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Towards understanding the Groundwater Dependent Ecosystems within the Table Mountain Group Aquifer: A conceptual approach

by

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Abstract

Understanding of Groundwater Dependent Ecosystems (GDEs) and their extent within the Table Mountain Group (TMG) aquifer is poor. To understand the dependence to basic ecological and hydrogeological concepts need explanation.

The use of current literature aided in identification and classification. From the literature it has come clear that groundwater dependence centers around two issues, water source and water use determination.

The use of Geographical Information System (GIS) showed its potential in proof of water sources. Rainfall data and a Digital Elevation Model (DEM) for the Uniondale area have been used to do watershed delineation, which is in line with locating GDEs on a landscape.

Thus the conceptual approach should be a broad one that sets a basis for both investigation (*scientific research*) and institutional arrangements (*management*).

On the scientific research aspect:

1) Methods used to ascertain groundwater dependence have been identified and described (for example *morphological traits*, *physiological traits*, etc.)
   a) Use of GIS to delineate watersheds in the Uniondale area, putting it as one of useful methods that can be used in locating GDEs in a landscape.
   b) Use of Digital Elevation Models (DEMs) to create both geological and topographic cross-sections. Topographic cross-sections are important to locate ecosystems along a landscape, while geological cross-sections are useful in conceptualising groundwater flow.
2) The Plant Functional Type concept, which puts together plant species regardless of phylogeny but rather on morphological, phenological and physiological/life history trait similarity, has been suggested as a useful concept for the TMG GDEs.

On the management aspect:

1) An ecosystem approach to understand groundwater has been identified and modified to suite the TMG GDE management.

2) A retention strategy useful to manage the TMG GDEs effectively has been suggested.

There are knowledge gaps that exist in the TMG aquifer about Groundwater Dependent Ecosystems.

Thus there is:

- *A need to identify GDE types that exist based on their degrees of dependency on groundwater.*
- *A need to classify the GDEs using a PFT concept.*
- *To compile a trait (morphological, phenological and physiological) database for TMG aquifer GDEs.*

Declaration

I declare that work ***TOWARDS UNDERSTANDING GDES WITHIN THE TMG AQUIFER: A CONCEPTUAL APPROACH*** is my own work, that has not been submitted for any degree or examination in another University. All of the people who wrote the literature are cited accordingly in the reference section, giving every single one credit that is due to them.

Signature:______________________ *Date:*______________________

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I would most of all like to thank God for all the energy and strength given during the time of this work.

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Table of Contents

List of Figures

List of Tables

Chapter 1

1 Introduction

Ecosystem dependency on groundwater in South Africa has recently caught the attention of ecologists, hydrogeologists, the agricultural experts and various other stakeholders in the whole country. Water is scarce in South Africa, and its development needs an approach that considers all the elements that need some portion of it to exist. The National Water Act (Act 36 of 1998) states there must be a determination of freshwater needed by the biophysical environment before abstraction. Therefore understanding ecosystems that are dependent on groundwater is necessary.

There has been a long-standing belief that aquifers are lifeless. Because of such belief, most water studies have looked at the health (chemical, physical and biological integrity) of surface water. However, in the past two decades there has been important evidence that has surfaced which is contrary to lifelessness of aquifers (Reddy, 2003). Most of the evidence comes from various other parts of the world. South Africa has made advances over the last eight years. The work currently undertaken by Sayomi Tasaki at the University of the North-West has revealed the Sterkfontein karstic caves are home to stygofaunic amphipods. However, there are no other similar studies carried out elsewhere in the country to get an idea about the national status of GDEs in South Africa.

Some previous work in South Africa on the subject has focused more on the ecological importance without necessarily linking that to groundwater dependence. Scott and Le Maitre (1998), Le Maitre *et al.* (2002) have put more emphasis on mostly *prima facie* rooting depth as meaning groundwater dependence. Water source and water use patterns of species can uphold the notion when seasonally determined. Fortuin (2004) identified eight 'type areas' of ecological importance within the TMG aquifer, which are at close to proposed groundwater development areas. The problem with the 'type-area' approach is that it clearly overlooks the plant physiology that is necessary to identify both water source and water use patterns. Further the 'type areas' are too far apart and obviously discounted many discharge zone ecosystems.

Investigations on GDEs within the TMG aquifer are sparse. In the year 2000, Mr. Ronnie Kasrils, the then Minister of Water Affairs and Forestry named the water of the TMG aquifer a "Great Hidden Treasure". There needs to be investigations about how much of this "treasure" is required by the environment. Balancing between needs of both human and the environment to ensure long-term survival of both is the essence of sustainability. Currently there is no enough data on the water source and water use patterns of vegetation within the TMG aquifer. Ecological sensitivity to groundwater development may rather make sense when water source for species is groundwater. Further, ecological sensitivity analysis should also include finding out water amount the species use. It is for such reasons that this study will later deliberate on methods to ascertain groundwater dependence. There can only be sound conservation for Groundwater Dependent Ecosystems once this groundwater dependence is ascertained.

1.1 Problem statement

GDE understanding within the TMG aquifer chiefly requires determination of water sources, water use patterns of floral species as well as understanding of structural geology. GDE understanding also requires the use of a trait-based (morphological, phenological and physiological), site-specific Plant Functional Types (PFT) concept. It also needs the use of Geographical Information Systems (GIS) to locate GDE on a landscape.

1.2 Study objectives

The objectives of this study are as follows:

1) *To introduce various types of groundwater dependent ecosystems and groundwater attributes. In-aquifer and discharge zone ecosystems will receive*

a special emphasis. This is because these two groundwater dependent ecosystems use groundwater but in variable amounts, whereas recharge zone ecosystems range from little to no dependence on groundwater.

2) *To explain scales of dependency.*
3) *To propose an investigation approach of GDE within the TMG by:*
   a) *Demonstrating use of GIS in understanding landscape and looking at possible areas of GDE by using the Uniondale case study,*
   b) *Suggesting a concept of Plant Functional Types as a more suitable approach*
4) *To suggest an effective management strategy for GDEs within the TMG*

This thesis will provide a general understanding of GDEs as well as possible approaches in finding out their existence and extent. Two important aspects on establishment of existence of GDE are both water source determination and understanding of water use patterns. These are the aspects that local studies have not addressed so far. As a result, literature cited is mainly on studies elsewhere in the world.

1.3 Background on basic concepts

1.3.1 Basic concepts of ecology

A proper understanding of groundwater dependent ecosystems requires an understanding of ecological concepts. This section will focus on basic concepts such as autecology and synecology. These concepts are important as they help in resolving ecological scale important when studying GDEs.

Autecology looks at the ecological and physiological aspects of a single organism. It involves ecological factors affecting the individual such as salinity, osmotic pressure, nutrition, light, oxygen, competition, reproduction and development.

Synecology on the other hand looks at the group (population, community or even a biome) and how ecological factors affect it. A definition of a *population* is that it is a group of individuals of the same species able to exchange genetic material (Remmert, 1980; Brown and Lomolino, 1994; Odum, 1996). A definition of *community* is that it is an assembly of species (flora and fauna) mutually adjusted and sharing similar tolerances to environmental factors including climate (Clarke, 1956; Remmert, 1980; Odum, 1996). However, the community concept is broad. There are large-scale communities (sometimes referred to as regions) that have uniform environmental conditions and therefore resemble principal habitat conditions and such communities are *biotopes*. Examples of biotopes will be mudflats, sandy beaches, deserts, etc. According to the World Wildlife Fund (2003), the term biotope refers to quantum units of a *habitat*. The habitat refers to a place where an organism occurs. The term *niche* refers to the role of an organism within a habitat.

There are also communities called *biocoenosis* that have everything (salts, nutrient, favourable temperature, etc.) provided locally. Möbius first proposed biocoenosis in 1880 on a study done on oyster beds. The fundamental laws for biocoenosis are as follows:

- *The more variable the environmental conditions, the larger the number of species present but few individuals for each species,*
- *The more uniform the environmental conditions, the greater the chance of domination by few species.*

The term *biome* refers to a major biotic community that occurs wherever a particular set of climatic conditions prevail, but floristically may have different taxa in different regions. However, the biome is not a geographical place and it refers only to and strictly biotic communities.

An *ecosystem* on the other hand refers to the ecological unit that includes both biotic and abiotic factors with their structuring and functioning.

Ecosystem *structure* includes biodiversity (species richness and relative abundance) and biomass (living weight). Biodiversity definition is not simple to define because of the scale issue. Biodiversity may be at three levels and they are:

- *Genetic (diversity of genes in individuals of same species or genes among populations)*
- *Species (diversity of species that make up a population) and,*
- *Ecosystem (richness in different processes to which genes contribute)*

Ecosystem *function* includes energetics (nutrient and energy flow). Energetics includes different modes of production in an ecosystem namely *autotrophic* and *heterotrophic* production.

Autotrophic production also refers to *primary* production. In this production, plants and algae absorb light and CO_2 to produce carbohydrates and O_2, by a process known as *photosynthesis*. Photosynthesis also comes in different kinds and has resulted in different plant forms with different water use efficiencies (WUE) (Lambers *et al*., 1998). Water use efficiency is important in water balance modelling and recharge estimation because different water use efficiencies will be important for evapotranspiration estimations. Some plants start carbon dioxide fixation by forming a three-carbon compound (C_3 plants), while others start CO_2 fixation with a four-carbon carboxylic acid (C_4 plants). Other plants [CAM (crassulacean acid metabolism) plants] absorb carbon dioxide during the night and store it as an organic acid, which will then be broken down to CO_2 during the day. When light becomes available, stomata of such plants will close. Crassulacean Acid Metabolism plants are mostly succulent desert plants (for example Cacti).

Heterotrophic production also refers to *secondary* production. In this production, herbivores, predators, saprophytes and scavengers consume energy already produced for them by *primary* production. Once information about how much an ecosystem can produce (as a source) and how much it receives from other ecosystems (as a sink) is available, estimation of *productivity* is possible.

Energetics is important as they lead to different forms of energy production and therefore different plant forms.

Once a geographical place is mentioned, then one talks of an *ecoregion*. An ecoregion is an area of ecological potential that is large, and has a combination of biophysical parameters (climate and topography). It also contains a distinct assembly of communities with boundaries that almost approximate the original extent of natural communities prior land-use change (Odum, 1996; WWF, 2003).

The biotope concept suits the GDEs best, especially for in-aquifer ecosystems that have lost connection with the surface. In-aquifer ecosystems do not have all the trophic levels (Gibert and Deharveng, 2002). Biocoenosis may also be applicable for in-aquifer ecosystem because all nutrients are offered locally. Chapter two will explain the functionality of in-aquifer ecosystems.

Studies on Groundwater Dependent Ecosystems need to follow the orthodox ecosystem investigation. The orthodox approach looks at the ecosystem dynamics involving:

- *Cycling of matter for example water (which groundwater forms part), carbon, nitrogen and oxygen*
- *Energy input and outputs – this also considers productivity (amount of organic substance received by an individual or population or ecosystem eachr unit time)*
- *Interspecific and intraspecific competition*
- *Trophic structure*

Figure 1.1 represents a typical ecosystem and may be applicable to GDEs.

As will be discussed in chapter six, not all trophic structures exist in aquifers (Engel *et al.*, 2001; Gibert and Deharveng, 2002; Forti *et al.*, 2002). It however needs to be mentioned that a collapse of any of the trophic levels for the in-aquifer ecosystems will certainly have detrimental effects. In terms of trophic structure and energy inputs the same cannot be said with discharge zone ecosystems, which are characterised by all trophic levels together with solar energy as a key provider of energy.

Based on the above discussion, it is rather premature to talk of GDEs under a biome concept if one considers the biome definition and the work that still needs to be done in South Africa with regards to poorly understood ecosystems like those in aquifers and discharge zones.

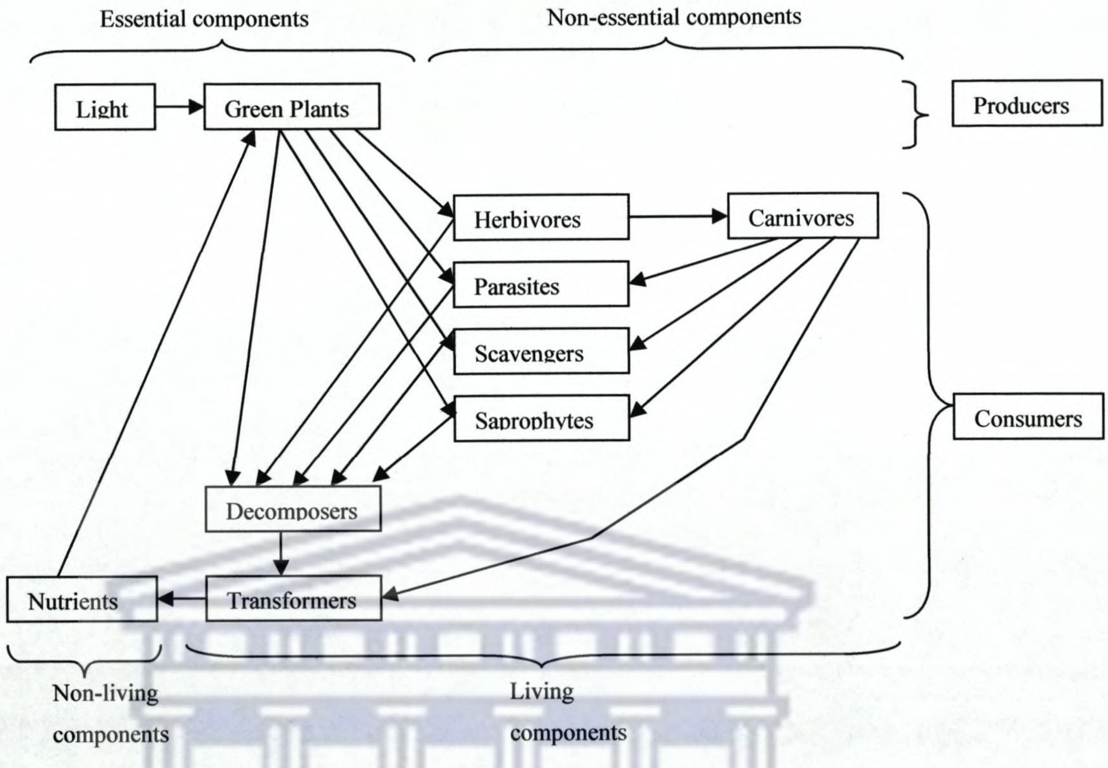


Figure 1.1: Principal steps and components in a self-sufficient ecosystem

1.3.2 The geology of the Table Mountain Group Aquifer

The Table Mountain Group is the lowest succession of quartz arenites (>4000 m thick) in the Cape Fold Belt (CFB) and includes some of the world's thickest and voluminous quartz arenite deposits (Tankaard *et al.* 1982). The rocks of the CFB have an extension of 1300 km along the western and southern tip of the African continent. Some similar rock fragments found in other fragments of Gondwana, such as the Sierra Australes in South America and Ellsworth Mountains in Antarctica (Booth and Shone, 2002). Strata of the CFB are thought to be 8000m thick sequences of clastic sediments of the Early to the Late Palaeozoic (~505 – ~330 Ma) (Tankard *et al.* 1982). The Cape Supergroup overlies the Pre-Cape (pre-Cambrian) rocks. The pre-Cape rocks are prominent in the western part of the CFB, where Cape granite intrusives and the Malmesbury Formation outcrop. The Cango fault just north of Oudtshoorn has exposed the pre-Cape Cango Group. In the area just west of Cape Recife, Port Elizabeth, three faults (namely Laurie's

Bay, Elandsberg and Gamtoos faults) have resulted to the exposure of the pre-Cape Gamtoos Formation (Booth and Shone, 1992).

The tectonic history of the Cape Fold Belt as explained by Hälbich *et al.* (1983) reveals that there are six structural zones in the east-west limb of the belt. Two zones (1 & 2), which are the most northerly zones, are less affected by deformation, while zones 3 to 6 have extensive horizontal shortening of the crust. The Cape Fold Belt and the overlying Karoo Supergroup were deformed by 4 paroxysms (Hälbich *et al.*, 1983) that occurred from the early Permian to the early Mesozoic.

The 1st paroxysm, took place circa 278 ± 2 Ma in the early Permian. This agrees with the estimated age of the upper Witteberg Group, which is Devono-Carboniferous in age, and suggests the middle to late Carboniferous for Dwyka sedimentation. This paroxysm produced the Kango anticlinorium and proto-Swartberg and lasted for 5 to 10 million years.

The 2nd paroxysm, circa 258 ± 2 Ma, resulted in the George anticlinorium with some 70 % horizontal shortening. Proto-Outeniqua and Langeberg ranges formed part of this and shortening decreased towards the west. The deposition of the Beaufort Group was during this time.

The 3rd paroxysm, circa 246 ± 2 Ma there was folding of the Ecca as well as the deposition of sediments from the lower Beaufort and Ecca, which consists of debris from the Cape Supergroup and some pre-Cape basement. Thrust faulting also characterised this period.

The 4th paroxysm, circa 229 ± 5 Ma resulted in listric thrusting and folding of the lower Beaufort and Ecca.

The end of these paroxysms came with the Cretaceous faulting and deposition, about 140 to 70 Ma and is the present erosion profile.

Because of the described orogeny, the rocks of the Cape Supergroup outcrop in two "arms", a southern predominant east-west arm and the western north-northwest arm of about 200 km in extent (Booth and Shone, 2002). Bate and Malan (1992) stated there are along-strike normal faults and to a lesser extent strike slip faults (Booth, *et al.* 1999) that resulted from the Mesozoic break up of Gondwana.

The Cape Supergroup has three lithostratigraphic groups and they are the Table Mountain, Bokkeveld and Witteberg Groups. Each of these groups have their separate subgroups and formations whose nomenclature is different in the East and the Western Cape (SACS, 1980). However the Cedarberg Shale Formation has retained its name in both Western and Eastern Cape.

Table 1.1 gives the lithostratigraphy of the Cape Supergroup. Figure 1.2 shows distribution of the TMG.

Table 1.1: Lithostratigraphy of the Cape Supergroup after SACS (1980), Shone (1983).

Supergroup	Group	Subgroup	Formation	Dominant lithology	Age (Ma)
Cape	Witterberg	Kommadagga	Dirkskraal	Sandstone	~330
			Soutkloof	Shale	
			Swartwaterspoort	Sandstone	
			Miller	Diamictite	360
		Lake Mentz	Waaipoort	Shale	
			Floriskraal	Sandstone/Shale	
			Kweekvlei	Shale	
			Witpoort	Sandstone	~375
			Weltevrede	Shale/Sandstone	
	Bokkeveld	Traka	Sandpoort	Shale	
			Adolphspoort	Siltstone	
			Karies	Shale	
			Boplaas	Sandstone	
			Tra-Tra	Shale	
			Hex River	Sandstone	
			Voorstehoek	Shale	
			Gamka	Sandstone	
			Gydo	Shale	410
	Table Mountain Group		Baviaanskloof	Shale/Sandstone	
			Skurweberg	Sandstone	438
			Goudini	Sandstone	
			Cedarberg	Shale	
			Peninsula	Sandstone	~500
			Sardinia Bay	Sandstone/mudrock	
			Graafwater	Sandstone/siltstone/ Mudstone	
			Piekinierskloof	Coarse conglomerate with sandstone interbeds	

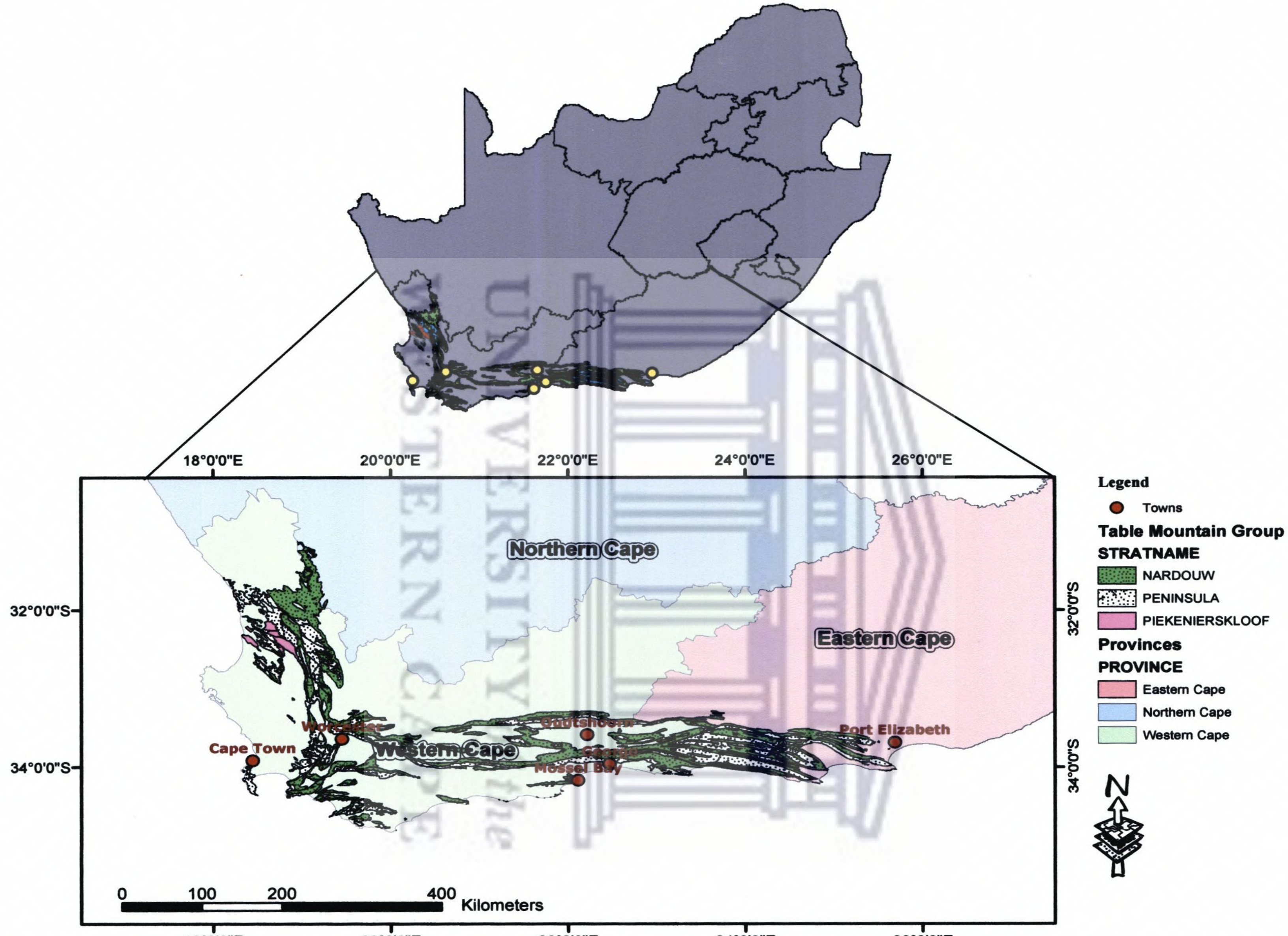


Figure 1.2: The distribution of the Table Mountain Group

Chapter 2

2 Methodology

2.1 Literature survey

The introduction stated that studies about Groundwater Dependent Ecosystems are lacking in the TMG aquifer. Therefore, this thesis mainly uses the existing literature to define and describe the GDEs to meet the first and the second objectives. The literature covering GDEs from other parts of the world is extensive. The synthesis of the literature here tries to identify and describe the GDEs within the TMG context. However, the literature for the type with similar environmental setting (especially geology) to the TMG aquifer is rare.

2.2 Geographical Information Systems

GIS is a system of storing and visualising spatial data. This thesis uses GIS to locate possible GDE areas in a landscape. There are various types of data that have been collected and used during this study and they are:

2.2.1 Maps and Images

Getting and scanning of a 1:50 000 geological map (1969) of the Uniondale area from the Council for Geosciences (Bellville) ensured is availability in digital format. Further, use of a LandSat 7 image of the same area helped identify geological structures.

2.2.1.1 Automation

Georeferencing ensures that existing datasets match and enables further operations like digitising. To achieve automation, ArcInfo uses its menu-based interface

ArcTools and ArcEdit to georeference the scanned maps and to digitise respectively. The digitised geology was saved as a separate coverage.

2.2.2 WR90 Software

The WR90 software was used to get rainfall data from various rainfall station readings around the Uniondale area. The rainfall data used is from 1920 to 1989 and this study then used it for the stream delineation covered later in this chapter. The use of ArcInfo GRID module interpolated the rainfall data.

2.2.3 1:50 000 Shapefiles

1:50 000 contour shapefiles from Surveys and Mapping were converted to coverages and then projected to Universal Transverse Mercator (UTM), which was the projection for all the other coverages. ArcEdit helped with to correct broken contour lines. The coverages were then used in the generation of the Digital Elevation Models.

2.2.4 Digital Elevation Model (DEM)

Digital Elevation Models represent and store three-dimensional elevation data by a regularly spaced grid. DEMs quantify the characteristics of the land surface and are thus are useful in terrain modelling. Isoline data are often readily available from the Department of Land Affairs (Surveys and Mapping). ArcInfo has the built in system that allows for generation of DEMs. ArcInfo GRID module corrects the DEMs to get rid of sinks and peaks. The elevation model can also help calculate slope and aspect. From the DEM the following were achieved:

2.2.4.1 Flow direction

Flow direction is achieved by finding the direction of the steepest descent within the elevation model, such that flow is always from the cell with a higher value to a cell with lower value. Figure 2.1 shows Flow direction.

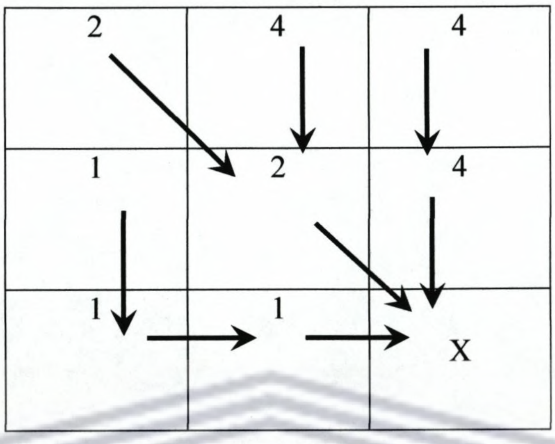


Figure 2.1: Flow direction computed for an elevation grid

2.2.4.2 Flow accumulation

Flow accumulation creates a grid of accumulated flow to each cell. It accumulates all the cells that flow to the down-slope cell, resulting in greater accumulation down-slope. By weighing the flow direction grid with the precipitation grid the result is the Flow accumulation grid.

2.2.4.3 Stream delineation

Application of a threshold value to the flow accumulation grid in ArcInfo results in the stream delineation. This is the most important step before delineating a watershed. Stream order can then be derived from the stream delineation.

2.2.4.4 Stream links

Stream links are stream sections that connect at specific junctions. The junctions are meeting points of two successive links. This is another important step before delineating a watershed because tiny streams link from upslope joining in a downslope direction. The Figure 2.2 shows the stream links.

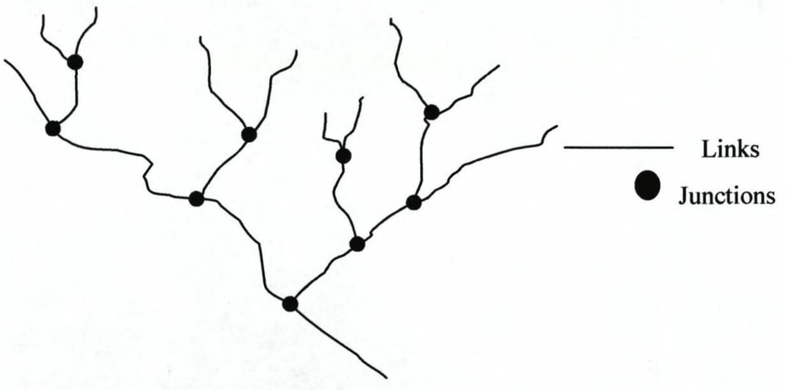


Figure 2.2: A diagram showing the stream links.

2.2.4.5 <u>Watershed delineation</u>

A combination of a flow direction grid with stream links grid results in delineation of a watershed. The lowest stream link in the given watershed forms the pour point (lowest points of the boundary of the watershed). Figure 2.3 shows the watershed.

Figure 2.3: A diagram illustrating a watershed and sub-watersheds.

2.2.4.6 <u>Surface profiles and geological cross-sections</u>

Generation of surface profiles from the DEM was done using ArcPlot in ArcInfo workstation. Completion of geological cross-sections from the surface profiles is possible with ArcEdit as long as the geological information like strike, dip and bed thickness is available.

2.3 Field visits

Some field visits were conducted during the period of this study. The visits were mainly to look at the terrain setting rather than to do hands-on fieldwork. The rationale for not doing that was to try to develop a conceptual understanding for the TMG-type of an environment. The lack of studies related to GDEs within the TMG aquifer also influenced the decision to develop a conceptual approach. Observations in the TMG involved looking mostly at geological structures (faults, joints, fold styles, and bedding planes) because they influence groundwater.

Figure 2.4 gives the summary of the methodology used for this study.

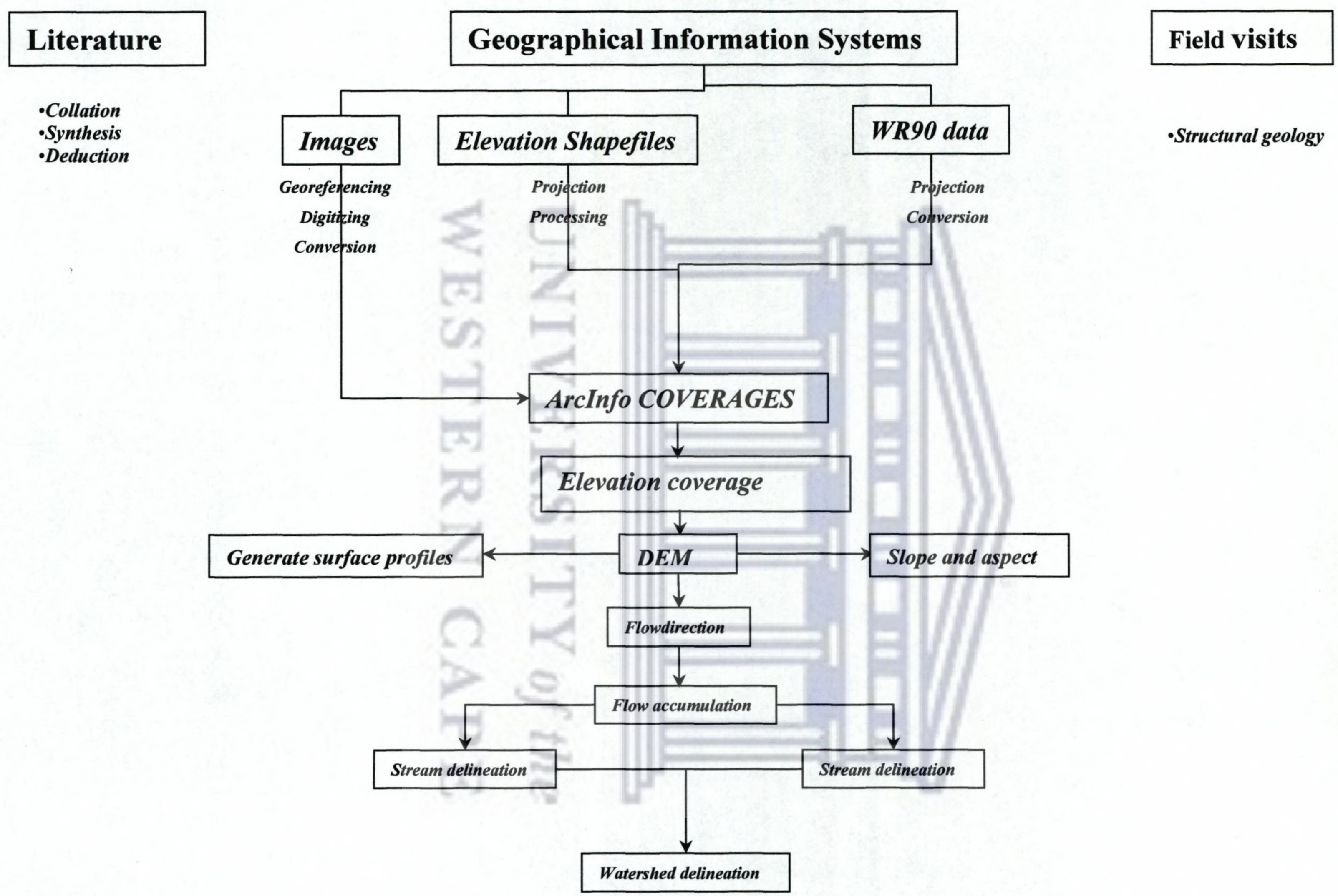


Figure 2.4: The summary of methodology used for this study

Chapter 3

3 Groundwater Dependent Ecosystems

3.1 Introduction

Groundwater dependent ecosystems require groundwater input either as a main or as a surrogate water source to exist. Thus there are various degrees of dependence as summarized in Figure 3.1. This thesis will look at these ecosystems separately.

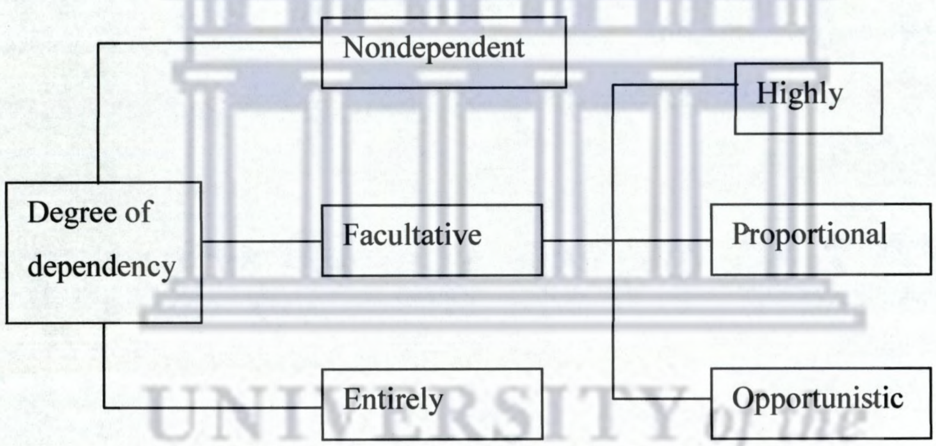


Figure 3.1: The different degrees of groundwater dependency in ecosystems

3.1.1 Nondependent ecosystems

These are the ecosystems that occur mostly in recharge areas and have no connection at all with groundwater. At times dependent ecosystems (fens of the discharge zone) may fall on this category because of peat that may amass at the bottom of the fen. The discussion on discharge zone ecosystems later in this chapter will cover the fens.

3.1.2 Facultative dependency

These are the ecosystems that range from being opportunistic to being highly dependent on groundwater. Ecosystems that are *highly* dependent are those that need large amounts of groundwater for both nutrient and water needs, but are also subject to some proportion of meteoric water and water from overland flow. Most wetlands (fens, marshes, swamps) belong to this category. Ecosystems that are dependent *proportionally* are those that use any moderate amounts of available water, this water may be groundwater or soil moisture. Changes in groundwater storage or flow regime will have a moderate to even high impact on this GDE. An example of this type will be the hyporheic zone, described later in this chapter. Normally it is not easy to distinguish between proportional and opportunistic dependency. *Opportunistic* dependency is when ecosystems use groundwater only as a mere surrogate, but may not alter at all when groundwater level drops.

3.1.3 Entirely dependent ecosystems

Entirely dependent ecosystems are fully dependent on groundwater to exist and the example is the in-aquifer ecosystems. These ecosystems will perish when groundwater levels drop or become polluted. In-aquifer ecosystems section later in this chapter will cover the entirely dependent ecosystems.

3.1.4 Occurrence of GDEs

This is one of the most important topics to cover when dealing with GDEs. This is because most opportunistic GDEs, mainly terrestrial (and to some extent hyporheic and riverbank), are dependent on local water table (shown in Figure 3.2). The in-aquifer, riverbank and hyporheic zone ecosystems are mostly dependent on regional water tables. It is important to separate local and regional processes as it helps decide the scale to study these ecosystems. Scale is also important because both local (climate, land use patterns) and regional processes (faults extending thousands of kilometres and temporally invariant) need to be treated differently.

Figure 3.2 shows the aquifer setting and location of these ecosystems. This thesis has used a Uniondale case study to show how usefulness of GIS in location of GDEs on a landscape.

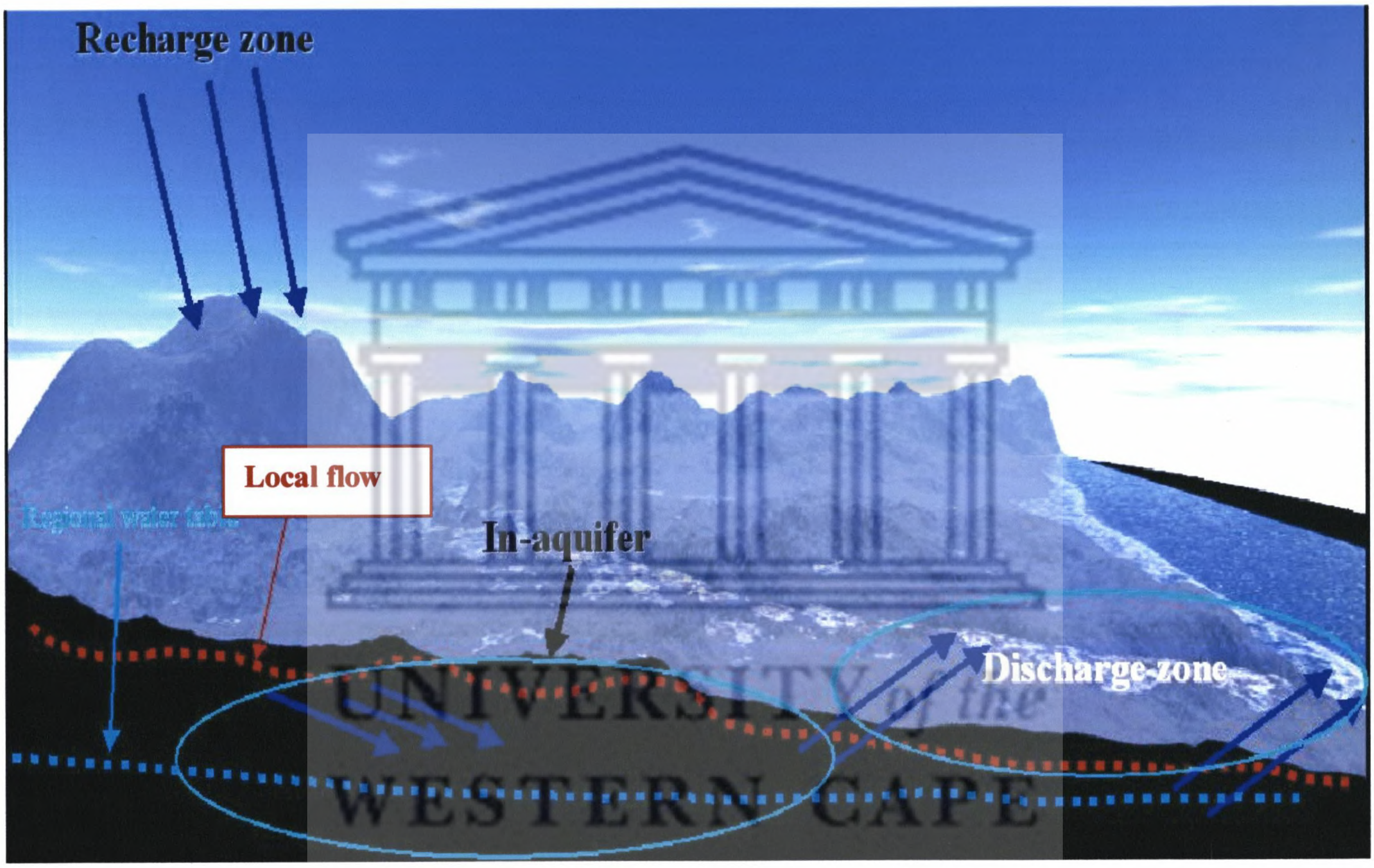


Figure 3.2: The aquifer setting and the three ecosystem zones (recharge, in-aquifer and discharge zone). Digital Elevation Model (DEM) created in ArcGIS 8.3 package and Terragen.

3.1.5 Hydrogeological attributes necessary for GDEs

Zeppel *et al.* (1999); Johnson and Wright (2001) identified four basic groundwater attributes needed by GDEs and these are flow or flux, level, pressure (aquifer and water) and quality. This thesis will refer to these groundwater attributes as hydrogeological attributes. This is because hydrogeology does not only focus on water properties, but also those of the aquifer media. These attributes are:

- Intrinsic properties (porosity, permeability, compressibility, storativity, etc); and
- Flow regime (puts together flux, level and pressure together).

3.1.5.1 Intrinsic properties

Intrinsic properties are important in understanding the interactions between ecosystems and aquifers. These include both the aquifer and liquid media properties.

3.1.5.2 Aquifer properties

Fracture connectivity is the most important property when it comes to fractured rock aquifers like the TMG aquifer. Dijk *et al.* (1999) asserted that fractures are key conduits through which water and contaminants can pass. There are two principal types of fractures namely joints and faults. Joints form during orogenic events as well as by erosion, while faults form during tectonic events. The TMG aquifer has undergone all these phases and therefore presents both the joints and faults. For water to pass through the fractured rock aquifer the fractures must connect. Berkowitz (2002) stated that percolation theory characterises fracture connectivity, because heavily fractured domains do not necessarily mean they are well-connected. The percolation theory leads to the derivation of the power law relationship. The relationship looks at physically observable quantity like hydraulic conductivity in relation to number of fractures (both total and threshold number). Equation 3.1 below shows the relationship.

$$A \propto (N - N_C)^{-X} \tag{3.1}$$

Where A = geometrical or physically observable quantity (such as hydraulic conductivity), X = exponent specific to A, N = total number of fractures in the system, N_c = number of fractures at threshold.

Chapter four will discuss importance of the fracture connectivity.

Porosity is an important intrinsic property and is defined as voids in a rock usually expressed as percentage or by decimal fraction (Freeze and Cherry, 1979; Domenico and Schwartz, 1990; Nonner, 2003).

$$n = \frac{V_v}{V_T} \times 100 \tag{3.2}$$

where n = porosity, V_v volume of the voids (m^3), V_T = total volume (m^3)

The void spaces are important in storing and allowing water to pass within the rock. Freeze and Cherry (1979) identified two types of porosity, primary and secondary porosity. However porosities are different, there is one that requires connections between void spaces (effective porosity) and that which does not require connections (total porosity). For the TMG, the rock porosity will depend on dimensions of opened-up joints, fractures, bedding plane contacts and solution openings as briefly described earlier in the subsection.

Permeability, which is the measure of how permeable the aquifer medium is, is important as it affects groundwater advection rates required by various ecosystems dependent on groundwater. The advection rate promotes water exchange among various portions of the aquifer and thus helps in transport of nutrients, oxygen, etc. Coefficient of permeability (K), which describes the relationship between various components, is expressed as:

$$K = kk_w = \frac{K\rho g}{\mu} \tag{3.3}$$

Where K is the coefficient of permeability (m/day), k is intrinsic permeability (m^2), k_w is water permeability [1/ (m*day)] d^2, ρ = density of the liquid (kg/m^3), g = gravitational force (m/day^2) and μ = dynamic viscosity [kg/ (m*day)]

Compressibility is another important intrinsic property of both liquid and aquifer media and it describes the change in volume induced by material under stress. For unconfined aquifers, both water and porous media help determine compressibility. Compressibility of the water is small, especially in comparison to that of the aquifer because of the overburden that induces vertical stress on top of the aquifer.

3.1.5.3 <u>Liquid properties</u>

The liquid properties include both physical (viscosity, density and temperature) and chemical properties. As for the temperature, it is stable for groundwater (Freeze and Cherry, 1979). The chemistry of groundwater is also important for the health of GDEs. Further, chemistry is important to identity water sources because surface water and groundwater have unique or characteristic isotopic signatures. Identification of water sources is important if the aim is to ascertain groundwater dependence of ecosystems. Chapter four of this thesis will deal with the water source determination methods for plants.

3.1.5.4 <u>Flow regime</u>

This is an important attribute that is required by groundwater dependent ecosystems. Understanding flow regimes helps in understanding local and regional processes, which also includes a separation of confined and unconfined aquifers. Flow regime includes the flow rate or flux, level (for unconfined aquifers) and pressure (for confined aquifers) and their variation over time. Studies (later discussed in this thesis) like that by Schwartz (2003) and that by Moore (1997) have revealed that flow regime is important in ascertaining groundwater advection rates in estuaries. The drop in groundwater flow rate alters the process of advection, which is a dominant transport process for nutrients and pollutants (Domenico and Schwartz, 1990; Berkowitz, 2002). Advection occurs both in the horizontal and vertical directions (Gerber and Boyce, 2001) and both are important for GDEs. Groundwater (water table) level is important because vegetation can only extract water from "reachable" depths. Groundwater pressure as in confined aquifers is important especially for in-aquifer fauna, which have adapted to pressure environments like the *Trogloglanis pattersoni* (blind catfish) that has lost its swim-bladder (Sneegas and Hendrickson, 2002). Ecosystems often exploit local water tables because they are at shallow depths (Ferone and Devito, 2004; Hurst *et al.,* 2004). Regional water tables on the other hand are normally deep and only accessible in zones where the water table intersects topography, resulting in springs (sketched in Figure 3.3). Regional groundwater is accessible in zones such as riverine landscapes, estuaries, and the coastal marshes.

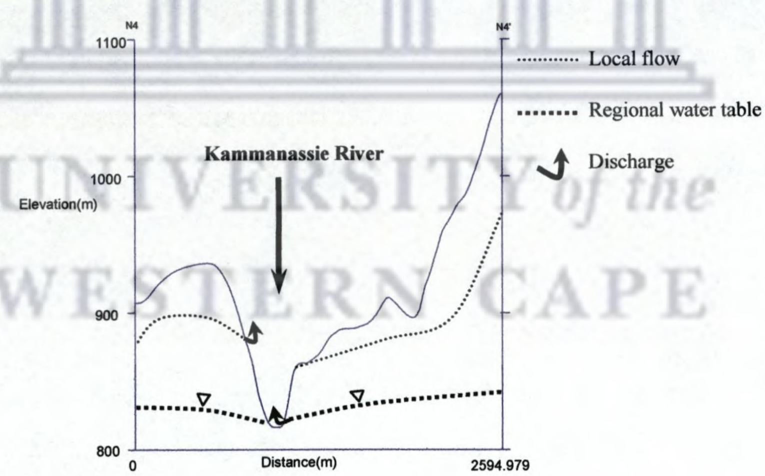


Figure 3.3: A cross-section showing a water table intersecting topography resulting in a spring (vertical exaggeration ×3).

3.2 Discharge zone ecosystems

3.2.1 Introduction

This GDE in the TMG aquifer is important because water tables within the aquifer are thought to be out of reach for plant roots. Even the shallow groundwater instance stated by Rosewarne (2002) at St Francis-on-Sea (on the eastern section of the TMG) had its optimum reached at 90 meters. Secondly, the quartzitic nature of the TMG aquifer prevents deep plant rooting. This has led to a pragmatic belief that within the TMG, most groundwater dependence is at the discharge zone. The discharge zone includes wetlands, springs, estuaries and riparian (baseflow) ecosystems.

3.2.2 Wetland Ecosystems

Wetlands have several definitions, but there is a consensus in all definitions that wetlands are ecosystems that are seasonally waterlogged or permanently under water (Ramsar Convention, 2000; Brown, 2001; EPA, 2002; Nĕgrel *et al.* 2003). Hunt *et al.* (1998) asserted the value of the wetlands can be understood by consideration of their great biodiversity and the role they play in conservation and management of freshwater. Wetlands serve as water-storage areas that reduce flooding by holding excess water and releasing it to streams, and are also favourable sites for migratory birds. Wetlands also play a major role as pollution filters especially in removal of nitrates (Lin *et al.,* 2002; Pauwels and Talbo, 2004). This role of removing organic materials has been exploited and enhanced anthropogenically as a rehabilitation strategy in various places across the globe.

In appreciation of these vast ecosystems a convention was held in Ramsar, Iran in 1971, with 138 states present.

The role of groundwater in wetlands is variable, ranging from those that are isolated from groundwater to those that are groundwater dominated (Carter and Novitzki, 1988). Wise *et al.* (2000) evaluated the hydraulic connectivity between a wetland and groundwater. The approach used pumped out water from the wetland and checking the recovery induced by flow from the underlying aquifer. This approach is called wetland aquifer interaction test (WAIT). Limitations of such a method include the size of the wetland and the ability of wetland species to recover. Other than the limitations, the method confirms the groundwater wetland interaction, when it exists. The most preferred approach often used to prove groundwater input to wetlands is hydrogeochemistry. Hydrogeochemistry helps with identification of isotopes, cation and anion composition in groundwater as well as providing information about weathering processes within the aquifer. Malcolm and Soulsby (2001) used a hydrogeochemical approach to prove spatial variations in groundwater chemistry of an aquifer feeding a dune-wetland complex. The study analyzed the spatial and temporal variations of groundwater chemistry feeding the dune-wetland complex. Spatial variations looked at the various geochemical processes within the different hydrogeological units, while temporal variations looked at seasonal events affecting recharge. The study contributes to an understanding of freshwater requirements for wetlands dependent on groundwater.

There classification of wetlands varies and as a result there are four types of wetlands and they are:

- *Marshes*
- *Swamps*
- *Fens*
- *Bogs*

The Ramsar Convention was amended in 1990 to included coral reefs. This addition emanates from a broad definition of wetland given by the Convention that wetlands are lands with water depth that does not exceed six meters during a low tide.

3.2.2.1 ***Topographic occurrence of wetlands***

Wetlands may occur in relation to topography. Rodhe and Seibert (1999) used topography as a covariate for soil moisture and groundwater levels distributions, which resulted in an aggregation of soil-vegetation-atmosphere-transfer (SVAT) model. Since topography has a major impact on hydrological processes in a catchment, it is widely used in hydrological catchment modelling. The TOPMODEL approach (Rodhe and Seibert, 1999) is normally used to determine wetness distribution patterns. In its approach, the TOPMODEL uses the topographic index to represent topographical heterogeneity in a simple way. To stress topography importance, the following steady state flow equation is often used:

$$RA = T(z_g)b\frac{dh}{ds} \qquad \textbf{(3.4)}$$

Where z_g = depth to groundwater, R = rate of recharge, A = local catchment area, T = transmissivity, b = width of the elementary area that is perpendicular to slope of the groundwater table, dh/ds = slope of the groundwater table.

Equation 3.4 is obtained from conditions of continuity and Darcy's Law. The local groundwater table follows the pattern of surface topography (Freeze and Cherry, 1979), and thus groundwater slope can be estimated from the slope of the ground surface (Rodhe and Seibert 1999). The depth to water table is determined using equation 3.5:

$$z_g = -\frac{R\alpha}{K\tan\beta} + z_0 \qquad \textbf{(3.5)}$$

Where z_g = depth to groundwater, R = rate of recharge, α = A/b (local catchment area per unit contour length), K = Hydraulic conductivity, tanβ = ground surface slope, z_0 = lowest depth below which the ground is no longer permeable.

3.2.2.2 __Wetland types__

Understanding wetland types is of paramount importance as it may be easy to confuse them with springs, for not all wetlands receive groundwater contribution. Carter and Novitzki (1988) noted some variations in wetlands from those that are isolated from groundwater, to those that are groundwater dominated.

3.2.2.3 __Marshes__

Marshes are found at the coastal terrestrial interface and are often referred to as estuarine systems. Most of these systems are exposed to tidal action (tidal marshes) and have 'emergent' herbaceous vegetation (Jeffrey, 1987). Tidal marshes are of biological interest in that they are evidence of convergent evolution, as terrestrial plants have adapted to the marine environment. Plants in these systems are known as halophytes (salt adapted plants) and they contribute detrital particulates to tidal water. There are also non-tidal marshes, what is known as 'freshwater marshes', which receive water from both surface and groundwater.

The schematic diagram (Figure 3.4) shows a cross-section of a typical marsh. The three marsh zones (from lower to transitional) show the topography importance in the marshes. Bockelmann *et al.* (2002) proved there is a correlation between shore height and inundation frequency, as well as variation of species with shore height. Assuming normal conditions for groundwater (no pumping) and surface water inputs, there will be an inverse proportion between salinity and shore height. Freshwater supply may decrease naturally, during drought periods when recharge rates are low (Charette *et al.,* 2003). The focus will be on the groundwater linkage of marshes.

Rama and Moore (1996) used Radium (^{228}Ra, ^{226}Ra, ^{224}Ra and ^{223}Ra) to ascertain groundwater input in a salt marsh. The findings were that the high values of ^{228}Ra and ^{226}Ra suggested another source other than surface thorium decay. The source was found to be groundwater. The activity of Ra measured also matched the groundwater signature. The fluxes suggested there is groundwater advection to the marsh driven by the inland hydraulic head. Such a hydraulic head is important as submarine groundwater discharge brings nutrients to the marshes (Charette *et al.,* 2003). When these nutrients are in excess, they are released into the ocean. Marshes represent a wetland type that is dependent on groundwater.

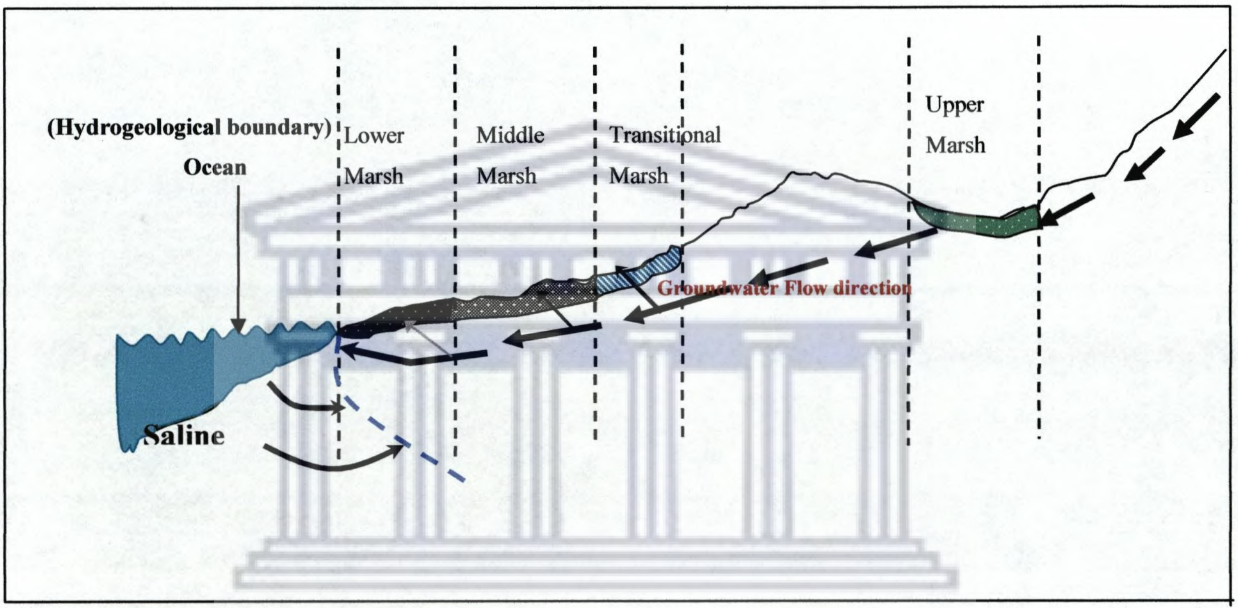


Figure 3.4: Schematic diagram of a typical marsh setting (modified from Jeffrey, 1987).

3.2.2.4 Swamps

Swamps are important for the ecology of the near shore zone in terms of nutrient exchange (because of highly organic soils) and being nursery areas for fish and other organisms (Ridd, 1996). Swamps are similar to the marshes except for the vegetation.

Interaction between swamps and groundwater has recently been appreciated. Raisin *et al.* (1999) presented a case study to show how groundwater influences the water balance and nutrient budget of a swamp. Groundwater regimes, whether deep or shallow, were separated using the chloride method. Like other wetland types, the swamp contributed about 230 kg.y^{-1} of total nitrogen and 24 kg.y^{-1} of total phosphorus. The wetland was found to be a significant discharge area and that groundwater contributes 97% of surface water leaving the system and 50% of total nitrogen and phosphorus.

Ridd and Sam (1996) noted that swamp flora account for the salt concentration reduction of groundwater in sediment layers of mangrove swamps. Variations in salt concentration determine the growth of mangrove species. Ridd and Sam (1996) ascribed three mechanisms that are utilized by swamps for the salt concentration reduction and they are:

- *Low water loss by evapotranspiration reducing the salt concentration.*
- *Transfer of water from the sediment to the overlying water. This may be achieved by water flowing through numerous animal burrows (Ridd, 1996); and*
- *Biological salt reducing mechanisms by some mangrove species include concentration of salts in old leaves, which are later shed.*

3.2.2.5 Fens

Fens are peat-forming wetlands that receive water and nutrients from sources other than precipitation (EPA, 2002; Faubert, 2004). These water sources include both surface water sources from higher altitudes as well as groundwater, hence *minerotrophic*. According to the International Peat Society (IPS), peat is a heterogeneous mixture of more or less decomposed plant material that has accumulated in oxygen deprived waterlogged environment. Faubert (2004) defined peat as an organic deposit that forms because of decomposition rate that is lower than a production rate. The former statement separates coastal wetlands (swamps and marshes) from peatlands (fens and bogs) easy because the former types have equal decomposition and production rates.

Fens have low productivity, but have high species richness that has increased their conservation importance (Schot *et al.,* 2004). There are various definitions for species richness. Southwood (1978) defined species richness as the total number of species found in an area (regional scale). Brown and Lomolino (1994) defined species richness as the number of species present in a given sample (local scale). The two definitions are the same except for the scale. The definition of Brown and Lomolino (1994) is suitable for GDEs, as it is dangerous to extrapolate yet for TMG GDEs because of the poor understanding. Boeye *et al.* (1995) and Schot *et al.* (2004) asserted the nutrient poor alkaline groundwater is necessary to preserve the richness in the fens. The further assertion was the nutrient poor groundwater has enough supply of Ca^{2+} ions that control phosphorus. Jansen *et al.* (2001) confirmed that indeed phosphorus is sorbed by calcium on the exchange complex of the soil under pH 7 conditions, but questions the situation is the same when calcium-rich groundwater is discharged into fens. The pH of groundwater in the TMG is not alkaline, but rather ranges from weakly acidic (5.2) to weakly basic (7.8).

Schot *et al.* (2004) identified the presence of rainwater lenses on top of ***regional*** groundwater that feeds a fen. Freshwater lenses prevent the upwelling of nutrient-supplying groundwater, resulting in reduced fen vegetation. Schot *et al.* (2004) further asserted that anthropogenic activities (especially pumping), topography and permeability may further result in rainwater lenses that behave as local groundwater.
As mentioned earlier fens are peat-forming wetlands, they often change to bogs, another wetland type. Progressive peat accumulation may isolate a fen from its groundwater supply exposing it to rainwater influences (Boeye *et al.,* 1995). Bog species may then invade, the pH of the peat land becomes acidic, in that stage the groundwater discharge to the fen stops. Occurrence of the fens within the TMG needs to be established because in terms of groundwater influence, they are the wetland types that are highly dependent on groundwater.

3.2.2.6 Bogs

Bogs are *ombrotrophic* (nutrient poor because rain is the only source) peatlands that derive their water solely from precipitation (Faubert, 2004).
This wetland type will not be discussed in this section because:

- *Bogs are not discharge zone but rather recharge zone wetland ecosystems (Boeye et al., 1995); and*
- *Bogs are not groundwater dependent, instead, depending on the peat mass that may result in hydraulic head gradient, and they may recharge groundwater (Boeye et al., 1995).*

3.3 Estuarine ecosystems

There are various definitions of an estuary. An estuary refers to a coastal body of water that is in intermittent contact with the open sea and within which sea is measurably diluted with freshwater from land drainage (Cameron and Prichard, 1963; Day, 1981). Dalrymple (1992) defined an estuary as the seaward portion of a drowned valley system, which receives sediment from both fluvial and marine sources and contains faces influenced by tide, wave and fluvial processes.

Estuaries are recognized as one of the most biologically productive ecosystems on Earth and act as ecotones between terrestrial and marine environments (Mulkins *et al.,* 2002). Periodically the estuaries may be freshwater dominated (isostatic) during a flood or may be seawater dominated (eustatic) during a high tide.

3.3.1 Groundwater – estuarine interactions

Estuaries are regarded as areas where groundwater discharge may play a major role. This section will look at various examples where groundwater contributes to the estuarine systems.

Various attempts have been made to assess the groundwater input and role in the estuarine systems. One of these methods is the isotopic analysis, since isotopes act as groundwater signatures. Uranium (^{238}U *and* ^{234}U), Radium (^{228}Ra, ^{226}Ra, ^{224}Ra and ^{223}Ra), ^{18}O, Radon (Rn), ^{3}H, ^{2}H (deuterium) are the most commonly used to identify and quantify groundwater fluxes into these estuarine ecosystems. Schwartz (2003); Hussain *et al.* (1999), identified zone of submarine groundwater discharge by studying excess radon (^{222}Rn) in various estuaries. Studies of this nature are normally related to or driven by increased eutrophication that results in algal blooms in coastal areas. Apart from that disadvantage, groundwater discharge to estuaries and the ocean contributes to the whole nutrient budget of the coastal ecosystems. Normally, use of ^{222}Rn is driven by that it is often 3 to 4 orders higher in groundwater than it is in coastal seawater. This is due to its separation from its parent ^{226}Ra following decay (Hussain *et al.,* 1999). Another advantage of using it in estuaries is because it is not longer-lived like its parent ^{226}Ra and as such can be used to evaluate contribution of groundwater. A study by Moore (1997) correlated presence of Ra isotopes with barium (Ba). The results revealed that high levels of ^{226}Ra and Ba during low river discharge were a result of groundwater input.

Land and Paull (2001) used thermal gradients for estimating advective groundwater rates to the White Oak River in North Carolina. The calculation was based on the thermal structure of shallow estuarine sediments, and results obtained have contributed to an understanding of temporal variations in groundwater flow rates. This is important for groundwater dependent ecosystems because groundwater flux is one of the critical attributes GDEs require.

Bornman *et al.* (2003) showed a South African example of how hydrogeology influences the estuarine plant, *Sarcocornia pillansii*. The study sought to address a question of water source for *S. pillansii*, since there had been no flooding for the past 60 years. The methods involved an analysis of the relationship between vegetation and groundwater, soil/water tissue potential determination, rooting depth and groundwater depth. The study revealed that for *S. pillansii*, there is a negative correlation between its distribution and groundwater depth and electrical conductivity (salinity). Tidal events were found to have an influence on the groundwater water table levels in coastal areas, similar results were found by Li and Barry (2000) and Li *et al.* (2000).

There are not many studies that look at aquifer properties at a boundary between upland and estuaries and between groundwater and surface water within the TMG aquifer. Schultz and Ruppel (2002) tried to find out constraints on hydraulic parameters by looking at the boundary between upland and estuary. The results of the study were that creek sediments had lower hydraulic conductivities than adjacent upland sediments. The likelihood was that such differences were a result of presence of clogging by clay and silt, vegetation cover as well as creek morphology. Further the results showed the groundwater flux, an important attribute for GDEs, is possible to find out.

Now that these interactions are obvious, it then presents an opportunity to find out the estuarine groundwater ecosystems for the TMG.

3.4 Spring ecosystems

These ecosystems are often confused with wetland ecosystems. Firstly, wetlands can be areas of groundwater discharge, but this is not always the case. Secondly, groundwater input in wetlands is variable, ranging from little or no input to total input, whereas in springs it is always one hundred per cent. Studies that have covered spring ecosystems have been done elsewhere in the world (Särkkä *et al.,* 1998; Kemp and Boynton, 2004). Särkkä *et al.* (1998) asserted that springs could be viewed as ecotones between hypogean and epigean environments. Wetzel *et al.* (2000) noted that springs reflect the physical and chemical composition within the aquifer. The reflection is by mineral composition of rock strata as well as the chemicals that percolate to the saturated zone. Unlike surface water, there is normally less variation in groundwater physical and chemical environment; hence faunal endemism is apparent in springs. Faunal orders often associated with springs include Gastropods, Annelids, Isopods, and Amphipods.

Shallow groundwater circulation forms cold springs, while deep flow results in hot springs. The conceptual diagrams (Figure 3.5) below show the aquifer conditions that lead to formation of springs. Thus variations in thermal regimes are important for spring ecosystem. There are no spring ecosystem studies so far in the Table Mountain Group aquifer, except for some observations made in some of the springs. Figure 3.6 below shows the floral existence in Brandvlei hot spring near Worcester. There is a need to study and understand such rare systems in the TMG aquifer. Also, the names of the flora found (no matter how small in extent) in the hot springs need to be recorded. The factors that govern distribution of the different flora in the springs will also need to be established.

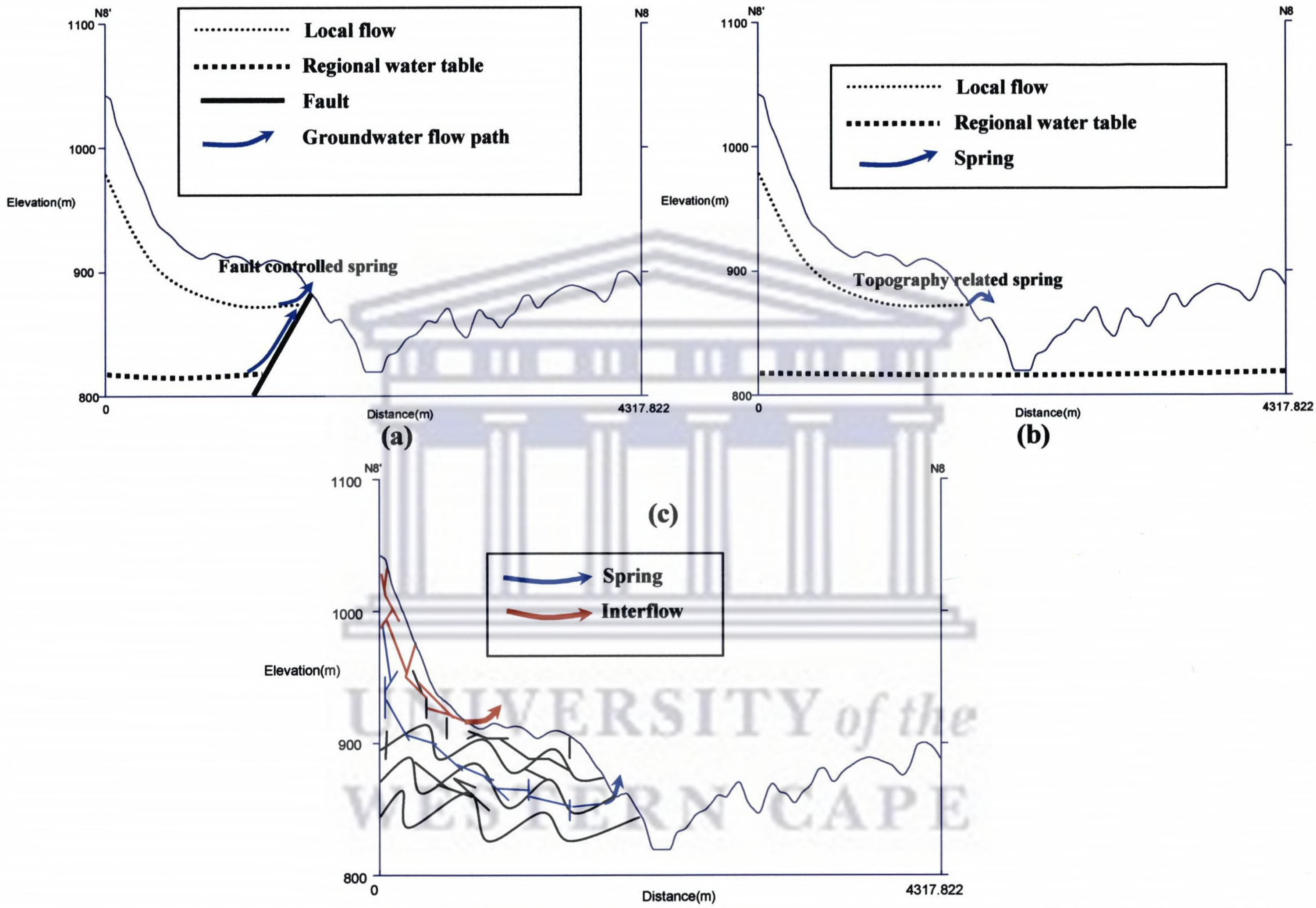


Figure 3.5: The conceptual diagrams showing the conditions of spring formation. Sealed faults block groundwater flow resulting in a spring illustrated by **(a)**. The local water table intersects topography resulting in a spring illustrated by **(b)**. Groundwater flow through a network of connected fractures and bedding planes resulting in a spring as illustrated by **(c)**.

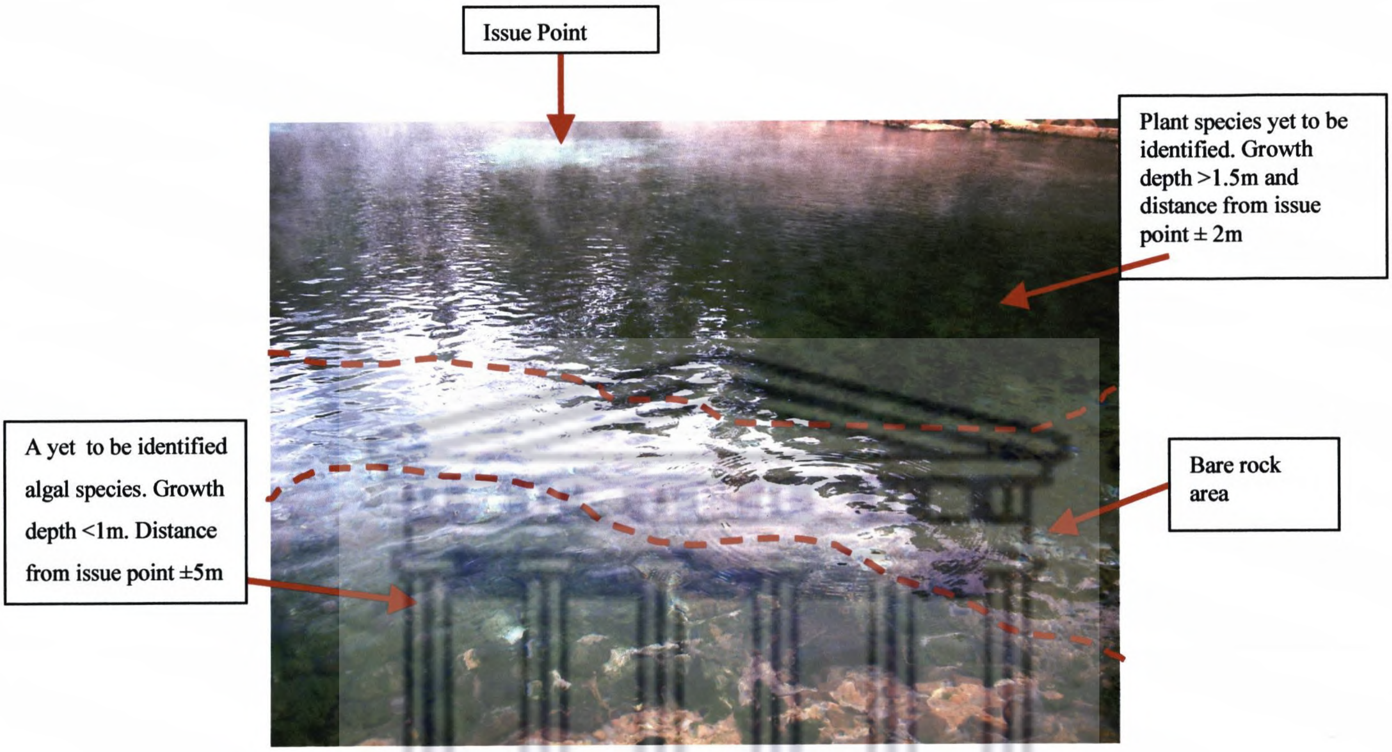


Figure 3.6: The species distribution pattern observed at the Brandvlei hot spring. The red broken line signals demarcation of both species.

3.5 Baseflow ecosystems

Chorley (1973) defined baseflow as the proportion of stream flow that is derived from bank storage and groundwater discharge. Fujieda *et al.* (1997) defined baseflow as the water gained from groundwater, hillslopes and interflow. A similar definition has been given by Xu *et al.* (2000) who referred to baseflow as 'low flow' that is drawn from both interflow and groundwater. Baseflow results from the slow response of long-term changes in the regional aquifers (Freeze and Cherry, 1979) and sometimes signals geochemical variations along the regional flow path (Uliana and Sharp, 2001). The geochemical variations may lead to identification of recharge periods whether recent or old, and finding out hydrochemical facies based on which anion dominates (for example sulfates, bicarbonate and chloride) (Uliana and Sharp, 2001).

Classification of ecosystems that are found in areas where there is baseflow contribution is difficult. This is because there are no studies or identification of these ecosystems within the Table Mountain Group aquifer. Nonetheless, these ecosystems are defined as vegetated floodplains that are found within the river landscape (Bornette *et al.*, 1998; Carlyle and Hill, 2001). However, unlike in wetlands, these ecosystems have their nutrient transport regulated by stream flow from the uplands.

Groundwater is important in these ecosystems because it helps keeping phosphorus. Carlyle and Hill (2001) noted that when groundwater dissolved oxygen was low, soluble reactive phosphorus would be high and conversely.
Iqbal (2001) noted baseflow importance by its contribution of nitrates to the riparian zone and the stream. Nitrogen flux is useful for plant nitrogen needs, revealing the nitrate source (often agricultural activity), as well as recharge direction (whether lateral or vertical) (Iqbal, 2001).

A proper ecosystem approach for baseflow ecosystems needs to look at the energy balance (inputs and outputs), productivity, trophic structure and the fluxes of water. The baseflow ecosystems are hard to distinguish from those of the hyporheic zone. This thesis will separate the two ecosystems and will refer to hyporheic ecosystems as those that form the ecotone between channel or lake water and groundwater, while baseflow will be those on the groundwater side of this ecotone.

3.6 In-aquifer ecosystems

In-aquifer ecosystems are ecosystems that are found beneath the water table. Because of their underground occurrence, they are by far the most fascinating of all ecosystems. Gibert and Deharveng (2002); Reddy (2003) noted the change in the dogmatic view that underground is an inhospitable environment, and further stated the change started at least two ago decades with the realization that groundwater supports animal life. Since then biological studies that have been carried out in groundwater ecology have revealed a high endemism and species richness in aquifers.

The interest mainly emanates from the question about processes involved in adaptation to the stygian realm. Knott and Jasinska (1997) provided three answers to the possible reasons fauna go underground and they are:

1) The stygian realm has abundant space that makes it colonisable,
2) Stygian realm provides a protection against visually hunting predators,
3) The subterranean environment has no prominent climatic variations as there are on the surface. Because of this the stygian realm can offer a cool and moist environment even in periods of hot and dry climate.

However the second reason may not be favourable considering the antagonistic relationships that are characteristic of these ecosystems. Recognition of these relationships in ecology came as early as the turn of the 19^{th} century. Clarke (1956); Remmert (1980) and Odum (1971) have all recognized the existence of these antagonistic relationships and have asserted that they are linked to natural selective responses to balance the predator-prey relationships. This means that with an advance in prey escaping method, there will be an improvement in efficiency of the predator capturing method.

Knott and Jasinska (1997) gave an ecological classification of the cave dwelling fauna based on the adaptation. These classes include:

1) *Trogloxenes* – those that use the cave for sun shelter during the day.
2) *Troglophiles* – Those that use the caves facultatively, doing their breeding on the surface.
3) *Troglobites* - These are the obligatory cave dwellers. These are the fauna that are sensitive with even a single unit change in groundwater.

However, there must be no confusion between the troglofauna (cave dwelling animals) and stygofauna (groundwater inhabitants).

Gibert *et al.* (1994) gave three types of stygofauna and they are:

1) *Stygoxenes* – spend only one part of their life cycle in cave waters, otherwise the rest of the cycle is in the epigean (biological domain at/or above the earth's surface) realm
2) *Stygophiles* – these show no morphology (troglomorphies) that is characteristic of stygobites. There are three types of stygophiles, *occasional hyporheos* (larvae of some aquatic insects that spend some time in water), *amphibites* (requiring both surface water and groundwater) and *permanent hyporheos* (all life stages in the groundwater or benthic habitats),
3) *Stygobites* – obligate aquatic species with morphological characteristics that show subterranean adaptations. These are often found either in alluvial groundwater *(obligate hypogean forms)* or in deep groundwater.

Troglobitic morphological characteristics, which also occur in stygobites, include reduction or lack of eyes, lack of skin pigmentation, longer appendages and sensory structures (Knott and Jasinska, 1997). Wetzel *et al.* (2000) identified the same morphological characteristics as above, but added that troglobites have elongated bodies. Stygobites on the other hand are small, suitable for interstitial spaces (Gibert *et al.,* 1994). Sneegas and Hendrickson (2002) differ with the fact that bodies are elongated and have noticed shortening during their investigation on the blind catfish. Sneegas and Hendrickson (2002); Gibert and Deharveng (1994) looked at the physiology of species as well, which included prolonged developmental stages, longer life spans and the low reproductive rates. From the mentioned characteristics, conclusion can be that troglobites and stygobites have adapted an adversity-type strategy, formerly known as the K-strategy. Krebs (1997) assigned K-strategists to type I and type II survivorship curves as shown in Figure 3.7. Type I curve reflects low mortality rate at young age as well as the middle-age, but high mortality rate at old age. Type II curve illustrates a fairly even mortality rate throughout the life span. Table 3.1 summarises the K-selective strategy.

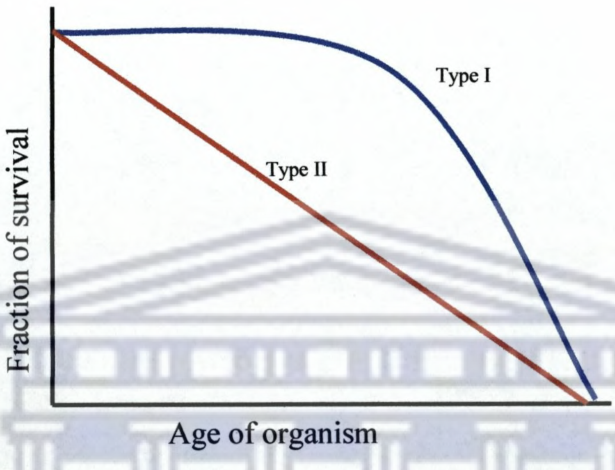


Figure 3.7: The survivorship curves associated for *K* selection, in this case troglobites.

There is currently no certainty about the exact age of these ecosystems, but since evolutionary paths are generally long (often millions of years) it is thought that they have come to existence a long time before present. Wetzel *et al.,* 2000; Knott and Jasinska (1997) share a similar view that the in-aquifer biota evolved from once surface individuals, of which most are now extinct. Schlegel and Bulog (1997) did a study that added to the understanding of how subterranean fauna evolve. The study contributed to an understanding that:

- *Species colonise hypogean life over time*
- *Species may be relicts of older forms before some isolation (after passing a bottleneck); and that*
- *Physiological experiments are important in determining the type of evolution, whether regressive or progressive evolution.*

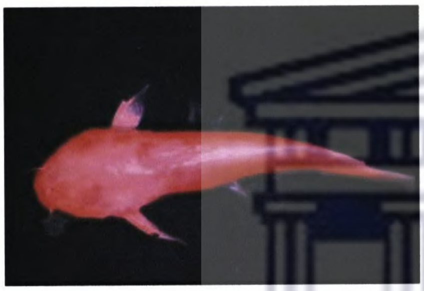
Table 3.1: The K selection (modified from Remmert, 1980)

Parameter	*K* selection
Climate	Little to no fluctuation, hence predictable
Mortality	Depends on density and more selective for example mostly the old individuals
Intraspecific and Interspecific competition	Normally vigorous
Selection favors	1. Slow development 2. Greater competitive ability 3. Lower threshold of resources 4. Delayed reproduction 5. Greater weight 6. Repeated reproduction
Life span	Long, more than a year

Wetzel *et al.* (2000) estimated that most of these fauna have not been present on the surface since the Mesozoic (248 – 65Ma). But Knott and Jasinska (1997) further added that some of these ecosystems may also reflect surface changes that have taken place because of the Pleistocene glaciation/interglacial cycles about 2 million years ago. Schlegel and Bulog (1997) have also shared the same view that troglobitic life form evolved since the Pleistocene glacial and interglacial periods. Some major animal phyla showing troglobitic characteristics are members of Annelida (segmented) worms, Chordata (especially bony fishes), Platyhelminthes (flatworms), Arthropoda (crustaceans), Amphibia (especially salamanders and frogs), Insecta and Acarina. A study carried out by Sayomi Tasaki at the University of the North-West has discovered the existence of stygobtic amphipods in the karstic Sterkfontein caves in South Africa. However the area where the stygobitic amphipods have been discovered is far-out of the TMG aquifer. Figures 3.8 to 3.12 show some images of different aquifer fauna.

Members of the Phylum Chordata that have evolved to be stygobitic with Toothless Blind catfish and Wide mouth Blind catfish given as examples. All photos obtained from the Edward Aquifer Research and Data Centre (EARDC) (http://www.edwardsaquifer.net/species.html).

Trogloglanis pattersoni



Satan eurystomus

Figure 3.8 and Figure 3.9: Stygobitic fish (Gulf of Mexico)

Members of the Phylum Arthropoda include the Dryopid beetle and all cave amphipods and copepods.

Stygoparnus comalensisis (Dryopid beetle)

Stygobromus pecki (amphipod)

Figure 3.10 and Figure 3.11: The stygobitic beetle (left) and stygobitic amphipod (right) (Gulf of Mexico).

Members of the phylum Amphibia are the ones that dominate the caverns around the world. There are also variations in them and because they are vast they have contributed to understanding of origins of troglobites.

Figure 3.12: The Texas blind salamander *Typhlomolge rathbuni* (EARDC).

3.6.1 Subterranean biodiversity

This subtopic serves to address one of the most common questions that surround the biodiversity of the subterranean realm. Brewer (1979) defined biodiversity as the variety of both faunal and floral species in an ecosystem, which also includes their relative abundance. Groundwater communities are in isolation from one another (Gibert and Deharveng, 1994) and as a result the scales of diversity that one can look at these ecosystems are both *alpha* and *beta* diversities described in Brown and Lomolino (1994). Botosaneanu (1986) estimated the global biodiversity in subterranean ecosystems to be just below 7000. Table 3.2 shows the stygofauna recorded in Botosaneanu (1986). There have been assertions that estimations by Botosaneanu (1986) may not be globally reflective because most of the areas in the world were under sampled. So Culver and Holsinger (1992) proposed a different figure ranging from 50 000 to as high as 100 000 obligate species. The same assertion has been shared by Gibert and Deharveng (2002). Novarino *et al.* (1997) showed that it is not only metazoans that are found in aquifers, but also members of the phylum Protista. The members of Protista include amoebae, single and dinoflagellates. Members of the phylum Protista are small and are the most possible members to occur in the TMG aquifer. This is because of the nature of the fractured quartzitic TMG aquifer. Culver and Sket (2000) compiled hotspots for subterranean biodiversity but it excluded Africa, Asia and South America.

Table 3.2: The summary of stygofauna in relation to world's total fauna (Botosaneanu, 1986).

Aquatic fauna	Stygofauna mundi	World fauna
Protozoa	1015	30800
Minor invert. phyla	481	9300
Porifera	15	5000
Cnidaria, Ctenophora	24	9000
Plathelminthes	199	12200
Nematoda	322	12000
Bryozoa	3	4000
Brachiopoda	2	350
Mollusca	456	50000
Annelida	510	12000
Crustacea:	2870	39000
Cladocera	5	
Ostracoda	309	
Copepoda	997	
Remipedia	5	
Mystacocarida	13	
Syncarida	154	
Mysidacea	22	
Mictacea	1	
Isopoda	569	
Amphipoda	664	
Thermosbaenacea	10	
Decapoda	121	
Insecta	24	751000
Arachnida	590	63000
Achinoderma	5	6100
Urochordata	12	1250
Cephalochordata	0	23
Vertebrata:	106	
Agnatha	0	63
Chrondrichtyes	0	843
Osteichthyes	92	18150
Amphibia	14	4184
Reptilia		6300
Aves		9040
Mammalia		4000
Total	6634	1047603

3.6.2 Evolution of subterranean fauna: possible existence in the TMG aquifer?

Evolution of in-aquifer ecosystems is a widely debated and heavily speculated subject. Indeed, how fauna can suddenly desert the surface for a dark, food depleted and spatially constrained realm is intriguing. This subsection is included to assess whether there is a likelihood of stygofauna in the TMG aquifer. So far classification of the species living in the subterranean environment has been suggested by Botosaneanu (1986). Figure 3.13 shows the classification by Botosaneanu (1986).

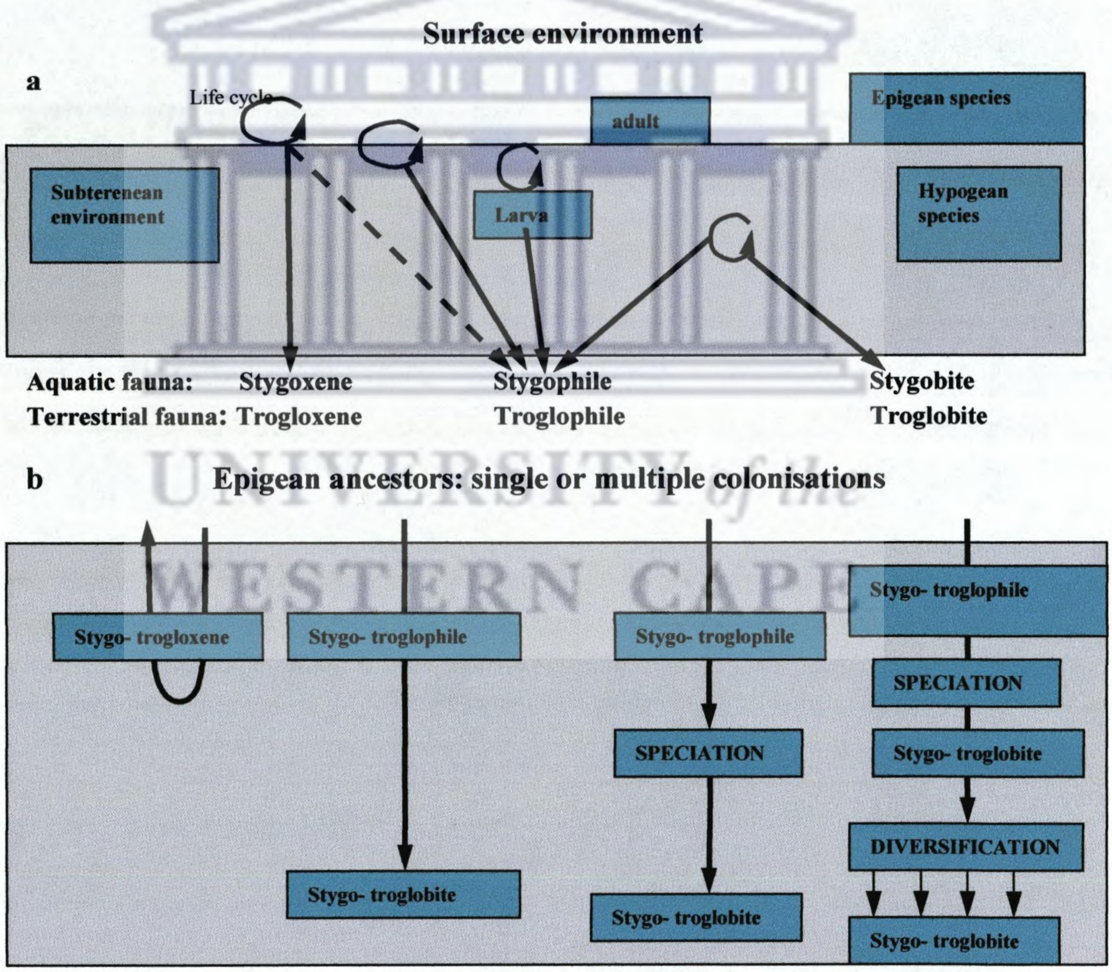


Figure 3.13: Ecological classification of species living in the subterranean ecosystems (Botosaneanu, 1986).

The classification puts the three types (stygo-/trogloxene, stygo-/troglophile and stygo-/troglobite) of subterranean fauna as well as a colonisation model from surface to subterranean environment. This subsection will first look at the types of colonisation models. Evolution theories have been covered as early as the 18^{th} century. Lamarck's model argued that individuals evolve because of environmental influences and will pass those changes to offspring. The model argued for retention of acquired characteristics, which are then passed to offspring. Wallace and Darwin's models in the late 19^{th} century have challenged such arguments independently and both argued that natural selection of advantageous inherited differences is how species evolve. According to the Darwinian model, there is a relationship between physical features of species and their physical environment. Wallace and Darwin's models suggest that species did not arise independently, but that they are descendents of other species.

Knott and Jasinska (1997) gave six reasons for subterranean evolution as follows:

- *Inefficiency in escape theory – which means that species with poor eyes will remain trapped once fallen into a cave and will be doomed to subterranean life.*
- *Direct selection – this agrees with the Lamarckian model in stating that having eyes in the dark environment instead of extrasensory organs is not an option since injury possibilities are high*
- *Energy economy – use of energy for non-adaptive structures is a waste.*
- *Material compensation – there is nutrient partitioning, that is, allocation is according to importance of each individual body part.*
- *Pleiotropic effects – pleiotropy is the ability of a gene to give rise to different structures simultaneously (for example loss of pigment, eye reduction or loss, etc.)*
- *Mutations resulting in random genetic drift, for example mutation may affect the whole gene pool, resulting in their removal from the population by selection.*

There are several colonization models given by several ecologists working on groundwater ecology.

The 'two-step' model shows transition via surface waters and transition via littoral interstitial waters and is illustrated in Figure 3.14. According to this model there are two types of stygobites:

- *limnicoid stygobites – those that have marine ancestors that lived in freshwater before colonising the groundwater environment; and*
- *thalassoid stygobites – those that have colonised groundwater from marine environment via littoral interstitial zone during a marine regression* (Coineau and Boutin, 1992).

The 'two-step' model suggests there are two transitions that groundwater colonising species had to undergo and they are ecological and geographic transitions.

The 'adaptive zone model' suggested by Stoch (1995) separates the colonisation process from speciation process. It explains subterranean colonisation by two methods and they are:

- *Colonisation – speciation-adaptive radiation (niche differentiation); and*
- *Multiple colonisation – speciation (with no radiation occurring)*

Both active and passive colonisation mechanisms are allowed by the 'adaptive zone' model, which is illustrated in Figure 3.15.

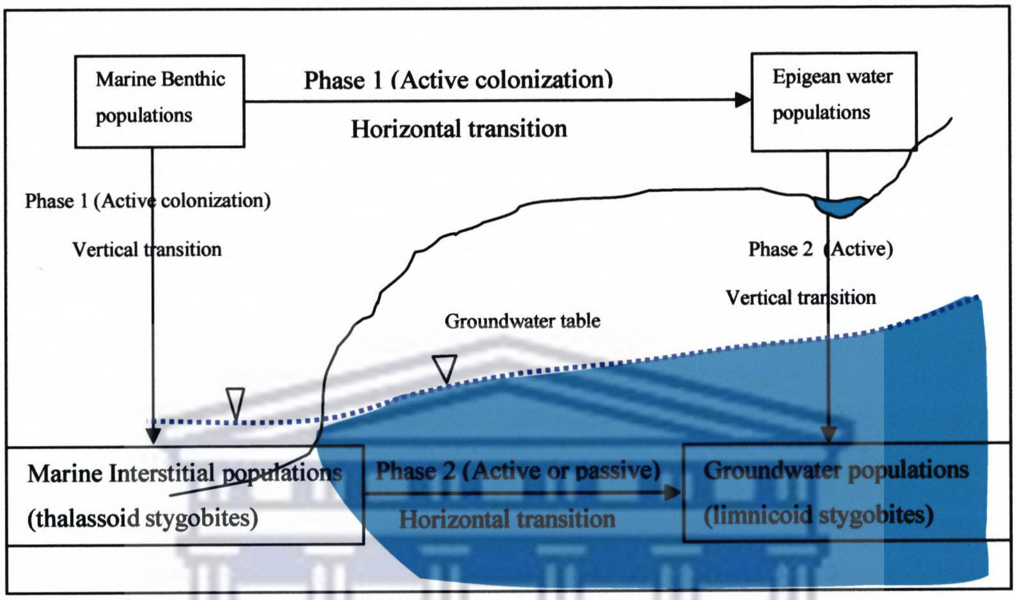


Figure 3.14: The 'two-step model' [adapted from Coineau and Boutin, 1992].

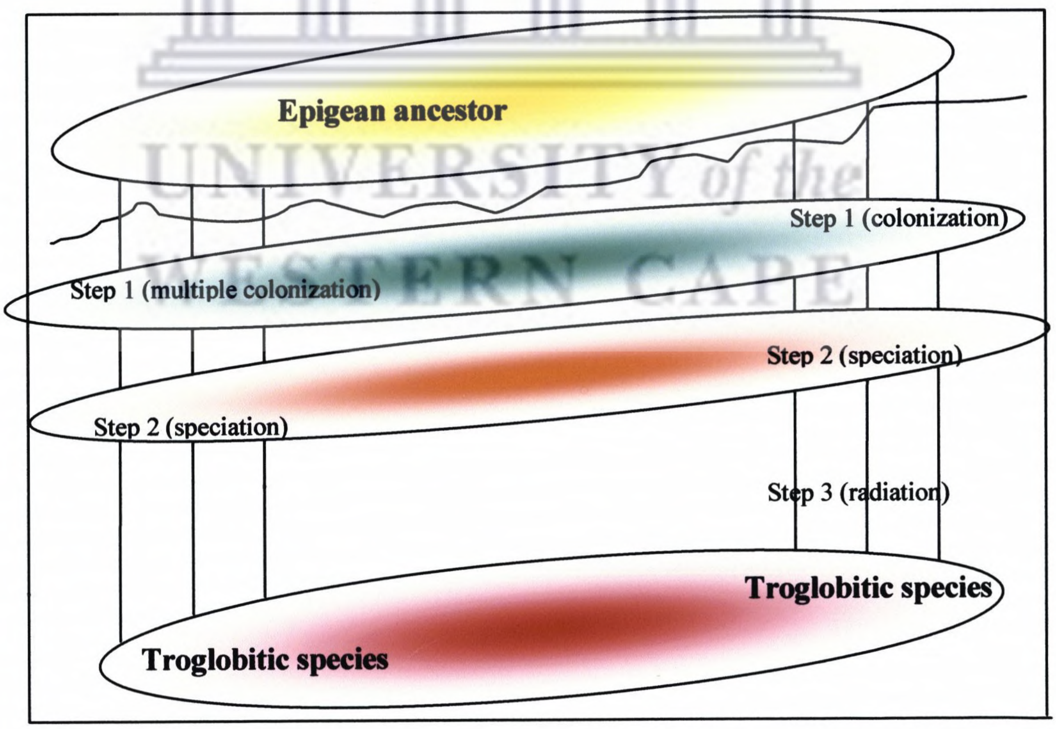


Figure 3.15: The 'adaptive zone models' [modified from Stoch (1995)].

Most of the work done about groundwater ecosystems has been in karstic environments. In karstic environments groundwater dissolves the carbonates to form caverns. It is in these caverns that most groundwater fauna exist. The TMG aquifer is a mainly quartzitic and there is no known existence of caverns. Instead field observations and borehole data show the aquifer is made up of a series of joints and big fractures. Two Figures 3.16 and 3.17 show both the joints and macro-fractures respectively.

Figure 3.16: Nardouw Subgroup outcrop showing open vertical joints at Uniondale Poort.

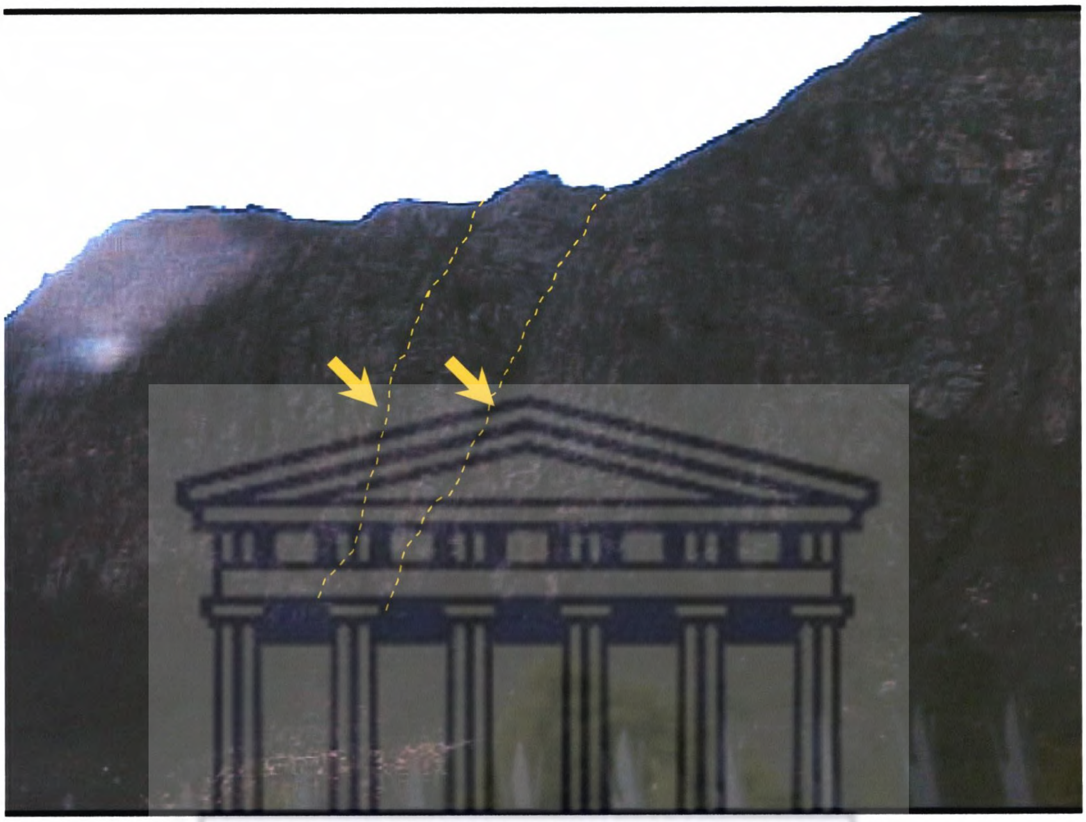


Figure 3.17: Macro-fractures (indicated with red arrows) in the Peninsula Formation near Franschoek.

Though caverns are absent, that should not rule out the possibility of existence of stygofauna. Currently there is no knowledge whether the fractures remain open with depth. It is thought the fractures narrow considerably with depth because of pressure imposed by overburden.

The valleys that drain the TMG are incised mainly on joints and cleavage as illustrated by a cross-section (Figure 3.18). In Figure 3.18 the Kammanassie River is exploiting the joints of the upper Nardouw (Baviaanskloof Formation). The cross-cutting fractures may offer refuge for invading epigean species. The existence of stygofauna in the TMG may be a result of epigean species that invaded the upper fractures. The sea level drop in the late Miocene (Partridge and Maud, 2000) may have isolated such species, thus forming stygofauna. This would agree with the age of nine to five million years ago given by Leys *et al.* (2003), which is thought to be the age of stygofauna emergence.

The other possibility for stygofauna may be a result of downward migration from the stream as proposed by the 'two-step' model described earlier in this section.

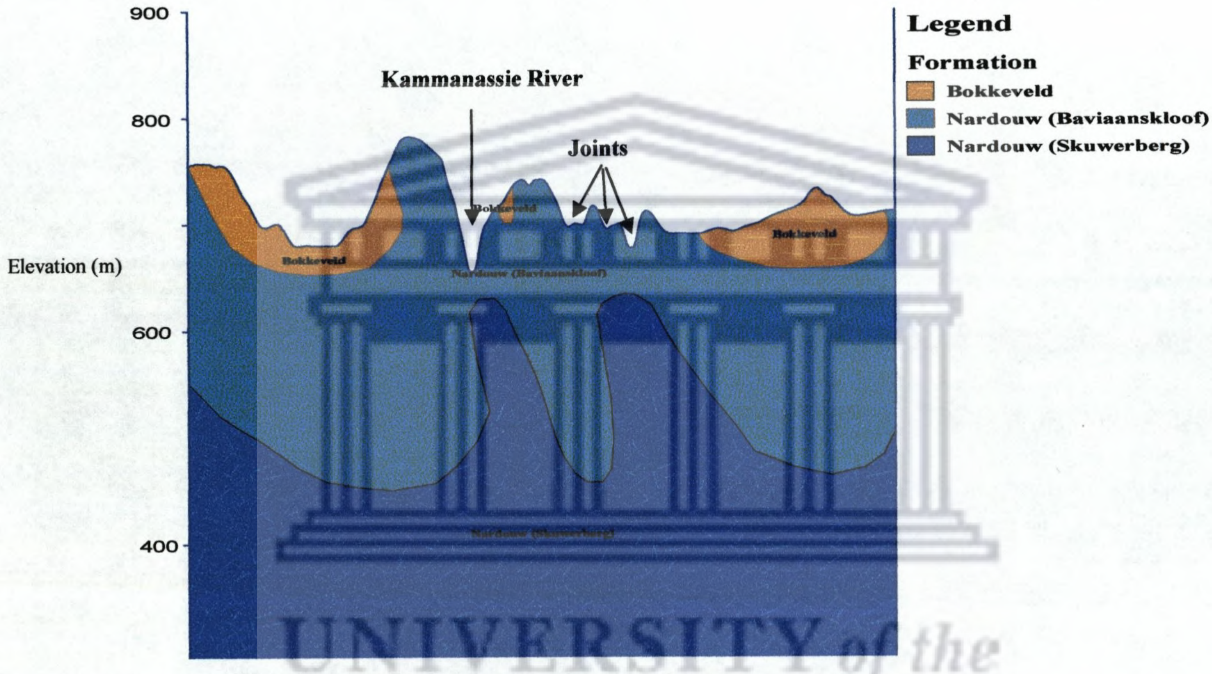


Figure 3.18: A cross-section for an area near Uniondale (generated using ArcInfo) showing the location of the Kammanassie River.

3.6.2.1 Functional patterns of biodiversity

Gibert and Deharveng (2002) described the importance of functional aspects of biodiversity. This approach often gives information about how groups of species with similar ecological roles respond to the similar biogeochemical factors. These patterns look at the trophic levels that exist in subterranean habitats. Figure 3.18 shows the four trophic levels of a typical ecosystem.

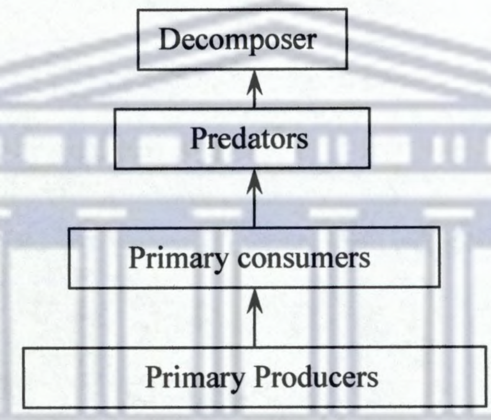


Figure 3.18: The basic trophic levels that are normally found in a typical ecosystem.

Gibert and Deharveng (2002) mentioned that only two of the trophic levels exist in subterranean ecosystems and they are the predators and decomposers.

Engel *et al.* (2001) did an ecological assessment as well as the analysis of geological significance of microbial communities from Cesspool cave in Virginia, USA. The study revealed that existing sulphur (whether from abiotic or microbial sulfate reduction) could be used by sulphur oxidizing microbes as an energy source, resulting in production of sulphuric acid. Sulphuric acid dissolves carbonate rocks like karst, thus forming or extending caverns. The study discovered that these chemoautotrophic microbes could produce enough energy as primary producers in the complex cave ecosystem. Forti *et al.* (2002) did a similar study in Movile and Fresassi caves and discovered that hydrogen sulphide (H_2S) and methane (CH_4) oxidation was an important energy source for fauna occupying caves.

3.7 Recharge zone ecosystems

These are the ecosystems that are found in the recharge zone and thus are not necessarily groundwater dependent. Instead, they are important for taking up a good portion of the water before it reaches the groundwater table. This is by diffuse discharge (root uptake) that impacts the net recharge. As mentioned earlier in the discharge zone ecosystems, fens (groundwater dependent) may accumulate peat (Faure, 2002) and form bogs (not groundwater dependent).

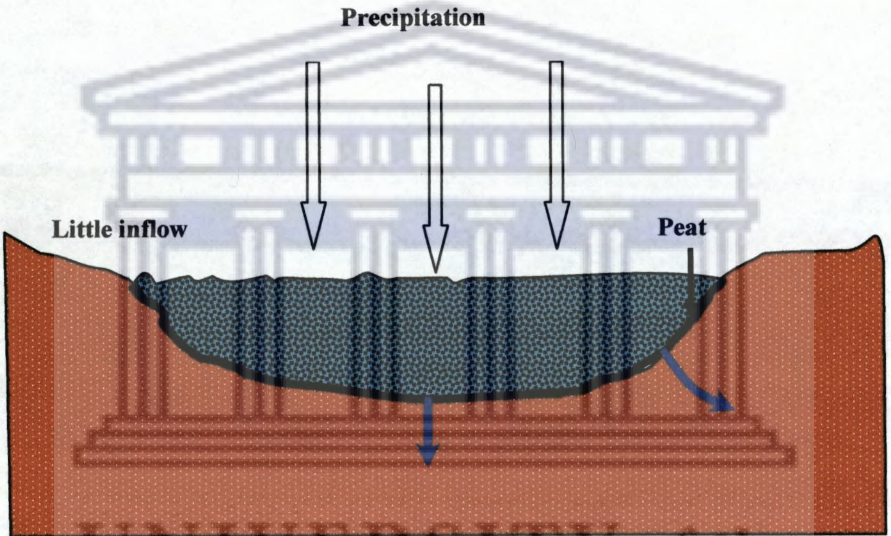


Figure 3.19A typical bog with its water source predominantly meteoric and with no influence whatsoever from groundwater.

Temporarily, fens become bogs (illustrated by figure 3.19) by accumulation of peat, which blocks the groundwater inflow (Faure, 2004). Species such as *Sphagnum* may invade and create acidic conditions thus forming a bog. During a rainy season the peat may splinter because of the water mass and thus the water will infiltrate and recharge groundwater (Weller, 1981).

3.8 The hyporheic zone

A notable amount of work worldwide has been done on this zone (Edwardson *et al.*, 2003; Boulton *et al.*, 1998; Hinkle *et al.*, 2001). In this section, the discussion will not dwell much on the hydrological factors (especially physical) so that it stays in line with the objectives of the thesis. Discussion of the hyporheic zones is covered because in these zones there is groundwater contribution. Therefore identifying these zones is a step towards establishing GDEs existence in the TMG. However these hydrological factors are the core in the hydrological studies that entirely focus on the groundwater-surface water interactions. Thus the focus of this section is to touch on these physical and chemical properties in trying to explain the biological component in this rather complex zone. The ecosystem approach in this zone should seek to explain the community structure and the interactions of the organisms within the hyporheic zone.

There are various definitions for the hyporheic zone. But here it is defined as the less conductive layer beneath or adjacent to a stream or lake where groundwater and surface water interact, resulting in ecotone conditions. Such conditions are influenced by factors such as bed thickness and topography, streambed permeability and porosity as well as longitudinal shape (convex or concave) of the stream. Figure 3.20 below shows the hyporheic zone.

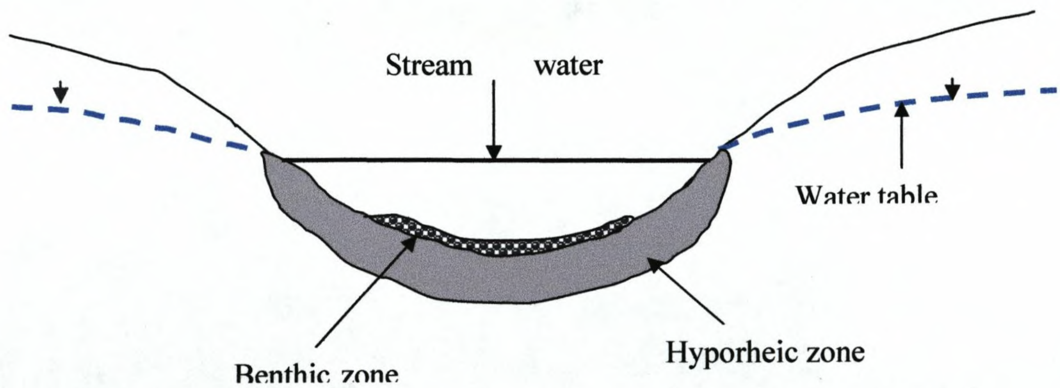


Figure 3.20: The hyporheic zone

Because this zone is an ecotone it means that it has a complicated structure. Ecotones exist because of mixed habitat conditions, obtaining uniqueness from either of the two habitats that they border (Odum, 1996).

Boulton *et al.* (1998) discussed the functional significance of the hyporheic zone to streams and noted the following:

- *The activity of the hyporheic zone (nutrient transformations, respiration rates) - upwelling groundwater supplies the stream organisms with nutrients, while downwelling water provides dissolved oxygen (DO) and organic matter to microbes and invertebrates in the hyporheic zone; and*
- *The connectivity of the hyporheic zone – hydrological exchange.*

The connectivity is important and is the degree to which the landscape can help with or block movement of organisms among resource patches (Pringle, 2003). It is this connectivity that has been used to explain the three spatial dimensions of the river landscape (Ward and Stanford, 1989a). Interactive pathways of rivers are said to be governed by a single temporal dimension (time-scales) and three spatial dimensions. These spatial dimensions are:

- *Longitudinal – where the headwaters come to connect with estuaries*

- *Lateral – where the river interacts with the riparian zone or floodplain;* and
- *Vertical – interaction of river and groundwater.*

Another important hyporheic zone role in stream biology is that it offers refuge to surface water benthos during sporadic pollution and high flows (Nelson and Roline, 1999). This refuge concept was tested and proved by Fowler and Death (2001). This zone also plays a critical role in regulating metal fluxes between surface water and groundwater (Gibert *et al.,* 1994; Fowler and Death, 2001).

Boulton *et al.* (1998) further addressed the question of scale at which hyporheic zone studies can be conducted and identified three scales, and they are:

- *Sediment scale – looking at factors such as particle size, interstitial flow pathways and microbial activity,*
- *Reach scale – looking at flow paths and hydrological retention;* and
- *Catchment scale – hyporheic corridor.*

Scale is important because it provides a framework for organizing a wealth of information on a subject as well as assessing the hierarchy of processes.

Understanding the dynamics within this zone is important as this helps create a picture of what is happening in this complicated ecosystem. These dynamics include finding out the zone (depth) of mixing and the proportions of groundwater and surface water in the 'mix'. They also include hydrochemistry, nutrient content, and faunal and floral distributions. Understanding of factors such as recharge, discharge and flow-through, which govern the interactions, is also of importance.

Locating the zone of mixing, the hyporheic zone, is not static and varies spatially and temporally (EPA, 2002; Fraser *et al.*, 1996; Edwardson *et al.,* 2003; Fox and Durnford, 2003). Lambs (2004) discovered that groundwater and surface water mixing is localized along the riverbanks and beneath the river flow especially in the river confluences, and asserted that groundwater-surface water boundary is not fixed.

It needs to be stated that approximating this boundary based on epigean and hypogean species distributions may be inaccurate as the distinction between the hyporheic zone species and the true groundwater species may be unclear.

Some studies like that by Fraser *et al.* (1996) have included hydrogeological measurements (water level, hydraulic head and velocity of flow) to quantify the boundary between surface water and groundwater. The boundary of interaction was discovered to coincide with the seasonal discharge patterns and to be regulated by the upward force of baseflow and the downward force of advective surface water.

Lambs (2000) asserted the fluvial plain is a point where complex interactions occur between groundwater and surface water. Rhoads and Kenworthy (1995); as well as Lambs (2003) noted the confluences of rivers are often the zone of mixing because of complex hydrodynamic conditions associated with confluences. Rhoads and Kenworthy (1995) asserted the hydrodynamic features associated with confluences include:

1) *A zone of stagnation (where groundwater discharge occurs most) at the junction of the two streams*
2) *The shear layer between merging flows with helical cells on either side of the shear layer (but two helical cells are common with symmetrical confluences; and*
3) *Separation of flow from its original channel immediately downstream from the confluence*

Rhoads and Kenworthy (1995) further noted the angle of merging flows (whether symmetrical or asymmetrical) is important in identifying water sources found in the confluence.

The intensity of these hydrodynamic features is a function of confluence symmetry as well as momentum flux ratio of the two combining flows.

Franken *et al.* (2001) conducted a study on the biological, chemical and physical characteristics of both the downwelling and the upwelling zones of the hyporheic zone. These zones are at the reach scale that was identified by Boulton *et al.* (1998).

The findings of the study showed pH, dissolved oxygen (DO), temperature and nitrate to decrease significantly at the upwelling zone. This can be attributed to the respiration occurring in the riffle side of the hyporheic zone. This respiration is because of the existence of microbial biofilms (immobilized biomass of cells at a substratum embedded in an organic polymer matrix of microbial origin). These biofilms are also responsible for the high protein content in the hyporheic zone (Spáčil and Rulík, 1998). This microbial activity combined with the physical and chemical reactions control the storage, retention, transformation and cycling of matter, which reveals there is intense heterotrophic activity in this zone. Sediment fauna and plant tissue are also the sources of organic material, which occurs as either particulate organic matter (POM) (decaying organic particles) or as dissolved organic matter (DOM) (Franken *et al.,* 2001).

Unlike Franken *et al.* (2001), Edwardson *et al.* (2003) found the nitrate and ammonium to be higher in the hyporheic zone than in surface water and hence the source, but had similar findings with the CO_2 concentration in the Arctic region of Alaska. Fraser *et al.* (1996) also identified the groundwater that feeds the hyporheic zone had higher alkalinity and conductivity compared to surface waters. Lefont and Malard (2001) assessed the composition and distribution of the oligochaete communities in the Roseg River, southeastern Switzerland. The study revealed the distribution of oligochaetes (segmented worms) was associated with upwelling groundwater and that the groundwater was the only upstream dispersal route. The findings of the study also suggested that most, if not all oligochaetes in that particular area might have evolved from groundwater and not the other way round.

Like most other ecosystems, the hyporheic zone is not immune to environmental instability. Fowler and Death (2001) compared 'hyporheos' (fauna found in the hyporheic zone) in streams of different stability using water chemistry as well as bed stability analysis. The epigean fauna were found to be dominant in areas of decreasing environmental stability (increased surface water-like chemistry) while the hyporheos were noted to be dominant in groundwater dominated sites. Epigean fauna were found to seek refuge in the hyporheic zone during periods of disturbance. This may be important especially in explaining evolutionary pathways of surface and groundwater fauna. Since the 19th century developments such as those of industrialization, man has become a threat to the stability of many ecosystems, and the hyporheic zone is one of those.

Extensive pumping leads to unsaturated conditions in the hyporheic zone. The result is the hyporheic zone aeration (normally low in dissolved oxygen) and thus impacting on the biogeochemical processes such as ammonification, nitrification and denitrification as well as phosphorus availability (Boulton *et al.,* 1998). Thus anaerobic conditions are important in this zone especially for nutrient transformations. Where transmissivity is low, intensive pumping may result in dwindling of ecosystems that require a groundwater input to exist.

Apart from pumping, the use of the rivers as disposal sites for factories and mines is also another environmental impact imposed by man on these systems. Nelson and Roline (1999) found that heavy metals from a mine drainage tunnel impacted on the community structure downstream because the hyporheic zone was a sink for heavy metals. Nelson and Roline (2003) noticed the hyporheic zone is also impacted by multiple stressors such as river regulation and mine drainage, and noticed that the impacts were more on the community structure than function. Since structure involves factors such as relative abundance and richness, impacts of this nature are serious for the TMG aquifer, which up-to-date does not have a single species, recorded in this zone. Before dam construction, an impact assessment up to so far only involves impact analysis downstream, and only for surface water.

Attention needs to be paid to the hyporheic zone such that there can be an understanding of ecological water requirements for this ecosystem.

Defining this zone needs to be broadened to include zone of mixing between saline surface water (seawater). Moore (1999) suggested that this zone is a subterranean estuary.

Chapter 4

4 Methods to ascertain groundwater dependence

Methods to ascertain groundwater dependence of ecosystems within the Table Mountain Group aquifer is a challenging task. This is because detailed understanding of aquifer characteristics is not enough to understand the groundwater flow properly. The flow regime is important to address issues like temporal and spatial patterns of water availability.

4.1 Morphological traits

There are various morphological traits exhibited by vegetation that is dependent on groundwater. For example plants can have rugged roots that make it possible to reach high depths in sometimes resistant rock formations (Campbell and Dick-Peddie, 1964). In this thesis the focus will only be on rooting depth, since it has been the most widely assumed attribute of groundwater dependent vegetation.

4.1.1 Rooting depth

Canadell *et al.* (1996) asserted the depth at which plants can root has important implications on the whole ecosystem hydrological balance. This is true because root function is to anchor a plant, absorb and store nutrients as well as transporting water up the plant. Schenk and Jackson (2002); Canadell *et al.* (1996) stated that various vegetation types differ in root biomass, vertical root distribution and maximum rooting depth. These are the properties that make each vegetation type different from the next by fluxes of water, soil nutrients and soil fauna distribution. Roots are also pathways for carbon and nutrient transport into deeper soil layers and for deep-water infiltration (Smith *et al.*, 1999). Canadell *et al.* (1996) gave rooting depths of different vegetation types across the globe. The desert plants such as *Prosopis glandulosa* extend their roots as far as 53 m and tap the water table. Species that are alien in the TMG like the *Eucalyptus* have root depths averaging around 40m (WWP, 2003). Schlerophyllous shrubs of the Fynbos found within the TMG have root depths ranging from 1 to about 3.5 meters (*Leucadendron salignum*). The rooting depths Figure 4.1 shows rooting depths from Global Change Terrestrial Ecosystems (GCTE) (http://www.gcte-focus1.org/root.html).

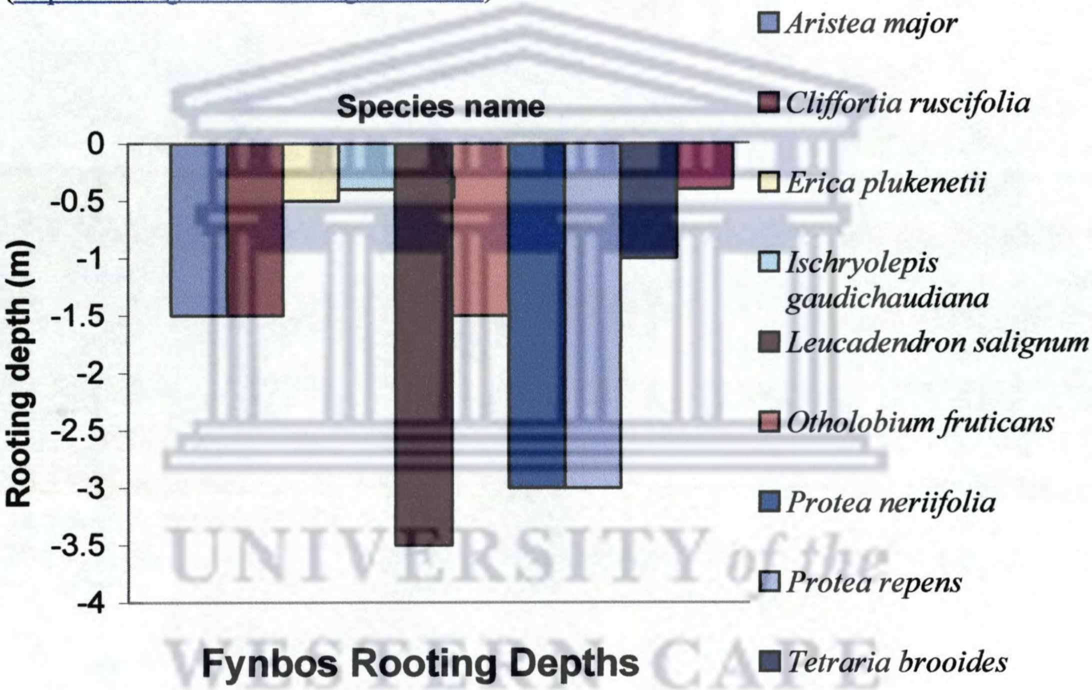


Figure 4.1: The Fynbos rooting depths (data plotted acquired from GCTE).

Higgins *et al.* (1987) that a phreatophyte cross-section root shows an increase in the number of xylem vessels. This is important for the needed "hydraulic lift" to take the water up the plant.

Some studies have shown that deep rooting is not the only option to tap the water table Hurst *et al.* (2004). The study showed that sugar cane crops with rooting depths of ≤ 2 meters could tap shallow water tables.

Methods to determine the rooting depth are mainly *prima facie* observations in road cuttings, open-cut mines, trenches and mineshafts. Other methods to determine rooting depth include use of tracers (Haase *et al.*, 1995), auguring (Bornman *et al.*, 2003) and trenching (Scott *et al.*, 2000). The Table Mountain Group aquifer is mainly quartzitic arenites of Peninsula Formation and Nardouw subgroup (SACS, 1980; Tankaard, 1982; Shone and Booth, 2001). Thus it may be close to impossible to determine the rooting depth by such methods. A method that may be useful is the three step method that:

1) *Determines the water potential of plants (Ψ_{PD}) [predawn pressure, which can be achieved by using a Scholander bomb]*
2) *Determines the water potential of the soil (Ψ_S) [obtained by using any conventional thermocouple psychrometry and then average it with depth]*
3) *Comparison of depth averaged soil water potential with predawn water potential of plants, so that:*

$$RD = \psi_S - \psi_{PD} \qquad \textbf{(4.1)}$$

where *RD* is the rooting depth.

The formula can give the functional rooting depth estimate even for unsuitable terrain like the TMG aquifer.
However, of importance is that deep rooting does not obviously mean groundwater use (Snyder *et al.,* 1998, Scott *et al.,* 2000, Dawson and Ehleringer, 1991; Mucina *pers. comm.*). Deep rooting plants may show seasonal variation for groundwater use.

4.2 Physiological traits

Physiological traits are important traits that may help in finding out the sources of water available for plants. It may be helpful if one seeks to find out whether there is any form of dependency on groundwater. Physiological traits also help in determining water use patterns by vegetation. Again the advantage of this is that it gives predictive power and therefore effective management, such as determination of water requirements of the vegetation.

4.2.1 Isotopic analysis

4.2.1.1 Background

This may be the most reliable but least used and expensive method. It identifies the isotopic "signatures' that are common in groundwater such as $\delta^{18}O$, $\delta^{2}H$, and ^{36}Cl.
This brief background will summarise isotopic fractionations that occur in the global water cycle, during water uptake and eventual incorporation into plant biomass. Water is made up of oxygen and hydrogen, elements that have more than one stable isotope. Oxygen has three isotopes (^{18}O, ^{17}O, ^{16}O), but because ^{17}O is in low amounts, ^{18}O is used for determination of groundwater presence. Therefore the focus is usually on ^{18}O relative to ^{16}O. Hydrogen has two stable isotopes protium and deuterium (^{1}H and ^{2}H). The proportions are represented in parts for each thousand relative to Standard Mean Ocean Water (SMOW)
Vapour pressure of water containing isotopes species may differ, resulting in ^{2}H and ^{18}O concentration in the condensation phase. The fractionation factor (α) gives the difference, hence,

$$H_2O(vapour) \Leftrightarrow H_2O(liquid)$$
$$\alpha = \frac{R_{liquid}}{R_{vapour}} \tag{4.2}$$

At room temperature (25°C), the oxygen value is 1.0093 and hydrogen is 1.076. Equilibrium effects thus result in vapour having oxygen isotope depletion of 9.3 ‰ and ^{2}H depletion of 7.6 ‰. Precipitation has the isotopic composition of ^{2}H and ^{18}O similar to the original liquid because of that. Initially, the precipitation will be isotopically rich, but with continued precipitation, the remaining vapour will have isotopic depletion. To represent this progressive depletion in isotopes, a Rayleigh distillation equation is used:

$$R = R_0 \bullet \alpha \bullet F^{(\alpha-1)} \tag{4.3}$$

where R is the precipitation isotopic ratio leaving the vapour, R_0 is the isotopic ratio of the initial bulk vapour composition; F is the fraction vapour remaining and α is as described above.

Equation 4.3 shows that precipitation from the vapour is continuously becoming depleted in isotopes. There are instances where the condensed phase is in equilibrium with vapour isotopically, where D and ^{18}O can be correlated. Such a correlation yields the Meteoric Water Line (MWL), which is approximated by the following equation (Craig, 1961):

$$\delta D = 8 \bullet \delta^{18}O + 10 \tag{4.4}$$

4.2.1.2 Water source determination

Associating the above information to plant water uptake is a challenge. Plants use groundwater by root uptake and conduction through xylem tissue. There is no isotopic fractionation during water uptake from soil to root (Campbell and Dick-Peddie, 1964; Sternberg and Swart, 1987; Dawson and Ehleringer, 1991). However, this has nothing to do with preference for a particular isotope, thus the isotope ratio of stem water is the same as the source water (Sternberg and Swart, 1987; White *et al.,* 1985; Brunel *et al.,* 1995). Water source determination studies for vegetation must incorporate the following:

1) *An understanding of the hydrogeological setting. This includes site visits and geological cross-sections, which will aid in conceptualising groundwater flow paths before delving deep into the functional traits,*
2) *Isotopic analysis of water from different parts of the plant that is stems/roots/leaves (especially the xylem sap),*

3) ***Xylem functionality (hydraulic conductance and resistance to cavitation,***
4) ***Stomatal conductance and its impact on xylem pressure potential; and***
5) ***Ring cellulose isotopic composition.***

The analysis of stable isotopes is important for identifying water sources for the plant (Snyder *et al.,* 1998; Chimner and Cooper, 2004; Brunel *et al.,* 1995). These isotopic tests are normally performed on the xylem sap of the roots (if possible to sample), stem and the leaves (Dawson and Ehleringer, 1991; Snyder *et al.,* 1998). It has also been proven there is no fractionation of isotopes within the xylem because water has not been exposed to evaporative enrichment (Dawson and Ehleringer, 1991). So results from xylem sap isotopic analysis can be considered as a reliable indicator of source water (Brunel *et al.,* 1995). Most isotopic studies to find out water source for vegetation have concentrated mostly on stable isotopes of hydrogen (Donovan and Ehleringer, 1994). This is because of easy separation of hydrogen (H) and deuterium (^{2}H) because of the big atomic mass difference. Lin and Sternberg (1993) showed that stable isotope difference of hydrogen is not suitable in saline conditions, where roots discriminate ^{2}H associated with salt infiltration.

Some studies like that by Huddart *et al.* (1999) have only used ^{2}H and ^{18}O to find out groundwater inputs to ecosystem.

The method is efficient when coupled with flux determination but sometimes it is usually difficult to separate the isotopic signatures of soil water from those of groundwater (Hatton *et al.,* 1998). A compartmental model that separates different soil layers may sometimes be useful to deal with that type of a problem. Because of the limitation, tracers such as lithium chloride have been the used, coupled with the rooting depth (Haase *et al.,* 1995). Again the limitation of such a method is that it is suitable for small-scale areas of primary aquifers. It is unlikely that it may be useful in fractured rock aquifers as flow in such systems may take thousands of years (Freeze and Cherry, 1979).

4.2.2 Xylem functionality anatomy

There are various facets, from which the xylem functionality can be investigated, but because that is not one of the objectives of this thesis only two will be highlighted in the following subsections.

4.2.2.1 Hydraulic conductance

Xylem hydraulic conductance refers to the volume flow rate per pressure gradient per cross-sectional area (Sperry *et al.,* 2003). It is essential for the hydraulic lift required by the plant to transport water against the gravitational force and up the plant. Xylem conductance is necessary in ensuring uninterrupted transport of water, which is necessary for replacing water lost by transpiration and allowing the stomata to remain open for photosynthesis (Pockman and Sperry, 2000). It is this hydraulic lift that provides a mechanism for temporary storage each night of water external to the plant root, thus providing more water for supporting transpiration. It also buffers plants against water stress during water deficits. It thus has indirect effects on nutrient acquisition, biogeochemical nutrient cycling processes and root growth and persistence. Determining hydraulic conductance for species suspected to be phreatophytic, no matter the degree, is important. A careful look at the processes that affect this conductance, like xylem cavitation, is also important because cavitation influences plant distribution patterns (Pockman and Sperry, 2000). Caldwell *et al.* (1998) showed that deep-rooted plants with less resistant lateral roots to cavitation will lift less water than deep-rooted plants with resistant lateral roots. This shows there is a relationship between hydraulic conductance and rooting depth, therefore they must never separate investigation.

Hydraulic lift is also important in ranking of species according to their 'lifting' capacity, to determine the degree of dependence on groundwater. Currently there is no such list for the TMG aquifer.

*4.2.2.2 **Stomatal conductance and hydraulic conductance***

This is an important aspect to examine because there is a direct linkage between stomatal conductance and hydraulic conductance (Sperry, 2004). Plants do not open stomata continuously because and thus avoiding desiccation by cavitation. This means there must be some form of coordination between stomatal conductance and xylem cavitation, that is, in keeping the water demand at levels far less than those that would challenge supply. Atmospheric conditions triggers the water demand for the plants. A study by Sperry *et al.* (2003) has shown that stomatal response is within five minutes when there is a change in hydraulic conductivity. The study also found that stomatal response is proportional to hydraulic conductivity in that where the reduction is 50% for hydraulic conductance, there will be 50% reduction for stomatal conductance. Stomatal response translates hydraulic conductance into adjustments in gas exchange to regulate plant water status. So this makes up another trait to that needs investigation if there is intent to find out groundwater dependence.

Other physiological traits needing investigation at are predawn and midday water potentials. The water potentials are also helpful in determining the hydraulic conductance mentioned in the xylem functionality subsection above. Establishing groundwater dependence is a holistic approach that involves all of what has been stated above, from rooting depth and plant morphology through to physiological traits mentioned above.

*4.3 **Checking groundwater inputs***

This is another important step in finding out groundwater dependence, for without groundwater there is no sense in discussing GDEs. Both the availability and flow of groundwater are governed by structural geology. The structures within the TMG are at both local and regional scale reveal the complexity of the TMG aquifer. Structures such as faults and fracture connectivity facilitate or impede groundwater movement

(Berkowitz, 2002), hence needing investigation as part of the study of GDEs. The faulting is intense across the TMG emanating from Permo-Triassic orogeny (Hälbich, 1983; Booth and Shone, 1999; Johnston, 2000; de Beer, 2001; Frimmel *et al.,* 2001). Further orogenic events resulted from neotectonism stretching from the Miocene to the Pliocene (Partridge and Maud, 2000). The diagrams (Figure 4.2, Figure 4.3, Figure 4.4 and Figure 4.5) show the structural complexity of the TMG aquifer. A closer look at the diagrams leads to two assumptions about GDEs and they are:

1) That if the faults are sealed, the result is "compartmentalisation" of groundwater and this may be from local to regional flow. If this is the case, GDE investigation should then be based on the groundwater compartments. In Figure 4.2, large normal faults transect south of each thrust sheet in the Uniondale area. The normal faults should make up compartments at a regional scale, while thrusts make compartments at a local scale. Figure 4.3 also shows compartmentalisation by normal faults in the Piketberg area. Figure 4.4 shows this compartmentalisation for southern section of the Syntaxis in 3D. The compartmentalisation may also be a result of fracture connectivity. Areas at close distances may be different systems as shown in Figure 4.5. It is for this reason that looking at the vegetation only on the surface and ignoring geology may lead to wrong conclusions.
2) That some of the large faults (covering tens to a few hundred kilometres) may be open becoming groundwater conduits. Such types of faults have been called "hydrotects" (Hartnady and Hay, 2001). These types of faults may be important for the GDEs because vegetation may grow on the fault itself and thus tapping groundwater. Some faults are sealed but groundwater may flow adjacent to the fault. Vegetation growth on or adjacent to the fault (hydrotects) may need investigation to establish groundwater dependence.

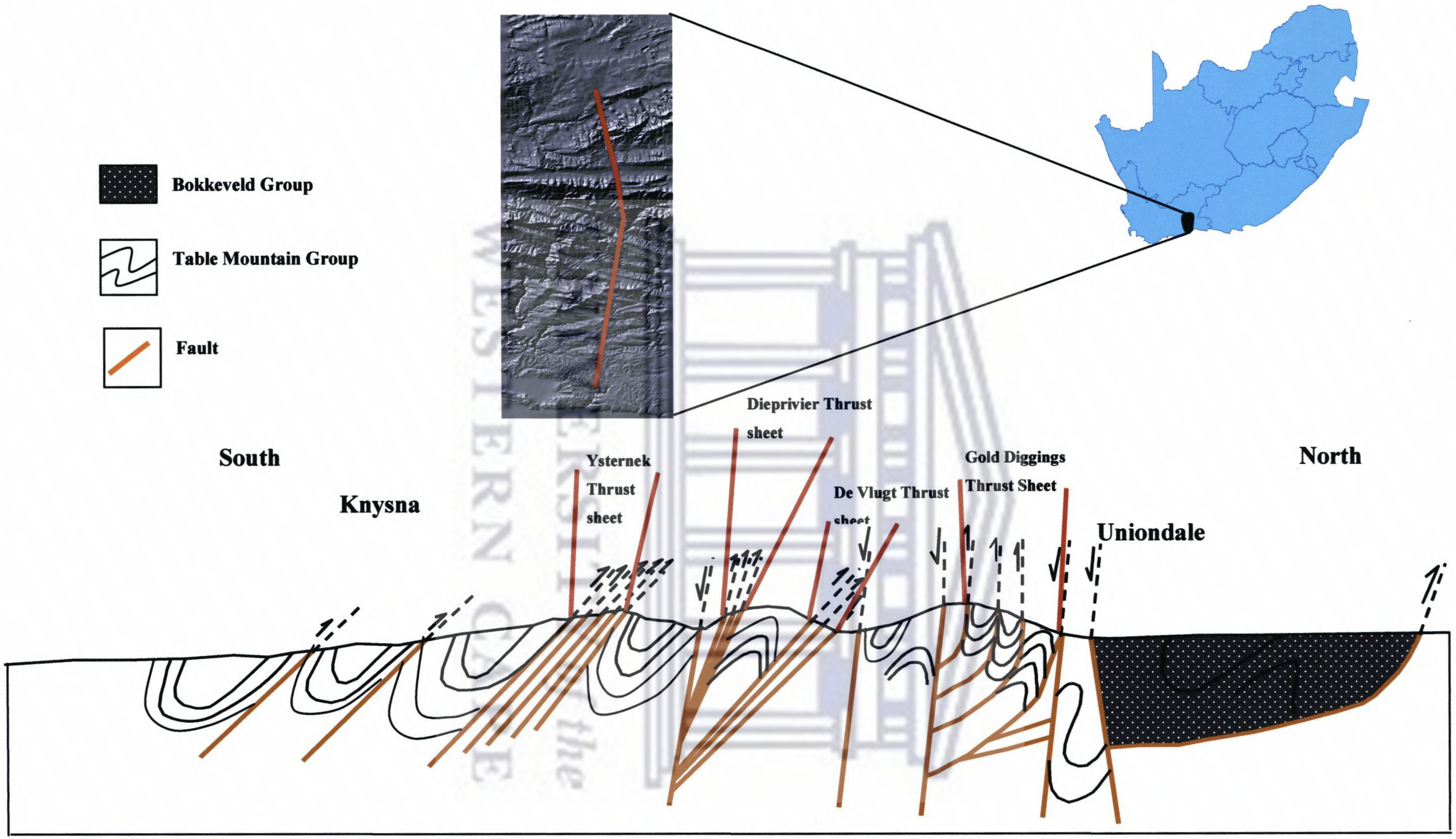


Figure 4.2: Structures near Uniondale (after Booth and Shone 2001; Murray, 1996)

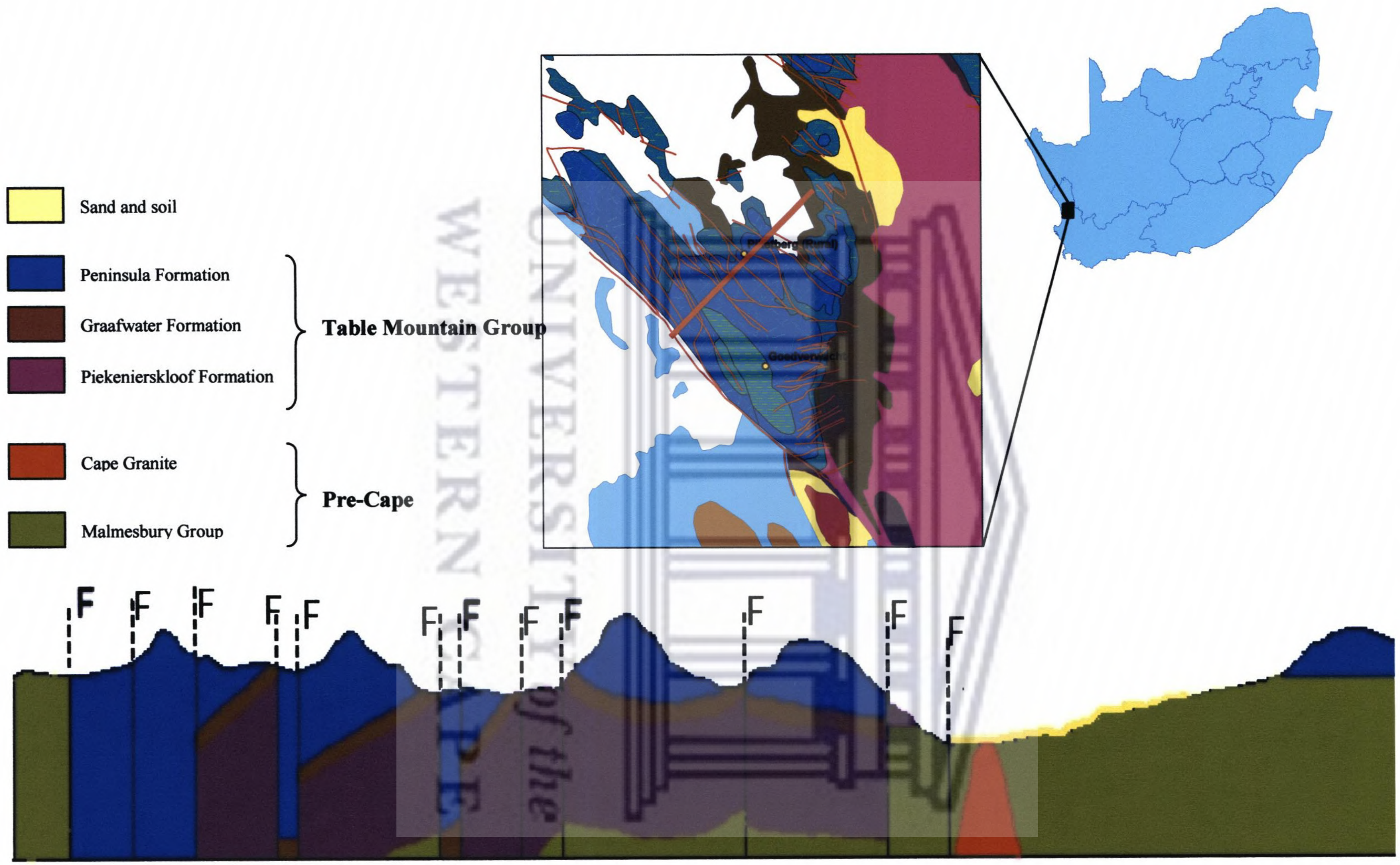


Figure 4.3: A cross-section near Piketberg (modified from de Beer, 2001).

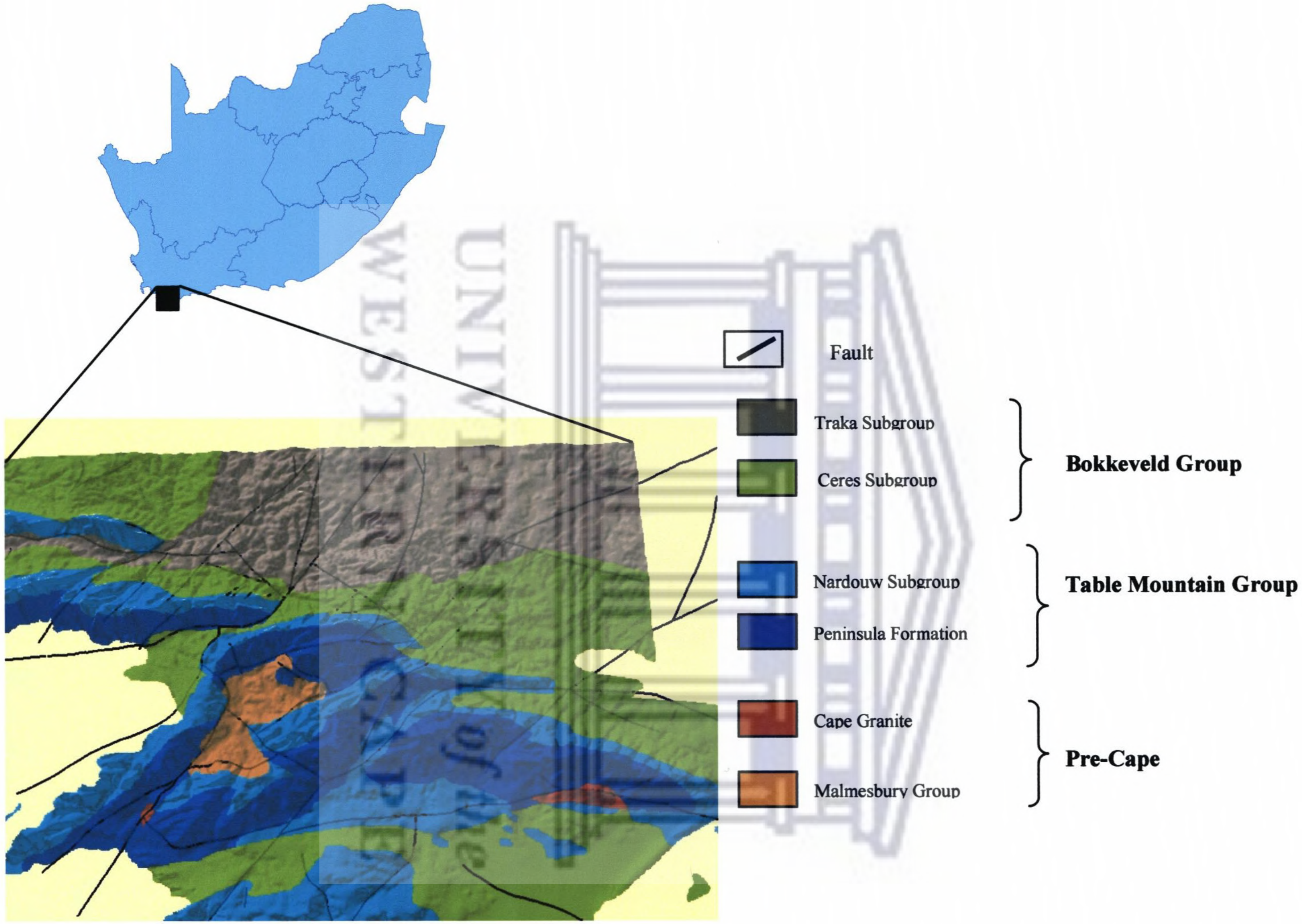


Figure 4.4: The geology of the Hermanus area showing faults that form compartments.

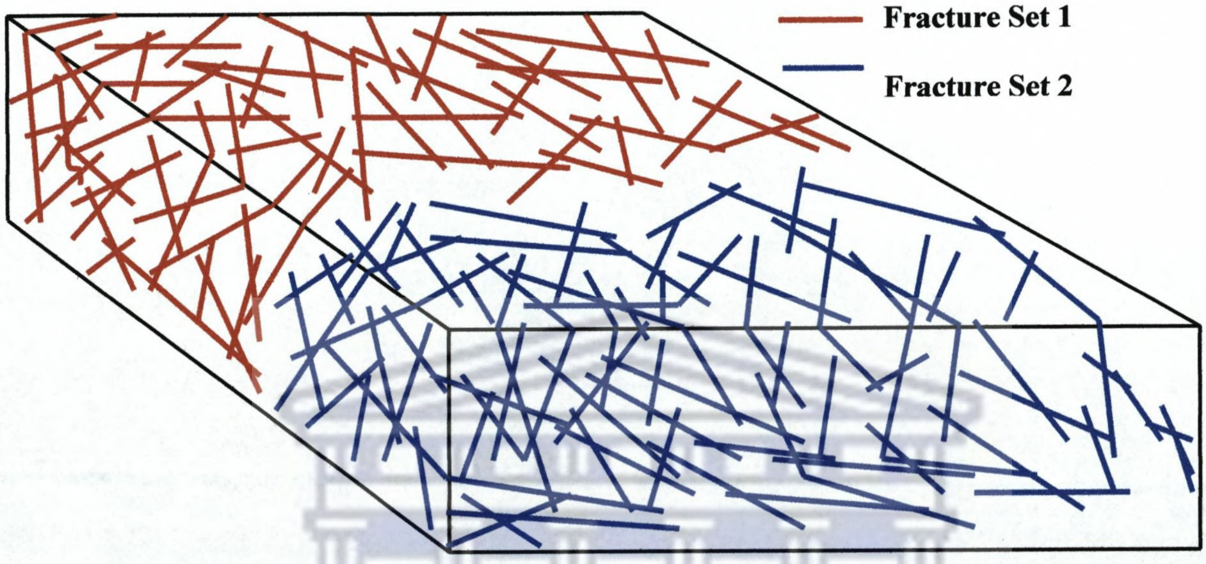


Figure 4.5: A diagram showing the compartmentalisation of the aquifer by two fracture systems.

4.4 Checking surface water inputs

Ascertaining groundwater dependence requires an understanding of surface water inputs as well, both temporally and spatially. To assess surface water inputs, surface water modelling is required. A sound understanding of the degree of dependency on groundwater has much to do with availability and accessibility of surface water. Nondependent ecosystems for example are the ecosystems that are dependent on surface water. This subsection will use a Digital Elevation Model (DEM) to delineate watershed in one area of the TMG. Watershed delineation is important because of its common use as a basic unit in resource analysis and because it has components that are interrelated and as a result viewed as single interactive ecological units. To achieve that objective, a DEM, rainfall and stream data are used to delineate a watershed. The DEM was created using 1: 50 000 topographic maps from Surveys and Mapping, Department of Land Affairs, South Africa.

The Uniondale area is used as an example to describe geomorphology and its relationship to surface water. There is not much work done on the geomorphology when at least compared to geology. Much of the geomorphology description given here will be based on a constructed DEM (using ArcInfo 8) and to a lesser extent the Satellite imagery (Landsat). The DEM can be useful in watershed delineation, creation of stream networks, stream order, as well as stream discharge.

Apart from modelling surface water inputs, another objective should be to check possible points of groundwater discharge. A common assumption (though not always true) is that the lowest point (pour point) of the watershed should be the possible point of not only surface water discharge, but also that of groundwater. So watershed delineation can be useful in ascertaining groundwater dependence.

4.4.1 The geomorphology

The geomorphology of this area is not much different from most areas within the Table Mountain Group, as previously described by King (1951).

4.4.1.1 Topography

The DEM shows the town of Uniondale placed on a depression flanked by at least three mountain ranges. On the south-most section of the 1:50 000 map (from which the DEM was created) is the limb of a huge anticline that makes the Outeniqua Mountains (Figure 4.4). These in turn are the mountains that block the precipitation from advancing further inland into the Uniondale area. This shows the orographic effect in the TMG area. The impact of these mountains is so great that the south-facing side of the Outeniqua has yearly rainfall averages of more than 1000 mm/a (Department of Water Affairs and Forestry). The north-facing side, the Uniondale area, has rainfall averaging 312 mm/a. Figure 4.5 shows the precipitation interpolation grid. Immediately from the eastern periphery of the town is another highland that forms part of the Kougaberge Mountains (Figure 4.4) with a maximum altitude of 1480 m. The orographic impact of these highlands is shown clearly on the interpolated rainfall distribution maps that will be shown in the drainage subsection.
At about ±10 km north-west of the town is another highland, the eastern section of the Kammanassie Mountains.

Figure 4.6 shows the geology of the Uniondale area (1:50 000 map from Council for Geoscience) draped onto the DEM. It shows the Peninsula Formation and Nardouw subgroup (Goudini, Skuwerberg and Baviaanskloof Formations).
The slope grid (Figure 4.7) shows the area to have sharp changes on sloping angles. The slope angles can be as steep as 80 degrees at Uniondale Pass (Figure 2.16).

4.4.1.2 Landforms

Craig (1997) and van Zyl (1997) described the landforms of the coastal area from George to as far as Port Alfred. Though the study only ended just south of the Uniondale area, but some of the landforms are present in the area. Gondwana valleys (which are ancient east-west trending valleys occurring on top of the Bokkeveld Group), are present in the area. The highlands that are a result of orogenic events dating back from the Permian to the Triassic (Hälbich *et al.,* 1983) can be observed in the area as described in the previous subsection. The African Surface (AS) capped by duricrusts of silica (silcrete) can also be observed and cover a great extent. There have been various assertions about the silica content and the origin of silcrete. Partridge and Maud (2000) found the silcrete to contain silica less than 85%, while Twidale (1988) found silcrete to have 95% silica.

The three-dimensional DEM of the area (Figure 4.8) shows the African Surface in the Uniondale area. The elevation of the silcretes around Uniondale vary between 800 and 960 m, which can be attributed to two tectonic uplifts in the Miocene (23 – 5Ma) and Pliocene (5 – 2.5Ma) (Dardis and Moon, 1988; Partridge and Maud, 1987).

4.4.1.3 Drainage

In the southern part the area the TMG outcrop is prominent and has several small catchments. In these small catchments the parallel drainage pattern (Moon and Dardis, 1988) is dominant. The parallel drainage pattern is expected especially in headwater streams, which exploit the fractures in the highlands. Figure 4.9 shows these small catchments. By increasing the drainage threshold, the catchment size increases as that connects the catchments that contribute towards the same direction. Figure 4.10 shows these large catchments (drainage basins) in the Uniondale area.

The main river in the area, the Kammanassie River cuts through the joints of the Baviaanskloof Formation (youngest formation of the Nardouw Subgroup) as illustrated by Figure 4.11 while Figure 2.18 shows the cross-sectional picture.

The stream order created using the Strahler model (Strahler, 1952) in ArcInfo Grid module shows the area to have six stream orders and Kammanassie assigned the 6th order, making it the major river in the area. Figure 4.12 shows the stream order.

The discharge grid obtained by using the stream grid weighted with precipitation grid shows discharge to be directly proportional with the stream order (Figure 4.13).

Apart from exploiting bedding planes, the valleys in the area, like all others found in the TMG have exploited regional fractures. Several valley cross-sections (surface profiles) have been constructed for the area, some through the Formations [Goudini (oldest), Skuwerberg and Baviaanskloof (youngest)] of the Nardouw Subgroup and others through the Peninsula Formation. Figure 4.14 shows the cross-sections (3X vertical exaggeration) showing the incised valleys (deep, steep dipping gorges). However, the valleys in the Peninsula Formation do not show the incision as pronounced as in the Nardouw Subgroup because of two possible reasons:

- *The extent of deformation (especially fracturing) in the Peninsula Formation across the TMG is extensive than all three Formations of the Nardouw Subgroup. The intense wide-aperture fractures can allow for water passage and erosion of the otherwise rigid quartzitic arenites.*
- *The intense faulting (thrust sheets) in the area that even saw the elimination Cedarberg Shale Formation. The Peninsula here is part of an anticline that formed as a 'pop-up' structure because of movement along fore and back thrusts (Booth and Shone, 1999).*

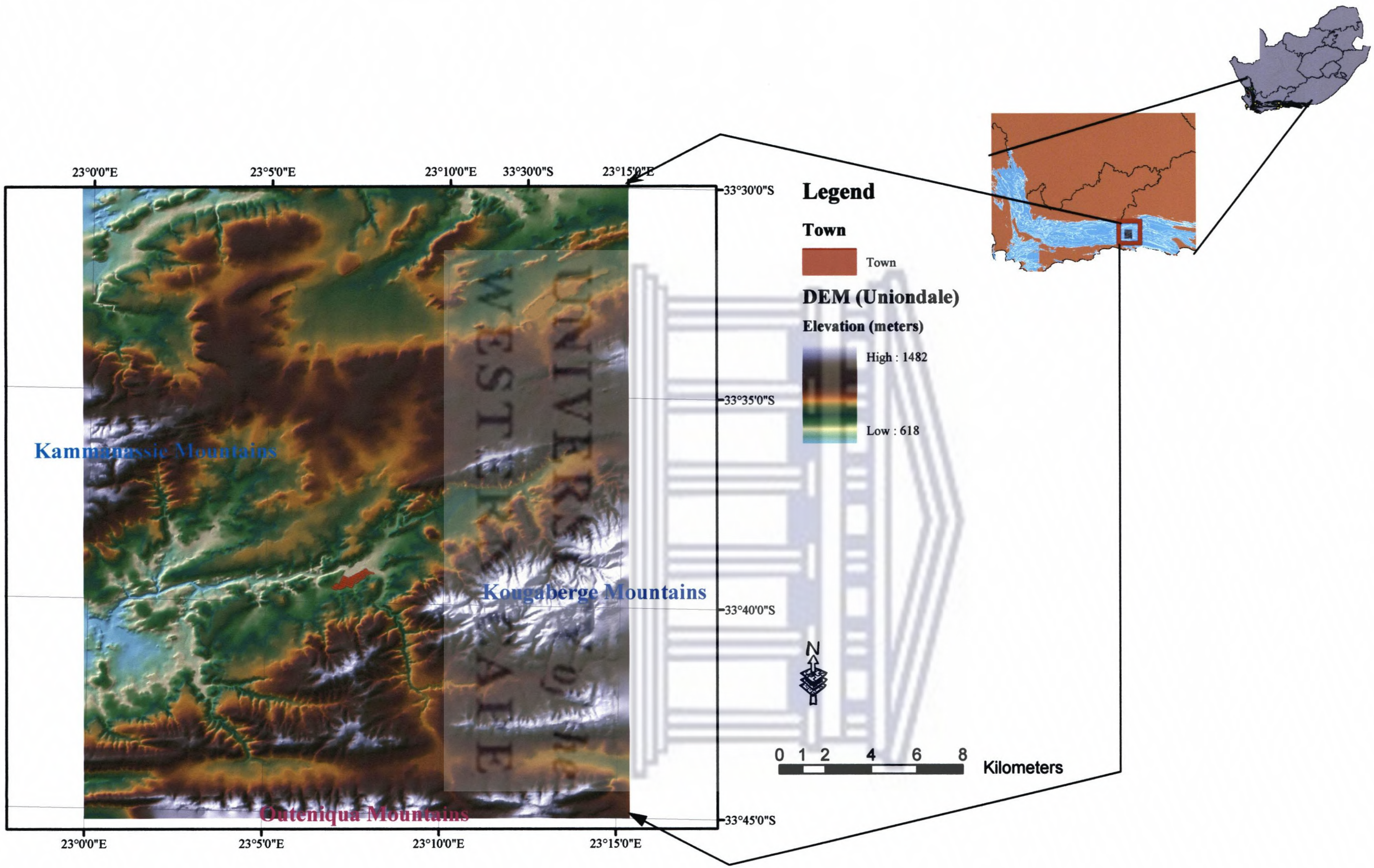


Figure 4.4: The DEM of the Uniondale area

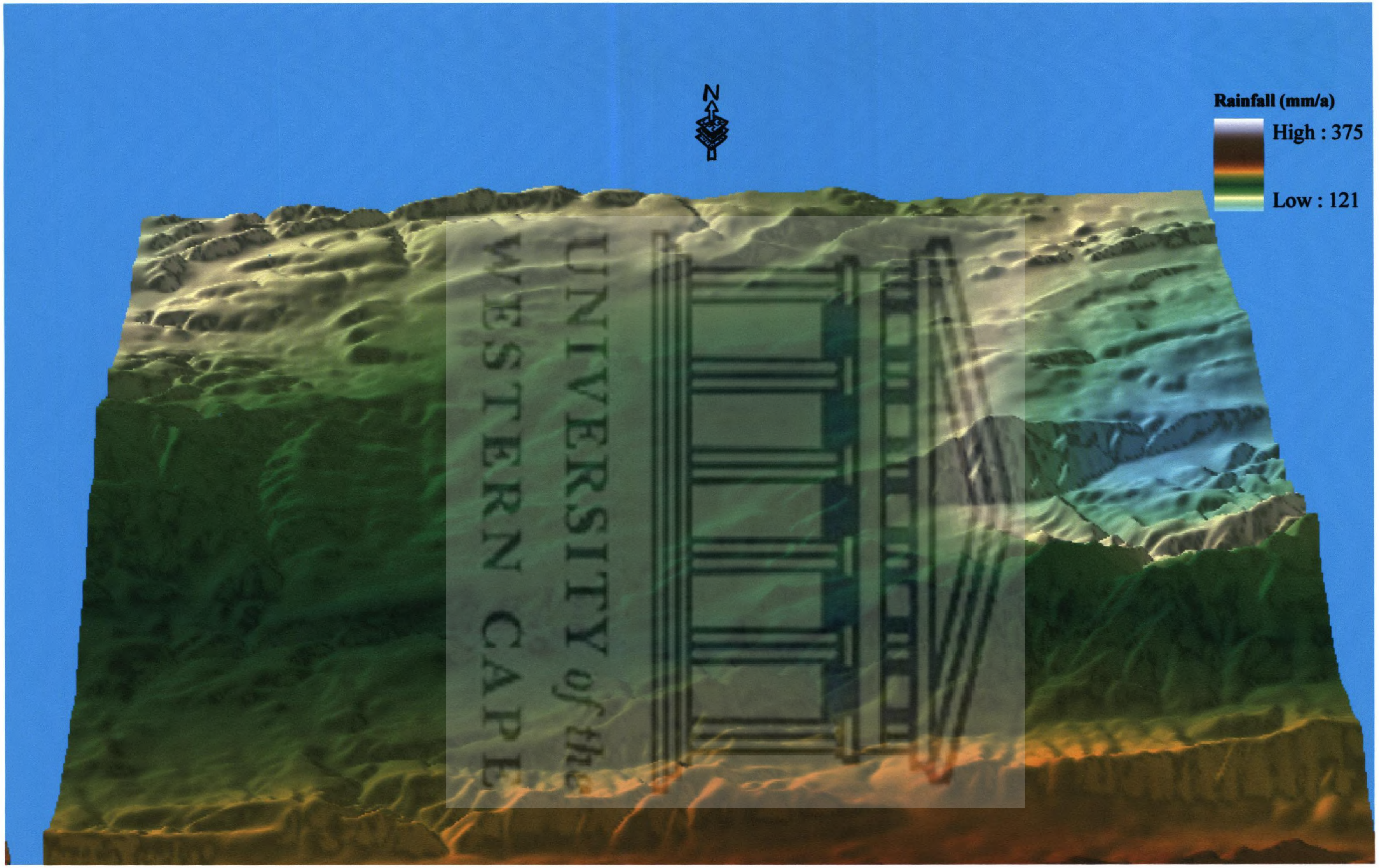


Figure 4.5: Precipitation interpolation grid of the Uniondale area using ArcInfo Grid module

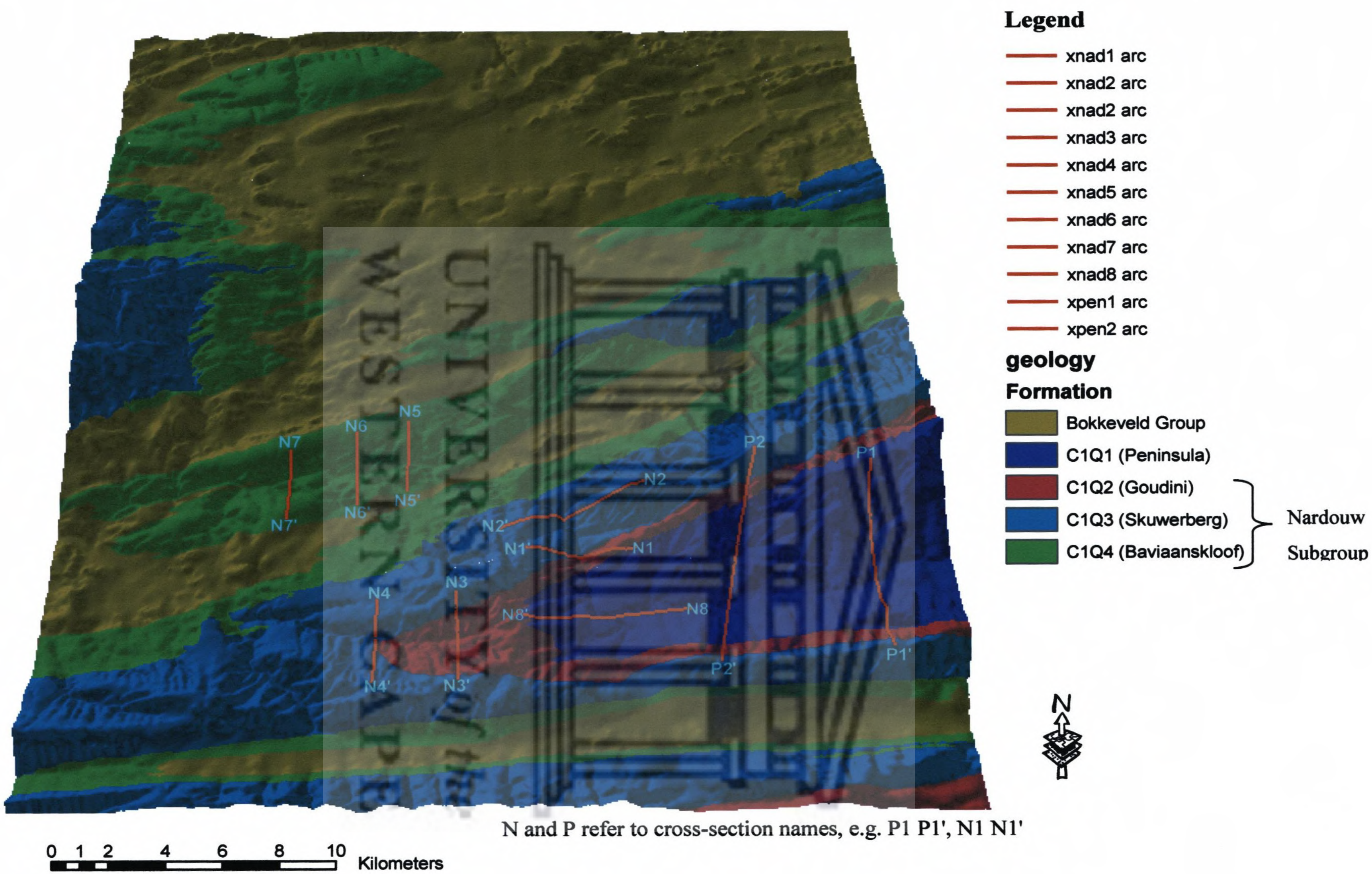


Figure 4.6: Geology of Uniondale area showing the cross-section lines

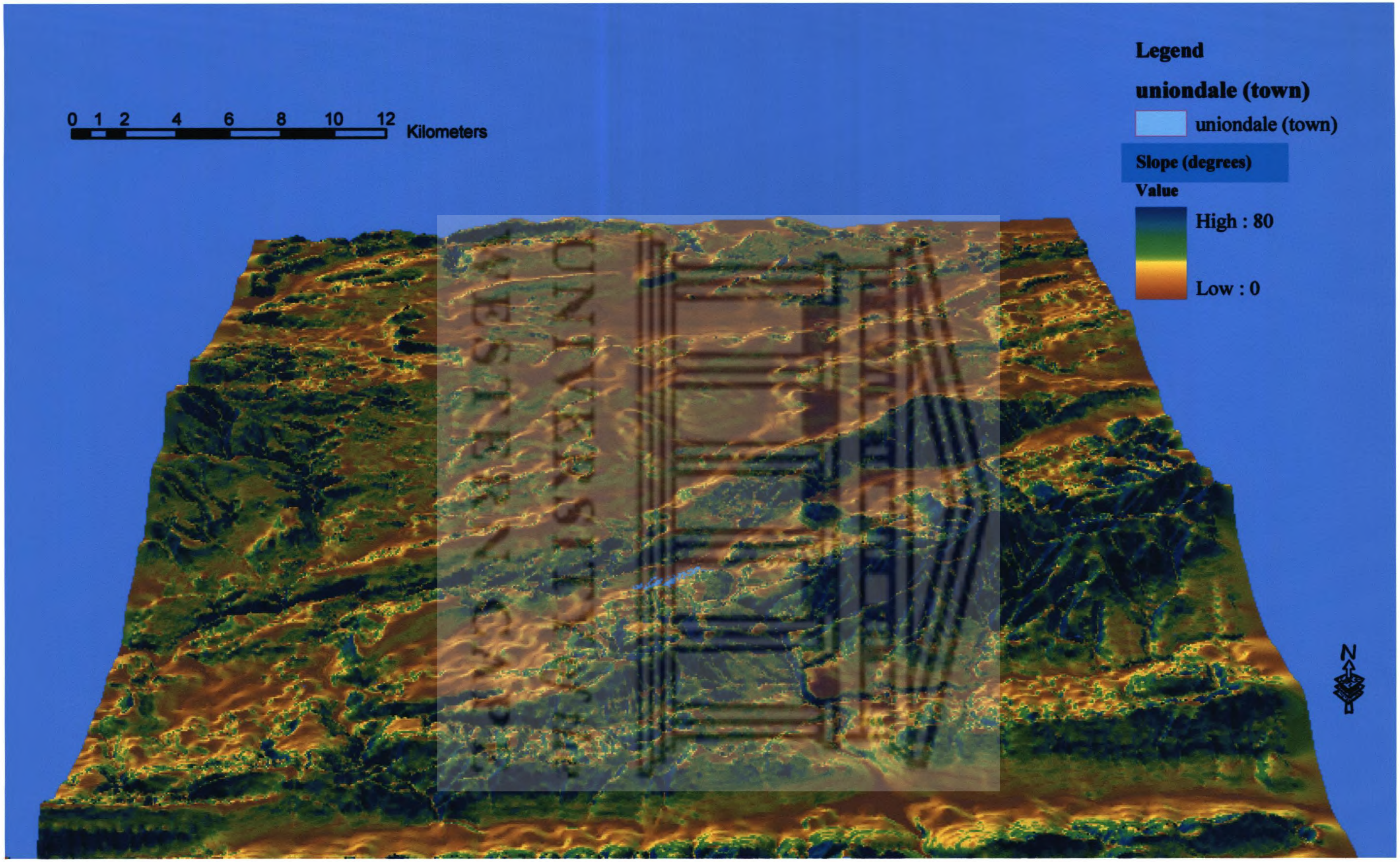


Figure 4.7: The slope grid of Uniondale area. Generated using ArcInfo Grid module

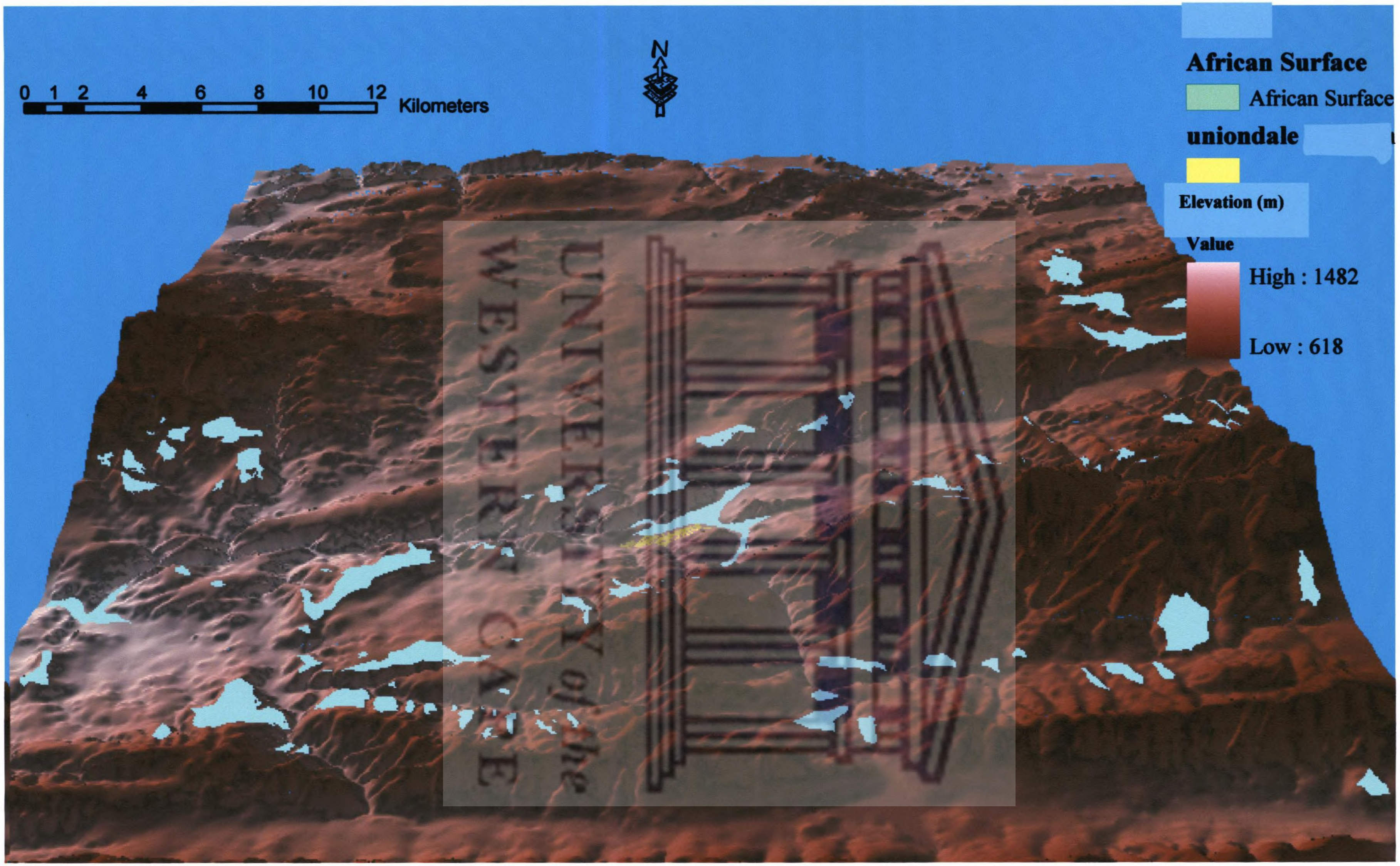


Figure 4.8: Three-dimensional view showing the remnants of the African Surface

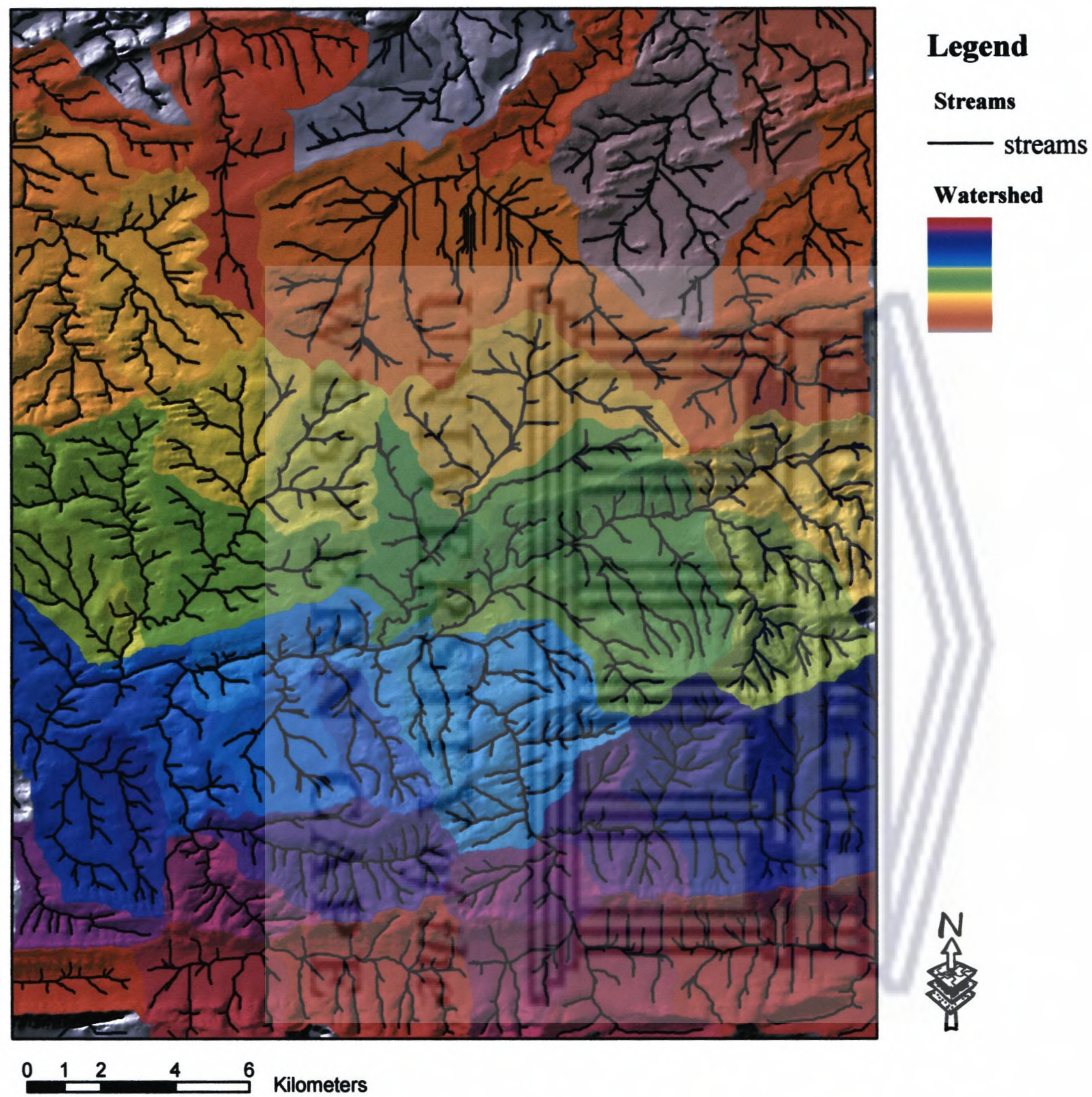


Figure 4.9: The watersheds of the Uniondale area. Delineation carried out in ArcInfo Grid module

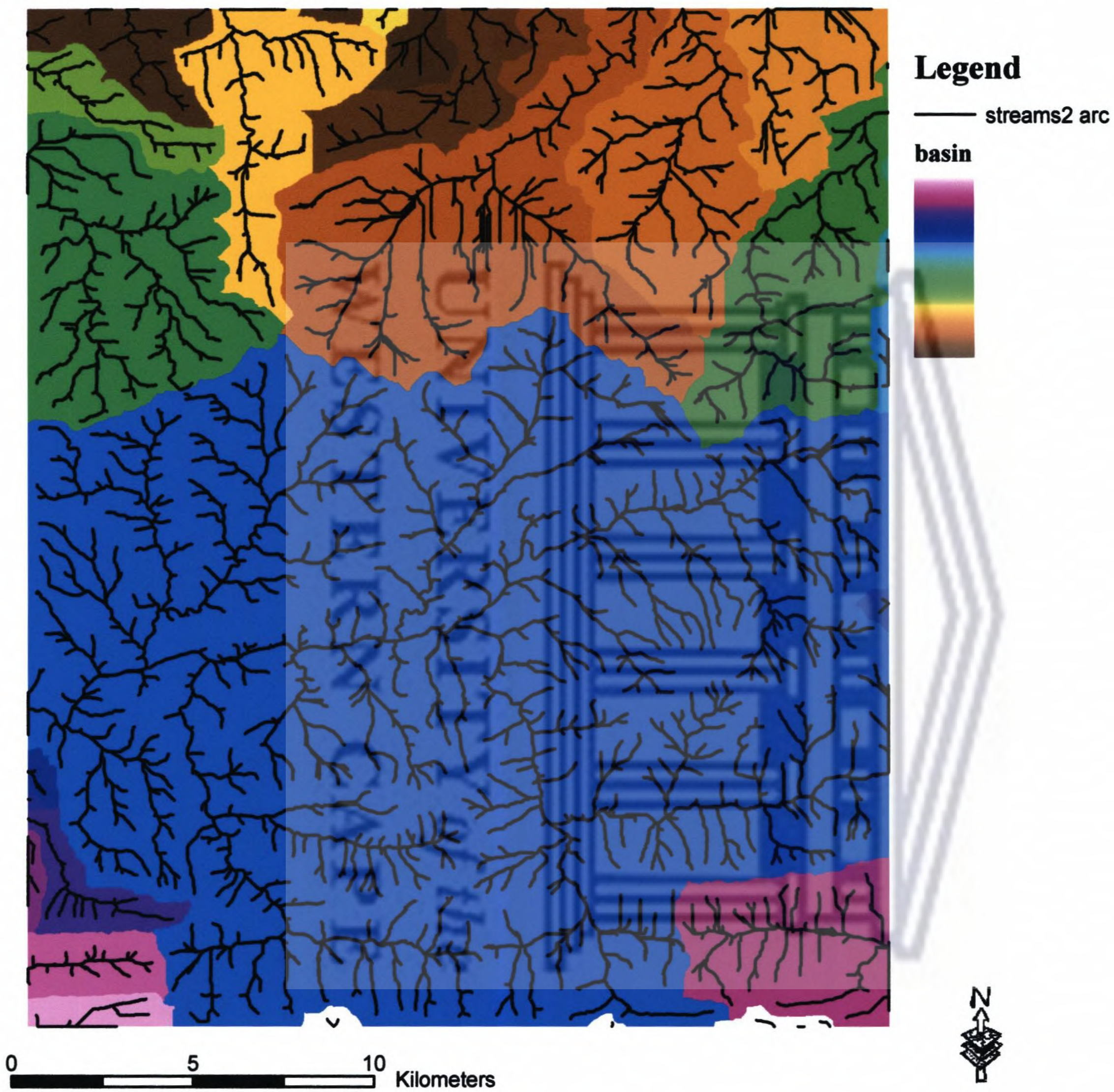


Figure 4.10: The basin delineation grid of the Uniondale area. Generated using ArcInfo Grid module

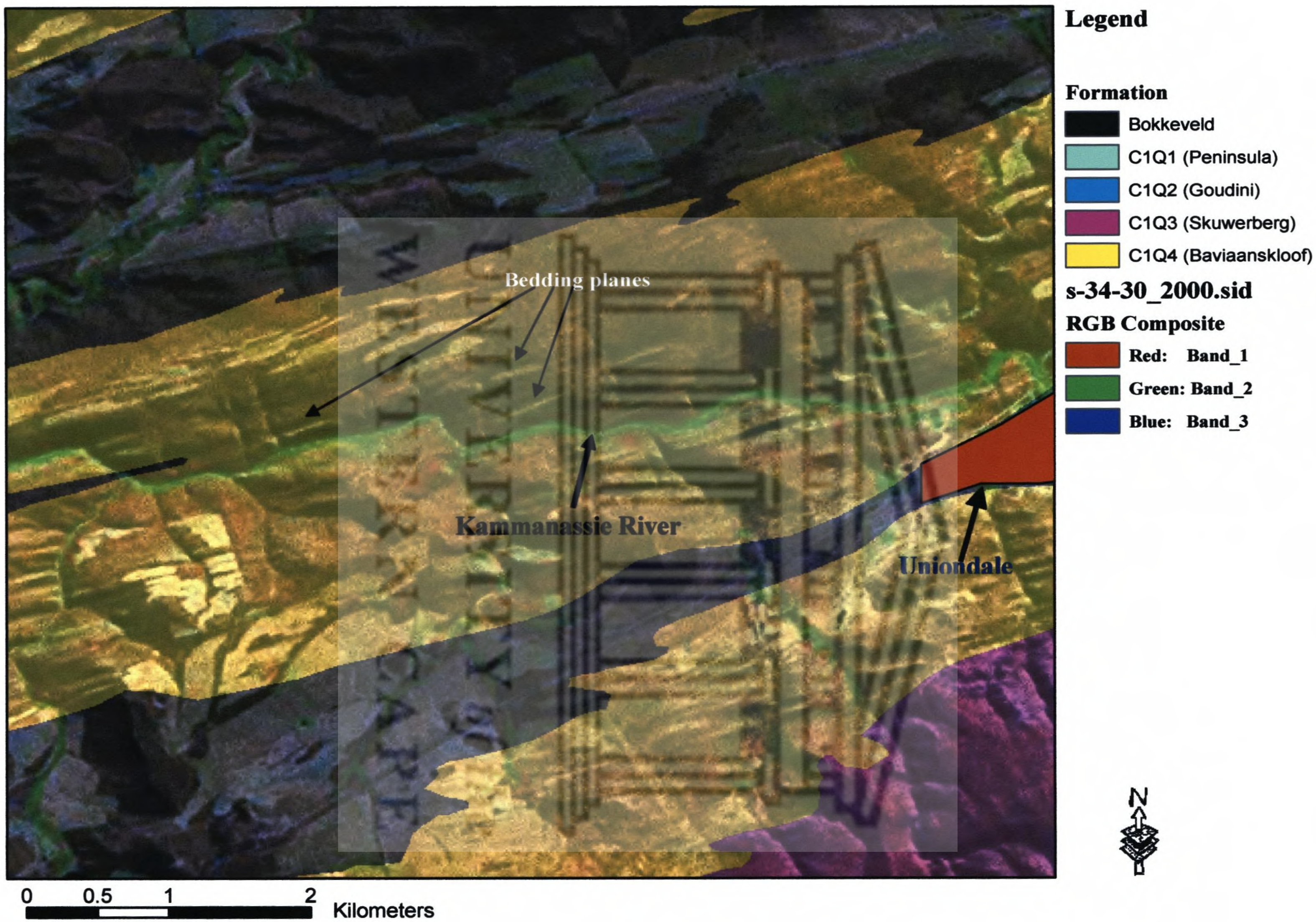


Figure 4.11: An image showing how the Kammanassie River exploits the bedding planes

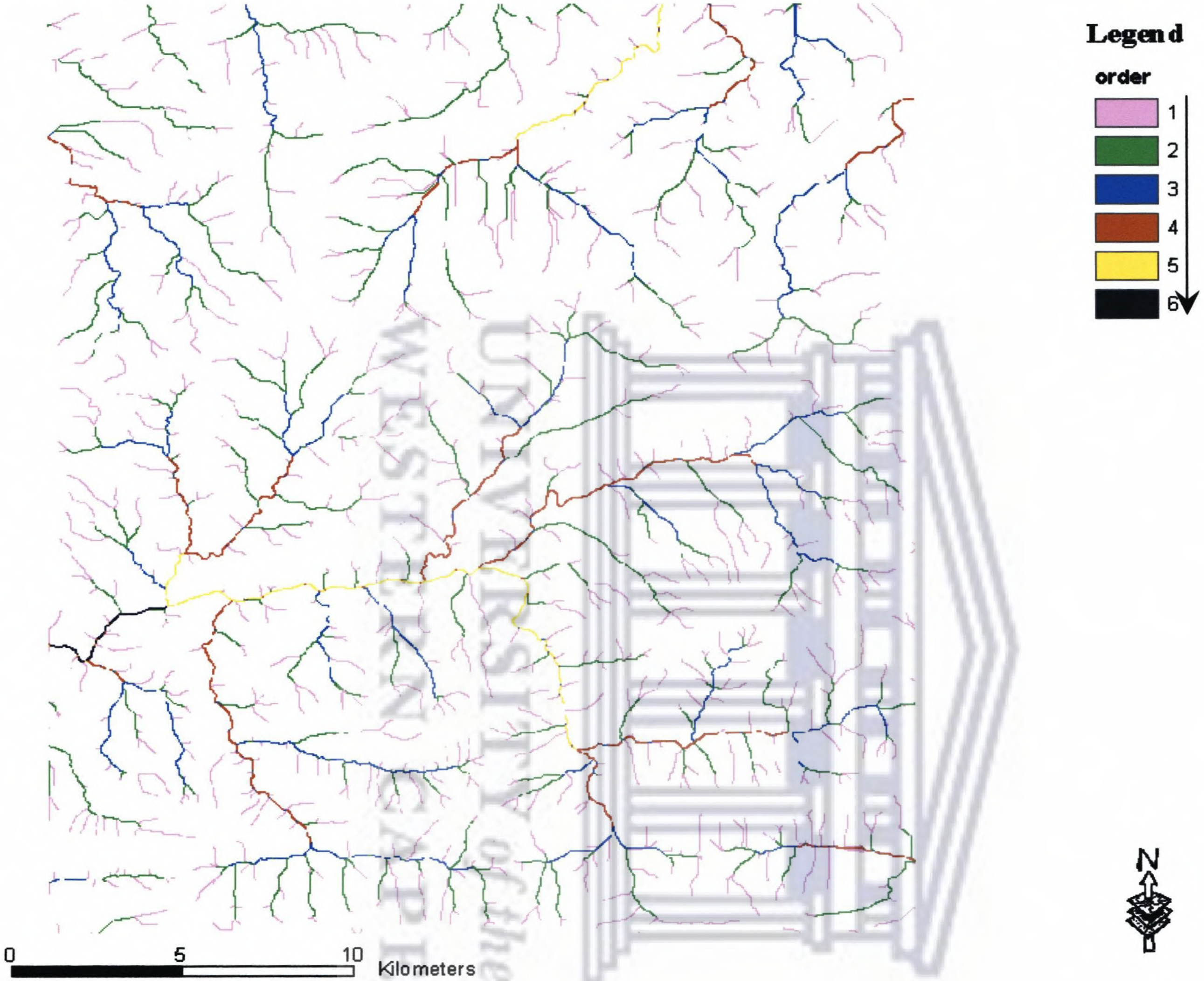


Figure 4.12: The basin delineation of Uniondale area. Generated using ArcInfo Grid module

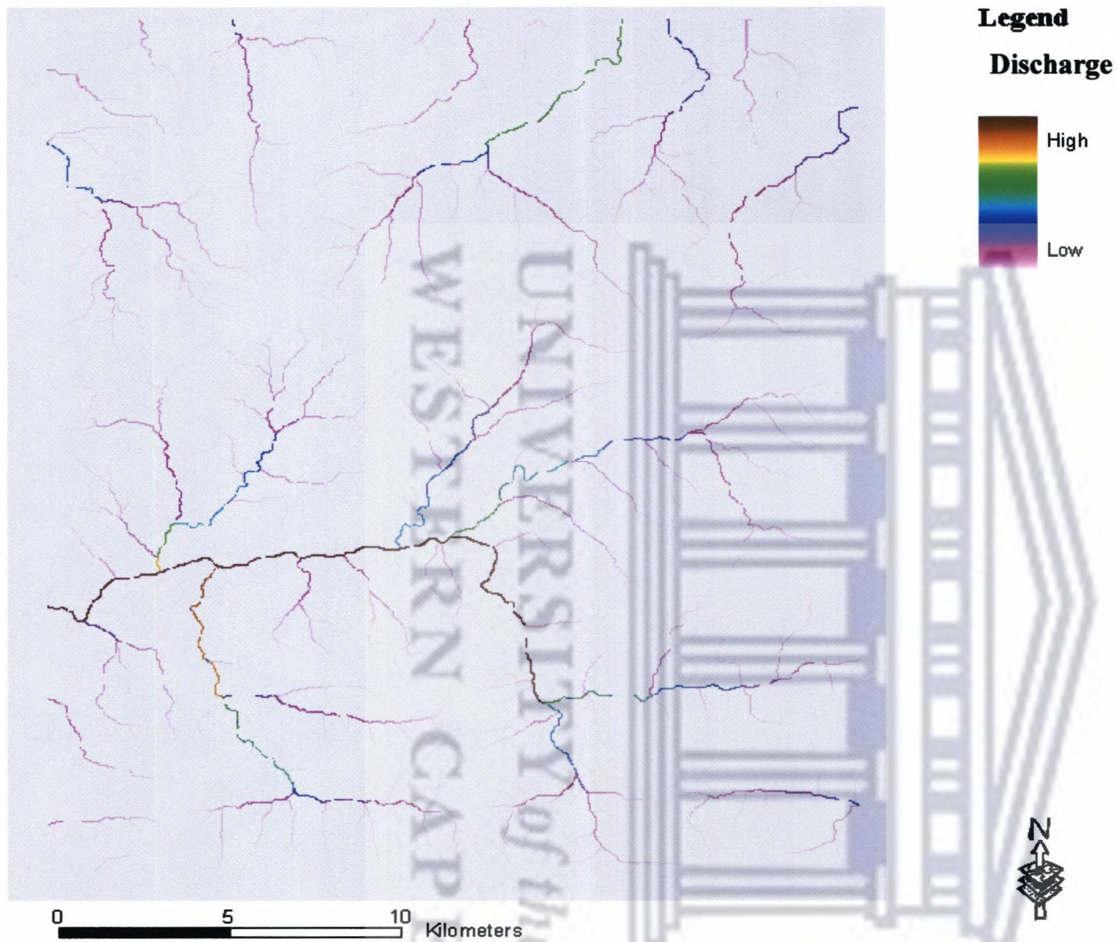
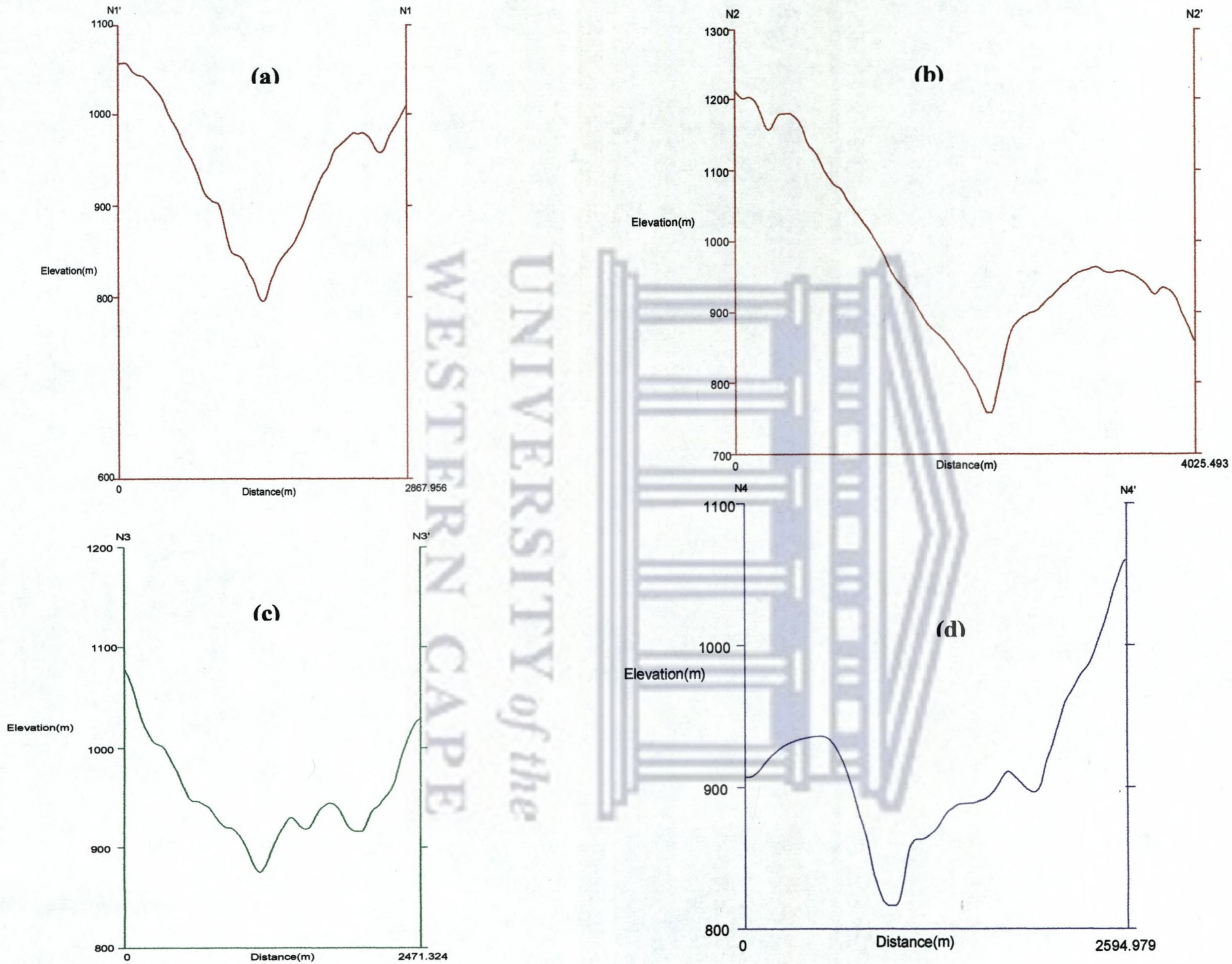
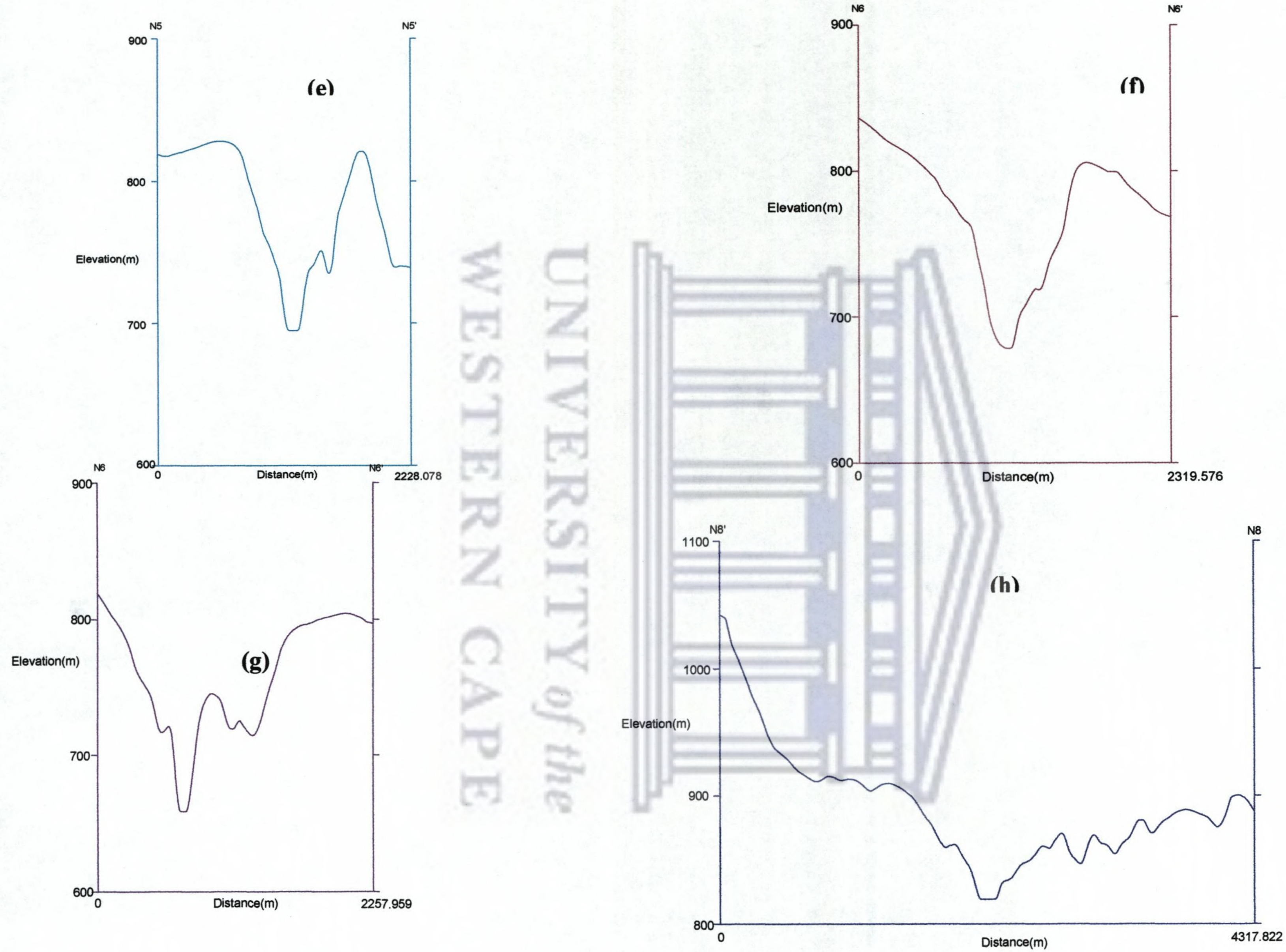


Figure 4.13: The river discharge of the Uniondale area. Obtained by weighting the stream grid with the precipitation grid using ArcInfo Grid module



(a)
N1'
N1
Elevation(m)
1100
1000
900
800
600
0
Distance(m)
2867.956
(b)
N2
N2'
Elevation(m)
1300
1200
1100
1000
900
800
700
0
Distance(m)
4025.493
(c)
N3
N3'
Elevation(m)
1200
1100
1000
900
800
0
Distance(m)
2471.324
(d)
N4
N4'
Elevation(m)
1100
1000
900
800
0
Distance(m)
2594.979



(e)
N5
N5'
900
800
700
600
Elevation(m)
0
Distance(m)
2228.078
(f)
N6
N6'
900
800
700
600
Elevation(m)
0
Distance(m)
2319.576
(g)
N6
N6'
900
800
700
600
Elevation(m)
0
Distance(m)
2257.959
(h)
N8'
N8
1100
1000
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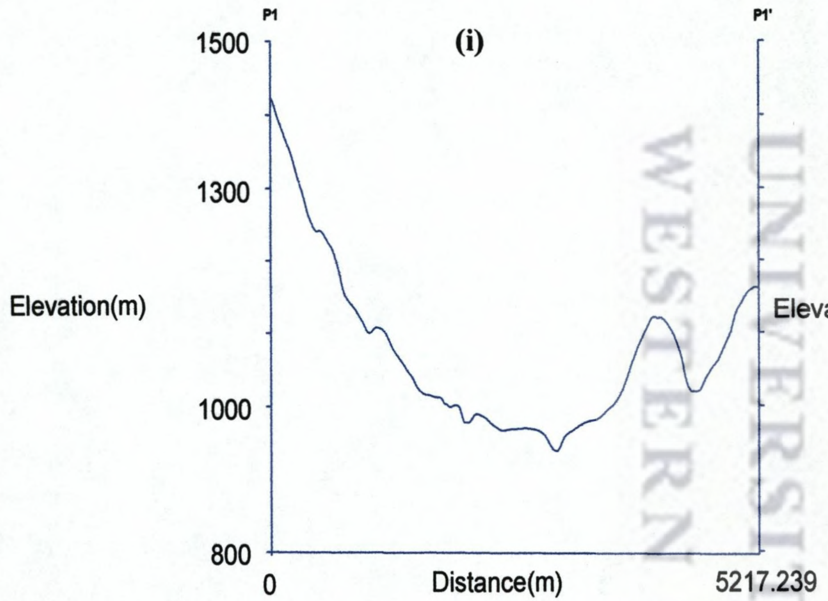
800
Elevation(m)
0
Distance(m)
4317.822



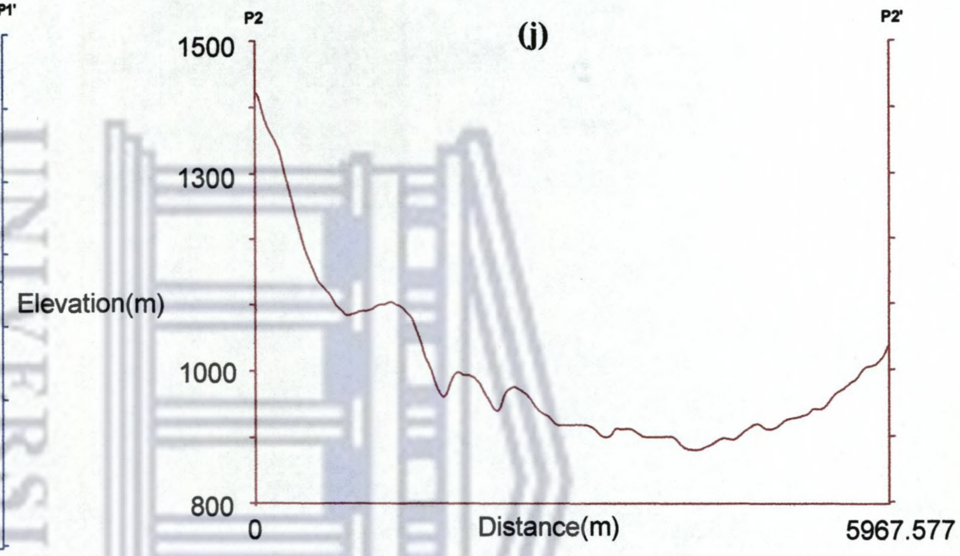


Figure 4.14: The cross-section profiles from the Uniondale area. Valleys in the Nardouw Subgroup [(a), (b), (c), (d), (e), (f) and (g) are incised. Both (i) and (j) in the Peninsula Formation have gentle sides. Cross-section profiles obtained using an ArcInfo AML script (Rossi *pers. comm.*) and ArcEdit.

Chapter 5

5 Groundwater Dependent Vegetation within the TMG: With PFT concept as a core to approach and understanding

5.1 Introduction

The previous chapter touched on the use of physiological traits in the description or characterization of species as being groundwater dependent. In this chapter the idea is to bring forward Plant Functional Types (PFTs). The PFT concept is an old concept recently revived in trying to answer questions of adaptation or response of plants to climatic or human induced changes. There may be problems on considering the GDEs within the TMG as biomes as earlier stated. The biome concept can sometimes be a useful top-down model involving such environmental parameters as water, the surface energy and momentum fluxes. Since there is little scientific knowledge of groundwater dependent vegetation available within the TMG, the top-down approach may be meaningless. The biome concept also excludes an important aspect, biogeochemistry that includes both photosynthesis and the carbon cycle. When this aspect is included in the biome concept, particularly mixed-life form biome, it is difficult. For instance the photosynthetic light response curve for the Fynbos, which has restioid, ericoid and proteoid elements (Moll and Bossi, 1983), cannot be the same. Also this difficulty stems from different life forms that have different rooting depths (Canadell *et al.,* 1996) and have different stomatal conductance (C3 and C4 plants). The biome concept is useful for single array species stands (monocultures).

To describe PFT concept here is useful for describing physiologically based ecosystem models because of its ability to link climate and ecosystem models (Duckworth *et al*., 2000).

5.2 *What are PFTs?*

Defining PFTs varies, with some authors defining it by resource use and others by response to perturbation. Here a PFT definition is coined as a nonphylogenetic set of characters defined by morphological, phenological and physiological or life history trait similarity. This gives them an adaptive value (bioclimatic tolerance) in a specific environment (Laurent *et al.*, 2004; Gerdol 2004; Jian, 2003; Duckworth *et al.*, 2000; Chapin *et al.,* 1996).

The response to the perturbation definition is that PFTs are groups of taxa with similar response to environmental resources and disturbance associated to common traits (Cousins and Lindborg, 2004).

Projecting PFTs can help with an understanding and description of plant communities (Diáz *et al.*, 1998) and can also be of use in understanding roles of plants in dynamics and function of the ecosystems (Lavorel *et al.*, 1999). Figure 5.1 shows the schematic breakdown of PFTs. This scalar applicability of PFTs makes them more suitable than the biome concept. The scale advantage associated with the PFT concept also helps to determine which types of attributes are important. At least at an ecosystem scale, the PFTs provide classification with greater detail and are able to provide linkages between ecosystem structure and function (Diáz and Cabido, 1997; Diaz *et al.*, 1998). In Chapter 1 mentioned that autecology is important for understanding the GDEs at species level, but this is useful when achievable. In an event that this becomes unachievable, stemming from taxonomic complexities, the PFT concept may be useful.

Assume that GDEs perform functions simultaneously depending on groundwater availability at a site. That may result in consideration of those ecosystems as being part of one group by the plant physiologist, but may be placed into several different groups by a taxonomist or a population biologist. So the PFT concept is useful in flattening taxonomic complexities (Duckworth *et al.,* 2000), which are otherwise inherent to the autecological approach.

For the TMG the scheme presented in Figure 5.1 may be applicable, starting from the objectives of finding out water source and use crossing through to measuring responses to perturbation. The first logical step to achieving this for the TMG would be to use both induction and deduction. Induction is suitable in that one has to initiate research methods, while with deduction facts synthesized from theory are used to do research. For instance choice of traits presumed useful for identifying or delineating groundwater dependence may be tested for validation. The traits tested must cover the important three elements, which are physiology, morphology and life span.

A statement in Chapter three was that dependence of ecosystems varies along the landscape. Also stated was the assumption that groundwater dependence in the highland outcrops of the TMG vary from low to non-existing. Microbes in the in-aquifer ecosystem of fractured rock aquifers like the TMG elsewhere in the world have been reported (Fredrickson and Onscott, 1996). This suggests the discharge zone needs investigation for pragmatic reasons. It is in this zone that groundwater, whether from regional water tables or local water tables, comes out. This means that wetlands, baseflow, spring and estuarine ecosystems should be targets for investigation regarding groundwater dependence. The choice of species to which the chosen traits need investigation, may be in these areas. The testing has to be through intensive field and laboratory work. This will enable the investigator to then classify and do ordination of species according to functional type. Having done that, the result is twofold as stated in the definition, because it allows for both increased ecological understanding and increased accuracy of prediction about impacts. This means that PFTs are suitable for addressing and assessing sustainability of ecosystems.

5.3 PFTs as indicators of response to perturbation

This chapter will later discuss projecting this PFT concept into an ecosystem approach. This subsection covers the usefulness of PFTs as indicators of perturbation. This is useful in effective land management (Duckworth *et al.* 2000). Here the argument is that PFTs can be useful in revealing changes in groundwater, whether chemical or physical. For the case of the TMG, an aquifer earmarked for potable water, PFTs can be useful as indicators of groundwater abstraction. PFTs provide knowledge of traits (which are morphology, life history, physiology, phenology and vegetative ecology) and they are important for understanding impacts of disturbance. Once there is an understanding of the disturbances, it can be possible to determine tolerance thresholds, like for instance, what variations in water availability can be tolerated by facultative phreatophytes?

5.4 PFT concept application to conceptual approach

So far this chapter has focused on defining the PFTs, but something pending is how useful PFTs are for the conceptual approach to understanding GDEs within the TMG.

The first step is to resolve the scale issue, involving both the geology and the second step would be to analyse the geomorphology. Figure 5.2 shows the two-step approach that can be applicable for investigation of GDEs within the TMG aquifer. Because of the lack of information about GDEs within the TMG, a geological scale refining is necessary. In Chapter three compartmentalisation of the TMG by faults was suggested and it is in these units that the PFTs need investigation. Such an investigation may lead to a refinement of these units by including the ecological component, which in the long run may result in some classification.

The second step after resolving the geology would be to look at the geomorphology. Differentiation of the area into land systems may be useful. Land systems refer to an area or group of areas of similar topography, soil and vegetation (NSW NPWS, 2000). It is from these areas that one can further differentiate land facets. Land facets are smaller areas that make up land systems. For the case of the TMG, the different facets may be rock outcrops, slopes and valley floors. It is in the land facets that an investigation of PFTs may be initiated, for example at the riparian corridor, or a spring, situated at a particular land facet.

Once the scale issue is resolved, one can initiate an in-depth investigation of PFTs.

Having identified PFTs as in Figure 5.3, then the dependency analysis is a necessary step. Dependency analysis includes both determination and degree of dependency. The dependency analysis is divided into assessing water regime and determination of water requirements.

Assessment of water regime includes identification of sources of water, processes of water requirements and patterns of water usage. Identifying the water source is critical because extrapolation-determined water use by empirical formulae will remain inaccurate as long as there are doubts about the source of water (Scott *et al.,* 2000). Both the patterns of water usage and processes of water requirements, which are important for both phenology and life span, are also important in determination of dependency. Another important aspect in assessing water regime is to determine the degree of dependency, whether facultative or entirely dependent. This may allow one to rank the dependency within the land system under investigation.

Water requirement determination of the system is another important aspect of the dependency analysis as it helps with the effective management planning. Here responses to perturbation, which forms part of the PFT approach, get consideration. Murray *et al.* (2004) gave a hypothetical representation of how ecosystems may respond to groundwater changes in terms of ecosystem health. Some may show linear response (alpine bogs, etc.) while others may show a stepped response (for example wetlands and salt marshes). It is in this aspect the threshold analysis may be carried out. The threshold analysis seeks to find out the extent of impacts of water extraction, to establish whether the ecosystems will go through a collapse, moderate or minor impact.

The above description is important for an effective management strategy. The effective management strategy includes three elements, *threat analysis*, *establishment of a retention strategy* within the context of an *ecosystem approach*. The threat analysis involves identifying threats as well as testing the ability to withstand such threats. The ecosystem approach is a holistic approach that involves ecological elements as well as institutional elements. Chapter six will cover the ecosystem approach. The retention strategy on the other hand involves a method of comparing vulnerability to irreplacibility, with an objective to suggest areas that need high conservation status. Chapter six also covers GDE management in more detail.

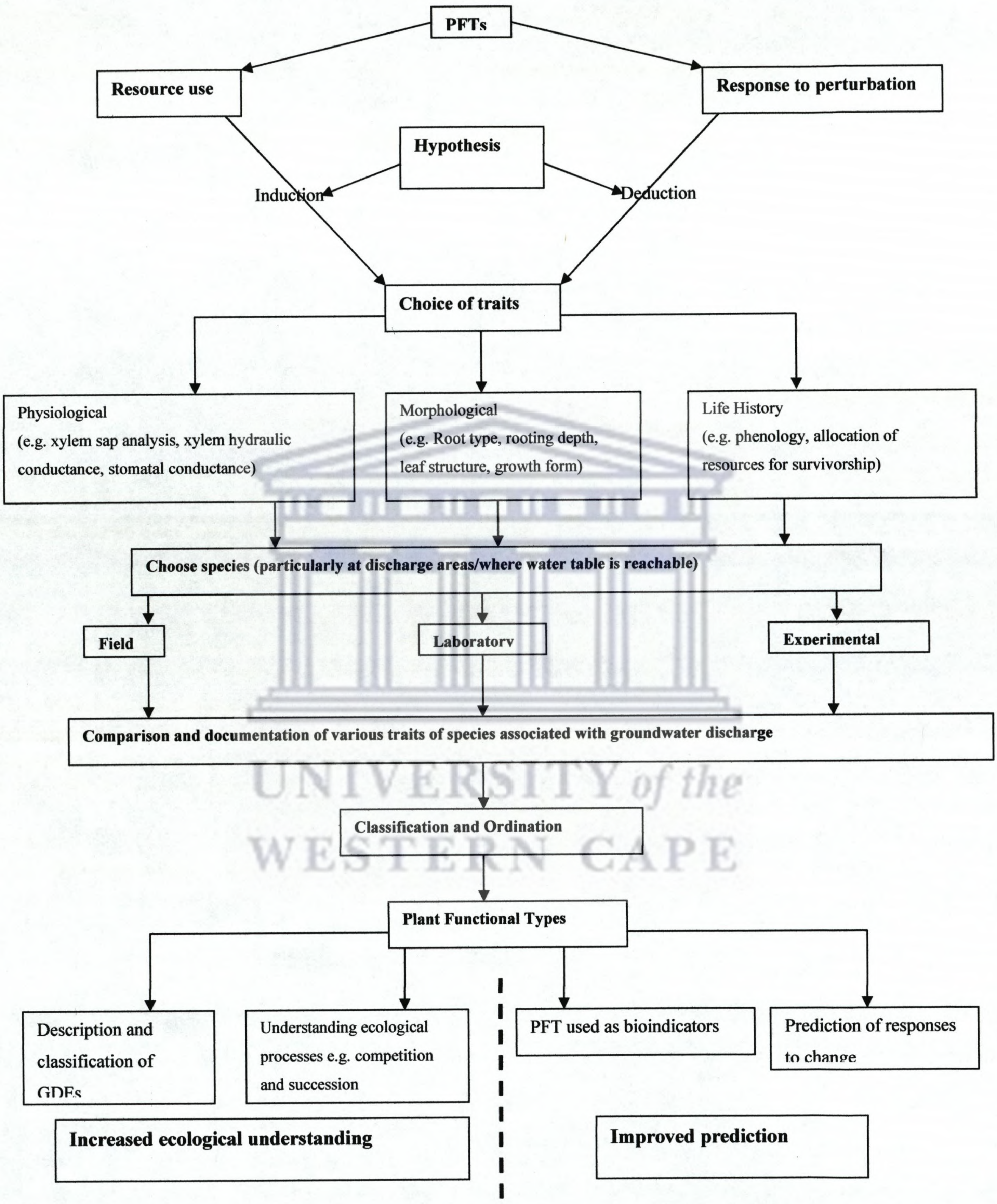


Figure 5.1: The scheme summarizing the concept of PFTs (modified from Duckworth *et al.*, 2000)

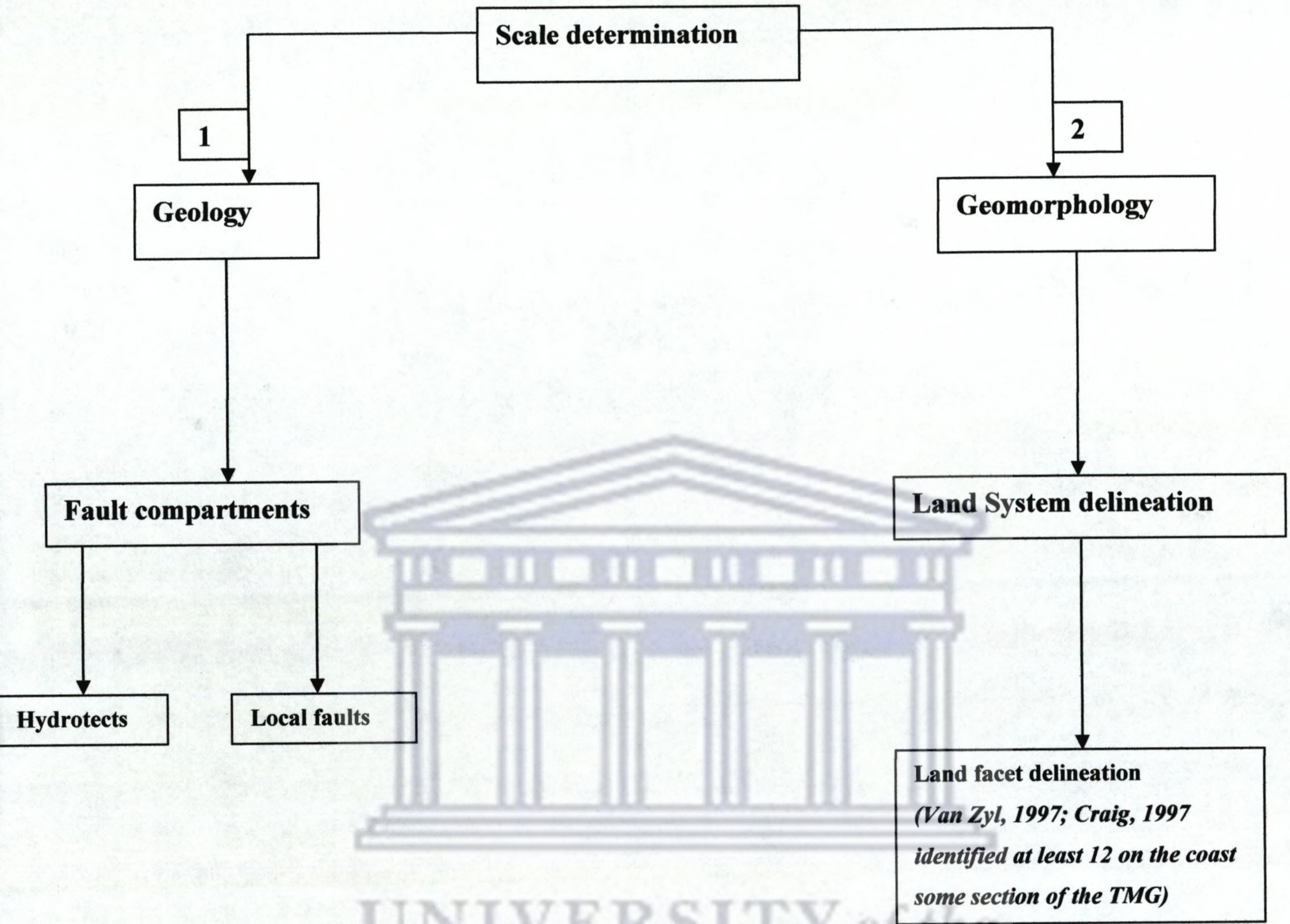


Figure 5.2: The two-step groundwork approach required for setting study sites in the TMG aquifer.

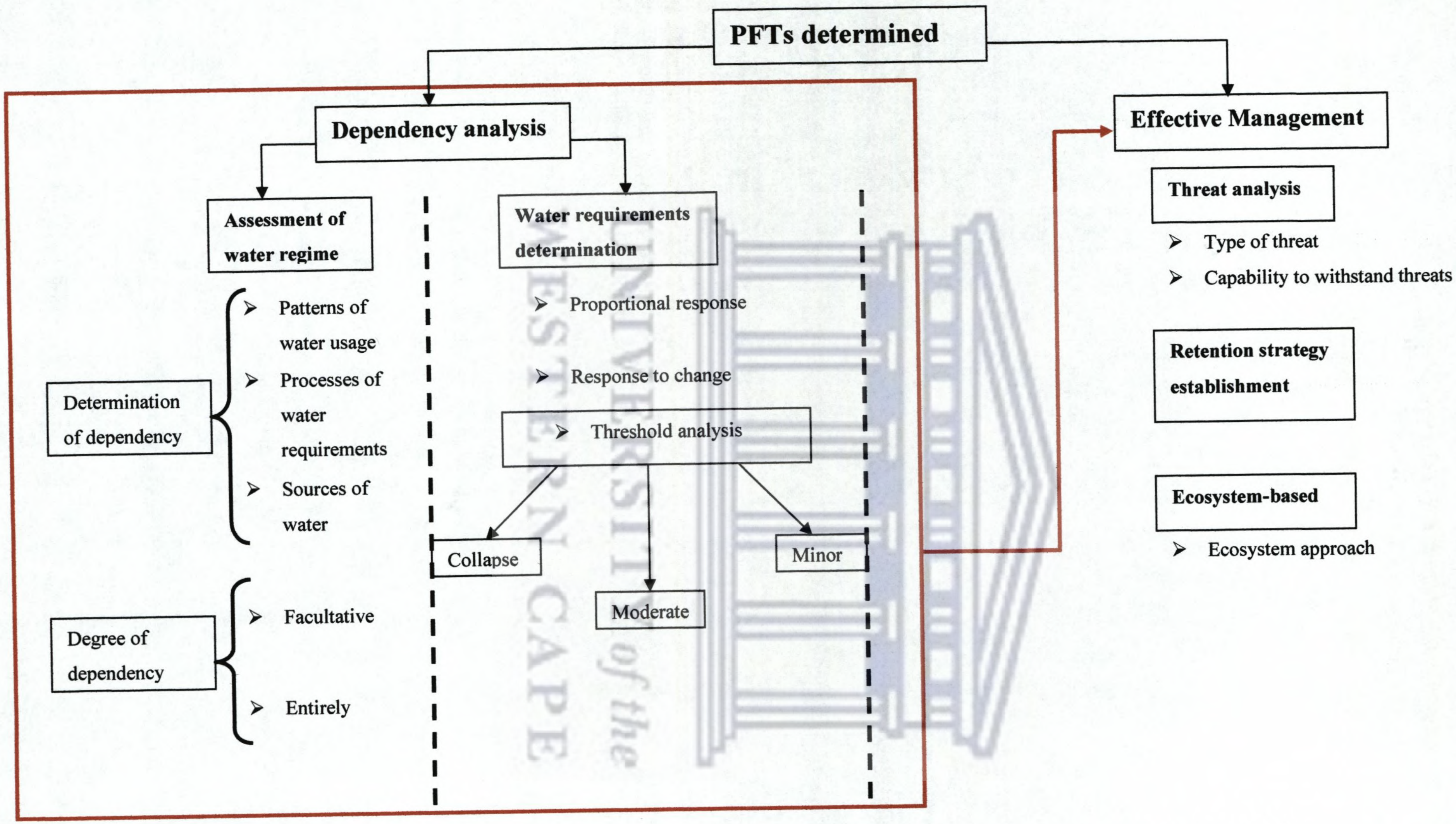


Figure 5.3: Flow chart of how work done on PFTs can be used for effective management of GDEs within TMG aquifer

10.1 Summary of PFTs

11 They are plants that are similar in morphology, physiology and life history traits.

12 Nonphylogenetic groups of species that show similarities in their resource use and response to environmental and biotic controls.

13 They are useful in flattening taxonomic problems as taxonomically unrelated species may have similar ecological requirements.

14 They are useful for predicting ecosystem response to anthropogenic impacts.

15 They can be projected to both community and ecosystem understanding.

16 They are useful as not all ecosystems can be modelled (Global Change Terrestrial Ecosystems).

Chapter 6

6 Management of the GDEs within the TMG

From the discussions in chapters 4 and 5 it can be asserted that when groundwater dependence occurs, it will be localized. Observations in the TMG suggest that groundwater discharge is a localized event along faults, springs and seeps. The Policy and Strategy for Groundwater Quality Management in South Africa (2000) recognizes the usefulness of groundwater especially for rural communities and the fact that there is a need to act fast because of the increase in human induced threats.

First and most important to ecosystem management is a classification of plants according to functional adaptations, which are:

- *Some species (whether animal or plant) are persistors.*
- *Some are disappearers or avoiders, and*
- *Some are colonisers.*

As mentioned earlier, effective management can only be through a holistic yet systematic approach, the *ecosystem approach*. The ecosystem approach is a comprehensive basis for designing groundwater strategies that are community-based, and within a regional context (Neufeld, 2000). The ecosystem approach has two arms, the ecological and the institutional arms.

The ecological arm can be further subdivided into four properties, which are *boundaries*, *objectives*, *functions* and *cumulative effects*.

On the *ecosystem boundaries* there is an expansion from site-specific conditions to regional scale. For the case of the TMG, the consideration would have to be on the compartments. The importance is that one may be able to check the hydrologic regime (catchments) linking physical, chemical and biological components of the ecosystem (Neufeld, 2000; Ward and Stanford, 1989a). The groundwater-surface-water interaction, whether in the stream, hyporheic zone or in estuaries is another key boundary issue.

The *ecosystem function* is a property that deals with the linkage of processes (physical, chemical and biological). Functions performed by ecosystems include storage and cycling of nutrients and chemicals, biological productivity and diversity as well as hydrological fluxes.

The *ecosystem objectives* are necessary because every management strategy must have specific goals and objectives. This is the property that recognizes that human health and welfare relies on natural resources. There needs to be a focus on ecosystem health and integrity.

Cumulative effects represent the property that offers a platform for assessment and monitoring of effects and responses. Effects and responses may hamper with the ecosystem structure as well as ecological functions at various scales.

There are four subdivisions of the institutional arm, which are *adaptable, integration, coordination* and *catalytic*.

The *adaptable* property is essential because it encourages the learning strategy adoption that is based on innovation and experimentation. It also allows for decision making even when data is not enough. It is also a platform to review and reformulate goals, methods and strategies based on ecosystem monitoring and research.

The *integration* property raises the sustainability question, and recognizes that it is only through integration rather than discrete efforts that can ensure achievement of long-term goals. It ensures a mix of clear regulation, voluntary action and economic incentives

The *coordination* property is essential in the sense that it ensures linkage of resources and efforts, and encourages exchange of information, discussion of common interests and cooperative decision-making.

Catalytic property is an important one because it encourages community involvement and responsibility. It also encourages communities to interpret and apply ecosystem principles to their own activities. It is the activities of the people that put more pressure on ecosystem structure and function (Odum, 1971), so management can only be effective when they are responsible.

Figure 6.1 summarises the ecosystem approach.

It is from this ecosystem approach that a *retention strategy* can be set. Through a retention strategy, one can:

- *Find out species that will disappear from the landscape if nothing is done.*
- *Identify threats to persistence of species for example intensive pumping.*
- *Group species according to processes that threaten them.*
- *Identify those that will be affected most by such threat processes, and hence*
- *Determine managing of such threats.*

A hypothetical plot (Figure 6.2) of irreplaceability versus vulnerability (Margules and Pressey, 2000) can be useful for such a strategy. However the scale issue is important for this task because:

- *Measurement of the regional flux is a huge task, to set priorities whether areas are groundwater dependent ecosystems*
- *Measuring their vulnerability and rank them (GDE) according to irreplaceability can be a challenging issue.*

So the theoretical plot would be useful at a small catchment scale, to focus more locally than regionally. This means establishing scale of investigation of the GDEs will be important before any investigations. Once the dependence on groundwater is proved and patterns of water use determined, effective management of water resources will be needed. This will be possible because water fluxes (including evapotranspiration) could be accurately measured.

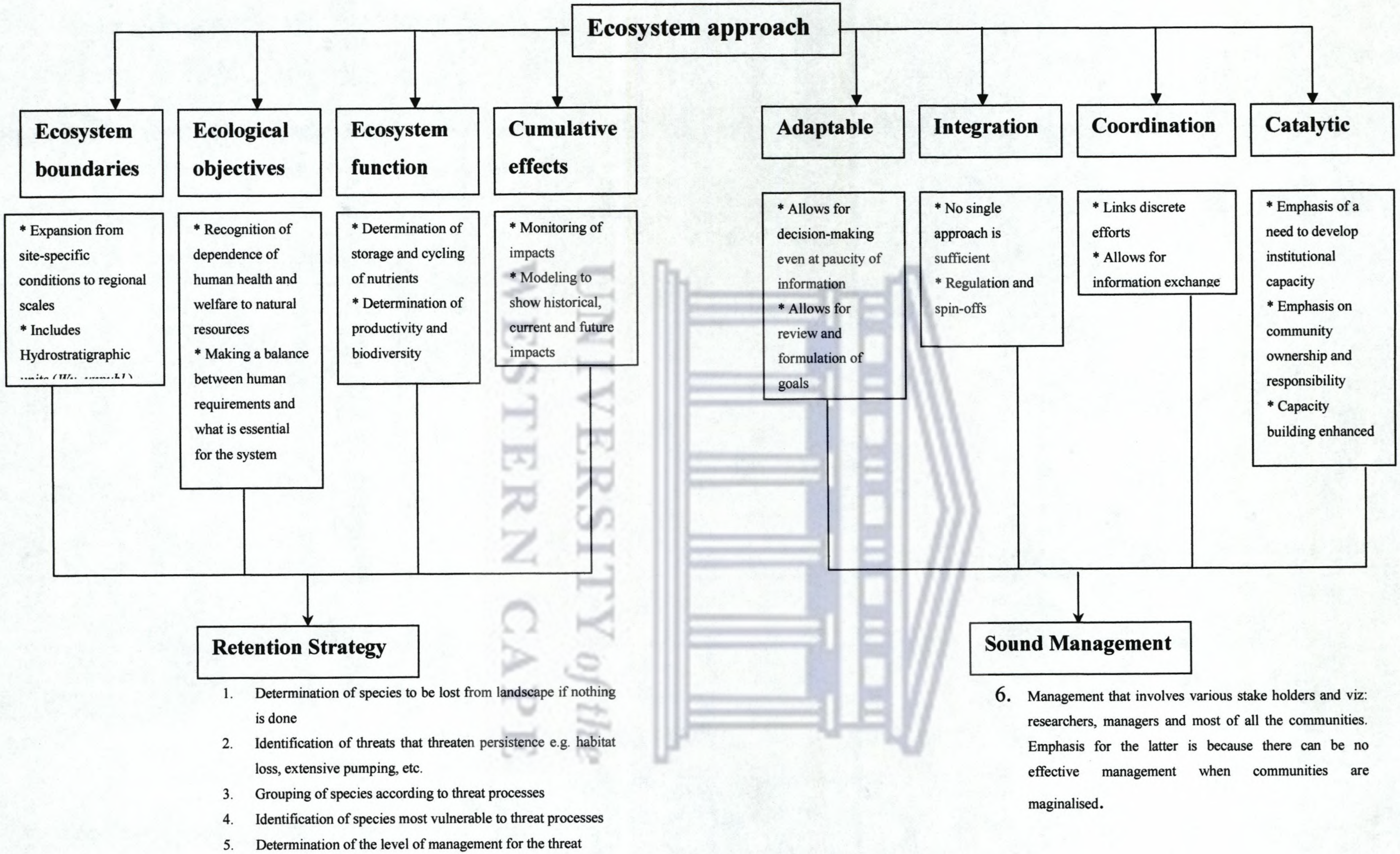


Figure 6.1: The ecosystem approach (*modified from Neufeld 2000*)

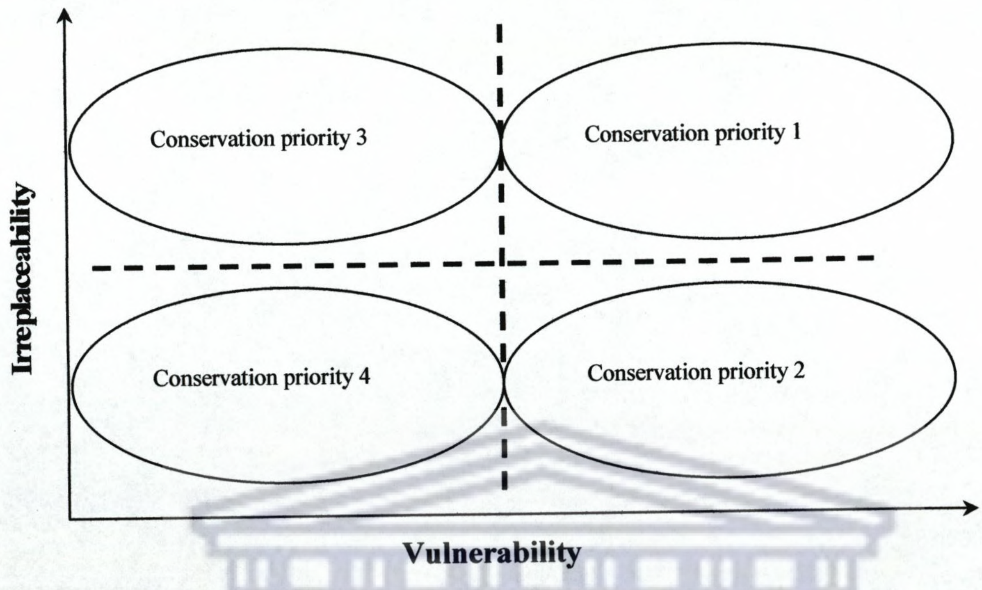


Figure 6.2: A hypothetical curve showing how a retention strategy can be set upon. (Modified from Margules and Pressey, 2000)

Chapter 7

7 *Conclusions and Recommendations*

7.1 Conclusions

Understanding GDEs within the TMG is difficult as there is little information. The lacking information about water sources and water use patterns of plant species is the main reason for the poor understanding. The conceptual understanding carried out here is the first necessary step to understand GDEs within the TMG aquifer. So far the GDE research in the TMG has been "curiosity-driven" rather that "practically oriented". The conceptual understanding in this thesis has different components and they are:

1) **Literature survey** – *Collation and synthesis of currently existing literature in trying and meet the first and second objectives of this thesis. The three types of ecosystems introduced are recharge zone, in-aquifer and discharge zone ecosystems. TMG aquifer structure description has led to elimination of the recharge zone as a possible area of groundwater dependence. This is because of the thinking that water levels are far too deep for roots to reach up in the mountain areas. The other challenging area in the TMG aquifer is the in-aquifer ecosystem. This is because the TMG, unlike the karst or dolomite systems, has no caverns. The literature so far has revealed association of in-aquifer ecosystems with caverns. However the possible existence cannot be ruled out especially in fractured areas drained by streams. The discharge zone received more emphasis, mainly for practical reasons. The discharge zone is vast and made up of several ecosystems and they are wetland, baseflow, spring and estuarine ecosystems. These discharge zone ecosystems must be target areas for further investigation.*

2) **Geographical Information Systems** – *This is useful in locating GDEs along a landscape and provides a platform to store, manipulate and to display data. The data may include rainfall, groundwater, elevation, chemical, soil and vegetation data. Chapter four proved watershed modelling to be useful in checking surface water inputs into the ecosystem and are also useful in checking groundwater inputs. The use of the Digital Elevation Models is important in watershed modelling. In the TMG, data related to GDEs is yet to be collected and organized in databases for manipulation in GIS. The databases may help with the understanding which should include geological, hydrogeological, hydrological, vegetation and soil data.*

3) **Plant Functional Type concept** – *The PFT concept has been defined and described to suggest it as a more reasonable approach in the understanding GDEs within the TMG. This concept has not been receiving much attention in South Africa and more favour has been for the biome concept. Because it puts more emphasis on functional biology means that it is going to be useful in developing trait (groundwater dependent vegetation traits) database that is lacking at the moment. The trait database will make it possible to do dependency analysis.*

4) **Management of GDEs** – *The suggested ecosystem approach is a possible effective management strategy for the GDEs within the TMG aquifer. Management of ecosystem is important especially when resources they depend on have a potential for human consumption. Since the ecosystem approach includes the capacity building element, it is important for a developing country like South Africa. There is also a need for integration of various stakeholders especially when there are pending critical developmental issues as raised by the Millenium Development Goals (MDGs) as well as the World Summit on Sustainable Development held in Johannesburg in 2001.*

7.2 Recommendations

1) There is a definite need to identify GDE types within the TMG aquifer. This would be possible by determination of water sources for vegetation as well as the water use patterns to find out the degree of dependency.

2) There is also a need to classify GDEs using the PFT concept. That would relate or measure plant functional traits, whether the functional trait response is related to groundwater use.

3) There is a further need to compile the trait database for the GDEs. The database can then need regular updating and manipulated on a GIS platform.

Establishment of groundwater dependence in the TMG needs a complex investigation and because of this the scale issue has been recurrent in the discussions in this thesis. A greater challenge for fractured rock aquifers lies in creating a 3-dimensional picture of groundwater flow. At the moment the flow models are mainly 2-dimensional, which is not representative of the actual flow. Without understanding groundwater flow, th understanding of GDEs will not be adequate.

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