groep (TBG) te evalueer deur van afstandswaarneming en geografiese inligtingstelsels gebruik te maak. Geohidrologiese studies het getoon dat die TBG gesteentes met sy veelvuldige nate en breuksones, die tweede grootste geohidrologiese eenheid in Suid Afrika is. Die studiegebied beslaan 5660 km^2, waarvan 1336 km^2 deur Tafelberg Sandsteen beslaan word.

Vir hierdie studie is ‘n “Landsat Enhanced Thematic Mapper Plus (ETM+)” beeld gebruik in die identifisering van breuksones (lineamente). Verdere analises is uitgevoer om areas geskik vir grondwater ontginning te identifiseer. Geïdentifiseerde verskuiwings op Landsat beelde is met plantegroei, dreinerings patrone en bekende verskuiwings en fraktuur sones vanaf gelogiese kaarte vergelyk in ‘n poging om areas met belowende grondwaterbronne uit te wys. Bekende boorgat posisies en lewerings volumes was ‘n primêre databron vir die berekening van groundwater reserves.

Die studie het egter geen korrelasie tussen plantegroei en die voorkoms van lineamente gevind nie. Die riviere in die studiegebied word op verskeie plekke deur verskuiwings gekruis. Slegs 'n paar van die verskuiwings lê parallel met die dreinering. Daar is gevind dat vyf-en-veertig persent van bekende verskuiwings en fraktuursones met die geïdentifiseerd op Landsat beelde oorvleuel. Die mees prominente lineamente het ‘n NW-SO oriëntasie. Boorgate met lewerings van gemiddeld 12 l/s is binne ‘n 150m afstand van die verskuiwings gevind. Die verskuiwings is ook geanaliseer om die mees produktiewe areas vir grondwater ontginning te identifiseer. Landsat beelde, boorgate en ‘n Digitale Elevasie Model (DEM) is gebruik om moontlike boorposisies te identifiseer. Die mees produktiewe

verskuiwings en geologiese verskynsels het ‘n N135-180W en N0-45O oriëntasie, terwyl areas met ‘n helling < 40% vir die boor van boorgate geskik is.

Berekeninge oor die hoeveelheid water wat binne die TBG gesteentes beskikbaar is, is gemaak deur die hoeveelheid aanvulling en stoorkapasiteit van die TBG gesteentes te beraam. Grondwater aanvulling, soos bereken vanaf reënval data, is 5% van die totale presipitasie van ‘n gegewe area. Met ‘n gemiddelde jaarlikse reënval van 600mm in die studie gebied is die TBG se jaarlikse aanvulling ongeveer 30mm. Daar word beraam dat die totale aanvulling in die 1336km^2 TBG area 160-miljoen m^3 per jaar is. Geologiese profiele en dwarsnitte is gemaak om die stoorvermoë van die TBG te bepaal, en is beraam op 525-miljoen m^3.

‘n 1996 navorsing studie deur die Departement van Waterwese en Bosbou toon dat waterverbruik in die Kaapse Metropolitaanse gebied sal toeneem vanaf die 1990 vlak van 243-miljoen m^3 tot 560 miljoen m^3 teen 2020. Die berekende volume water wat binne die TBG gestoor word, kan die water aanvraag oor die volgende 10 jaar bevredig en as aanvulling dien vir oppervlak waterbronne. Die kwesbaarheid van die TBG akwifer vir besoedeling is met behulp van die DRASTIC indeks geëvalueer en gekarteer. Die resultate toon dat die TBG ‘n lae risiko vir besoedeling het.

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ACRONYMS AND ABBREVIATIONS

DEM	Digital Elevation Model
DPPI	DRASTIC Pollution Potential Index
DRASTIC	**D**epth to groundwater; **R**echarge; **A**quifer medium; **S**oil medium; **T**opography; **I**mpact of the vadose zone; Hydraulic **C**onductivity
EPA	Environmental Protection Agency
GCP	Ground Control Point
GIS	Geographical Information Systems
IDW	Inverse Distance Weighting
NDVI	Normalised Difference Vegetation Index
NGDB	National Groundwater Database
ETM+	Enhanced Thermal Mapper Plus
TMG	Table Mountain Group
WRC	Water Research Council
l/s	Litres per second
mm^3	Cubic millimetres
etc.	Et cetera

CHAPTER 1: INTRODUCTION

1 INTRODUCTION

The Western Cape is one of the provinces in southern Africa that has high water demand due to high population growth and economic development. Groundwater systems can be used as a primary or supplemental water supply source, especially in areas where there is high demand for water. Data and tools that can assist in the evaluation of potential water resources in the Cape Town metropolitan area were considered for this increasingly critical need.

For a number of decades groundwater resources had been excluded as a viable source of water supply. The hydrological data were used to evaluate water resources and were obtained through the collection and analysis of rain and stream gauge measurements, excluding the underlying fracture system (aquifer). Groundwater exploration programmes such as field mapping were the most used techniques. Integration of satellite imagery with Geographical Information Systems (GIS) has become a common technique in assessing groundwater resources (Kellgren et al 1997; 1999; 2000), indicating that the use of remote sensing and GIS improves the existing techniques. The major advantage of using remote sensing and GIS is that the exact position of features can be determined and readily referenced to specific longitude and latitude and that data from different sources can be overlaid and analysed.

The aim of this study was to estimate and evaluate groundwater resources in the Table Mountain Group (TMG). Mapping of highly fractured and faulted areas was a major requirement for groundwater resource evaluation and exploration. Remote sensing and GIS were used in analysis of data to assess these groundwater resources.

Groundwater exploration studies also involve the investigation of recharge potential, storage capacity of the TMG and contamination threats to this aquifer. The effect of contaminants depends on the physical characteristics of the soil, bedrock, depth to the water table and contaminant properties.
The extent of the study area is illustrated in the following section.

1.1 Study area

According to Weaver & Talma (1999), TMG is found to be the second largest hydrogeological unit in South Africa with high recharge potential. The study area is situated North and East of Cape Town, in the Western Cape province, as shown in Figure 1.1.

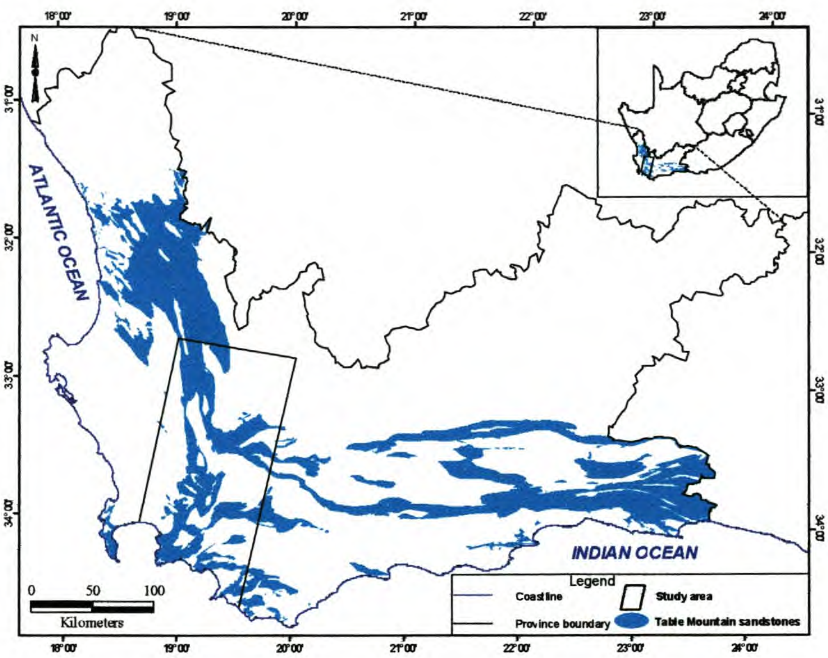


Figure 1.1 Location of the Table Mountain Group and the study area

The extent of the study area is approximately 5660km^2 with TMG covering 1336km^2. The study area lies between 18° 15' to 19° 30' east and 33° 19' to 34° 45' south. The study area falls in a Mediterranean climate region with wet winters and dry summers. Seventy per cent of the annual rainfall occurs during the months of May to October. The TMG constitutes the mountainous areas, which in turn influences precipitation to a significant extent. The annual rainfall ranges from 200mm in low lying areas to >1500mm in the mountains and tends to decrease from southwest to northeast (Figure 1.2). In winter, the highest mountains are often covered with snow. The summers are dry and hot with southwesterly and southeasterly winds. The average daily maximum temperatures are 30°C in summer and 15°C in winter (Morel, 1998). This area was chosen because of the availability of hydrogeological data and the fact that some groundwater studies have been initiated in this area.

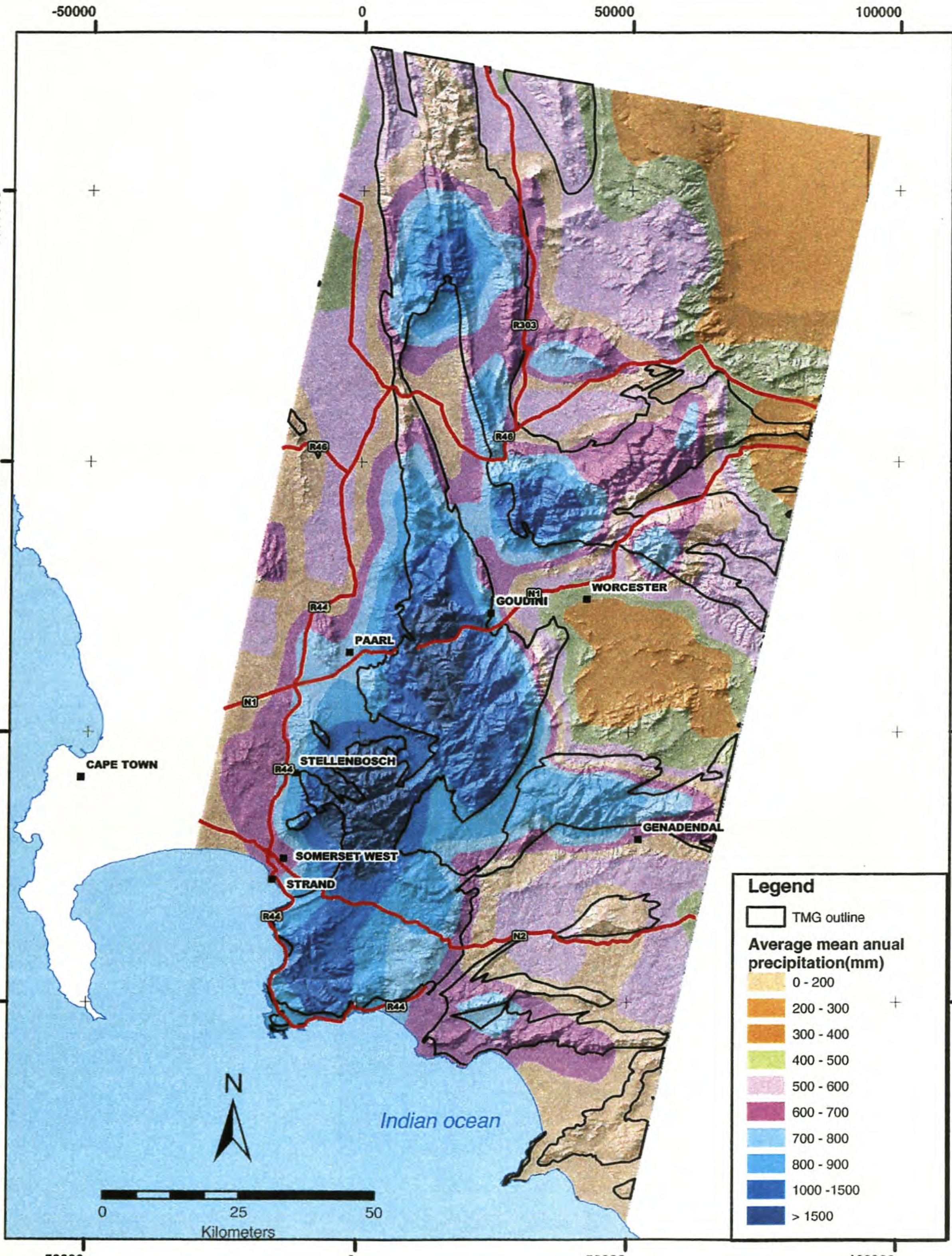


Figure 1.2 Rainfall distribution

The TMG belongs to the Cape Supergroup along with two other groups, Witteberg and Bokkeveld. It overlies the Precambrian-Cambrian metasedimentary and granite basement and is subdivided into seven formation listed in Table 1.1.

Table 1.1 Detailed stratigraphy of the Cape Super Group

Age ([1]Ma)	Group	Subgroup	Formation	Thickness (m)	Lithology
300			Waaipoort	50	Shale
CARBONIFEROUS		LAKE MENTZ	Floriskraal	60	Shale Sandstone
360			Kweekvlei	130	Shale
	WITTEBERG		Witpoort	310	Sandstone
			Swartruggens	450	Shale Sandstone
		WELTEVREDE	Blinkberg	80	Sandstone
			Wagen Drift	70	Shale Sandstone
			Karoopoort	50	Shale
			Osberg	55	Sandstone
DEVONIAN		BIDOUW	Klipbokkop	170	Shale
			Wuppertal	65	Sandstone
			Waboomberg	200	Shale
	BOKKEVELD		Boplaas	30	Sandstone
			Tra-Tra	85	Shale
		CERES	HexRiver	100	Sandstone
			Voorstehoek	115	Shale
			Gamka	135	Sandstone
			Gydo	160	Shale
			Rietvlei		
408		NARDOUW	Skurweberg	500	Sandstone
SILURIAN			Goudini		
438			Cederberg	120	Shale
	TABLE MOUNTAIN		Pakhuis	40	Sandstone
ORDOVICIAN			Peninsula	1550	Sandstone
			Graafwater	440	Sandstone, Shale
500			Piekenierskloof	800	Conglomerate, Sandstone

Source: (Geological Survey, 1980)

It is about 4000m thick and consists of quarts arenites, conglomerates and mudstone (Geological Survey, 1980). The Nardouw subgroup and Peninsula formation are of special interest in storage capacity assessment. The Peninsula formation is the prime

[1] Ma represents million years

target for obtaining groundwater, because of its large open fractures that are capable of sustaining high yielding boreholes (Weaver & Talma, 1999) as compared to the Nardouw subgroup, which has on average lower density and shorter length of fractures (Kotze, 2000). The TMG represents a multi-porous medium that essentially consists of fractures and micro-fractures within the rock. The fractures serve as permeable channels for the rapid movement of groundwater, whilst the micro-fractures form the main storage (Woodford, 2000).

1.2 Research objectives

The main objective of the study is to estimate and evaluate groundwater resources within the TMG using remote sensing and GIS. The following objectives were also set:

- Assess recharge potential;
- Estimate the storage capacity of TMG;
- Assess groundwater vulnerability to contamination; and
- Identify potential drilling sites using current borehole yields.

The estimates from the above objectives will determine the potential of TMG as a water supply source.

1.3 Literature review

A literature review of reports and published papers was conducted to investigate existing groundwater exploration methods.

1.3.1 Groundwater recharge studies

The studies discussed in this section illustrate methods used to determine the rate and volume of aquifer recharge. This is an important step in groundwater exploration and is the means of determining the amount of groundwater available for long-term supply.

Weaver & Talma (1999) used hydrochemical and isotope time-series to gain insights into recharge and groundwater evaluation in the TMG. The hydrochemical time series showed the variations of chemical parameters (silica, alkalinity, chloride and calcium) that were measured. The isotope time series showed concentration variations between oxygen-18 (^{18}O) and chloride ion. Chloride and $\delta^{18}O$ measured in five cumulative rain samples were compared with groundwater from a borehole in the mountain recharge zone. The results showed an estimated aquifer recharge of 50% on an annual basis. This was outside the experience of Southern African hydrogeologists who are more comfortable with an annual recharge ranging from 5% to 15%.

Hydro Source Associates (1998), conducted their recharge calculations in Georgia, New York, Connecticut, Venezuela and Massachusetts by using precipitation data, soil types and degree of saturation, density and vegetation types, records from previously installed wells, land elevations and slope, runoff and evapotranspiration statistics. In cases where appropriate rainfall data were not available, the relationship between precipitation and elevation was modeled.

Goes (1998) investigated the recharge volume in the Hadejia river system between Hadejia and Nguru in Nigeria. This was estimated using the water-budget method based on the amount of water table rise. The following equation was used:

$$\text{Recharge} = S_y \rho s A + Q_a + Q_o \qquad [1]$$

Where S_y = specific yield, ρs = water table rise, A = area affected by the water table rise (m^2), Q_a = groundwater abstraction from the area during the recharge period (m^3), and Q_o = lateral subsurface outflow (m^3).

Salama et al (1999) and D'Agnese et al (1999) used remote sensing and GIS techniques to develop maps that described recharge and discharge in the Death Valley region. These techniques allowed the integration of disparate data types from various disciplines, including hydrogeology, soil science, and plant ecology to develop a spatially complex representation of surface and subsurface hydrologic processes. Multispectral remote sensing data were evaluated using image classification methods to produce a vegetative cover thematic layer. This provided data for estimating rates of both evapotranspiration and infiltration. Salma et al (1999) used a model called WAVES to provide recharge estimates required for the net flow simulations.

D'Agnese et al (1999) developed groundwater recharge estimates by refining an empirical, area-altitude method developed by Eakin and others in 1951. Both methods required information about the soil depth, soil layering and the hydraulic characteristics of each layer, climate and vegetation. WAVES also required the type of vegetation cover and the extent of ground cover. Remote sensing imagery and analysis techniques involving airborne, advanced and very high resolution reflectance (AVHRR) and landsat TM data were used to infer the temporal and spatial patterns of Leaf Area Index (LAI is the area of leaves per unit area of ground taking one side of each leaf into account). GIS was used to combine geological and topographical data with the vegetation information to produce a map showing recharge potential.

Ghanem et al (1998) used thirty-year records of precipitation, evapotranspiration, wind, humidity and runoff to determine the water budget and to estimate the recharge rate in Faria basin, NE of the West Bank. The global groundwater balance equations were modified and used to estimate the recharge volume as well as infiltration coefficient. The estimated volume of recharge was calculated to be 60 million cubic meters (mm^3) for the whole area (320 km^2) and 40.1 mm^3 for the Upper Faria (75% of the area). The rate of recharge was found to be 26% of the yearly average rainfall values ranging between 196 and 598 mm.

In the above studies different methods have been used to estimate recharge. The study by Salama et al (1999) and D'Agnese et al (1999) show that remote sensing and GIS are useful tools in assessing recharge. The most important datasets used in these studies include precipitation, vegetation cover, soil, geology and topography. The availability and accuracy of the data is important in recharge studies.

1.3.2 Studies in groundwater storage

The studies in this section describe the methods used in estimating aquifer storage capacity. The volume of water in storage can be determined by assessing the amount of water that can be abstracted from the aquifer. Excessive abstraction can result in lowering of the water table with time if not monitored and properly managed.

Murray & Tredoux (1998) conducted a study to assess the feasibility of using artificial recharge technologies in South Africa for community water supplies. Aquifer storage capacity is one of the determinants of water volume that can be artificially recharged to an aquifer.

The study suggests that the volume of water in storage (V) of the aquifer can be determined by using the equation below:

$$V = A.\ b.\ S \qquad [2]$$

where V is the volume of water (m^3)

A is the area of the aquifer (m^2)

b is the mean aquifer thickness (m)

S is the storativity (dimensionless)

The area of the aquifer can be determined from geological and geophysical mapping and an inventory of existing boreholes and their geological stratification. Where such information is not available, the area of the aquifer can be estimated from geological and topographical maps and aerial photographs. The aquifer thickness can be determined from a detailed hydrogeological study, borehole lithological logs and geophysical methods. Storativity is defined as the volume of water released from storage per unit surface area of the aquifer per unit decline in the component of hydraulic head (height of a column of water above a reference plane) normal to that surface (Kruseman & de Ridder, 1990).

Dudas (1999) calculated the approximate storage of groundwater in Oro Valley, Arizona. The overall approach used was to generate spatial characterizations of aquifer properties and storage volumes throughout time, and then to develop a simple hydrologic model of the aquifer system. The hydrologic model was then used to simulate aquifer storage under conditions of projected population expansion. The modeling was conducted in a GIS environment. The GIS software utilized was ESRI's ArcView and ARC/INFO. A water table map was interpolated from borehole data and subtracted from elevation to give water level value above mean sea level. These water levels were multiplied by the aquifer specific yield to generate estimated water storage.

1.3.3 Groundwater vulnerability studies

The studies in this section describe methods used to demonstrate where groundwater is most susceptible, or least susceptible, to pollution. This depends on the geology and on criteria of travel time through the unsaturated zone.

In Lynch et al (1994); Kim and Hamm (1996) and Matoti et al (1999), the DRASTIC Index was used to determine how easily a contaminant can be carried through overlying material to groundwater. The DRASTIC Index evaluates the following parameters: depth to water table, recharge, aquifer medium, soil medium, topography, and impact to the vadose zone and hydraulic conductivity. Each parameter is rated on a scale of one to 10 and scaled by a weighting factor of one to five depending on the ability of the parameter to affect pollution transport. The weighted ratings were summed to obtain the DRASTIC Index that helps to evaluate groundwater pollution potential. The following equation was used:

$$\text{DRASTIC Index} = 5D + 4R + 3A + 2S + T + 5I + 3C \qquad [3]$$

where D = depth to water table, R = recharge, A = aquifer medium, S = soil medium, T = topography, I = impact to the vadose zone and C = hydraulic conductivity.

The DRASTIC index has become a common method used to determine the risk of an aquifer to contamination. The GIS has allowed overlay and analysis of different data types and assisted in discovering areas that are vulnerable to contamination.

1.3.4 Studies in targeting groundwater drilling sites

High yielding groundwater zones need to be identified carefully before any drilling can take place. Use of remote sensing data, existing borehole information, topographical and geological data will increase the chance of siting high yielding sites.

Ramakoae (1999) used aerial photographs to identify lineaments that were not indicated on the geological maps. Sander (1996) used Landsat TM and SPOT images for groundwater assessment. In both studies a GIS was used to integrate the aerial data and to facilitate the location of potential drilling sites. Borehole yields were determined from the minimum and maximum drilling yields of the existing boreholes. Ramakoae (1999) created a groundwater exploration potential map from overlaying lineaments, boreholes, and areas with a slope of less than 40 percent that lie within the 1km buffer zone of the villages under investigation. Sander (1996) did not take slope into consideration. The relationship between the borehole yields and geology provided good results in identifying prime drilling target areas. Data integrated in GIS was found to be an ideal basis for decision, for time and cost-effective selection of well sites or drilling sites.

Sander (1996) used a probabilistic approach using Bayesian statistics to identify targets for groundwater exploration in hard rock terrain. The advantage of this approach is that professional judgements can be applied and data can be updated when additional data become available.

Availability of geological and topographical maps, remote sensing data and borehole information increases the chances of making correct decisions in identifying drilling sites. Groundwater conditions for siting drilling sites also depend on the rock transmissivity factors such as fractures, permeability of the material for storage, and sufficient recharge for sustainable supply.

1.3.5 Remote sensing studies in groundwater exploration

This section summarises various articles on methods and techniques used to identify potential aquifers using remote sensing and GIS.

Vadeveer & Carter (1992); Minor et al 1994; El-Baz et al 1994; Woldai et al (1997) and Kellgren et al (1997) used Landsat 5 images to detect and map drainage patterns, fracture and fault systems. Image processing techniques (radiometric and geometric correction, filtering, stretching, ratioing and colour composite creation) were used to extract the maximum information required. The effective spectral band combinations for lithological discrimination were different in most of the studies. Vadeveer & Carter (1992) used bands 4, 5 and 7 whereas Woldai et al (1997) preferred 5-4-3 and 5-3-1.

The criteria for lineament identification were the same in most of the studies and are as follows:

- Lines of varying length and continuity differentiated by change in tonal contrast in images.
- Alignment of topographic features and drainage lines.
- Association of vegetation and cultural features along linear trends.

Vadeveer & Carter (1992) conducted a study in De Aar in which Landsat 5 images taken during the winter season were used because of minimum vegetation cover. The images were spectrally enhanced to highlight lineaments and geological formations.
In most of the studies a GIS model was used to integrate and manipulate hydrogeological data used to identify groundwater indicators. These studies were successful and the most productive well sites were identified.

Robinson et al (1999) and McGregor et al (1999) used RADARSAT to reveal fluvial features beneath a surface cover of desert sand. Robinson did his study in the north western Sudan and McGregor in Canada. Features such as fractures and faults that were not observable in Landsat images were detected. This expertise was combined with traditional geological field mapping to help evaluate groundwater resources.

Kellgren et al (1997) also used a panchromatic SPOT image, which has a higher spatial resolution and allows detection of narrow fractures in or near outcropping areas. The study was conducted in the Limpompo Province in South Africa. The borehole data from the National Groundwater Database from the Department of Water Affairs and Forestry was used to determine the correlation between the existing boreholes and lineaments. The hydrogeological evaluation of mapped lineaments, using the borehole database did not indicate that lineaments are valuable targets for groundwater exploration. The features on the geological map displayed a low correlation with the identified lineaments from Landsat images and these displayed a strong N to NW trend, observable on the geological map.

In the study conducted by Grover (1999) it was discovered draping geological data over the Digital Elevation Model (DEM) is a powerful way of examining the relationship between lithology and landforms.

Satellite imagery has enabled scientists to examine synoptic views of linear features at the earth's surface that might be fault lines or fractures in bedrock. The particular selection of bands depends on the specific objectives of the interpreter.
The studies show that the integrated field data, GIS, remote sensing and aerial photography gives a combined strength in locating, developing and protecting high yield groundwater supplies. In other studies the lineaments were not used as valuable targets for groundwater due to low correlation between the geological map and lineaments identified from the Landsat image.

1.4 Research methodology

The research methodology for this study has two phases, which involve lineament mapping and estimation of groundwater resources as shown in Figure1.3. A literature review of reports and published papers was conducted to investigate existing methods of groundwater exploration and to develop a research strategy for this study.

Data types that were used for groundwater assessment were satellite imagery, geology, vegetation, soil and topographic maps, borehole location and related hydrogeological information such as borehole yield and water levels. Geological maps (3318 and 3319) at 1:250 000 scale were used to capture mapped faults and fractures. These maps were scanned and georeferenced with a 1:50 000 scale road dataset obtained in digital format from the Directorate of Surveys and Mapping. A Digital Elevation Model (DEM) and river dataset were also used to determine drainage patterns.

Lineament mapping involved identifying linear geological structures (lineaments) using a Landsat 7 Enhanced Thematic Mapper Plus (ETM+) image. The image was captured in November 1999 and was obtained from Earth Resources Observation System (EROS) data centre for the United States Geological Survey (USGS). Erdas Imagine image software was used to capture lineaments on screen from the image at 1:250 000 scale. The identified lineaments were compared with vegetation, drainage patterns, fractures and faults from the geological map and borehole data to increase the level of confidence in the identified features. A Normalised Difference Vegetation Index (NDVI) image was extracted from the Landsat image.

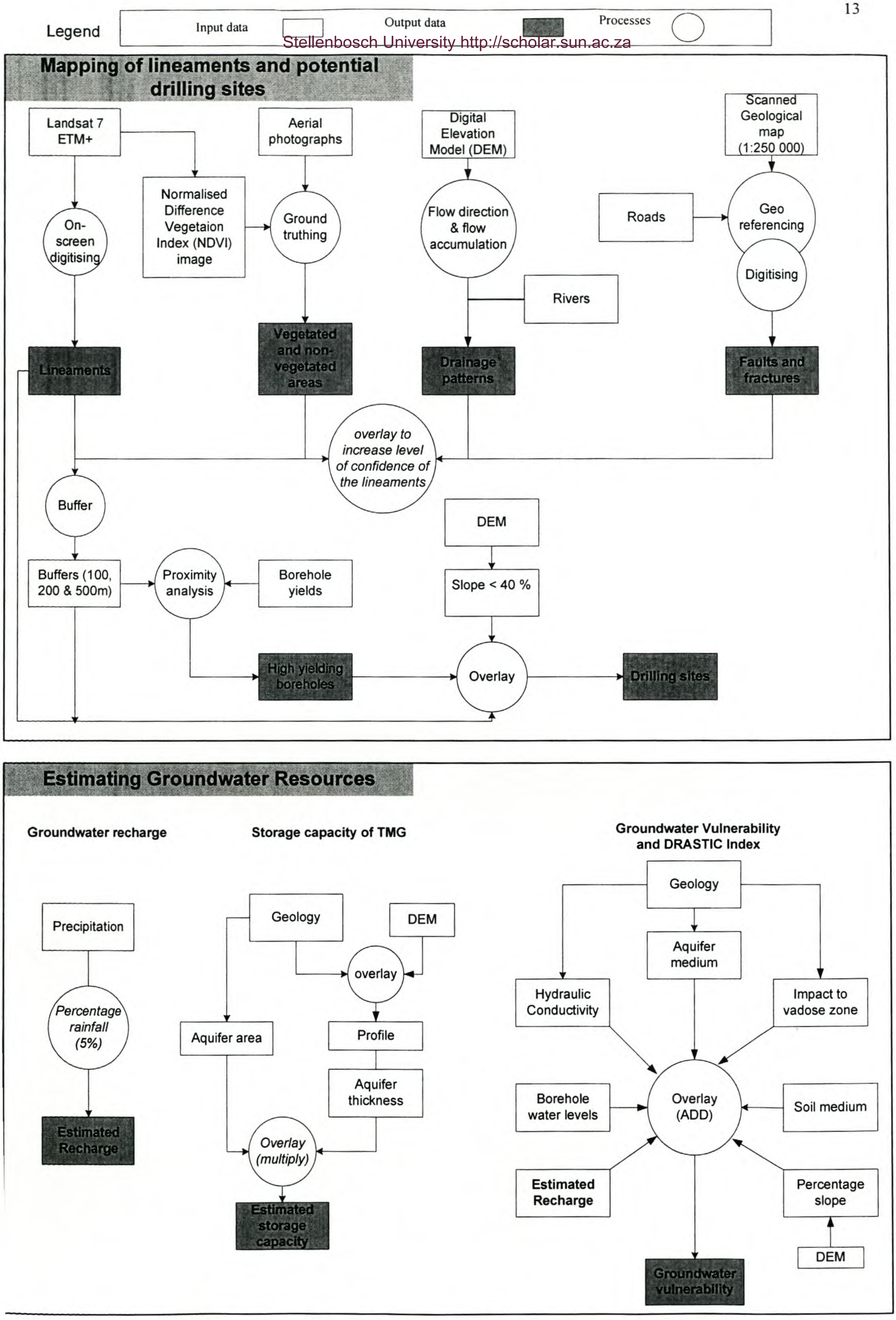


Figure 3.1 Different variables applicable to groundwater assessment

Aerial photographs were used to distinguish between vegetated and non-vegetated areas in the NDVI image.

GIS was used to determine drainage patterns from a 50m x 50m DEM, which was obtained from the Department of Geography and Environmental Studies at the University of Stellenbosch. The DEM was also used to eliminate areas which are not accessible for borehole drilling. The borehole data with borehole positions, yields and water levels were obtained from the National Groundwater Database (NGBD) owned by the Department of Water Affairs and Forestry (DWAF).

Groundwater resource estimation involved assessment of groundwater recharge, estimation of storage capacity, assessment of groundwater vulnerability to contamination and identification of potential drilling sites. The groundwater recharge estimate was derived from rainfall data, which were obtained from the national rainfall map developed in 1990 by the Water Reasearch Commission. Data were collected monthly from rainfall stations for a 70-year period (1920 to 1989). The TMG storage capacity was estimated from geological cross-sections drawn manually from the geological map and profiles extracted from the DEM. Groundwater vulnerability to contamination was assessed using aquifer parameters such as depth to groundwater (water table), recharge, aquifer medium, soil medium, topography, impact of the vadose (saturated) zone and hydraulic conductivity in the DRASTIC Index. The potential drilling sites were determined from topography, lineaments and borehole yields of existing boreholes from the NGDB.

Data analysis was performed in a GIS where the digital data were integrated and projected to the Transverse Mercator projection, using the 19°E as the central meridian and the Hartbeesthoek 99 datum.

The structure of this report is as follows, the next chapter, chapter 2 covers methods and techniques used in lineament mapping together with results of the spatial analysis. Chapter 3 deals with groundwater resource assessment, which involves groundwater recharge, storage capacity of TMG, groundwater vulnerability and siting of drilling sites. The discussion of results, conclusion and recommendations are discussed in Chapter 4.

CHAPTER 2: DATA COLLECTION AND PREPARATION: LINEAMENT MAPPING

2.1 Introduction

This chapter discusses the methods used in collecting and assembling various spatial data used in predicting the groundwater potential within the TMG and results from the spatial analysis. The main sources of data used are an Enhanced Thematic Mapper Plus (ETM+) Landsat image, geological map, DEM and borehole information.

The Landsat ETM+ image has eight bands which record radiation in the near and medium infrared portion of the electromagnetic spectrum. The spatial resolution of bands one to five and band seven is 30m, and band six has a 60m resolution. Band eight is panchromatic with a resolution of 15m that provides much more spatial detail. The best combination of these spectral bands varies according to the purpose of the study, season, geographic region and other factors.

2.2 Lineament mapping

The Landsat ETM+ image was already corrected and georeferenced by the vendor. The details of this process will not be discussed in this study. A number of colour composites were generated to determine the best spectral band combination to be used in identifying lineaments from the image. Various image enhancement techniques were used to enhance the geological features in the image. These included linear contrast stretch and high pass filtering. These improved the visible contrast of the image and sharpened the appearance of the geological features.

Lineament interpretation was performed visually and directly on-screen using Erdas Imagine. Linear features that appeared as linear trends along vegetation and drainage lines and as tonal discontinuities, were digitized on-screen at a 1:250 000 scale. This scale was chosen because the study area covered a large area and the geological maps from which lineaments were to be compared to were captured at 1:250 000 scale. Because of the scale used for analysis purposes, features less than 500 meters in length, were not captured. Two sets of lineaments were interpreted independently by the researcher (Matoti) and a hydro-geologist (Murray) to increase the level of confidence in the identified features.

The enhanced images of bands 5-4-3 and 4-3-2 were found suitable for identifying lineaments. Figure 2.1 shows lineaments captured from the Landsat ETM+ image. As digitised from Landsat ETM+ imagery, these range in length from 2930m to 58920m with average length of 16500m. In comparison, the faults and fractures digitized from the geological map range from 750m to 51000m with an average of 11360m. Lineaments identified from the 1:250 000 satellite image are longer than the air photo lineaments. Lineaments also depend on the scale and resolution of the remotely sensed data (Greenbaum, 1992). In images with broad scale and course resolution lineaments are more subtly expressed (Campbell, 1987). High spatial resolution is useful in mapping of narrow geological features (Kellgren, 1999).

Figure 2.2 shows rose diagrams, which represent the orientation frequency of the lineaments. The length of each rose sector is proportional to the frequency of orientations that lie within that sector. The lineaments length can be taken into account by grouping them in classes on the basis of their statistical distribution. Most of the lineaments captured from the Landsat image lie in a NW-SE direction. The lineaments digitised from the geological map are mostly in a NE-SW direction. These results are similar to those found by Kellgren (1999), where the features on the geological map displayed a low correlation with the identified lineaments and a strong NW-SE trend was not observed in the geological map. The reason could be that some of the identified lineaments are joints related to the main faults. In theory, joints occur in the immediate vicinity of a fault plane and intersect the main fault at an acute angle pointing in the direction of relative movement of the rock (Hobbs et al, 1976). Another reason could be the sun-angle effect, for example if the sun's rays come from a SE position at a moderate elevation angle, fractures occupying depressions that trend NE are shadowed on their NW side, and hence, stand out in the image as shadow relief. Whereas those trending NW are equally illuminated on both sides and hence largely invisible and easily missed (Short, 1999).

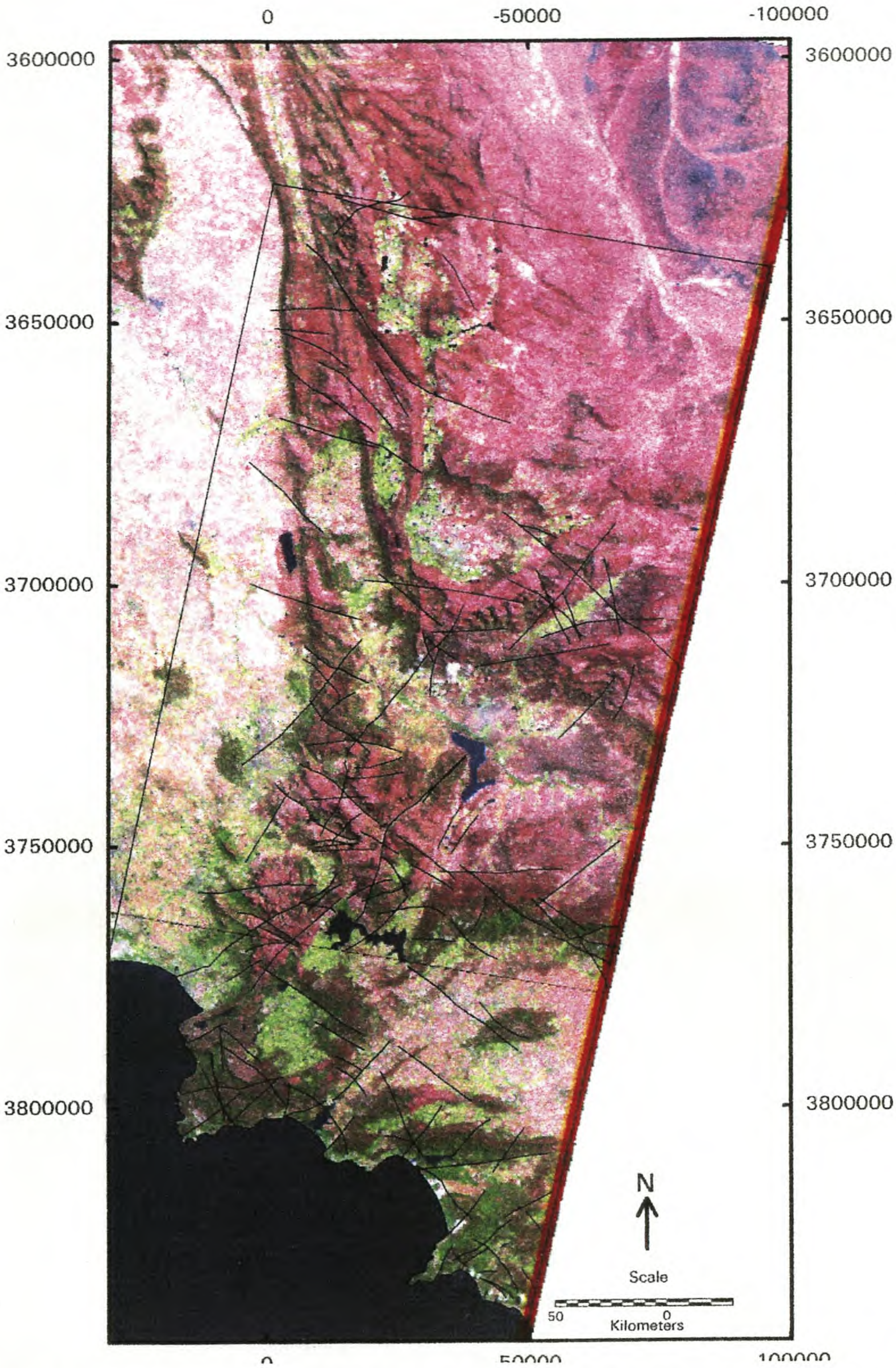


Figure 2.1 Landsat 7 ETM+ image, 175-083, Band 543 (RGB) and identified lineaments

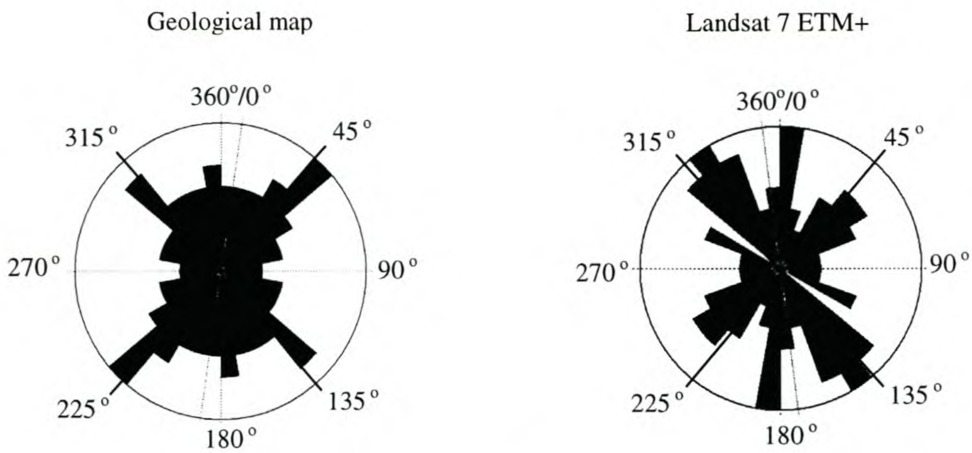


Figure 2.2 Azimuth and orientation of lineaments digitised from the Landsat image and the geological map.

From the groundwater exploration point of view, the hydrogeological value of interpreted lineaments captured from remote-sensing imagery is very difficult to estimate without extensive geophysical investigations with subsequent exploratory drilling (Kellgren et al, 1999). These were not included in this study. Instead other methods were used to increase the hydrogeological confidence of the interpreted lineaments. These involved correlation analysis with other data such as vegetation patterns, drainage, existing geological lineaments and borehole data.

2.3 Using vegetation as the indicator of groundwater

Kellgren et al (1999) showed that vegetation types and patterns were good groundwater indicators. Vegetation can be identified with remote sensing by using visible to near infrared radiation (Kellgren et al, 1997) and vegetation indices. Ratio indices such as the ratio vegetation index (RVI), the normalized difference vegetation index (NDVI), the transformed normalized difference vegetation index (TNDVI), and the soil-adjusted vegetation index (SAVI) use various ratios of red and near-infrared bands to determine presence of vegetation.

Both RVI and NDVI measure the slope of the line between the origin of the red-near infrared space and the red-near infrared value of the image pixel. Linear indices such as NDVI and SAVI are the most commonly used.

An NDVI image was created from the Landsat ETM+ image to separate green vegetation from senescent vegetation and is defined as:

$$\text{NDVI} = \frac{\text{Near IR band} - \text{Red band}}{\text{Near IR band} + \text{Red band}}$$

For Landsat ETM+ this is (band 4 - band 3)/(band 4 + band 3). The output image was classified into six classes using unsupervised classification. This classification was used because less was known about the vegetation data before classification. Six classes were used to find meaningful patterns in the data. The unsupervised classification generates signatures based on the groupings of pixels in the image. Erdas Imagine uses the ISODATA algorithm to perform unsupervised clustering. The ISODATA algorithm uses the minimum spectral distance formula to form clusters. It begins with either cluster means or means of the existing signature and repeats the clustering each time until a number of maximum iterations have been performed, or until a number of maximum percentage of unchanged pixels assignments between two iterations have been reached (Erdas, 1999).

To attach meaning to the resulting classes, aerial photographs were used together with the NDVI image to identify vegetated and non-vegetated areas. The output image was converted into a grid in ArcInfo GRID with vegetated and non vegetated areas. The grid was overlaid with lineaments from the Landsat ETM+ image to investigate the relationship between lineaments and vegetation (Figure 2.1).

Comparison of lineaments with vegetation and drainage lines adds value to identified features. As explained in Section 2.3, traces of faults and fractures may be revealed by vegetation especially in a dry season image. Faults may offer areas of water movement and thus moisture for growth. Vegetation can therefore be used as a potential indicator of fracture systems. Greenbaum (1992) found that dry season vegetation can be used to identify areas with promising groundwater resources, because open fractures support vegetation even under dry conditions.

The Landsat ETM+ image used in this study was taken in November 1999 after the wet season. The NDVI image showed better vegetation cover. By visually comparing the NDVI image and aerial photographs, most vegetated areas were discovered to lie in the valleys and foothills of the outcropping TMG. Figure 2.3 shows a selected area with lineaments where vegetation density is high. The correlation between lineaments and vegetation was not evident. This could be due to evenly distributed vegetation cover related to soil moisture and shallower seasonal groundwater resources (Kellgren et al, 1999). It is also possible that dense vegetation obscures some of the lineaments. Wet season images can assist in lineament detection although vegetation response in the bedrock areas is more a result of surface flow than base flow (Kellgren et al, 1999).

2.4 Association of drainage patterns with lineaments

The degree of fracturing, weathering and resistance of strata are factors contributing to the shape of the drainage pattern (Kellgren et al, 1999). Drainage patterns can indicate the amount of water discharged through surface run-off, demonstrating that an area of high drainage density has low groundwater potential (Greenbaum, 1985). Mapping of drainage patterns was therefore necessary to evaluate the groundwater potential of the TMG area. The relationship between drainage lines and lineaments is important to evaluate the potential concentration of water in fracture zones.

Drainage lines were extracted from the DEM using ArcInfo GRID. To accomplish this, a flow direction grid was created from the DEM by using the *flowdirection* command, which determines the flow direction by finding the direction of steepest descent from each cell to its neighbouring cells. A grid of accumulated flow to each cell was then created, by accumulating the weight for all cells that flow into each down-slope cell using the flow direction grid and a rainfall grid. The rainfall grid was created from a digital rainfall dataset captured by Water Research Commission (WRC). A stream network was created from the flow accumulation grids where the amount of flow that passes through each down slope cell was determined.

A Boolean operator where cells having more than 25, 50 or 100 upstream pixels was applied to determine cells with high accumulated flow. The output accumulative grids were drapped on the DEM to view a grid with more realistic stream network. The more realistic stream network was converted to a vector dataset that was overlaid with the lineaments (Figure 2.3). The drainage lines of the study area derived from the DEM have a dendritic pattern.

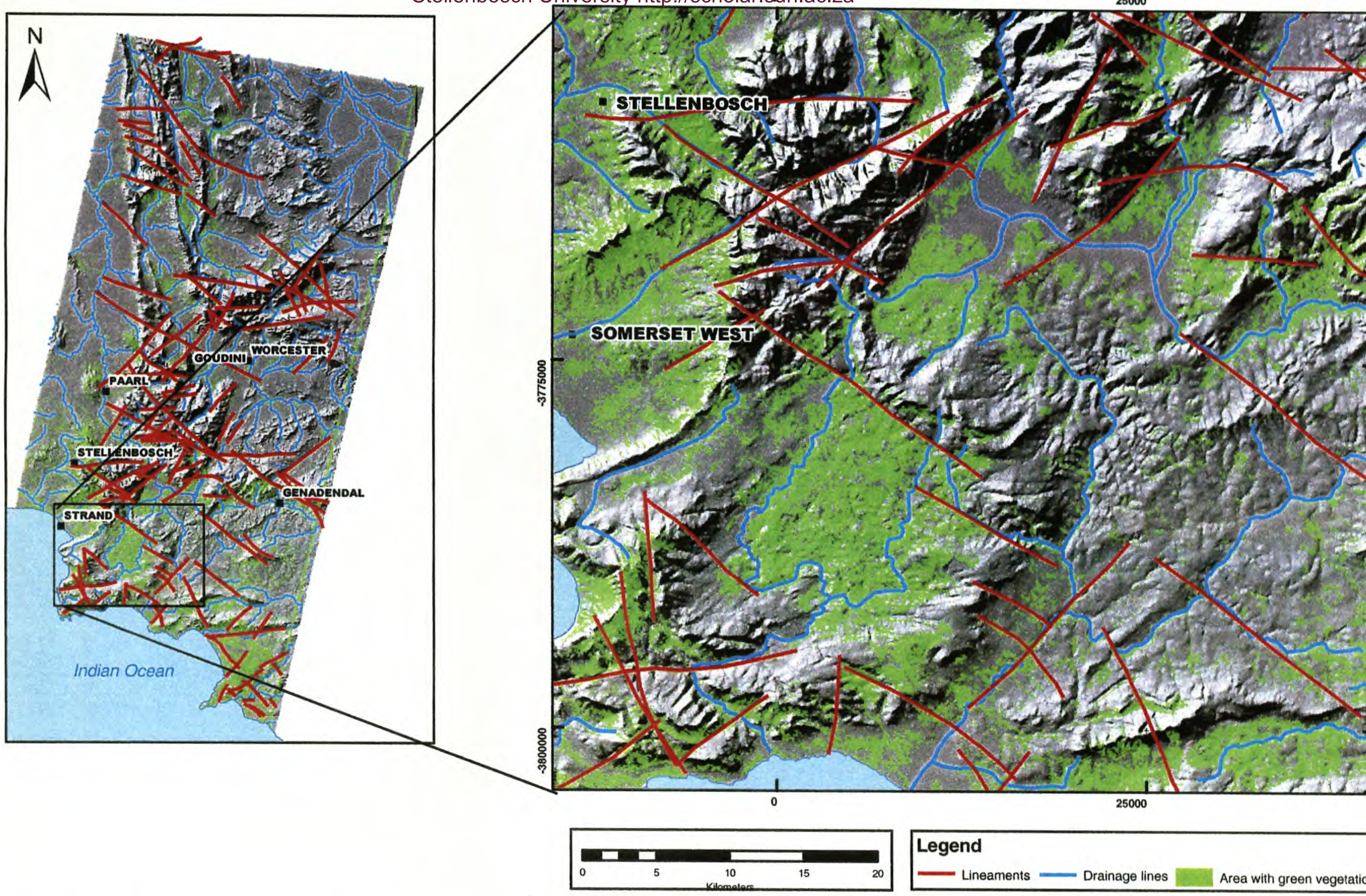


Figure 2.3 Vegetation based on NDVI and draingae lines derived from the DEM with lineaments

The structure of the drainage lines shows that the area is highly fractured. Most of the lineaments intersected drainage lines at some points, and a few were parallel to the drainage lines as presented in Figure 2.3.

These results show some correlation between drainage patterns and lineaments. This demonstrates that some of the drainage lines may be developed by faults.
Drainage patterns are determined by the structure of the underlying lithology and are a reflection of the infiltration compared to the runoff. Drainage patterns are indicators of fracture zones and enhance groundwater recharge and storage potential (Kellgren et al, 1999) and they assist in understanding groundwater occurrence (Greenbaum, 1985).

2.5 Geological map fractures and faults versus Landsat lineaments

The geological data captured from aerial photographs can provide complementary information on the hydrogeology of an area and increases the reliability of the mapped lineaments.

The geological maps (3318 and 3319) were scanned and georeferenced using the road data from the 1:50 000 topographical map series as reference points. The two sets of Landsat lineaments captured by Matoti and Murray were compared to corresponding faults and fractures digitized from the 1:250 000 scale geological map. The overlapping lineaments were assigned values to differentiate between which features overlap. Overlapping Landsat lineaments and geological map fractures and faults were assigned a value of one, overlapping Landsat lineaments from the two sources were assigned a value of two and lineaments that did not overlap with any of the above were assigned a value of three (Figure 2.4). This also assisted to determine the level of agreement among the three sets of lineaments.

Forty-five percent of the lineaments identified on the Landsat image by Matoti and Murray had good spatial agreement (Figure 2.4). These features together with the results from the proximity and azimuth analysis can be used as a guide to locate the most promising features for further groundwater investigations.

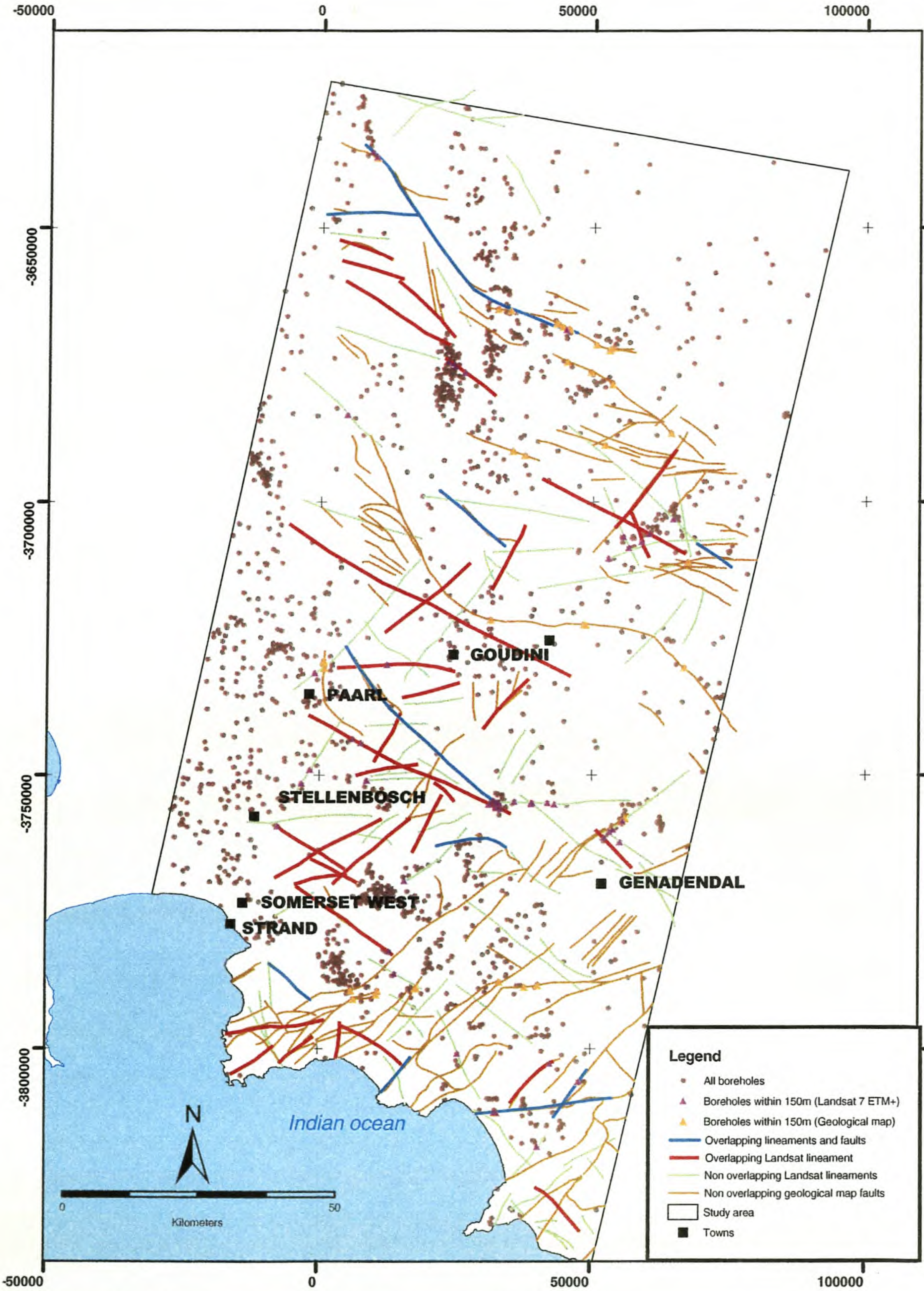


Figure 2.4 Overlapping and non overlapping lineaments

2.6 Borehole data and lineaments

A common approach in lineament studies is to analyse borehole position and capacity versus distance to lineaments (Kellgren et al, 1999). The proximity analysis of borehole yields and distance from the lineaments has been used in many studies (Kellgren et al, 1999) in assessing how they are related to each other. It is also important to determine whether lineament orientation has any influence on the yield of boreholes.

From a hydrogeological point of view, zone of influence around a fracture or fault is expected to be less than 150 m (Greenbaum, 1992). To prove this, proximity analysis between lineaments and borehole yield was performed. Buffer zones of 100m, 150m and 500m were created around the
lineaments, and boreholes that were within the buffer zones were selected for statistical analysis.

The NGDB data had a number of boreholes with zero yield values. This could mean that these boreholes were not viable (i.e. dry boreholes), or measurements were not recorded. Due to the significant variation in the borehole yield values, an assumption was made that the boreholes with zero values were not measured. Therefore, data were trimmed down to contain only boreholes with values greater than zero, and an average yield and standard deviation were calculated.

The influence that the direction of lineaments has on the yield of boreholes was also investigated. This was accomplished by analyzing lineaments with respect to frequency and azimuth. These lineaments were classified into 10^{o} azimuth classes. Average yield of boreholes within 100m, 150m and 500m from the lineaments were calculated.

The borehole yields within 100m, 150m and 500m distances from the lineaments and geological feature and the standard deviation for each distance are shown in Table 2.1 and Figure 2.5.

Table 2.1 Average borehole yields within and outside the 500, 150 and 100m buffer zones around lineaments.

	Geological map lineaments (yield l/s)			*Landsat image lineaments (yield l/s)*		
Distance (m)	**Boreholes**	**Mean**	**Standard deviation**	**Boreholes**	**Mean**	**Standard deviation**
100m	5	5.46	5.68	19	12.45	10.98
150m	10	6.83	5.73	24	11.59	10.23
500m	36	8.29	7.76	74	9.84	7.38
>500m	735	6.78	7.64	627	6.89	7.72

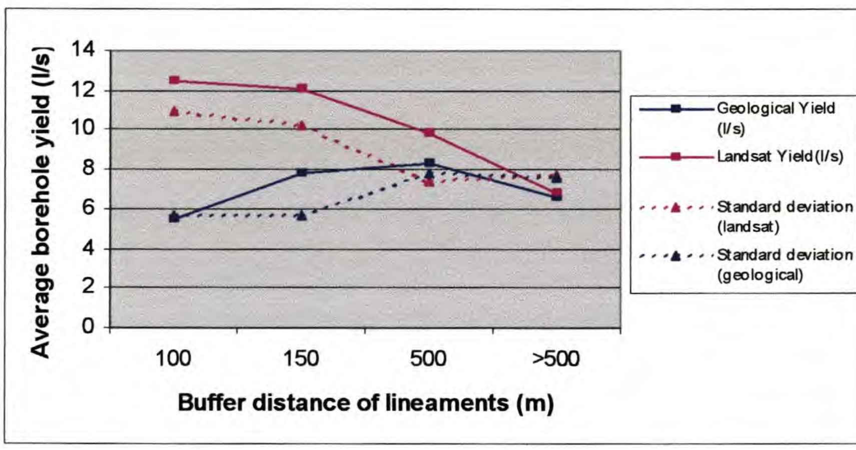


Figure 2.5 Average borehole yields and standard deviation with buffer distances from Landsat lineaments and geological features.

The maximum borehole yield from the NGDB data is 37 l/s. The borehole yields within 100m and 150m from the lineaments, range from 0.03 l/s to 38 l/s with an average yield of 12 l/s. These have high average yields compared to the average of all the boreholes, which is about 7 l/s. The standard deviation of borehole yields beyond the 500m buffer shows that the data are distributed around the mean for both landsat and geological features. The results indicate that as the distance from the mapped lineaments increases to 500m, the borehole yields decrease, and they decrease even further beyond this distance. Borehole yields also decrease as the distance from the geological features digitised from the geological map increases. This confirms the importance of distance from lineaments in siting boreholes or drilling sites. The standard deviation of data below 150m buffer shows that data around landsat lineaments are more spread around the mean as compared with geological features. The lineaments oriented in the 0-45° and 135-180° directions have high yielding boreholes (Table 2.2 and Figure 2.6). The low yielding lineaments are oriented in a 90-135° direction. The fractures and faults digitised from the geological map also show similar results. The high yielding lineaments associated with groundwater are oriented in a 135-180° direction and the low yielding are in a 0-45° and 90-135° direction (Table 2.2 and Figure 2.7).

Table 2.2 Average borehole yields versus the direction of lineaments

	Average yields(l/s) Landsat image			**Average yields(l/s) geological map**		
Azimuth (degrees)	*500m*	*150m*	*100m*	*500m*	*150m*	*100m*
0 – 45	3.65	12.21	15.13	10.10	3.8	3.8
45 – 90	7.64	3.03	3.30	5.47	7.58	2.67
90 – 135	2.86	2.3	2.3	2.3	4.42	0
135 –180	10.85	14.28	14.18	9.85	9.57	9.09

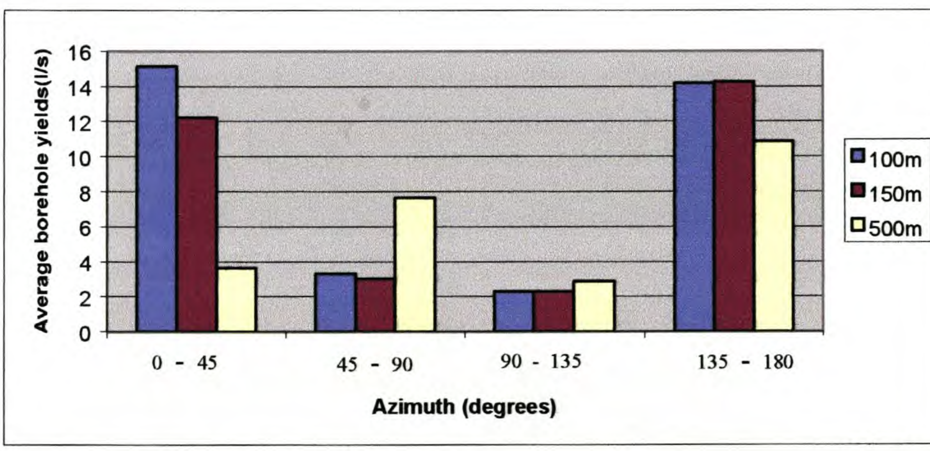


Figure 2.6 Average borehole yields (l/s) along Landsat lineaments at different angles

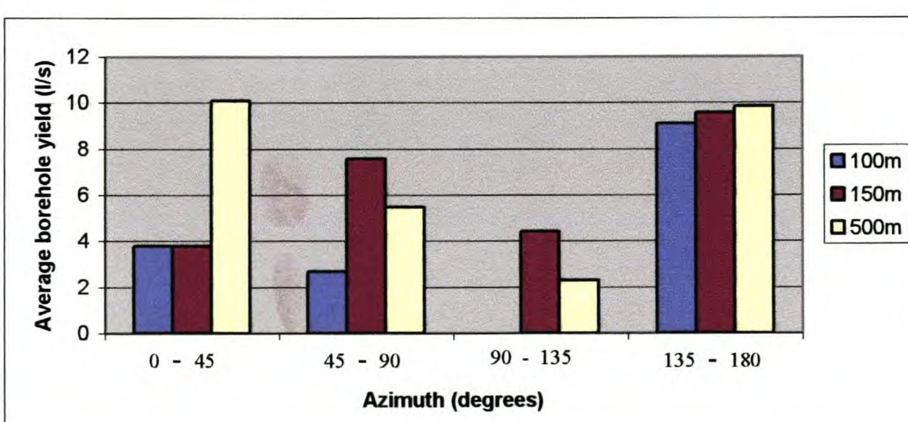


Figure 2.7 Average borehole yields (l/s) along geological faults and fractures at different angles.

The synoptic view provided by satellite imagery is useful for evaluating fracture patterns over large areas. The landscape features such as vegetation and drainage patterns can help in identifying presence of lineaments. Mapping of lineaments using different interpreters is also a valuable way for increasing the confidence in the mapped lineaments.

The following chapter illustrates methods used to estimate groundwater resources by assessing groundwater recharge, determining TMG storage capacity and its vulnerability to contamination and siting of potential drilling sites. The results of the analysis are also discussed in the relevant sections.

CHAPTER 3: METHODS FOR ESTIMATION OF GROUNDWATER RESOURCES

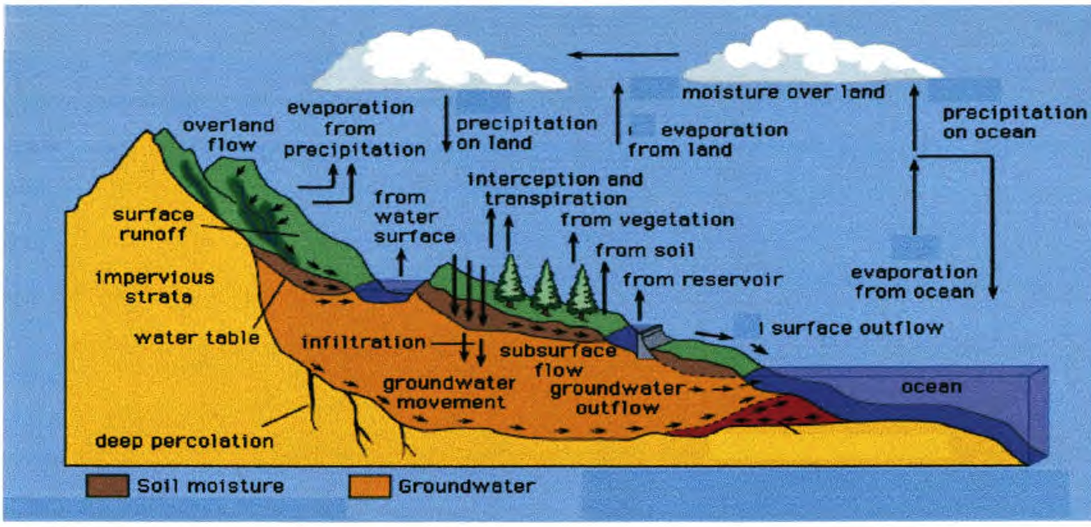
3.1 Introduction

An advantage that groundwater sources have over surface water sources is that water evaporation losses are minimal. Sometimes groundwater resources are depleted when extraction from an aquifer is not matched by recharge. This can happen by over extraction or by decrease in groundwater recharge due to drought. In high rainfall periods the aquifer can be replenished. The volume of groundwater available in an aquifer is determined by both volume of recharge and amount in storage. Therefore, it is necessary to assess the volume of groundwater recharge and water held in storage.

The quality of groundwater also needs to be considered. Sometimes groundwater contamination occurs naturally, but serious contamination is usually the result of human activities such as hazardous wastes generated from farming activities and mining. Since groundwater moves slowly, it may take some time to detect it in groundwater depending on the aquifer characteristics such as soil medium, geological material, hydraulic conductivity etc. Even if release of the contaminant is stopped, it may take many years for an aquifer to purify itself naturally. It is also necessary to understand the flow pattern of groundwater within the area and the impacts upon installation of pumping of boreholes.

3.2 Groundwater recharge

Groundwater recharge may occur in several ways, but the main source is precipitation. Groundwater recharge is defined as that part of precipitation which reaches the groundwater table through the soil and unsaturated zone. Some precipitation runs off directly across the land surface to streams, some is dissipated by evaporation from the land surface or from vegetation, some is transpired by plants, and some percolates downward to the zone of saturation (Figure 3.1). In addition to the direct infiltration of precipitation, the aquifer may be recharged by the infiltration of water from stream channels above the water table or by sub-surface inflow from nearby areas.



Source: (Encyclopedia Britannica, Inc., 1994)

Figure 3.1 Major components of the hydrologic cycle

Quantifying groundwater recharge and groundwater flow is crucial for efficient development and management of groundwater resources, as well as for minimizing pollution risks to the aquifer and connected surface water. Groundwater recharge can be estimated by a number of different methods, including hydrological and tracer methods (Sharma, 1986). The accuracy of these is highly dependent on the scale of the investigation.

Due to the unavailability of detailed data for the entire study region, these sophisticated methods for this study were not used. Instead, a simple rainfall/recharge relationship was used (Bredenkamp et al, 1995).

Lack of detailed data lead to a number of assumptions being made about the landscape properties and hydrology. These assumptions were as follows:

- evapotranspiration from the aquifer is negligible, and
- vegetation will not influence recharge rates.

Kotze (2000) and Woodford (2000) estimated that five percent of precipitation contributes to recharge in the Nardouw subgroup aquifer system. This percentage was used to estimate the recharge from the rainfall map (Figure 1.2) (WRC, 1994). The output map (5 % rainfall) was classified into zones (Figure 3.2) based on Reynders (1997) recharge classification.

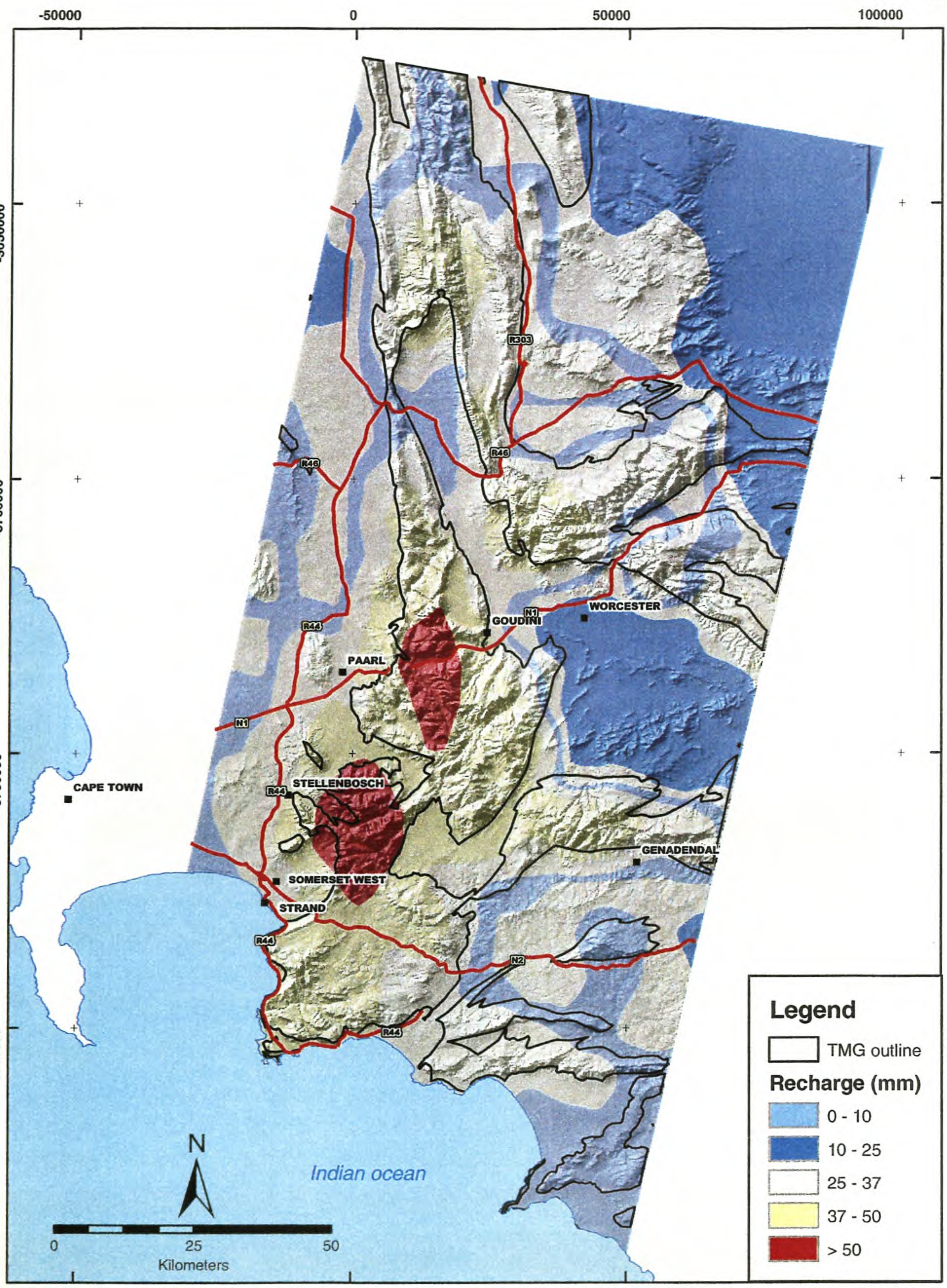


Figure 3.2 Groundwater recharge zones

The 'zonal statistics' command in ArcInfo software was used to calculate the average and total aquifer recharge from the grid. The zonal statistics records the statistics of the values of all cells in the value grid that belong to the same zone (Esri, 2000).

Fractured bedrock areas with thin, course-grained soils dominate the TMG and are considered to be percolation zones for precipitation. The rainfall ranges from 200mm to >1500mm per annum and tends to decrease from southwest to northeast and from mountains to valleys with mountains receiving higher rainfall (Figure 1.2). According to the classification of recharge zones by Reynders (1997), the valleys and foothills experience groundwater recharge that ranges between 0 to 25mm and the outcropping TMG between 25 to 75mm. Based on the rainfall average the TMG area has an average recharge value of 30mm per annum. The total recharge for the TMG area (which is 1336 km^2) is 160 million m^3.

The volume of water which can be recharged to an aquifer, is often best to estimate when the amount of water which can be abstracted from the aquifer, is also assessed (Murray et al, 1998).

3.3 Storage capacity of the TMG

The amount of groundwater in storage is the volume of water that the geological material holds in the voids between the particles and fracture zones of which these various geological materials are composed. In the case of porous rocks such as TMG, water can be stored in the rock fractures or in the formation itself. If the amount of water extracted on a continuous basis exceeds the amount of water recharged into the aquifer, the groundwater in storage will be depleted.

As mentioned in the first chapter, TMG has two aquifer units, the Peninsula formation and the Nardouw subgroup. The thickness of the Peninsula formation varies from 900m to 2000m and the Nardouw subgroup has a thickness of about 500m (Geological Survey, 1980). Within the study area the thickness of both the Peninsula formation and the Nardouw subgroup varies from 200m to 1700m (Figure 3.4).

The estimate of storage capacity was calculated from the area of the aquifer (m^2), the aquifer thickness (m) and storativity or specific yield of the aquifer (dimensionless). Storativity is the volume of water released from storage per unit surface area of the aquifer, per unit decline in the component of hydraulic head normal to that surface. In Arcview, the surface area of both Peninsula formation and Nardouw subgroup was estimated from the geological map and the aquifer thickness from the DEM.

The 1:250 000 scale geological map (3319) was used to obtain geological information in three dimensions and to draw cross-sections (Figure 3.4). An area of TMG was selected with the help of a hydrogeologist (Weaver) at the CSIR. A sample of six transect lines was drawn across the selected area as shown in Figure 3.3.

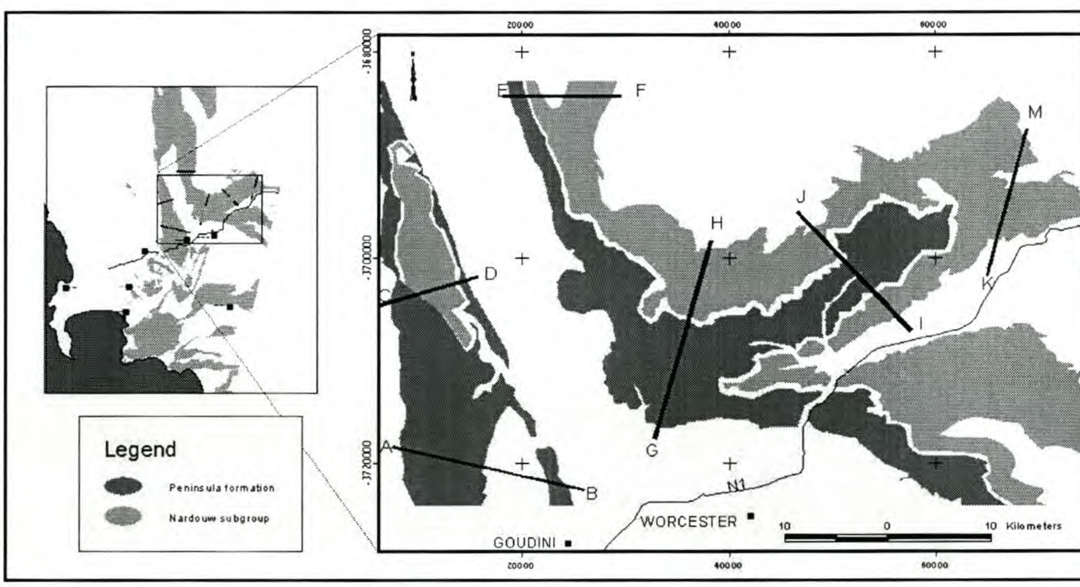


Figure 3.3 Occurrence of the Peninsula formation and Nardouw subgroup

In Arcview 3D Analyst, the geology coverage was overlaid on the DEM. Using the drawing tool in 3D Analyst, profiles from the overlays were drawn to determine lithology (Figure 3.4). For each profile, the strike and the dip of the geology taken from the geological map were used to draw the angle at which the geology dips below the surface. The strike is the direction of the line of intersection between a bedding plane and the horizontal, or the direction in which the inclination of the bed is zero. Dip is the direction at right angles to strike and the sum of the angle between the bedding plane and the horizontal (Lurie, 1994). Faults that show displacement of geology on the

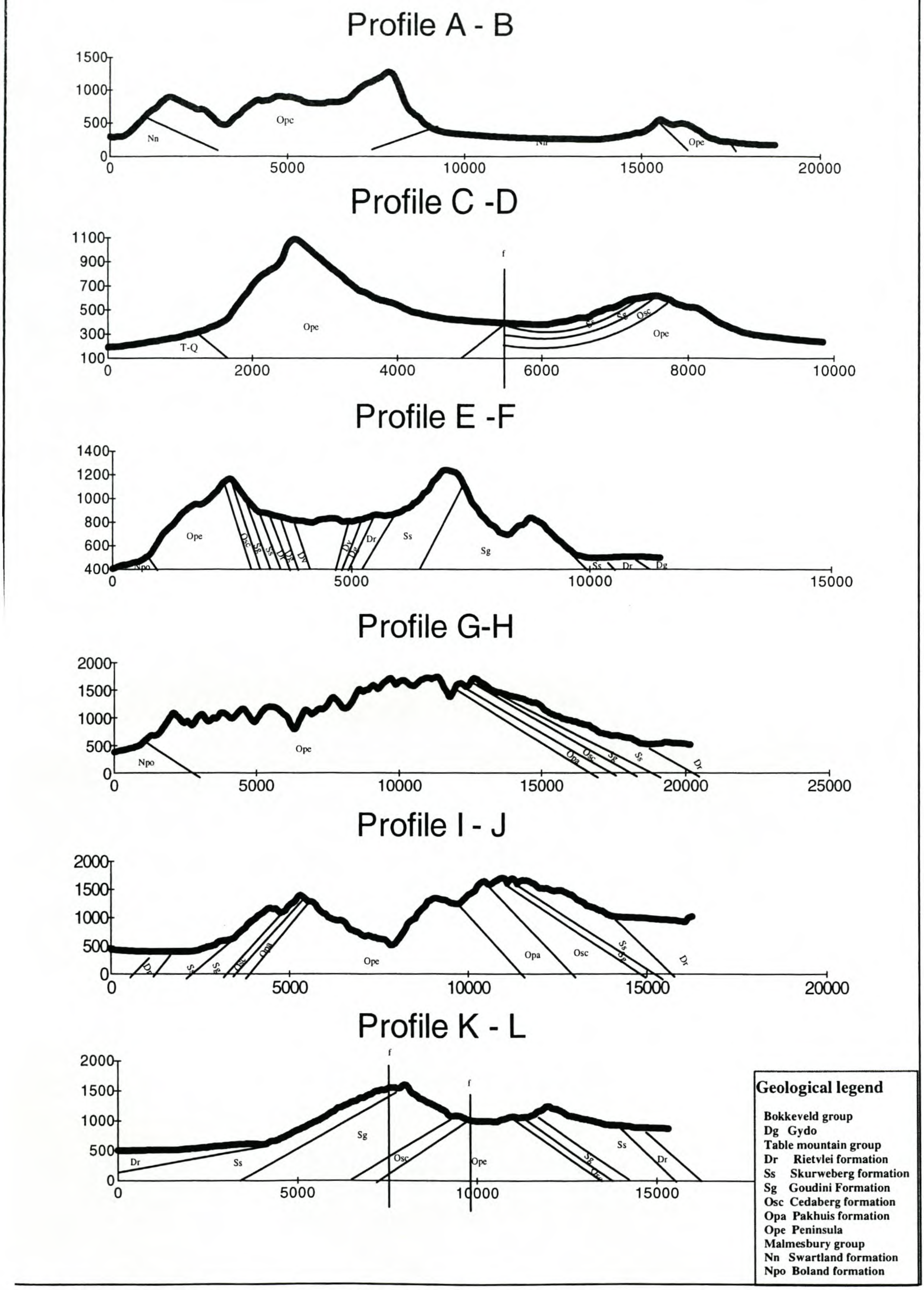


Figure 3.4. TMG cross-sections and profiles of the transect lines

geological map were also captured. Where the amount of displacement of the fault was not obvious on the geological map, it was ignored.

Assuming that the rock is saturated with water, the area of thickness was calculated by overlaying a grid of 200m x 200m cells on the cross-sections at a depth of 500m. The depth of 500m was based on the NGDB data, where the deepest borehole drilled was 500m. A 'predominant' method was used to assign data values to grid cells. This method involves assigning cell values to the surface with the largest area in the cell (Chou, 1997). With assistance from Weaver, a distance of 10 km from each transect line was used and was multiplied by the aquifer area. Equation 2 in Section 1.3.2 was used to estimate the storage capacity of both the Peninsula formation and the Nardouw subgroup.

Vegter (1995) classified hard rock storage and came up with the storativity value of 0.001 for fractured sedimentary rock. This is more conservative than the value of 0.01 value used by Weaver & Talma (1999) to calculate the volume of water available for Cape Town. The storativity value of 0.001 was used in the calculations. A correlation analysis was used to measure the strength of the relationship between the area and the volumes calculated for each transect. A correlation analysis tool in Microsoft Excel 2000 software was used to determine the correlation coefficient.

The Peninsula formation and the Nardouw subgroup form a rough topography rising to a maximum height of 1600m above sea level. The total area of the Nardouw subgroup in the sample area is 340 km^2 and the Peninsula formation has an area of 362 km^2. The average dip of the Peninsula and Nardouw is 30° and 40° respectively (Figure 3.4). The results show that the estimated storage capacity of the Peninsula formation and the Nardouw subgroup, at 500m thickness and 10 km from the transect lines, is 184 million m^3 and 168 million m^3 respectively (Table 3.1).

The correlation coefficient of the relationship between the area and the volume in the Nardouw formation was 0.97, and 0.93 in the Peninsula formation. The linear trendline in Figure 3.5 clearly shows that the volume increases as the surface area increases. The coefficient of determination (R-squared value) reveals how closely the estimated volumes for the trendline correspond to the surface area. The R-squared value is 0.906.

Table 3.1 Storage capacity of Peninsula formation and Nardouw subgroup.

Transect	Peninsula		Nardouw	
	Surface area (m^2)	Volume (m^3)	Surface area (m^2)	Volume (m^3)
A - B	102 million m^2	39 million m^3	0	0
C - D	64 million m^2	26.7 million m^3	20 million m^2	8 million m^3
E – F	32 million m^2	24 million m^3	56 million m^2	24.4 million m^3
G - H	108 million m^2	52 million m^3	58 million m^2	30 million m^3
I – J	40 million m^2	19.3 million m^3	84 million m^2	36 million m^3
K - M	16 million m^2	12 million m^3	122 million m^2	69.6 million m^3
Total	**362** million m^2	**184.8** million m^3	**340** million m^2	**168** million m^3

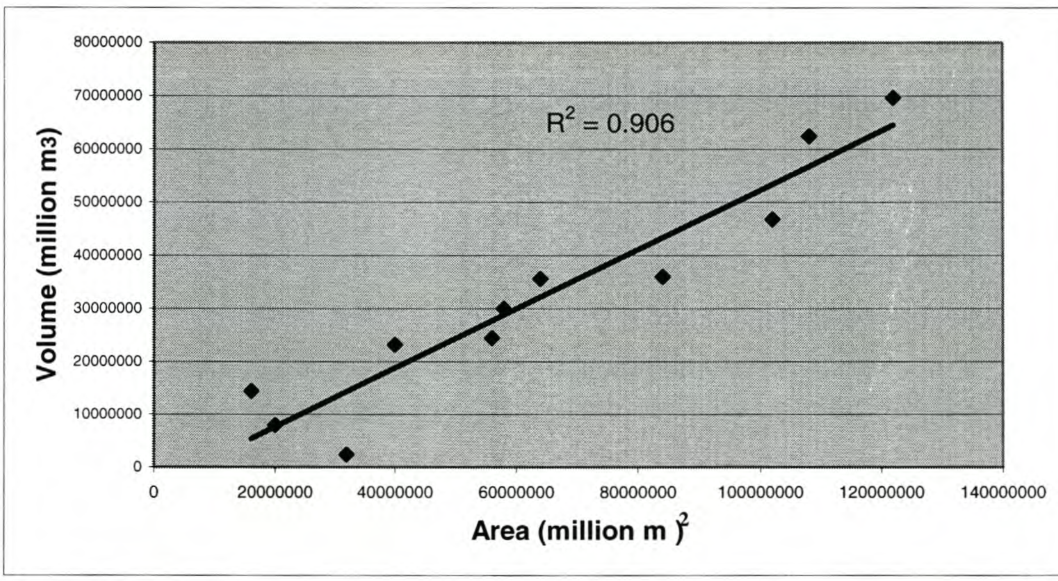


Figure 3.5 Volume vs surface area for both the Peninsula formation and the Nardouw subgroup.

Using this strong relationship, the total storage capacity of the Peninsula formation and Nardouw subgroup in the sample area is 255 million m^3 and 288 million m^3 respectively. Taking the area of both the Peninsula and the Nardouw formations (1313 km^2), thickness of 500m and a storativity value of 0.001, the total estimated storage capacity is 543 million m^3. Because of this large capacity and high recharge rate, this water can be extracted by means of boreholes and could be used to supply the Cape Town Metropolitan area and its environs. The anticipated water demand for these areas is from 243 million m^3 in 1990 to 560 million m^3 per annum in 2020. It is estimated that the water stored within the TMG should be sufficient for the next 10 years to supplement the existing surface water resources.

A number of boreholes are necessary to extract this volume of water, taking into account the location of the zone of greater transmissivity and the areas most sensitive to pollution discussed in the next section. Transmissivity is the rate at which a volume of water is transmitted through a unit width of aquifer under an unit hydraulic head (Murray et al, 1998). Owing to the extensive areas to be covered, the cost of abstracting the water would be high. This would require a long pipeline and heavy pumping. The TMG sandstones are also known to be hard, cross-jointed and difficult to drill into which results in a gradual narrowing of borehole diameter as depth increases (Woodford, 1994).

The areas contributing to recharge also need to be protected from contaminants to project the quality of the groundwater source. The following section discusses the ways to determine areas sensitive to contamination.

3.4 Groundwater vulnerability and DRASTIC Index

Groundwater can be contaminated by a wide variety of human activities. Primary sources of threat to groundwater quality are urbanisation impacts, such as residential sanitation and solid waste disposal, industrial and mining development and agricultural impacts comprising leaching of fertilizers and use of pesticides. Therefore, protection of groundwater resources in areas prone to contamination by human activity should be delineated. This can best be done through groundwater vulnerability assessments.

The DRASTIC Index developed in 1987 by the United States Environmental Protection Agency (EPA) was used as a method for assessing groundwater pollution potential. The main goal of the development of DRASTIC was to produce a standardised methodology that would give results suitable for screening regions with respect to groundwater protection, monitoring, and clean-up efforts (Aller et al, 1987). The method uses hydrogeologic settings as the basic mapping units. For each setting, the following seven parameters are evaluated:

- **D**epth to water,
- **R**echarge,
- **A**quifer media,
- **S**oil media,
- **T**opography,
- **I**mpact of the vadose zone, and
- Hydraulic **C**onductivity.

The DRASTIC Index assigns a rating to each parameter, on a scale of one to 10. The rating tables (Table 3.4) presented by Aller et al (1987) were modified by Reynders (1997) to accommodate South African conditions (Parsons & Conrad, 1998). This rating is then scaled by a weighting factor of one to five, and the weighted ratings summed to obtain the DRASTIC Pollution Potential Index (DPPI) for the mapping unit. The weighting represents the relative importance of each factor in its ability to affect pollution transport to, or within, the aquifer (Matoti et al, 1999). The higher the DPPI, the higher the groundwater vulnerability to contamination. The system consists of two major components, the mapping of hydrogeologic settings and the assignment of an index number, which helps the user to evaluate the relative groundwater pollution potential of these settings. This information can be used for preventive purposes through the prioritisation of areas where ground water protection is critical and can identify areas where special attention is needed.

Equation 3 in Section 1.3.3 was used to assess groundwater vulnerability to pollution. The Arc/Info GIS environment was used to carry out the analyses and to identify and display groundwater areas sensitive to contamination. The following physical parameters were evaluated:

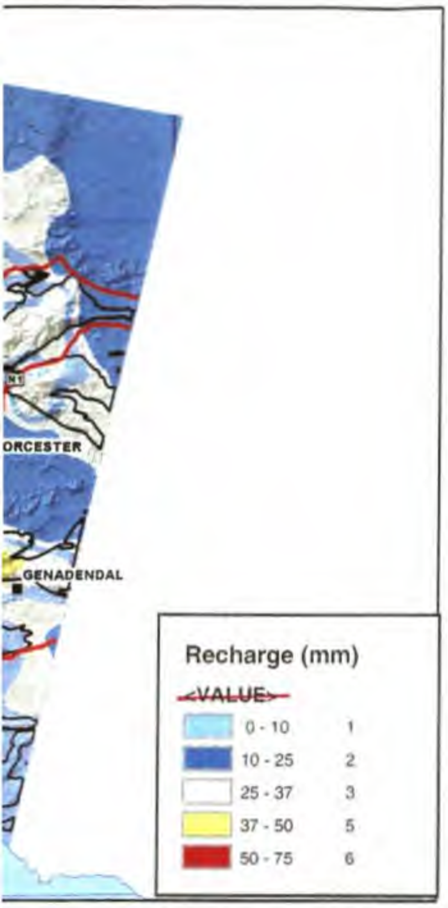
3.4.1 Depth to groundwater

Depth to groundwater is of primary importance because it determines the depth of material through which a contaminant must travel before reaching an aquifer, and the time during which a contaminant is in contact with the soil layer before it reaches the groundwater. Borehole water levels serve as the estimate of depth to groundwater (water table).

Table 3.1 Drastic Index parameters

Depth to groundwater (D)		Recharge (R)		Aquifer Media (A)		Soil Media (S)		Topography (T)		Impact of Vadose Zone (I)		Hydraulic Conductivity	
RANGE	RATING	RANGE	RATING	RANGE	RATING	RANGE	RATING	% SLOPE	RATING	RANGE	RATING	LITHOLOGY	RATING
0-10m	10	0-10mm	1	Fractured dolomite and limestone with	10	Sand	8 - 10	0-2	10	Dolomite, chert and subordinate limestone	10	Sand and gravel	10
10-20m	5	10-25mm	2	Massive dolomite and limestone	8	Shrinking and/or aggregated clay	7 - 8	2-6	9	Porous unconsolidated to semiconsolidated sedimentary strata	9	Solution channels/fractures dolomite and limestone	10
20-30m	3	25-37mm	3	Sand and gravel	8	Loamy sand	6 - 7	6-12	5	Consolidated porous to compact sedimentary strata	7	Igneous and crystalline metamorphic rocks - weathered and fractured	1
30-50m	2	37-50mm	5	Compact sedimentary rocks: weathered and fractured	7	Sandy loam	5 - 6	12-18	3	Compact, dominantly arenaceous strata	6	Compact sedimentary rocks - weathered and fractured	1
>50m	1	50-75mm	6	Compact sedimentary rocks: fractures directly below groundwater level	5	Sandy clay loam and loam	4 - 5	>18	1	Compact, dominantly argillaceous strata	5	Massive dolomite and limestone	10
		75-110mm	7	Igneous and/or crystalline metamorphic rocks: fractured and weathered	4	Silty clay loam, sandy clay and silty loam	3 - 4			Compact arenaceous strata	5	Compact sedimentary rocks - fractures directly below groundwater level	1
		110-160mm	8	Igneous and/or crystalline metamorphic rocks: fractured	3	Clay loam and silty clay	2 - 3			Compact sedimentary strata	5	Igneous and crystalline metamorphic rocks - fractured	1
		160-200mm	9	Compact sedimentary rocks with widely spaced fractures	2					Mainly compact tillite, shale and sandstone (Dwyka Formation, Ecca Group)	4	Compact sedimentary rocks and widely-spaced fractures	0.1
		>200mm	10							Assemblage of compact sedimentary, and extrusive rocks	4		
										Assemblage of compact sedimentary, extrusive and intrusive rocks	4		
										Mainly compact tillite and shale (Dwyka Formation, Ecca Group	3		
										Acid and intermediate lava	3		
										Mafic/basic lavas	3		
										Acid, intermediate and alkaline intrusives	3		
										Mafic/ultramafic, basic/ultrabasic intrusives	3		
										Mainly compact tillite	2		
Weight 5		**Weight 4**		**Weight 3**		**Weight 2**		**Weight 1**		**Weight 5**		**Weight 3**	

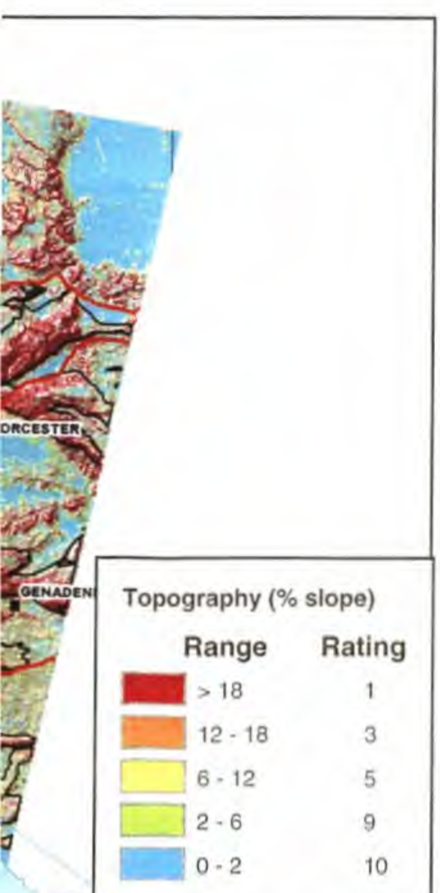
Source: (Reynders, 1997)

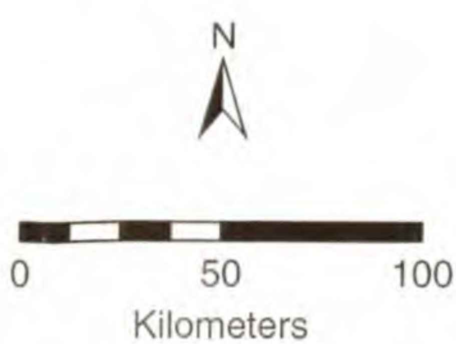


Range	Aquifer medium	Impact to vadose zone	Hydraulic Conductivity
Granite, Phylite	2	5	0.1
Sandstone, shale, tillite	7	7	1
Sand	8	9	10

Ratings

Figure 3.6c





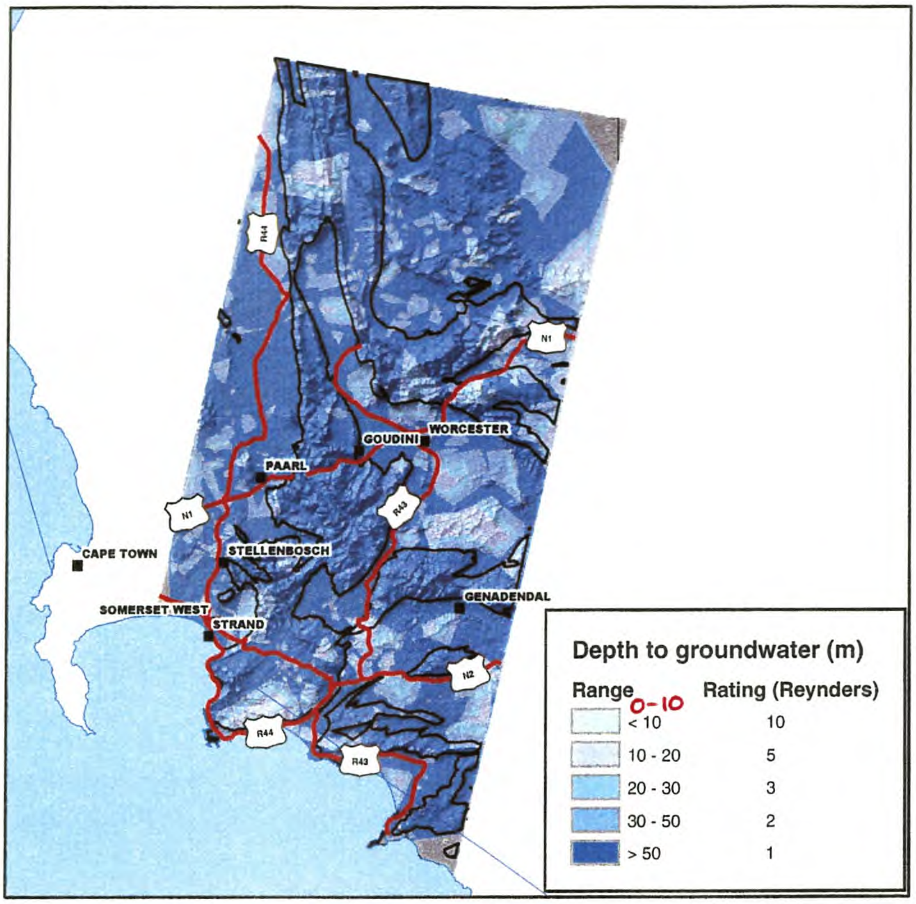


Figure 3.6a

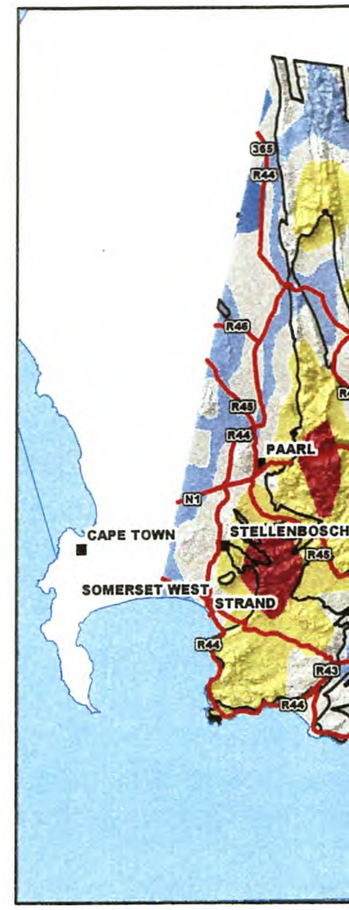


Figure 3.6b

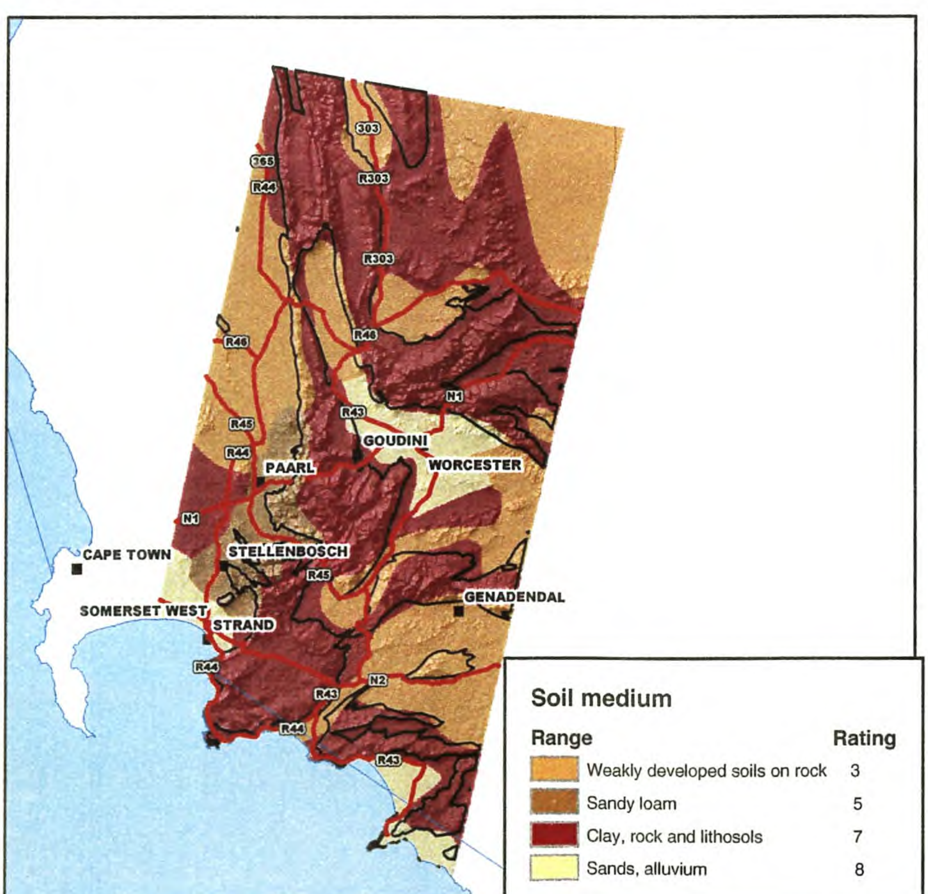


Figure 3.6d

Figure 3.6e

Figure 3.6a-e Physical parameters used in the DRASTIC method

Water levels from the NGDB data were used to create a triangulated irregular network (TIN) of water levels contours (Figure 3.6a). A TIN is the surface representation derived from irregularly spaced points. The water level values were rated using the South African ratings developed by Reynders (1997) (seeTable 3.2). The map of groundwater depth (Figure 3.6a) shows that most of the study area has water table depths ranging between10 and 50m.

3.4.2 Recharge

Recharge is the amount of water from precipitation that infiltrates through the ground surface to the water table. Recharge water is the principal vehicle for transporting contaminants vertically to the water table. The greater the recharge, the greater is the potential for groundwater pollution. Because specific estimates of recharge were difficult to obtain and specific recharge data for the aquifer were unavailable, an average annual precipitation estimate of five percent in section 3.2 was used (Figure 3.6b). South African ratings were used in creating zones of equal recharge (Table 3.4).
The recharge map (Figure 3.6b) shows recharge rates ranging between 0mm and 75mm across the study area.

3.4.3 Aquifer medium

Aquifer medium is the subsurface geology that influences groundwater movement and contamination. Movement of pollutants in fractured rock is unpredictable and pollutants can readily spread over large areas (Weigmann, 1996). A geological map at 1:250 000 scale was used in identifying the aquifer medium (Figure 3.6c) based onTable 3.2.
The aquifer medium (Figure 3.5c) comprises mostly of compact, weathered and fractured sedimentary rocks. These consist mostly of sandstone and shale in the outcropping areas with siltstone, mudstone and tillite in the low-lying areas. Bedrock consists of granite and phyllite, which covers about 20% of the area.

3.4.4 Soil media

Soil characteristics are very important in determining whether a contaminant breaks down to harmless compounds or pollutes the groundwater. Because most breakdowns occur in the soil, there is a greater potential for groundwater contamination in areas where contaminants can move quickly through the soil (Weigmann, 1996). Dissolved contaminants can move quickly through sandy soils and slowly through clay soils.

Due to the unavailability of soil data at a scale of 1:250 000 during this study, a soil map at 1:1 000 000 was used to classify the soil types of this area (Figure 3.6d). The soils were rated according to the soil medium ratings inTable 3.2.

Other areas are covered with sand and gravel (Figure 3.6d). These areas lie in valleys and at the foothills of the outcropping TMG. Some areas are covered with clay and lithosols, sandy loam and weakly developed soils.

3.4.5 Topography

Topography gives an indication of whether a pollutant will run off or remain on the surface long enough to infiltrate into the groundwater. A steeper slope provides lesser opportunity for a pollutant to infiltrate. Slope percentage between zero and two provides the greatest opportunity for a pollutant to infiltrate (Cooper et al, 1999).

The slope percentage was calculated from a 50m x 50m DEM and reclassified using the DRASTIC ratings (Figure 3.6e), which range from 1 – 10 (seeTable 3.2).

Ninety-five percent of the study area has a slope greater than 18 % (Figure 3.6e). Valleys have a slope ranging from 0-12 %. These areas with low slope tend to retain water longer, which can allow a greater infiltration of precipitation and a greater potential for contaminant migration. TMG areas with steep slopes have a large amount of run-off and a smaller amount of infiltration and are less vulnerable to groundwater contamination.

3.4.6 Impact of the vadose zone

The vadose zone comprises the zone below the surface soil layer, but above the saturated zone (Figure 3.7). It determines the attenuation characteristics of the material below the typical topsoil horizon and above the water table. The vadose zone was classified using the geological map lithology at 1:250 000 scale (Figure 3.6c). Table 3.2 was used to rate the effect of the vadose zone in transferring the pollutant. The vadose layer has porous, unconsolidated to semi consolidated sedimentary strata (Figure 3.6c). The area is covered with sand, siltstone and mudstone, tillite, granites and phillite.

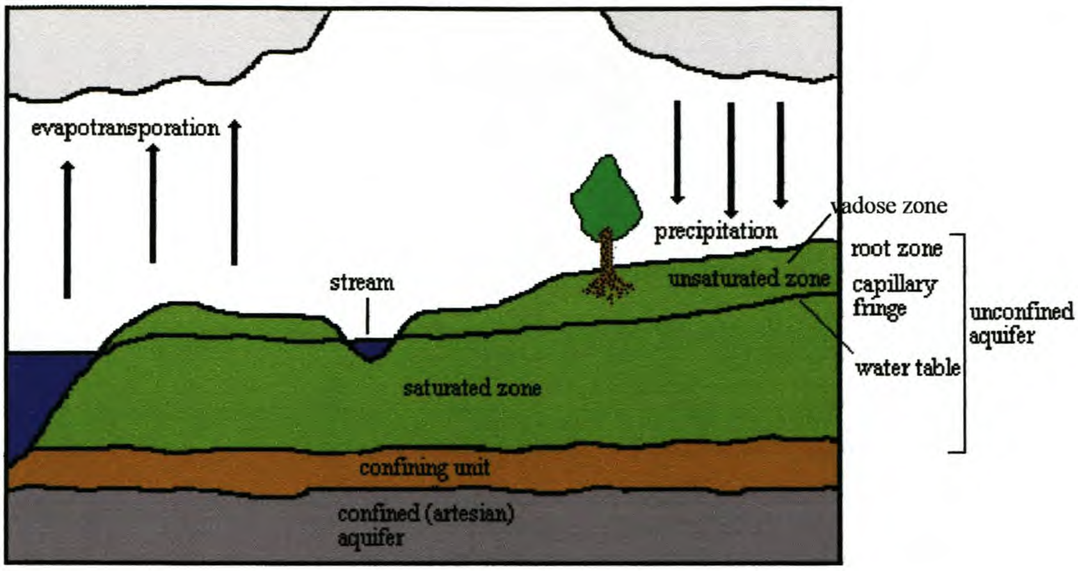


Figure 3.7 Saturated and unsaturated (vadose) zones

3.4.7 Hydraulic conductivity

Hydraulic conductivity refers to the ability of the aquifer material to transmit water, which in turn, controls the rate at which ground water will flow under a given gradient. Borehole yields and the grain size of the aquifer material may provide assistance in estimating hydraulic conductivity. The most accurate values for hydraulic conductivity are calculated from aquifer pump tests. Due to the lack of this information, hydraulic conductivity for this area was classified based on the aquifer media (Figure 3.6c).

The hydraulic conductivity (Figure 3.6c) in areas with granites and phyllite is 0.1; in areas with siltstone, mudstone, sandstone, shales and tillite it is one and 10 in areas covered with sand.

All the datasets of the above parameters were converted into 50m x 50m grids as shown in Figure 3.6a-e. Each grid was rated according to the DRASTIC ratings given in Table 3.2. For each cell, the DRASTIC rating from each input layer was multiplied by the DRASTIC weight for that layer and summed to determine the DPPI. The groundwater vulnerability map (Figure 3.8) was produced in colour, using the colour scheme suggested in Aller et al (1987).

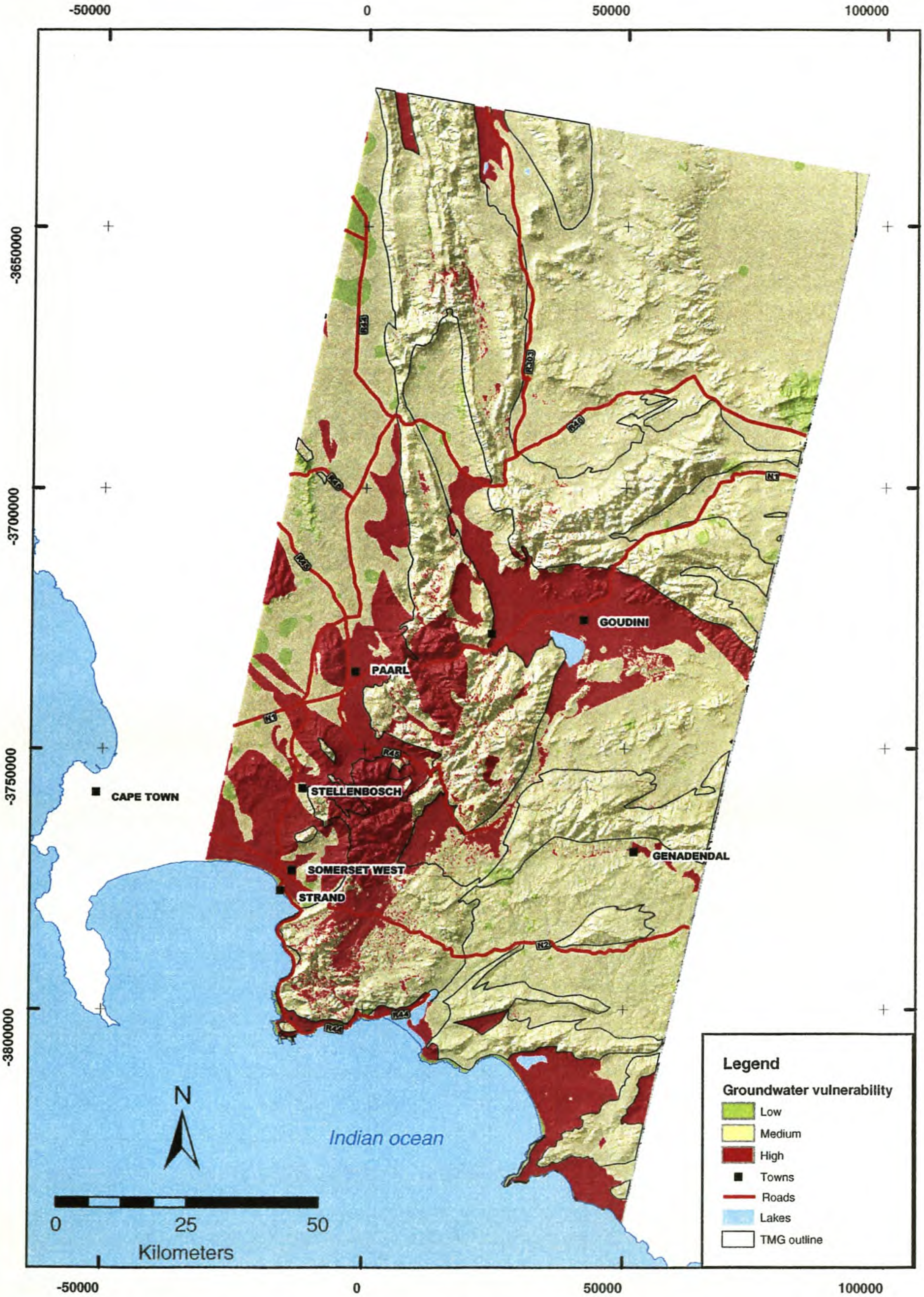


Figure 3.8 Groundwater vulnerability showing areas sensitive to contamination

According to Aller et al (1987) the possible range of DPPI is between 24 and 226. The values less than 98 represent low vulnerability, values between 98 and 140 represent medium vulnerability and those greater than 140 represent high vulnerability. The groundwater vulnerability histogram (Figure 3.9) shows DPPI values that range from 24 to 189. Three percent represented values less than 98, 77% values between 98 and 140, and 20% values greater than 140. This illustrates that most of the TMG in the study area are moderately vulnerable to contamination and the areas in the valleys and foothills are the ones sensitive to the effect by an imposed contamination (Figure 3.8). It means that if pollution happens to these areas in future, they will be easily polluted. This could be attributed to the shallow groundwater that is affected initially by contaminant release. Because contamination has the mobility of water, groundwater from the affected areas could move and contaminate groundwater within the TMG through the fractures within the rock.

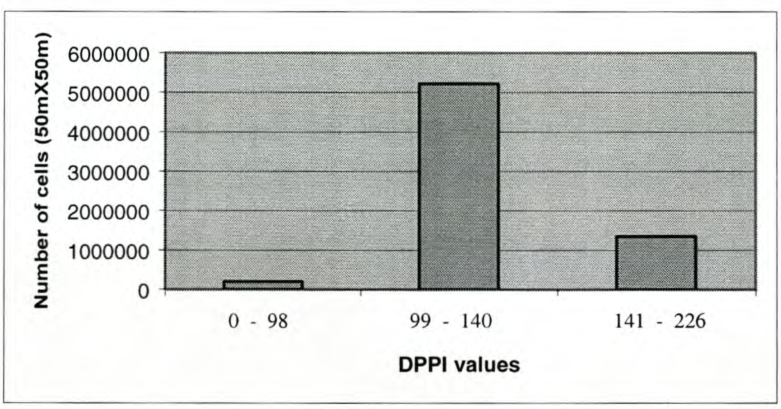


Figure 3.9 Number of grid cells showing the groundwater pollution potential of the study area.

Groundwater pollution cannot be easily detected and it takes many years to be identified in water withdrawn from boreholes. By that time, it may be too late to prevent serious contamination. Remediation is expensive because the cost of providing alternative water supplies is high, and restoration of polluted aquifers is difficult. Therefore, monitoring of the areas that can be easily affected is critical.

3.5 Siting potential drilling sites

Information on the hydrogeological conditions of an aquifer is necessary for borehole drilling. For instance, drilling in hard rock areas is associated with a high risk of failure. This is because borehole siting in hard rock depends on the presence of transmissive features such as fracture zones, enough permeable material for storage and sufficient recharge for a sustainable supply (Kellgren, 1999). Knowing the estimates of recharge and the volume of groundwater that can be stored within the aquifer can also influence the success to determine areas of abstraction.

Identification of areas of high-yield groundwater sources can help to alleviate current water shortage and provide water to accommodate and promote future economic development. The combination of geological data, topography and borehole information can result in well-informed decisions in siting these sources. Groundwater can be abstracted by means of boreholes to reduce the high demand on surface water resources.

The borehole yields, DEM and groundwater indicators such as lineaments were used to locate areas of potential drilling. Because of the outcropping TMG, a GIS grid of percentage slope derived from the DEM was used to eliminate areas which are inaccessible. These areas have slope greater than 40%. Lineaments were overlaid on the slope grid and areas of slope greater than 40 % were masked out leaving lineaments in areas of slope less or equal to 40%.

Proximity analysis was performed between lineaments and borehole yields. Buffer zones of 100m, 150m and 500m were used to extract borehole yields that are within these buffer zones. These helped to establish the best distance from the lineaments to be used for drilling purposes. Lineament azimuth and borehole yields were also assessed to find the most promising orientation.

Positive correlation between the lineaments and the existing high yielding boreholes will indicate potential drilling zones. Borehole data assist to characterize the transmissive properties of the fractured zones. The accessibility of these zones depends on the topography of the area under exploration.

The results from the borehole and lineament overlays have shown the optimum distance from the lineaments and the favourable orientation. These results also influenced the siting of potential drilling sites (Figure 3.10). Potential drilling sites were areas with slopes less than or equal to 40%. Areas with slopes greater than 40% were considered not accessible. Eighty percent of lineaments were found in areas with slope less than or equal to 40%. These results show that topography did not limit the siting of the high yielding boreholes. The comparison of borehole yields and the location of the lineament demonstrated that lineaments within 150m, with orientation in a 135-150^{o} direction, are better drilling sites than the geological features digitised from the geological map. Lineaments can be used as valuable targets for groundwater exploration, though other studies such as Kellgren et al (1997) found that there was no correlation between the existing boreholes and lineaments. The reason for this difference could be that few lineaments were mapped in the vicinity of the boreholes. This can be due to landuse practices and areas with deep sediments where structural features in the bedrock are not easily detected in remote sensing (Kellgren et al, 1999).

The use of remote sensing in identifying potential drilling sites was proved valuable. The spectral properties of remote sensing allow identification of geological features such as lineaments. Lineaments are believed to be groundwater indicators. Hydrogeological evaluation of these features helps in identifying potential drilling sites.

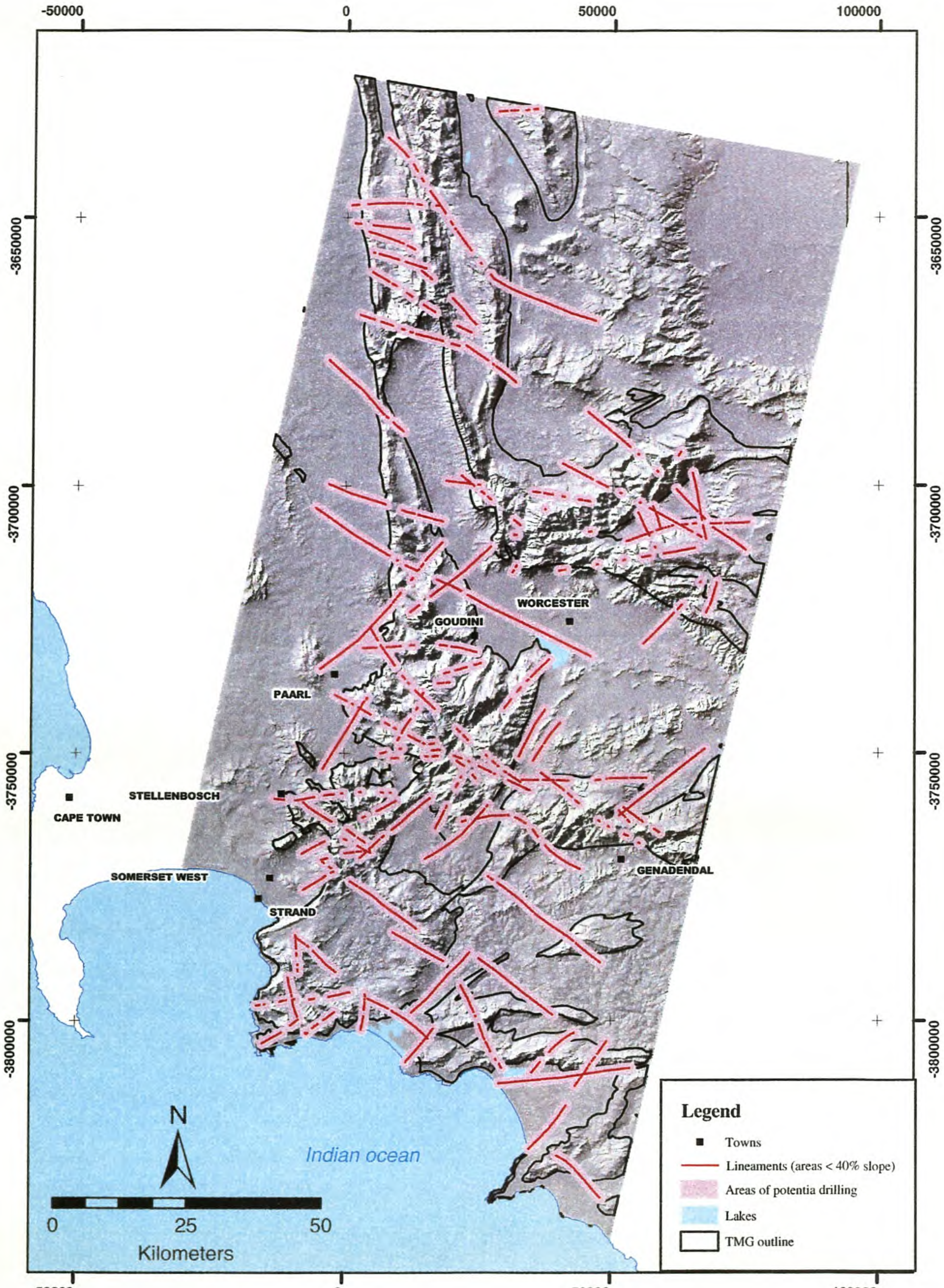


Figure 3.10 Potential borehole drilling sites

CHAPTER 4: DISCUSSION AND CONCLUSIONS

4.1 Introduction

In the previous chapter, various methods were used to assess groundwater resources by evaluating groundwater recharge, storage capacity, areas vulnerable to contamination and potential drilling sites. By using GIS and Remote Sensing, spatial data from different sources were combined and analysed. This chapter presents the discussion of the results from the spatial analyses performed, conclusions and recommendations.

4.2 Discussion and conclusions

This study was intended to form a desktop study in groundwater resource assessment within the TMG. The results found in this study can be used as references for more detailed future research.

The enhanced colour composites of bands 5-4-3 and 4-3-2 provided better lineament detection than other band combinations. Visually comparing lineaments mapped by different interpreters strengthened the value of the mapped lineaments. The relationships between lineaments and vegetation were unclear. This could be attributed to the time when the image was taken. The image used was captured at the end of the wet season and the dense vegetation may have obscured fracture-related groundwater resources. It is recommended that an image captured during the dry season should be used to compare with these results especially in areas that are not accessible during field studies. During the dry season, vegetation is an indication of moisture in the sub-surface areas. Some of the drainage patterns may be formed by faults because some overlapped with the lineaments.

The results demonstrate that lineaments captured from the Landsat image can be used as groundwater targets to obtain high yielding boreholes. The proximity analysis of borehole yields and the distance from lineaments serve as useful guides for identifying areas that are suitable for groundwater exploration. Most boreholes with high yields fall within 150m from lineaments, and the yields decrease as the distance increases.

The proximity analysis also demonstrates that the Landsat image lineaments oriented in a 0-45° and 135-180° direction are more favourable because of the high yielding boreholes found along them. The topography does not limit the siting of the high yielding boreholes.

The highly fractured TMG appears to have a high recharge potential and storage capacity. The results showed that there is a strong relationship between area and volume. Thus, the total estimated storage capacity of TMG, which is 543 million m^3 can hold enough water for consumption for the next 10 years and supplement surface water resources if the aquifer is recharged. The sustainability yield will also depend on the annual recharge.

According to the DRASTIC index, the water table depth and the vadose zone are the two most important factors in groundwater vulnerability assessment. They are five times more important than topography, which is the least important. In general, most of the area has moderate groundwater pollution potential especially within the TMG. Areas with shallow water tables pose a greater opportunity for the contaminant to reach the groundwater surface as opposed to areas with deep water tables.

Prevention of contamination is therefore critical in effective groundwater management. The vulnerability map should enable planners and managers to identify areas of high contamination potential as a first step in forming a groundwater protection plan for existing water supplies and for future economic development. The DRASTIC index can supply important data for conservation and water-resource management decisions.

4.3 Recommendations

Satellite imagery interpretations played an important role in assessing potential groundwater resources. These should be coupled with field investigation and the geological knowledge of the area. In the NGDB borehole data it was not clear whether the boreholes with zero values were dry boreholes or measurements were not taken for those boreholes, more information about the borehole data is needed for proximity analysis and the siting of drilling sites.

Due to the rapid population growth there will be high water demand in this area for the coming years, therefore water needs to be management in a more sustainable way.
Due to the fractured nature of the TMG, contaminants can infiltrate the surface and contaminate groundwater. Therefore, potential drilling areas should be protected from existing potential sources of contaminants for long term supply. The methodology used in this study in siting potential drilling sites can be used for further studies but field investigations need to be taken to confirm the promising sites.

The methododolgy used in the storage capacity estimates for the TMG was time consuming. For further research a different method can be used together with detailed geological and geophysical mapping.

This study has demonstrated that both remote sensing and GIS are useful tools in groundwater exploration. Remote sensing plays a significant role in delineating groundwater indicators such as lineaments, vegetation and drainage patterns. The information from the geological map also provided additional guidelines on geological features such as faults and fractures. The information provided by the GIS overlay of these data also assisted in siting areas of high recharge, high storage capacity, areas vulnerable to contamination and drilling sites.

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