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The Groundwater Flow Regime of the Kombat Aquifer, Namibia.

by

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DECLARATION

I declare that the thesis hereby submitted by me for the degree of Master of Science at the University of the Free State is my own independent work and has not previously been submitted by me at another University/faculty. I furthermore cede copyright of the thesis in favour of the University of the Free State.

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Abstract

The Kombat Aquifer, as investigated in this study, comprises the dolomite of the upper and lower Otavi Group, encompassing a radius of about 10 km around Kombat Mine.

Groundwater flow controls, structural influence, and hydraulic behavior of the groundwater flow system are investigated. The entire study area is initially conceptualized within a typical karst aquifer framework. Readily available data on climate, groundwater water levels, satellite geology, water chemistry, hydraulic tests, borehole hydrographs, borehole fracture logs, water strikes, geomorphology, supplemented with fracture field mapping and groundwater temperature logging, are used to delineate and study structures, structural controls, hydraulic response and to conceptualize the groundwater flow regime of the Kombat Aquifer.

The results indicate that tectonic facies, layering, geomorphology, relief and relative position along the flow system largely influence the distribution of storage, permeability, hydraulic head stability, vertical and horizontal flow patterns, as well as the geometry of the Kombat Aquifer groundwater flow system. A comparison of groundwater temperature of the recharge and the discharge areas shows a temperature increase of about 5^{o}C. An analysis of hydrograph recession curves enabled the understanding of the hydraulic response as well as the hydro_ dynamics of the flow system and confirmed the co-existence of two mutually inclusive groundwater flow components. The statistical examination of transport parameters reveals a very high tendency of dispersion, suggesting that extreme transport values could be more significant to groundwater flow parameterization than average values. A joint combination of blocky fracturing, flat relief and decreasing proximity to discharge zones enhance the long-term safe yield and hydraulic stability of production boreholes. Hence areas that are dominated by parallel fracturing, high elevation and long distances to discharge zones have the most unstable hydraulic head response and the lowest borehole yields. Results from hydraulic tests show that two permeability networks co-exist in different combinations and define the physical framework within which groundwater resides and moves. The connectivity between the two permeability networks characterise the hydraulic response of the Kombat Aquifer to groundwater withdrawal.

Key Words: Aquifer, structure, faults, fractures, Karst, groundwater flow, flow Regime, Kombat.

Glossary

Accessory pathways - The non-preferential groundwater flow sites in the saturated zone (see privileged pathways).

A conceptual model – An interconnected sequence of recharge areas, permeability distributions, and geologic substrates that collectively provide a visualization of the way in which water is added to the system, stored in the system, transmitted through the system, and discharged from the system (White, 2003).

A fault set - consists of a group of more or less parallel faults.

A fault system - consists of two or more fault sets.

A flow system - consists of flow pathways which are bound in space-time, with distinct flow geometry and flow dynamics. This concept infers distinct groundwater flow controls that can be separated distinctively in space, time and character from the recharge to the discharge zones within a specific domain of interest.

A fracture set - consists of a group of more or less parallel fractures.

A fracture system - consists of two or more fracture sets.

Allogenic recharge - Surface water injected into an aquifer at a swallet of a sinking stream and/or surface water transported from its original location to a distant recharge site.

Aquifer – A body of rock, consolidated or unconsolidated, that is sufficiently permeable to transmit groundwater and yield significant quantities of water to wells, boreholes, and springs.

The term aquifer is defined as a body of rock, consolidated or unconsolidated, that is sufficiently permeable to transmit groundwater and yield significant quantities of water to boreholes and springs. An alternative pair of definitions widely used in the water-well industry states that an aquifer is sufficiently permeable to yield economic quantities of water to wells, whereas aquicludes are not (Freeze and Cherry, 1979).

However, the term aquifer should always be viewed in terms of the scale and context of its use. Sometimes it is used to refer to individual layers, to complete geologic formations, and even to groups of geologic formations (Freeze and Cheery, 1979).

Autogenic recharge - Surface water that is trapped in a depression or relatively permeable on-site zone, and directed into the aquifer without being/forming part of run-off.

Brittle deformation regime - A form of deformation in which material failure is characterized by shuttering. In this study it is restricted to certain lithofacies and geologic contacts.

Collector networks - Fractures and other preferential water pathways in the vadose zone.

Concentrated flow or focused flow - An essentially 2D to 1D groundwater movement, related to the more open fractures and characterized by relatively fast flow (high permeability) and low storage.

Discharge area – An area in which there is an upward component of hydraulic head in an aquifer. Groundwater flows toward the land surface in a discharge area and escapes as a spring, seep, base flow to streams, or by evaporation and transpiration.

Dissolution induced phenomenon - Sinkhole plains, depressions, blind valleys, slope dissecting valleys, lakes, caves, and underground conduits that are associated with the dissolution nature of dolomite or limestone.

Diffusive flow - Essentially three-dimensional groundwater flow, related to less open fractures or fissures, and characterized by high storage and low flow velocities.

Endokarst - The suite of karstic features developed underground. For the sake of this study, the term endokarst will be restricted to the vadose zone.

Epikarst - The uppermost weathered zone of a carbonate aquifer, with a more homogeneous porosity and permeability distribution compared to the underlying aquifer.

Exokarst - A generic karstic geomorphic term referring to the suite of karstic features developed on the land surface.

Faults - Rupture surfaces along which the opposite walls of a rock mass have moved past each other.

Fracture - Divisional planes or surfaces in a rock mass, induced by secondary deformation processes, and along which there is no visible movement parallel to plane or surface. The term fracture denotes material failure by breaking under either tension or shear forces. For the sake of this study, it includes joints, sheared bedding planes, and fissures, but excludes undisturbed bedding planes. At a storage analysis level, this study will distinguish between fissure and fracture storage for the sake of scaling up the rate and nature of storage release.

Fracture geometry - The size, shape, orientation, and position relationships of fractures, fracture sets or fracture systems.

Fracture flow - Groundwater flow predominantly occurring in fractures.

Fractured flow system - consists of flow pathways bound in space-time, with distinct flow geometry and flow dynamics and where groundwater flow predominantly occurs in fractures.

Fracture flow regime - consists of more than one fractured flow system bound within a single groundwater recharge basin and/or hydrologic basin.

Function - How structural attributes facilitate and /or perform various processes and activities to accomplish certain outcomes within a flow system or flow subsystem.

Groundwater recharge basin - An area where all the groundwater flow and/or groundwater discharge comes from (confines within which all recharge makes its way to a single or group of discharge zones).

Hydrostratigraphic units - Bodies of rock with considerable lateral extent that comprise a geologic framework for distinct hydrologic systems (Maxey, 1964)

Internal run-off - Overland storm flow into a closed depression, where it enters the aquifer through sinkhole drains.

Karst - A terrain comprising of distinctive hydrology and landforms that arise from a combination of high rock solubility and well developed secondary (fracture) porosity, such areas are characterized by sinking streams, caves, enclosed depressions, fluted rock outcrops, and large springs.

Karstic terrain - A landscape containing or comprising caves, sinkholes, dolines, blind valleys, barren, springs, and dissolution-induced depressions or plains (Ford and Williams, 2003).

Inflow-outflow system - The sequence and interrelationships of the physical flow elements between recharge and the discharge zones.

Input landforms - blind valleys, barrens, sinkhole plains, dolines, epikarst.

Physiography - The study of landforms, their relationships and controls on drainage.

Privileged pathways - Preferential groundwater flow sites in the saturated zone.

Stratigraphy - A phase of geology dealing with the sequence in which rock formations have been deposited.

Structure - For the scope of this study, the appropriate definition of the term structure will follow that provided by Moon and Dardis (1988), which suggests that the term embraces rock type (lithology), the arrangement of strata (stratigraphy and tectonics), and changes of these properties. The term therefore refers to the static attributes of a fractured flow system. It attempts to delineate the major levels of organization of the units that comprise the flow system, including both internal and external forms. The concept also extends to incorporate the relationships of such organizational units.

Superposition of hydrodynamics - The situations in which two or more characteristically distinct flow types occupy the same space at the same time.

Tectonic facies or structural domains - Distinct deformation zones, e.g. the Southern Otaviberg grabben, embricates, overfolding, flexure fracturing, parallel fracturing, blocky fracturing and shearing.

Acronyms

BHA – Borehole Hydrograph Analysis

BGR - Bundesanstalt fur Geowissenschaften und Rohsthhe

CP – Central Plateau

CV – Central Valley

DWA - Department of Water Affairs

E - Escarpment

EC – Electrical Conductivity

GBC – Grootfontein Basement Complex

GRFAFM - Generalized Radial Fractured Aquifer Flow Model

KARM - Kombat Aquifer Recharge Model

KP – Karstic Plateau

KS - Kalahari Sandveld

KWF – Kombat West Fault

MAP- Mean Annual Precipitation

n = Number of values or flow dimension

NAo – Auros Formation

NBa – Abenab Formation

ND – Namib Desert

NGa – Gauss Formation

NHt – Huttenberg Formation

NKt – Kombat Formation

NMa – Maieberg Formation

Nosib FM – Nosib Formation

OML - Otavi Mountain Land

OVUS- Otavi Valley Uitkomst Syncline

REV – Representative Elementary Volume

TOC- Theory Of Constraints

S – Storativity

SDZ- Southern Discharge Zone

SI – Saturation Index

SLLA – Southern Low Lying Area

T – Transmissivity (undifferentiated)

T(flt) – Transmissivity of major faults

T(fr) – Transmissivity of joints and fracture zones

WCDA – Water Chemistry Data Analysis

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 INTRODUCTION

1.1 Background

This study develops a preliminary conceptual groundwater flow model for the Kombat Aquifer, by gathering, analyzing, and synthesizing readily available data (*geomorphic, geological, hydro geological climatic and water chemistry data*). The focus is on structural controls on the existence and transport of groundwater, whilst the emphasis is on the influence of the interplay of geological structure, relief and lithology on groundwater flow patterns of the study area.

The northern boundary of the study area (**Figure 1**) extends along northern anticline of the Otavi Valley syncline, and extends between latitude 17.62^{o} and 17. 75^{o}. The southern boundary coincides with the southern lithologic contact between the Otavi Group and the less permeable rocks of Grootfontein Complex, covering a total area of 314 km^{2}.

The purpose of the conceptual groundwater flow model is to allow focused fieldwork in the confirmation of the distribution of major flow zones, thereby enabling groundwater resource investigators, managers and regulators to efficiently control the development and the safe use of the study area's groundwater resource.

Besides groundwater managers and regulators, other stakeholders include Kombat Mine, farmers in the surrounding area, a resettled community 4 km south of Kombat Mine, and Namwater.

The geohydrology division of the Department of Water Affairs (DWA) as the primary stake holder envisions this study as an enabling platform towards judicious allocation of the available groundwater resources to the local farmers, as well as to bulk water supply authorities like Namwater.

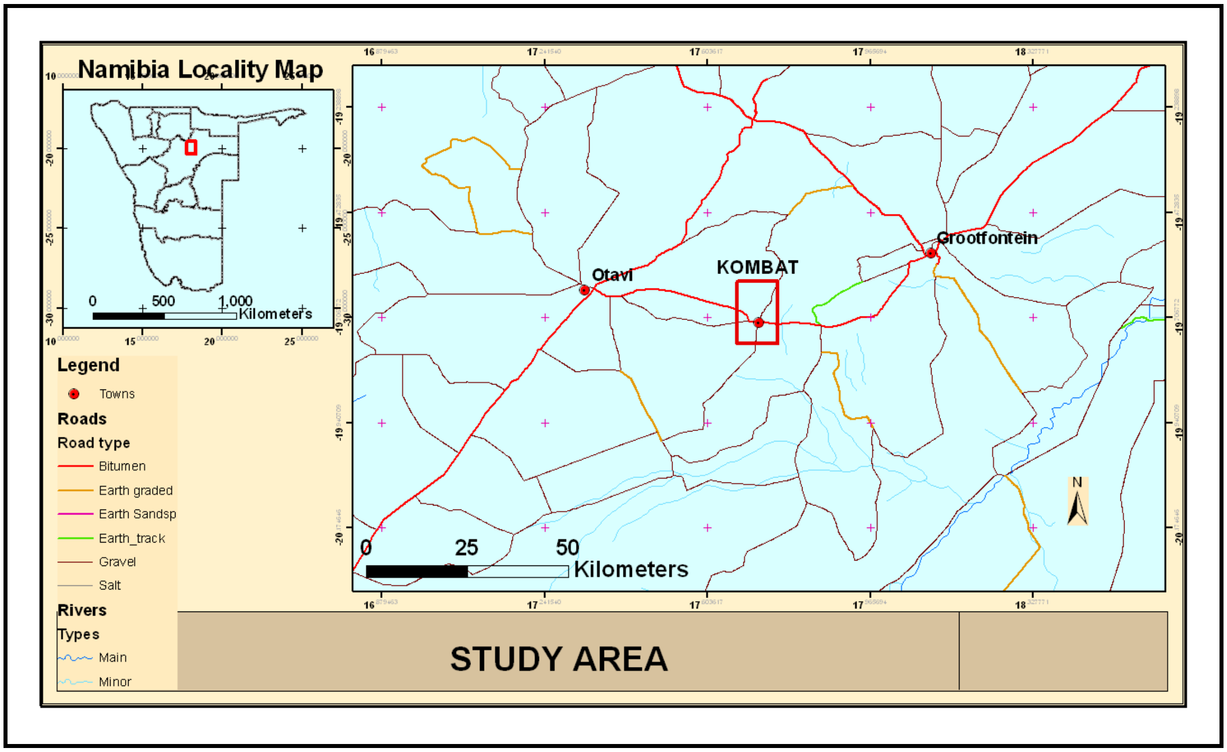

Figure 1: Locality map of the study area

From a geohydrological and strategic point of view, the study forms part of the sectional modeling of all the four west-east trending carbonate synclines of the so-called Otavi Mountain Land (OML). The OML is nationally considered a short-term source of water supply to the country's Waterberg Water Supply area, as well as to the central high lands, including Windhoek - the national commercial hub.

This study advocates that the opportunity to resolve the study area's groundwater problems can be realized by a shift from large-scale regional studies to localizing data, especially to scales at which water abstraction permits are granted.

This study argues that localizing data and information, coupled with incremental sectional modeling of the synclines of Otavi Mountain land, will lead to an in-depth understanding of the local groundwater flow constraints. This approach presents an alternative to previous efforts, especially in terms of improving the physical representation of the flow system.

1.2.1 Local Studies

The first large-scale groundwater investigation of the study area was initiated by the Geological Survey of Namibia in 1968. Since then, the study area has largely been investigated by way of assessing the groundwater supply potential of geological structures, especially faults and lithologic contacts (Campbell, 1980a; Seeger, 1990).

However, between 1994 and 2007, the mine contracted two hydrogeological consultants with the objective of studying hydrogeological aspects of the immediate surroundings of Kombat Mine. The aim of these investigations was to come up with hydrogeology-based scenarios of optimizing the Kombat Mine dewatering scheme.

Between 1994 and 1997, BGR conducted a large-scale study, oriented towards optimization of groundwater withdrawal, as well as environmental sustainability of the area; the emphasis of that study was to establish a better understanding of recharge dynamics and to apply groundwater modeling as a tool in distinguishing between areas with sufficient data, and those with inadequate hydrogeological data.

A summary of the focus of hydrogeological work in the study area is provided in Table 1.

Table 1: Prominent hydrogeology related studies around the study area

Year	Title	Focus	Author
1980	The hydrogeology of the Kombat Mine	Structural importance on recharge and discharge	Campbell
1989	Report on a visit to Kombat Mine	General hydrogeology and flood recovery	Campbell
1986	Ore Bodies of the Kombat Mine, South West Africa, Namibia	Relations between deformation and mineralization	Innes & Chaplin (Published)

1990	Evaluation of the Groundwater resources of the Grootfontein Karst Area	Groundwater supply potential of faults and lithologic contacts	Seeger
1992	Evaluation of the hydrogeology at Kombat Mine	Only a desk study was completed	SRK (pty) LTD
1994	A study of Faulting in the Asis West Mine, Kombat, Namibia	Fault controls on mineralization	Greenway
1995	The structural evolution of the Kombat deposit, Otavi Mountain Land, Namibia	Deformation and mineralization	Deane (Published)
1997	Hydrogeology & isotope Hydrology of the Otavi Mountain Land and its surroundings	Regional modeling.	Ploethner
2007	Preliminary Hydrogeological Assessment for the Kombat Mine	Hydro geological aspects of faults and dewatering	GCS (Pty) LTD

1.2.2 Recent Developments in Literature

In recent carbonate aquifer literature, fractured carbonate groundwater flow systems have been categorized as either dual permeability (Mohrlok and Sauter, 1999) or triple permeability groundwater flow systems (Worthington, 2003), depending on the presence and/or absence of primary permeability.

Both views are supported by the observation of borehole and spring hydrograph behavior, which exhibits two and sometimes three major response frequencies to recharge (Sauter *et al*., 1992).

The dualistic view assumes:
(a) A lower permeability fissured system with a high storage capacity that is drained by
(b) A high permeability but low storativity fracture/conduit network.

The triple permeability view assumes:

(a) A lower permeability matrix system with a high storage capacity and three-dimensional flow components. The permeability of the matrix system can either be due to primary porosity or small-scale secondary deformation at the level of fissures.

(b) An intermediate permeability fractured system with low storage, and a characteristic two-dimensional flow component, and

(c) A very high permeability conduit network system with direct recharge to discharge area connections.

Although hydraulic responses similar to those described above have been observed in the study area, there has been no information to confirm the existence of a conduit network system. Therefore a dual permeability approach, as opposed to a triple permeability approach, is suggested as the appropriate analytical framework for conceptualizing the Kombat Aquifer.

Karst Groundwater Recharge

The understanding, quantification and relative importance of various karstic recharge mechanisms has been the focus of recent carbonate aquifer studies (Harlow, 1997; Herczeg *et al*., 1997; Mohrlokc and Sauter, 1999; MC Kay, 2001; Geyer, 2006).

Karstic recharge mechanisms have been closely associated with distinct karstic landforms and classified on the basis of infiltration mechanisms supported by such karstic landforms (Herczeg *et al*., 1997; White, 2003; Klimchouk, 2004, and Lerch, 2005).

Founded on the concept of recharge mechanism, Herczeg *et al.* (1997) classify karstic recharge into two categories, namely diffuse and focused (point-source) recharge, while Lerch (2005) adopted a more conceptual and generic approach, classifying karstic recharge into either allogenic and autogenic.

What is common to the adopted recharge categories, is that both allogenic and focused recharge mechanisms are attributed to the same recharge mechanism – that is rapid and preferential infiltration, while the term autogenic recharge is wider than its counterpart - diffuse recharge. According to White (2003), autogenic recharge consists of two point source recharge components, namely a diffuse and a discrete recharge component.

Furthermore, autogenic recharge is often associated with *in-situ* soil cover or highly weathered zones (epikarst) of the elevated portions of karstic groundwater flow systems, which are capable of capturing and storing surface water for days or even weeks before releasing it to the underlying fractures (Berbert-Born, 2000).

However, allogenic recharge takes place along relatively open surface structures, such as sinkholes, vertical caves, bedrock fracture and blind valleys, which are directly connected to the groundwater table via extensive subsurface fractures and fault zones (Berbert-Born, 2000).

The investigative value embodied in this classification is that karstic recharge is confined to distinctively map-able geomorphic units, thereby evoking a geomorphic units-based model of recharge antecedents.

Anchored in conceptual understanding and resource limitations, a wide variety of recharge quantification methods have been applied on Karstic groundwater systems. These methods include techniques ranging from hydraulic tests, artificial and environmental tracers, hydrograph analysis, inverse numerical modeling, conventional Darcy flux and hydrochemical techniques (Harlow, 1997; Mohrlok and Sauter, 1999; MCKay *et al*., 2005). Most recharge estimation methods are quite useful, especially in combination. However, the artificial tracers, environmental tracers and inverse numerical modeling methods have proved to be more reliable than the others (Leaney and Herczeg, 1994).

Groundwater storage system

Long term borehole Hydrograph observations have illustrated the fact that the maximum groundwater levels in boreholes are read several weeks after maximum spring discharge, and the same is true for boreholes located within hydraulically active fracture zones compared to those completed in less fractured rock. This observation has led investigators to assume the presence of a sluggishly emptying storage, which is located in the epikarst and/or the fissured system (Worthington, 2003; Hovorka, 2004).

The epikarst storage model assumes that the bulk of recharge water is slowly released from the epikarst, while the aquifer storage model assumes that the bulk of recharge is conveyed via vertical shafts to the phreatic zone, where, due to the difference in hydraulic gradient, water flows from the conduit into the fissured system (Mohrlok and Sauter, 1999).

Groundwater discharge

The mechanisms and spatial patterns of groundwater discharge in karst aquifers are closely linked to recharge and storage processes. Worthington (2003) identifies two groundwater discharge mechanisms, namely rapid and slow discharge mechanisms. Worthington (2003) contends that discharge mechanisms are responsible for multiple segmentation of borehole and spring-discharge hydrographs and associates them to distinct permeability and storage elements.

According to Worthington (2003), the rapid discharge is highly temporal, associated with stormy recharge events, and conveyed through the higher permeability groundwater flow component, while the slow discharge mechanism is continuous, associated with both stormy and normal recharge events.

Owing to the fact that discharge mechanisms are conveyed through fissures and fractures, they are often correlated to fissure and fracture groundwater storage (White, 2003).

In line with Worthington's (2003) observations, Campbell (1980) and Mijatovic (1996), contend that groundwater discharge in karst aquifers is often associated with flattening hydraulic gradients and concentrates at particular points, for example; fountains, springs, and seepage faces.

The spatial distribution of groundwater discharge in fractured and partially karstified aquifers would therefore ideally be controlled by the spatial distribution of fractures and fissures. However, this is often violated, especially in drought prone arid to semi arid areas, because in response to pressure sensitivity differences, the slow discharge mechanism often feeds the rapid discharge flow component; hence the observed concentrated discharge.

1.3 Study Context and the Research Problem

A brief account of literature development on fractured carbonate hydrogeology shows that, in the last three decades, carbonate aquifers have been approached within the following frameworks;

- The simplest and the most commonly-used approach assume that fractures are of local importance, and that the fracture density is sufficient to treat the aquifer as an equivalent porous medium.

- The second approach recognises that fractures may be laterally extensive and more conductive than the undisturbed rock, in which case a double porosity model can be assumed.

- The third approach recognizes the existence of high permeability networks of conduits within the aquifer. However, despite cumulative evidence of the existence of preferential flow i.e. reported existence of sinkholes, dolines and solution cavities (Campbell, 1980; Seeger, 1990; Deane, 1995), whereas, the third approach has never been tested in the study area.

Theoretical karst hydrogeology advocates that ignoring preferential flow and/or the scale at which preferential flow is an active flow component, has the potential of leading investigators to narrow the scope of their investigations. As a consequence, investigators inherently apply the first approach and justify the use of readily available porous medium tailored software (Worthington, 2003; Martin *et al*., 2002; Hovorka *et al*., 2004).

Characterising carbonate aquifers as either porous or karst media is discouraged, and found inappropriate in modern karst literature (Worthington, 2003). This is because most carbonate aquifers have three types of porosity: Intergranular matrix porosity, fracture porosity, and large cavernous conduits (White, 1969, White and White, 1977; Smart and Hobbs, 1986, Worthington, 2003, Martin *et al*., 2002, Hudson, 2002)

It should be understood that the karstic and porous medium nature of carbonate aquifers represent the two end members of the natural state of carbonate aquifers, implying that there is no carbonate aquifer that is solely karstic, while most of these aquifers fall somewhere between the two end states.

Of parallel importance is the fact that studies based on boreholes as sampling and monitoring points concentrate on studying fracture and matrix (fissure) flow, and therefore little is known about rapid (conduit) flow. Conversely, spring flow and tracer tests studies concentrate on conduit flow. Therefore using either borehole or conduit/fast flow information only, leads to the partial characterization of carbonate groundwater flow systems.

In the absence of adequate borehole and conduit flow information, and using the premise that the understanding of the groundwater flow system is the key constraint to groundwater flow modeling and consequently to sustainable groundwater development and use, this study takes advantage of the cause and effect relationship between geological structure and groundwater flow behavior to pursue its objectives and advance the current understanding of the Kombat Aquifer groundwater flow system.

1.3.1 Research Question

In order to develop the research question to this study, a brief summary of the problems, objectives, and findings of the most comprehensive hydrogeological studies conducted in the study area is given. This summary aims to indicate the knowledge gap that the current study is addressing.

Between 1968 and 1970, the Geological Survey of Namibia conducted a preliminary large scale hydrogeological investigation that included the study area. The aim of the investigation was the abstraction of large volumes of groundwater, and the objectives were to delineate faults, sinkholes and joints using photogeology and field observations. The results of this investigation included four high-yielding productions boreholes in the study area.

However, it was soon realized that the four boreholes could not sufficiently meet the growing water supply demand; therefore another investigation aimed at estimating available groundwater resources of the whole Otavi Mountain Land was undertaken by DWA between 1981 and 1989, leading to Seeger's report in 1990. Using ground geophysics and geological mapping, the investigation expanded the water supply capacity of the first study by locating boreholes on geological contacts and faults. The groundwater supply capacity of area I, of which the study area is part, was estimated at 14 Mm^3/a. In his recommendations, Seeger (1990) suggested that:

- In order to reliably estimate the groundwater resources of area 1, an isotope study should be conducted.

- A mathematical groundwater model should be set up to distinguish between areas with sufficient data and those with inadequate geological and hydrogeological data, and

- The mathematical model should be able to estimate exploitable volume and to be used as a management tool.

Due to lack of capacity to implement Seeger's recommendations, DWA asked technical and financial assistance from BGR, leading to the 1994 to 1996 groundwater investigation, on which Ploethner reported in 1997. Some of the relevant findings of the study include: Groundwater recharge originates from rainfall, takes place at an altitude 1760 m amsl, recharge takes place only during exceptionally wet periods, and the process of recharge is rapid.

As a groundwater management tool, the mathematical groundwater model Ploethner (1997) developed was not very helpful (personal communication with the Deputy Director-Hydrogeology, 2007), hence the need for an alternative approach.

Borrowing from the field of project management, this study used the promises of the “Theory Of Constraints” (TOC) in the development a solution to this problem.

The TOC advocates that solutions to problems should be organized in the context of answering three basic questions (Jacob and McClelland, 2001):

1. “What to Change?” - in pursuit of the answer to this question, it was found that the representativity of the Kombat Aquifer groundwater flow system was not comparative to the scales at which it is managed. For instance, the well field at Kombat formed part of a numerical flow model set up for an area of about 600 km^2, thus encompassing the whole eastern half the Otavi Valley Uitkmost Syncline, commonly referred to as the D-Area.
2. “What to Change?” - it was then decided to localize the spatial scale of the Kombat Aquifer model to a size that is capable of simulating hydrodynamics at a scale suitable for well field management.
3. How to Cause the Change?” - in order to localize the spatial scale at which the Kombat well field would be managed (modeled), the following steps were considered appropriate:
    I. Delineating local hydrodynamic characteristics of the system
    II. Provide local variability characteristics of salient properties like permeability, storativity and fracture geometry
    III. Improve the hydrogeological conceptual model on which to base hydrodynamics and numerical models of the Kombat Aquifer/Well field.

Conceptualized within the TOC framework under TOC-Question 1, this study identified the misalignment between the scale at which the mathematical model of the area was implemented and the required level of resolution as the major limiting factor in the usefulness of the mathematical model as a groundwater management tool. This misalignment led to the over-simplification of the groundwater flow system, and consequently the adoption of an equivalent porous medium approach, thereby making the simulation of local hydraulic head variations difficult.

There is compelling evidence attesting to the inability of the equivalent porous medium approach in simulating groundwater flow details, especially in fractured carbonate aquifers. This is because, at functional levels, fissure permeability tends to store groundwater, whereas fracture permeability tends to transport groundwater. A model combining these two functions compromises its ability to account for detailed groundwater flow dynamics (Kiraly, 1975; Worthington, 2003). The equivalent porous medium approach is therefore less effective in fractured carbonate aquifers where most of the storage occurs in the fissures or the epikarst, and is only released when there are significant hydraulic pressure differences between the fissured and the fractured systems.

In line with the foregoing discussion, it would be prudent to reframe the modelling efforts of the study area from equivalent porous medium to a distributed parameter approach, especially if detailed groundwater flow dynamics are to be the outcome of modelling efforts.

In addressing TOC-Question 2, this study realized that, besides changing the modelling approach, reducing the scale of previous models could be beneficial; this would enhance the possibility of localizing data, and therefore increase the resolution of the distributed parameter approach.

At the level of TOC-Question 3, a conceptual framework was developed. The intention of developing a conceptual framework is to identify hydrogeological aspects that are important in explaining the hydraulic and hydrochemical trends observed in Kombat Aquifer. These aspects are referred to as groundwater flow controls and the flow constraint they impose on the Kombat Aquifer will be assessed in Chapters 4 and 5 of this thesis.

This discussion is considered in addition to literature reviews on:

(i) Judicious groundwater development and protection in fractured dolomite aquifers, in addition to an assessment of
(ii) Groundwater flow controls posed by geological structures in fractured carbonate aquifers.

Consequent to the above mentioned literature reviews, the following conclusions were drawn:

I. Due to the loss of structural cohesion of rocks along surfaces of rupture (*fractures*), fractures offer the pathways with the lowest groundwater flow resistance

II. Intense fracturing coincides with both prominent troughs in the potentiometric surfaces, and low electrical conductivity (EC) plumes of fractured groundwater flow systems.

III. Flow patterns and aquifer parameters are scale-dependent, and the scale effects are related to the anisotropy controlled by fracture orientation and connectivity, therefore

IV. The understanding and delineation of fracture controls on the groundwater flow system is of paramount importance to groundwater flow modeling, judicious groundwater development and groundwater protection in fractured hydraulic settings.

From the summary of literature reviews, an analytical framework (**Figure 2**) was developed, and within the methodology, the following research question is posed;

In which way do groundwater flow controls influence the Kombat Aquifer flow system and what impact do fracture controls impose on groundwater flow modeling and on the judicious groundwater development of the Kombat Aquifer?

In order to further clarify the research question, it is considered prudent to raise low-order questions pertaining to the hydrogeological settings and aquifer functioning. At this level, the following sub-questions are raised:

- Under what geohydrological framework is the water added to, stored in, transported and discharged from the groundwater system?
- What is the role of fractures in the way that water is added, stored, transported and discharged from the system?

- How can the groundwater flow heterogeneity of the Kombat Aquifer be best represented?

The scope of these questions demands a deeper reflection into the interrelationships of various groundwater flow controls (*climatic, geological, geomorphic and relief*) and their impact on groundwater flow behavior (*hydraulic response, hydrodynamics*) of the study area.

The elementary assumption underlying the scope of the above raised questions is that the understanding of the influence of groundwater flow controls on aquifer geometry and on flow dynamics is fundamental to groundwater modeling, and implicitly to groundwater development and management.

In an attempt to answer the question, this study employs triangulation of multi-sourced, readily available data from the following investigative methods: remote sensing, geomorphologic analysis, conceptual optimization, literature reviews, field work, geological section, borehole data, temperature logs, and water chemistry

1.3.2 Aims and Objectives

In their contribution to the structural control on groundwater flow of the study area, Campbell (1980), Seeger (1990) and Ploethner (1997) argue that in the Kombat area groundwater occurrence is confined to fractures, shears, lithologic contacts, and solution-enhanced bedding parallel fractured planes.

This creates the impression that groundwater flow in the study area is stored, transported, and is spatially patterned by fractures and fracture geometry, implying that structural constraints on groundwater flow must be directly measurable in quantitative terms or can be reliably read from the association of geological structure with other obvious groundwater flow aspects.

Although the importance of geological structure in groundwater flow is generally accepted (Campbell, 1980; Greenway, 1994; Deane, 1995; Ploethner, 1997), there is no study that has addressed structural constraints on the groundwater flow and the impact that geological structure imposes on long-term groundwater development and management of the study area.

This study takes a step further from the groundwater potential assessment of geological structures, which has been the focus of previous investigators to establish the flow constraints imposed by geological structures on the groundwater system of the study area.

Issues:

- Influence of geological structure on groundwater flow dynamics
- Effective groundwater development

Previous studies have extensively expounded the issues pertaining to macro aquifer geometry, as well as the groundwater potential of the secondary structures. As a continuation, this study will only give a descriptive review of those issues; the main focus will be on the restrictions imposed on the groundwater flow regime by climate, depositional and post-depositional heterogeneities.

The main objectives of this study are:

- To delineate and understand groundwater flow controls on the groundwater flow system.
- To determine the relevance of structural attributes to observed hydraulic behavior of the groundwater flow system.
- To compile an integrated conceptual groundwater flow model of the study area.

Envisaged Deliverables

- ARCGIS and WISH database of the study area.
- Maps of aquifer units with internal and external flow boundaries.
- A groundwater flow conceptual model, geared towards the inception of a planned quantitative data collection and numerical parameterization of the Kombat Aquifer.

1.4 Study Layout

This thesis consists of eight chapters:

- The first chapter positions the research in context by addressing the background, the aims and objective of the study. The chapter further reviews literature and formulates the problem statement, the questions and the proposed interventions.

- Chapter 2 presents the methods deployed to investigate and examine the problem at hand.

- Chapter 3 is the description of the study area. The chapter summarizes the physical attributes and dynamic aspects of the study area, with a focus on groundwater flow constraints.

- Chapter 4 presents evidence and the associated discussions; the chapter goes on to discuss key groundwater flow controls and provides support by referencing evidence.

- Chapter 5 presents the hydraulic results in form of diagnostic and derivative plots from hydraulic test datasets. These results are used to characterize and parameterize the aquifer.

- Chapter 6 develops conceptual models for each primary subsystem of the groundwater flow system. The models are centered on the concept of factual and statistical accountability of observed behavior.

- Chapter 7 presents abstraction scenarios and management options for the Kombat Well field, whereas

- Chapter 8 consists of the conclusion, and the way forward.

CHAPTER 2 RESEARCH METHODOLOGY

2.1 General

The research methodology adopted in this study consists of two tiers, namely the conceptual framework on the one hand and the research application on the other.

The conceptual framework is the logical structure within which the boundaries of the operational levels of the study are framed. It comprises of four interrelated aspects (**Figure 2**): the static characteristics (*Lithology, geo-structure, geomorphology*), the variant characteristics (flow geometry, permeability, storativity), the hydraulic dynamics (*recharge, discharge, flow patterns, volumetric storage*) and system representativity (*models*) of the flow system. The conceptual framework argues that the delineation of static characteristics of the flow system is prerequisite to the understanding of variant characteristic of the aquifer. It further postulates that once the variant characteristics are understood and parameterised, the comprehension of hydraulic dynamics will be logical and smooth, consequently improving system representation (modelling). The approach is therefore a map of the logical sequence of what should be done to make the next task easier.

The second part of the methodology is the research application itself; it consists of the methods, processes and validation of the processes and results. The strategy within the research application or execution is to start with broad brush investigations like geomorphology and thereafter focus on more localised and detailed methods of investigation. This helps to develop an incremental understanding of the system from a macro-scale to the fine structures of the problem at hand. Both the conceptual framework and research application converge on the research question and goals (**Figure 2**).

In summary, the methodology presented in Figure 2 defines the boundaries of the scope of work and determines the internal workings of the study. In this way, it informs the study design and provides the framework for relating findings to goals.

In conformity to the methodology of this study, the conclusions presented in this thesis are based on evidence from lithology, geo-structure, geomorphology, borehole hydrographs, water chemistry, groundwater levels and hydraulic tests. Periodic and systematic validity loops have been implemented at three levels, namely: at the level of data, the level of analysis and at interpretation.

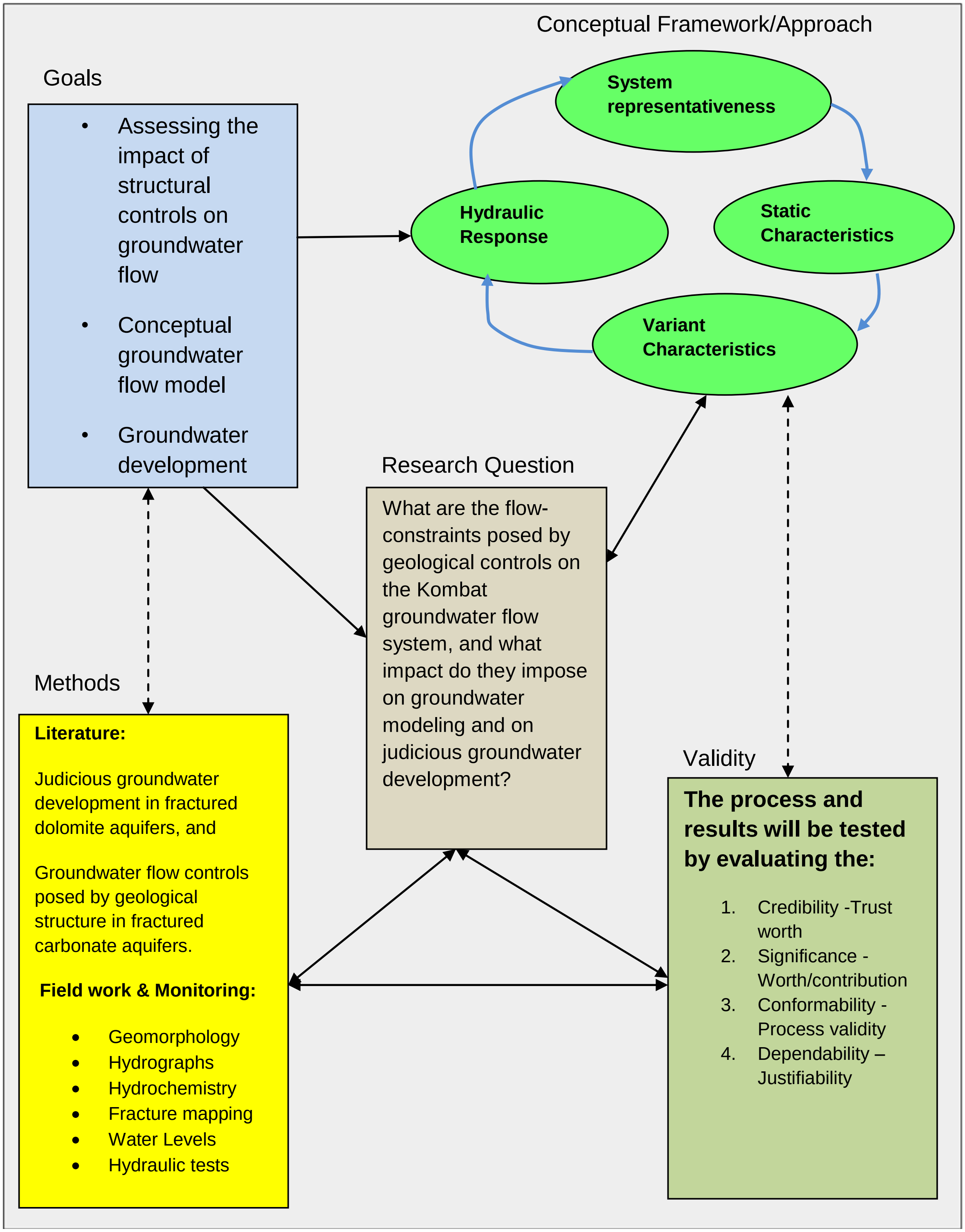

Figure 2: Research application and methodology

2.2 Introduction

In order to appreciate the value of methodology, modern literature advocates for two aspects of methodology that should be acknowledged by any research; the first being its tactful position in the research process, by way of enlightening the study on information requirements and how such information is to be developed into useful tools that can be applied to the research problem. The second is its dependence on meaningful assumptions, thereby demanding the advancement of theoretical positions through exemplified historic records and arguments (Neuman, 1997; O'Nell, 2001). On that basis, this study adopted a methodology based on the exploitation of the integration of readily available groundwater flow-related datasets, and the understanding of the assumption that knowledge is cumulative and tentative.

The following specific elementary assumptions constitute the basis of this study's methodology:

1. The key constraint to sustainable development and management of groundwater in fractured carbonate aquifers is the understanding of the groundwater flow system as a unitary entity (Sharp *et al*., 1999).

2. Climate and geological structure are the major controls of the spatial pattern, nature and magnitude of groundwater flow in the study area (Campbell, 1980; Seeger, 1990).

The subject to be explained in this study is the distribution and nature of groundwater flow, the unitary referred to as the flow regime of the study area - the Kombat Aquifer. What explains the groundwater flow regime of the area under review is the climate and structural heterogeneity within its boundaries.

The study explains the flow regime of the Kombat Aquifer by identifying its cause. The hypothesis is that structure in the form of folds provides the hydraulic driving force (groundwater hydraulic head), while the strata form and fractures prepared the preferential low fluid flow resistance zones that partition the nature and distribution of groundwater flow in the study area.

From a groundwater resource management point of view, and upon a rigorous review of abstracts of work done in similar hydro geological settings, the study has identified the understanding of the groundwater flow system as the key constraint to sustainable groundwater development and use (Sharp *et al*., 1999; David *et al.,* 2002; Mayer and Sharp, 2004; Lemieux, 2005; Morgan *et al*., 2005), this understanding, linked with the objectives and research questions raised in Chapter 1, form the basis behind the choice of methods of this study.

2.3 Methods

A summary of study methods and their associated significance is given in Table 2 below.

Table 2: Summary of methods, datasets, and their value to the study

Method	Dataset	Significance
Conceptual Optimization	Concepts, ideas, theories, views, theoretical frameworks	Identification of concepts, variables, develop hypotheses and create measures of variables, develop logical data review structures
Remote-Sensing Imagery	Physical attributes, i.e. Landforms, relief, and drainage.	Visual Understanding and representation of the study area, especially the delineation of landform system.
Specific Literature Review	Accepted facts, popular opinions, main variables, relationships between concepts and variables, methods used, shortcomings, limitations, relevance to current study, and further research areas.	Understanding, integrating, and summarizing what is known and what is not known about the groundwater flow system of the study area.

Structural Optimization	Position, nature and geometry of faults, joints, fracture zones, sinkholes and litho-contacts	Location of potential solution enhanced permeability zones, understanding of hydro geological evolution.
Geological Sections	Geology, fractures, topography	To facilitate the understanding of aquifer geometry, flow geometry by describing and explaining geology, hydrogeology and structural controls at a localized scale.
Borehole Hydrograph Analysis (BHA)	Response to pressure pulses (Precipitation then recharge, droughts, abstraction), borehole hydrographs	To discriminate and locate flow components
Physio-Chemical Analysis	Water chemistry, borehole yields, water levels, and water temperature.	Delimitation and parameterization aquifer response trends

2.3.1 Conceptual Optimization

Relevant articles, abstracts, and reports were used to develop and generate concepts, ideas, theories, views, conceptual relationships and theoretical frameworks, which informed the conceptual understanding of some hydrogeological aspects of the study area. The aim of the conceptual optimization method was to develop an understanding of structure and the impact this has on groundwater flow, especially its influence in terms of how resources have been and should be developed and quantified in the study area.

The conceptual optimization method informed the problem formulation (*shaping the study objectives, as well as the development of the research questions*) and solution development (*adopted study design and methodology*) of some components of this study.

2.3.2 Remote Sensing Imagery

Topographic maps, aerial photos, and Land Sat images were employed to expand and sharpen the visual understanding and representation of the external physical attributes of the study area.

1:50000 topographic maps 1917 DA and 1917DB (1997) were obtained from the Office of the Surveyor General - Windhoek. Physical aspects such as drainage, topography, vegetation distribution and cadastral information such as roads, mines, and land use are identifiable on the maps and photos, making the photos usable as base maps in field-based follow-up work.

Two Land Sat photos of the study area were obtained from Google Earth at a scale of 1:100000, from which three-dimensional visualization of relief is well-presented, ensuring a holistic over view of the locality of geomorphic units and their spatial relations.

Five black and white aerial photos of the study area were sourced from the National Hydrogeology Database at the Department of Water Affairs in Windhoek. Shades of different lithologies, relief contrasts, drainage patterns, and structural lineaments are fairly visible from the obtained aerial photos. In view of the scale at which the study is conducted, the quality of the obtained aerial photos of the study is satisfactory.

The absence of the extreme southern part of the study area posed a visualization limitation, even though this was to some extent compensated by topographic maps and Land Sat images.

The remote sensing imagery research method played an important role in navigation planning, in the delineation of the landform systems, as well as in the recharge basin characterization.

2.3.3 Specific Literature Reviews

Twelve geological and hydrogeological studies, ranging from 1980, up to 2007, were reviewed with the intention of integrating and synthesizing accepted facts, popular opinions, main variables, relationships between concepts and variables, methods, shortcomings, limitations, and further research areas. Despite huge groundwater and mining interest in the study area, only two of the twelve reviewed studies are published.

The paucity of published work in the study area can be a credibility limitation in view of the findings of the specific literature review study method. However, this study method enhanced the integration and understanding of what is known and not known about the groundwater flow system of the study area.

The year, authors, study focus and titles of the consulted specific literature are provided in Chapter 1, Subsection 1.2.1 Table 1: LOCAL STUDIES.

2.3.4 Structural Optimization

The structural optimization study method hinges on the principle of positive feedback in the dissolution-based enlargement of fracture apertures. The principle of positive feedback in karstification states that more dissolution takes place where there is greater flow, implying that larger apertures increase at the expense of small ones; however, it was found that deeper flow pathways also offer greater flow due to higher geothermal temperatures and the associated lowered viscosity of flowing water (Worthington, 2003).

In this study, the structural optimization study method attempts to locate structures that can offer high geothermal temperatures without the disadvantage of a longer flow path.

Worthington (2003) maintains that structural troughs such as grabens and synclines do offer both higher geothermal temperatures and the associated lower viscosity of flowing water. The optimal location of such structures would theoretically locate zones of enhanced permeability.

In the study area, four structural troughs are located and described as follows;
The first one is the zone between the Kombat West Fault and W270 Fault, which forms a series of westward-trending half grabens **(Figures 16 and 17**).

The second is the contact between the basal dolomite and the older rocks, as well as the contact between the Hutternberg Formation and the clastic rocks of the Mulden Group, which is not only synclinal, but also a brittle deformations zone.

The third is described as a graben structure formed by north-south trending faults and located south of Kombat Mine (Deane, 1995). This structure is not identified on available maps, but its association with other groundwater flow aspects, especially initial borehole yields, can be traced.

The fourth is also a graben structure along the northeast parallel Asis Ost Faults at Farm Nehlen, where fault-parallel dolines of up to 30m long were first observed by Seeger (1990) and confirmed in this study.

2.3.5 Geological Sectioning

A 1:330000 topographic/geological base map overlay was used to construct seven geological sections at 100m to 200m intervals. The geological sections are perpendicular to the general west-east trending lithologic strike; they are therefore north-south trending profiles, traversing the entire flow system.

The process of constructing the geological sections started with scanning a geological map and topographic map. In order to vectorizeise (live contour elevation value) the topographic contours, the overlay of the scanned geology/topographic map was transferred into the Vector Pro (VMAX Pro version 9.2) program. The live elevation contoured geology map was then transferred into AutoCAD MAP version 2000 for the assignment of xyz coordinates, before loading the map into an ARCGIS program for the generation of topographic sections, which were later filled in terms of the geology and structure using AutoCAD Land Developer. To facilitate greater visibility, the sections were finally constructed at scale of 1:33000

.

The geological sectioning method is aimed at augmenting the current understanding of aquifer and flow geometry by describing and explaining geology, hydrogeology and structural controls at a localized scale.

2.3.6 Borehole Hydrography Analysis (BHA)

The well hydrography analysis method takes advantage of the aquifer response to pressure pulses (*recharge, droughts, abstraction*) to discriminate and locate distinct flow components in a groundwater flow system. The method can also be used to relate hydrograph characteristics (*e.g. Time to peak TP, peak discharge QP, and flow recession coefficient FRC*) to geomorphologic properties of a recharge basin *e.g. drainage area, type of source land form, average catchment slope, nature of infiltration* (Shrestha *et al*., 2005).

A total of 14 borehole hydrographs were used to access and evaluate the hydraulic response of the Kombat Aquifer flow regime. The borehole hydrographs are concentrated in the southern part of the study area, with only five located on the northern limb of the Otavi Valley Syncline.

Observation from borehole completion reports indicates that boreholes of the study area source groundwater from multiple fractures and shears along lithologic contacts, faults, and fractured zones.

Water strikes range between 30 and 50 m below ground, while the deepest borehole is 260 m below surface. Compared to Kombat Mine dewatering dams, some of which are 800 m below ground, the water supply boreholes are exploiting the shallow water system of the Kombat Aquifer.

In the calculation of hydrography recession coefficients, care was taken in normalizing the hydrograph gradients for abstraction, although this data could not be conclusive.

The time to peak, time to base flow, recession curve coefficients, seasonal and the long-term trends of the hydrographs were used to discriminate and locate distinct flow components of the Kombat Aquifer flow system. The skew distribution of the hydrographs over the study area domain is considered to be the single most limiting factor in the applicability of this method, and possibly in some other methods as well.

2.3.7 Water Chemistry Data Analysis (WCDA)

The behaviour and evolution of a groundwater flow system is revealed by the spatial and temporal changes in its physio-chemical parameters (*electrical conductivity EC, saturation indices SI, temperature, and borehole yields*).

The WCDA method deployed the variations in physio-chemical parameters of the Kombat Aquifer groundwater flow system in the conceptual delimitation and parameterisation of the aquifer domain.

At a regional scale, about 350 samples of EC, borehole yields, and groundwater levels were utilised to study the Kombat Aquifer behaviour, with the aim of delimitating and parameterising the flow system.

Of all the physio-chemical parameters employed, only electrical conductivity (EC), water levels, hardness, Mg and borehole yield distribution exhibit patterned relationships. Three distinct flow zones could be inferred from the deployment of the WCDA method.

A common limiting factor in all the methods employed in this study is the mismatch between actual data distribution and the assumed data distribution underlying the applicability of the methods used.

CHAPTER 3 THE STUDY AREA

3.1 Introduction

The study area is situated in northern Namibia, about 500 km north of Windhoek, the Capital City. It is 48 km east of the town of Grootfontein, and located close to peak of a regional carbonate massif, generally referred to as the Otavi Mountain Land – OML (**Figure 3**).

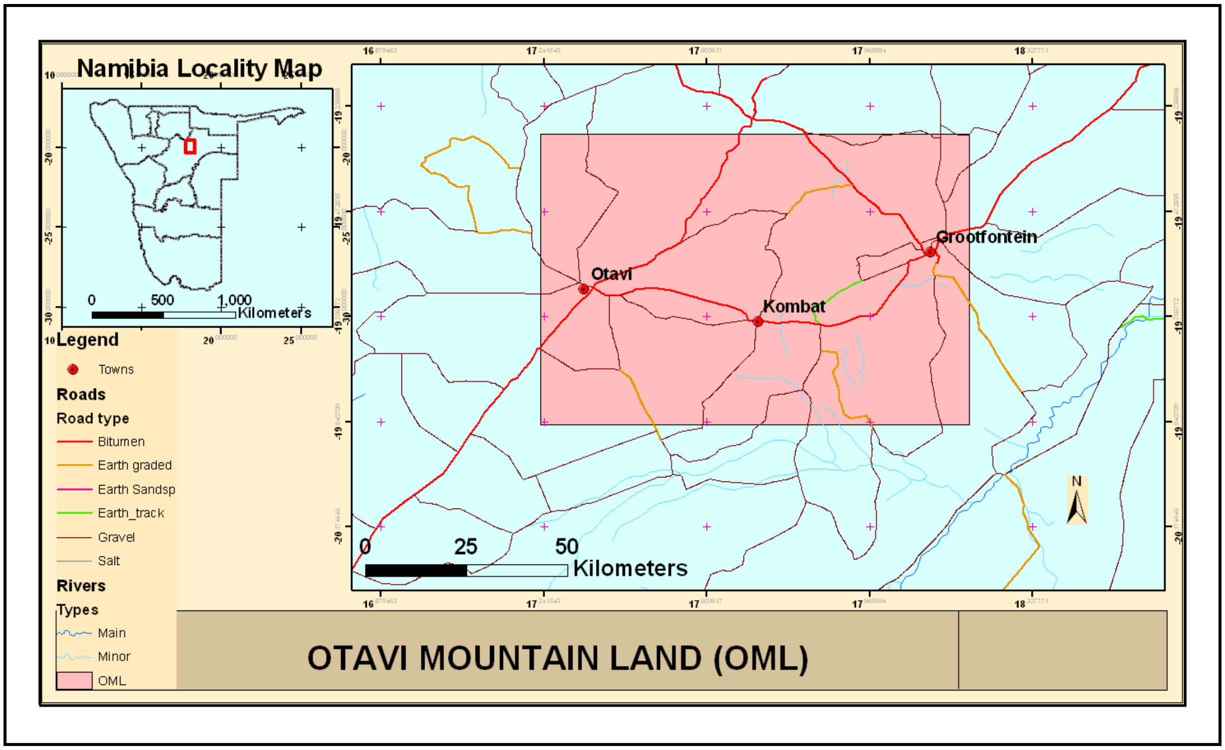

Figure 3: Locality map of the OML

The area has been a focus of mining activities for the past 50 years, and has attracted many geological and groundwater investigators.

The Otavi Mountain Land (OML) is located on the boundary of the stable platform, the southern edge of the Congo Craton (northern platform), and the northern rift of the intercontinental branch of the Damara Orogen. The northern rift underwent multiple phases of deformation, resulting in the formation of the Otavi Valley sub-basin, as well as the associated cessation of carbonate deposition (Miller, 1986).

From a water supply point of view, the groundwater resources of the study area are of national importance, in that they are a source of potable water to the central dry lands via the National Eastern Water Carrier, a pipeline that should convey potable water from the OML to the central business district (about 500 km away).

3.2 Geomorphology

In this study, the purpose of revising the geomorphology is drawn from the notion that variations in geomorphic elements have a direct influence on surface and groundwater movement, however, the opposite can also be true. Therefore a review of geomorphology informs groundwater studies on broad aspects of surface and groundwater interaction. In this subsection, the role of the geomorphology of the Kombat area is discussed at different spatial scales.

Due to the dissolving nature of carbonate rocks in the presence of water, the area's geomorphogeny subscribes to the term 'karst'. It therefore comprises of caves, sinkholes, dolines, blind valleys, barren, springs, and dissolution induced depressions or sinkhole plains.

These landforms regulate the physical hydrogeological and chemical processes, such as recharge, discharge, variations in hydraulic gradient, run-off, as well as the capacity of the available groundwater recharge basin (USGS, 2001). As a result, karst landforms provide a surface water/groundwater interface and constrain groundwater flow dynamics, especially in the recharge subsystem.

The nature and distribution of karstic landforms within an aquifer domain is therefore not only a valuable source of information on the nature of infiltration, recharge and discharge, but also improves the knowledge of the role of structure (physical attributes) in flow dynamics by providing a landform-based, three-dimensional visualisation of the way in which water is added to, and discharged from an flow system.

The Kombat Aquifer encompasses a surface area of about 420 km^2 within a 12 km radius around Kombat Mine. It is bounded to the north by the Northern Otaviberg, marking the northern surface and groundwater flow boundary (Seeger, 1990). To the west and east, the study area is bounded by local flexures in the Otavi Valley Uitkmost Syncline. The syncline therefore forms a closed geomorphic structure resembling, to a certain extent, the form of a boat (Campbell, 1980). The southern boundary of the study area is situated approximately 3 km south of the west-east trending Southern Otaviberg, and is marked by a geological contact between carbonate rocks of the lower Otavi Group and the less permeable rocks of the Nosib Group and/or of the GBC (**Figure 4**). Therefore the groundwater flow boundaries of the study area are to a certain extent defined by its geomorphology.

This study considers karst landforms as critical factors in routing surface run-off and recharge, and in recognition of their impact on the hydrodynamics of the study area, four functional landform categories are delineated (**Figure 4**), namely the Karstic Plateau, the Fluviokarst, the Central Valley, and the SLLA.

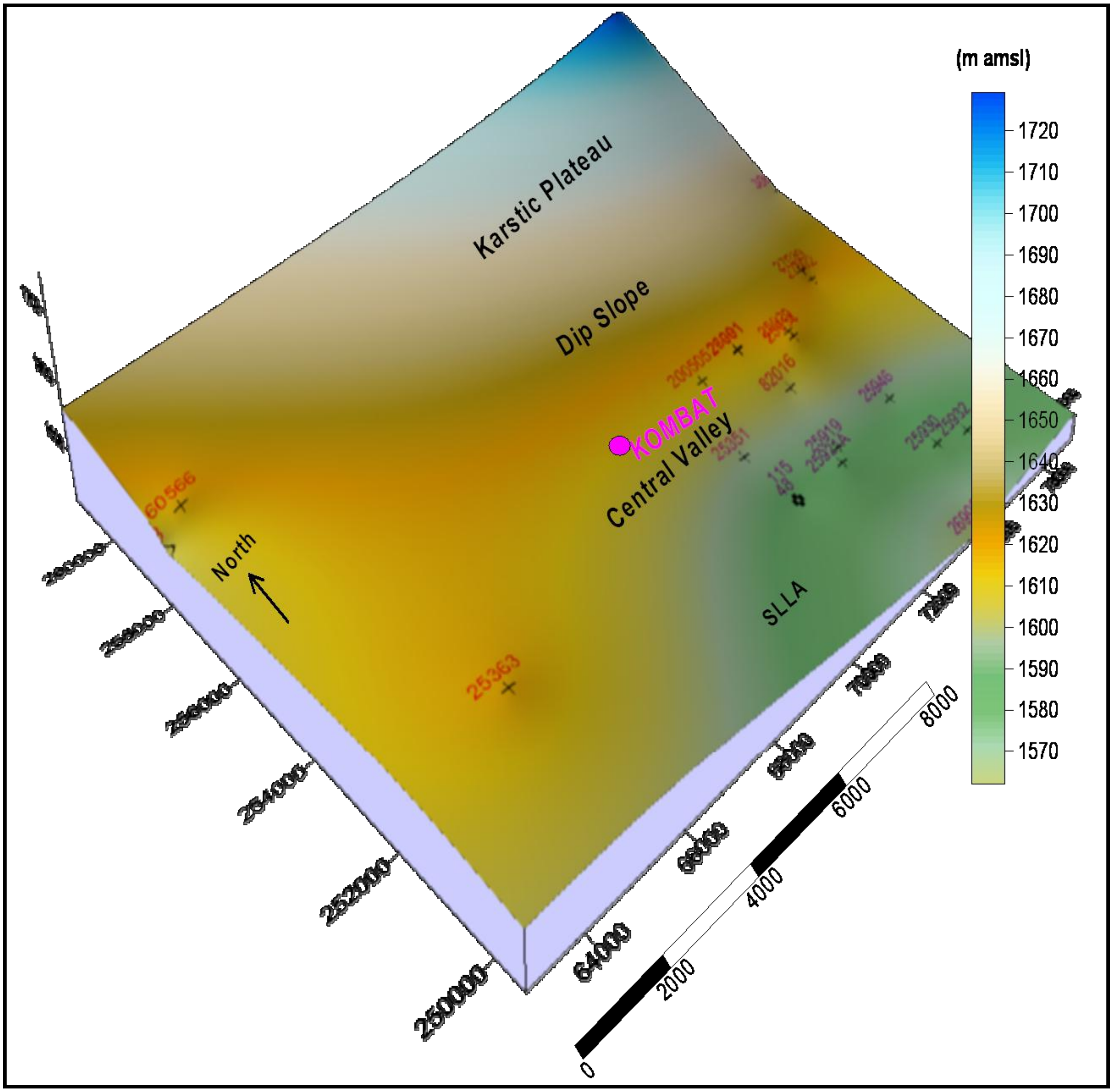

Figure 4: The topography and geomorphic units of the study area

The Karstic Plateau (KP): The Karstic Plateau or the Sinkhole Plain is at the highest elevation in the study area. It is underlain by rocks of the Gauss, Auros and Maieberg Formations (massive and bedded, fine-grained dolomite, limestone, minor chert, platy limestone, marl and shale). The KP is characterised by wide sinkhole plains, high density of sinkholes, and vertical shafts. The KP is regarded as the most significant surface water collector and groundwater recharge zone of the study area (Seeger, 1990; Ploethner, 1997).

An important aspect to the research question is the depth of weathered profile of the sinkhole plain. Geological borehole drill logs have shown that, in most places of the study area, only the first half meter to a meter of drilled depth is weathered, except in the sinkhole geomorphic zone, where the weathering profile can be as deep as nine meter. This sharp contrast in the weathering profile enables the sinkhole plain to sustain widespread deep vertical shafts and collapse depressions (Karst Plateau-**Figure 4**). Verbal communication with the owner of Farm Gauss revealed that, during wet periods, cattle farmers in the Karstic Plateau lose up to 20% of their calves to sinkholes.

The thick weathered depth profile in carbonate aquifers provides a temporal storage facility to infiltration (Mohrlock and Sauter, 1999). Therefore the sinkhole plain does not only collect surface water and concentrate groundwater recharge, but also temporarily stores the infiltrating water.

Fluviokarst Geomorphic Unit: The fluviokarst covers the inclined and rugged topographic setting of the Northern Otaviberg (the northern dip slope) and is overlain by carbonate rocks of the Maieberg and the Elandshoek Formations. The Fluviokarst geomorphic unit is a steep north-south trending slope situated north of Otavi Valley. From a fluvial erosion point of view, the fluviokarst is the most affected region of the study area. According to Seeger (1990), the dense, massive, pure and coarse fractured carbonate rocks of the Elandshoek Formation develop the most open fractures, due to their brittle deformation response to stress, making the Fluviokarst vulnerable to process of stream channeling.

Fluvial dissection is a consequence of external processes involving the interplay of preferential lithologic erosion due to preferential fracturing, jointing, chemical dissolution and high hydraulic gradients (Moon and Dardis, 1988). Moon and Dardis's (1988) findings suggest that the fluvial dissection of the Fluviokarst are underlain by fractured bedrock, and that it theoretically makes them preferential infiltration sites of run-off. Concomitantly, the Fluviokarst geomorphic unit is expected to facilitate rapid infiltration and form the southern boundary of the Kombat Aquifer’s recharge basin.

The Central Valley (CV): The central valley is a west-east trending, poorly drained floor of the Otavi Valley Syncline. It is underlain by less permeable phyllite, slate, arkose, siltstone and argillite of the Kombat Formation. The boundary between the CV and the Fluviokarst coincides with the lithologic contacts between the Hutenberg and the Kombat Formations, forming a regional north-south groundwater flow barrier (Ploethner, 1997).

Despite the low permeability of the rocks of the Kombat Formation, the central valley maintains a weak hydraulic connectivity between the northern highlands and southern discharge zones (Campbell, 1980). The central valley therefore encourages west-east groundwater flow movements due to the less permeable (impervious) nature of the Kombat Formation.

The Southern Discharge Zone (SDZ): The SDZ is a low lying area south of the Central Otavi Valley (**Figure 4**). It is characterised by short north-south dry stream beds and seepage faces (Seeger, 1990). In the past, the SDZ hosted several seasonal and permanent springs. The SDZ is bounded by the southern Otaviberg to the north and the geological contact between the carbonate rocks of the Abaneb Subgroup and the impermeable meta lavas, archean granites, and granite gneisses of the Nosib Group or the GBC (Innes and Chaplin, 1986).

The geomorphic summative points to geomorphology as a provider of the structures via which different recharge, drainage and discharge processes are enabled. It is also host to temporal storage of infiltration, and influences the aquifer response to input, groundwater chemistry, and the internal hydraulic pressure dynamics of the aquifer.

3.3 Physiograhy

The study area covers part of the eastern half of a west-east trending synclinal structure, which is locally referred to as Otavi Valley Uitkomst Syncline (OVUS). Due to uneven folding, the northern flank of the OVUS rises to more prominent mountain ranges and hills than the southern flank (**Figures 4 and 5**). From a hydrogeology point of view, the north-south elevation disparity created by the uneven folding has induced a steep hydraulic gradient, equivalent to 500 m of hydraulic head over a distance of about 20 km.

Approximately eight percent (8%) of the study area lies within the Otavi Valley Uitkomst Syncline (Ovus), which is about 270m and 122m below the Northern and Southern Otaviberg respectively. About 69% of the study area occupies the Northern Otaviberg (**Figure 5**), which is characterised by numerous north-south draining valley-lets and a number of northeast elongating surface depressions.

Thirteen percent (13%) of the study area occurs at the Southern Otaviberg, extending for about 7 km from the western boundary of the study area to around Kombat Mine, where southwest trending faults have dissected it, creating a widened valley. The southern boundary of the study area comprises a pediplain of the Late Cretaceous age (Marchant, 1980), and covers about 10% of the study area.

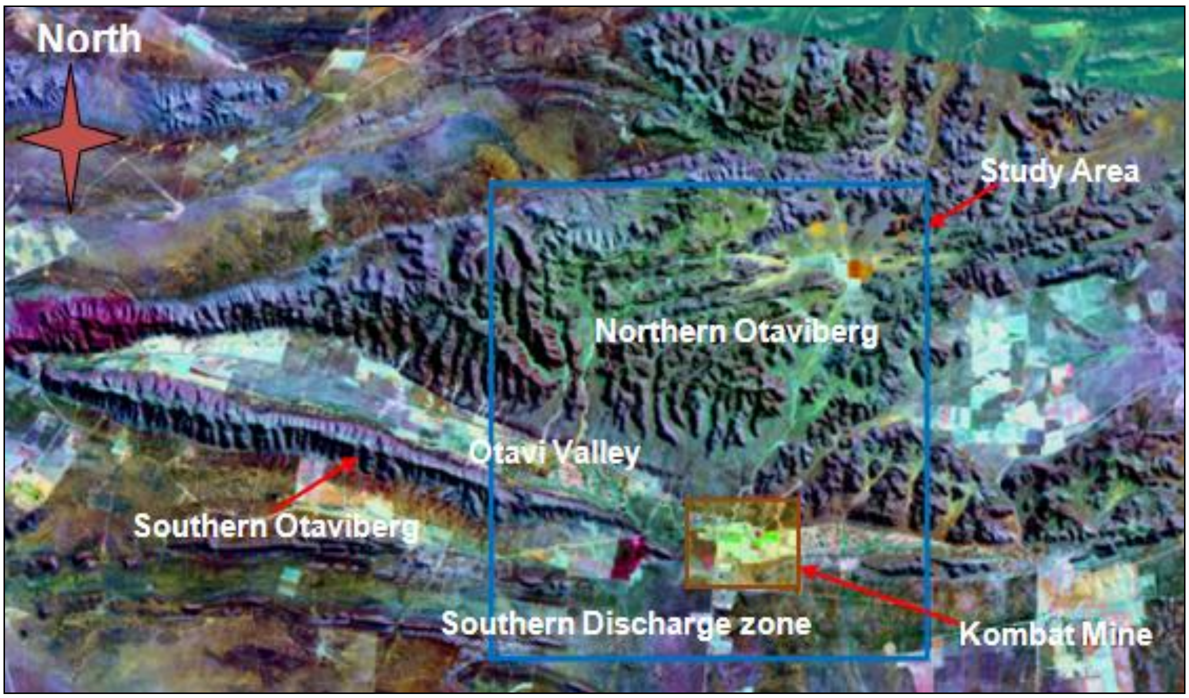

Figure 5: The physiography of the study area

Considering the strong linear regression correlation between topography and groundwater levels (**Figure 7**), a steep average topographic gradient of 1:40 results in a high hydraulic gradient. A steep hydraulic gradient over a short flow system of about 20 km has advantages and disadvantages, depending on the adopted point of view. Using Darcy's law as a foundation of analysis, higher hydraulic gradients translate into high specific groundwater flow fluxes; an aquifer property that is desirable to borehole-yielding capacities during groundwater abstraction. Yet there are also some disadvantages in steep hydraulic gradients, for example, in arid zones such as the study area, where recharge events are far between, steep hydraulic gradient induce net discharge hydraulic conditions. Such conditions negatively affect long-term reliability of an aquifer as a source of bulk water supply.

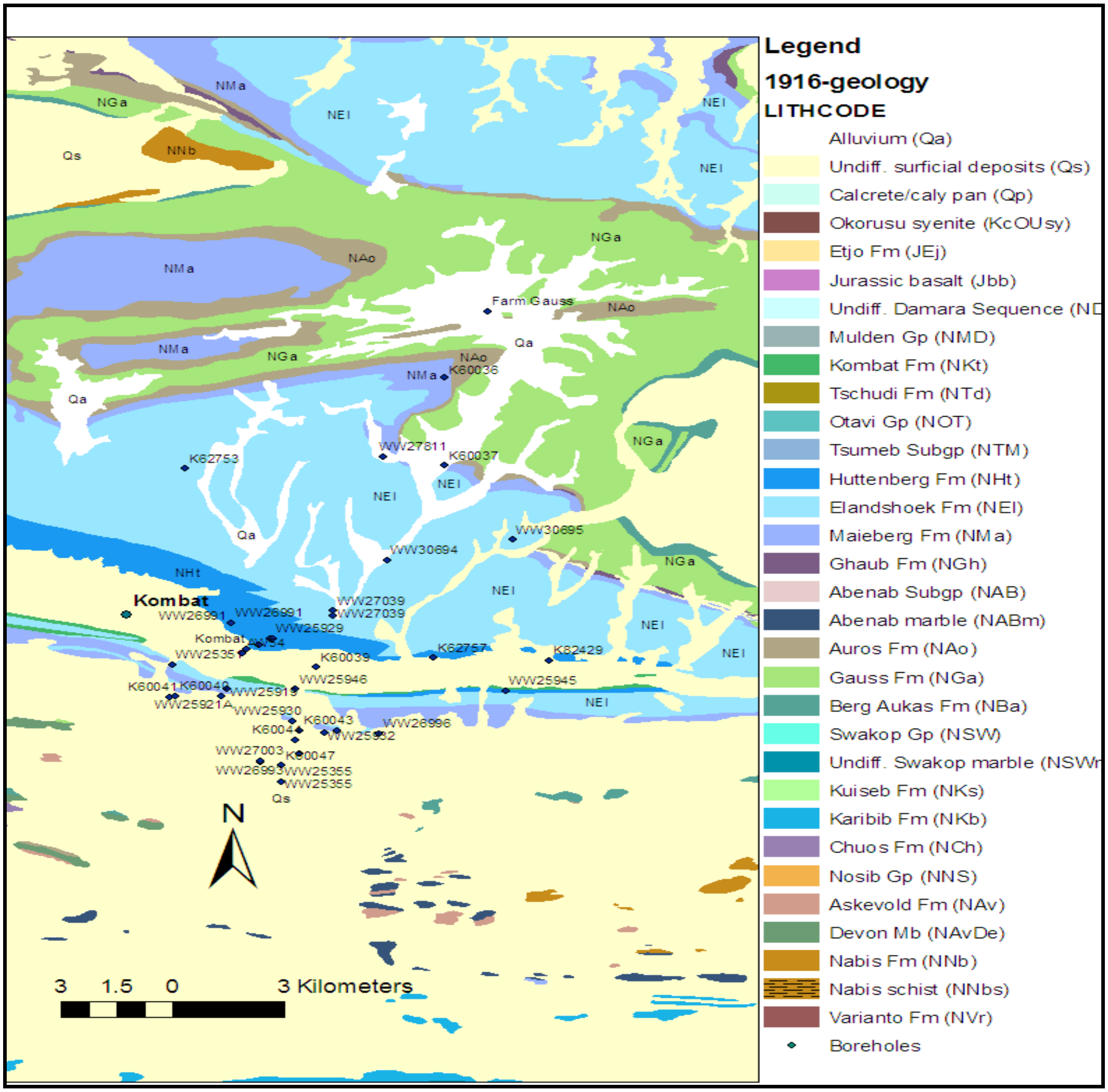

Figure 6: Distribution of boreholes overlain on geology

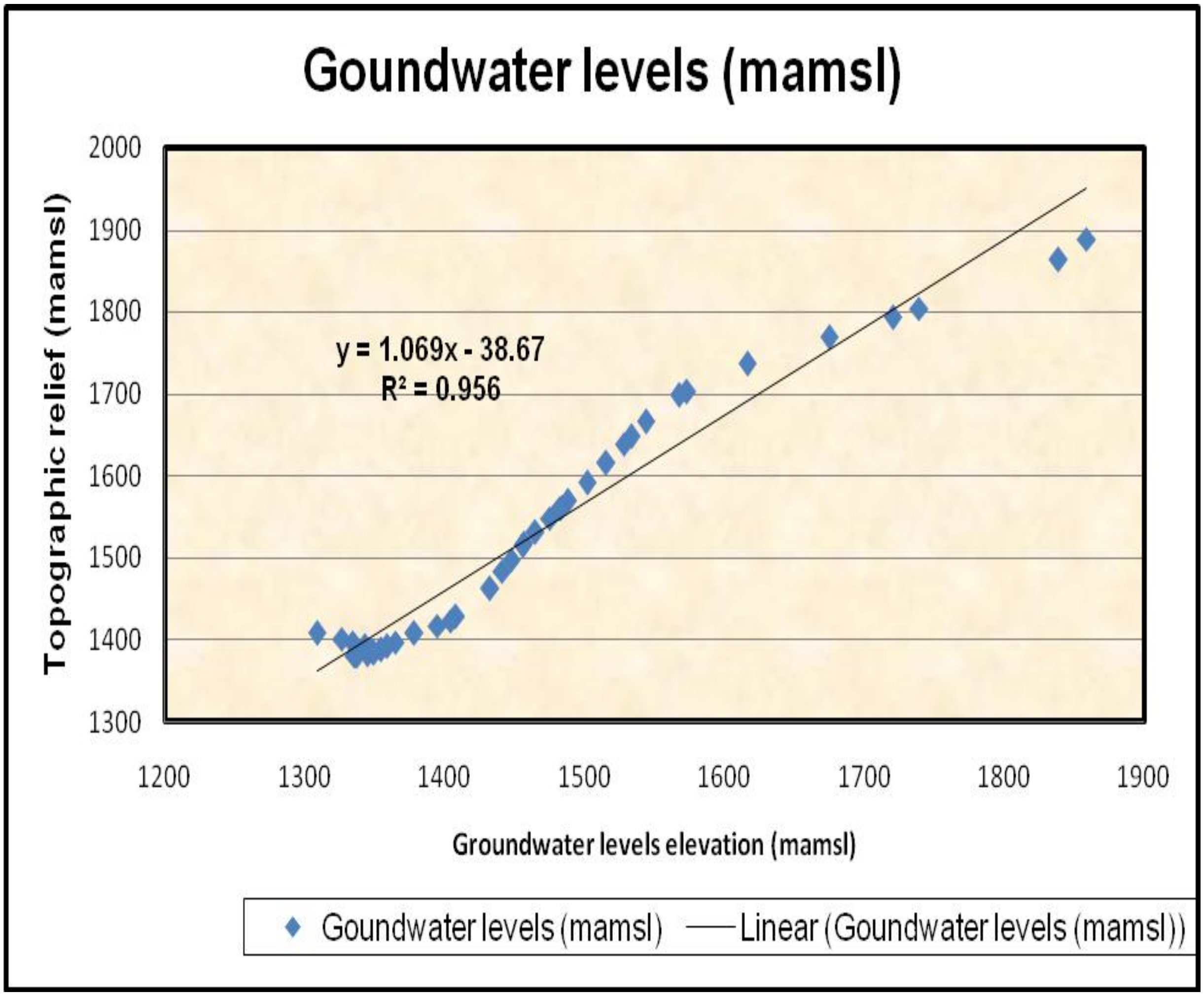

Figure 7: The cross-correlation between relief and groundwater levels

Figure 7 illustrates a strong correlation between topography and water level elevations, thus signifying that the Kombat Aquifer flow system is largely unconfined. However, it appears that there is a local discordant between 1550 mamsl and 1370 mamsl in this correlation, especially towards the discharge zone. The observed multiple segmentation, as well as the correlation mismatch of the discharge zone, as seen in Figure 7, will be examined and discussed under system characterisation in Chapter 5, Subsection 5.2.2.

3.3.1 Climate

The climate in the Kombat area is classified as semi-arid by the Namibian weather bureau, with the annual precipitation (which occurs as rainfall) varying between 300 mm and 900 mm. Rainfall intensity is reportedly increasing centripetally towards the peak of the Northern

Otaviberg (Ploethner, 1997), about 14 km north of Kombat Mine with a mean annual rainfall of 500 mm.

Most of the rainfall occurs between January and April, followed by a distinct dry winter season between May and August. March is the wettest month, with a mean monthly rainfall of about 52 mm. The mean annual temperature is about 28^{o}C. Winters are cool, while summers are hot.

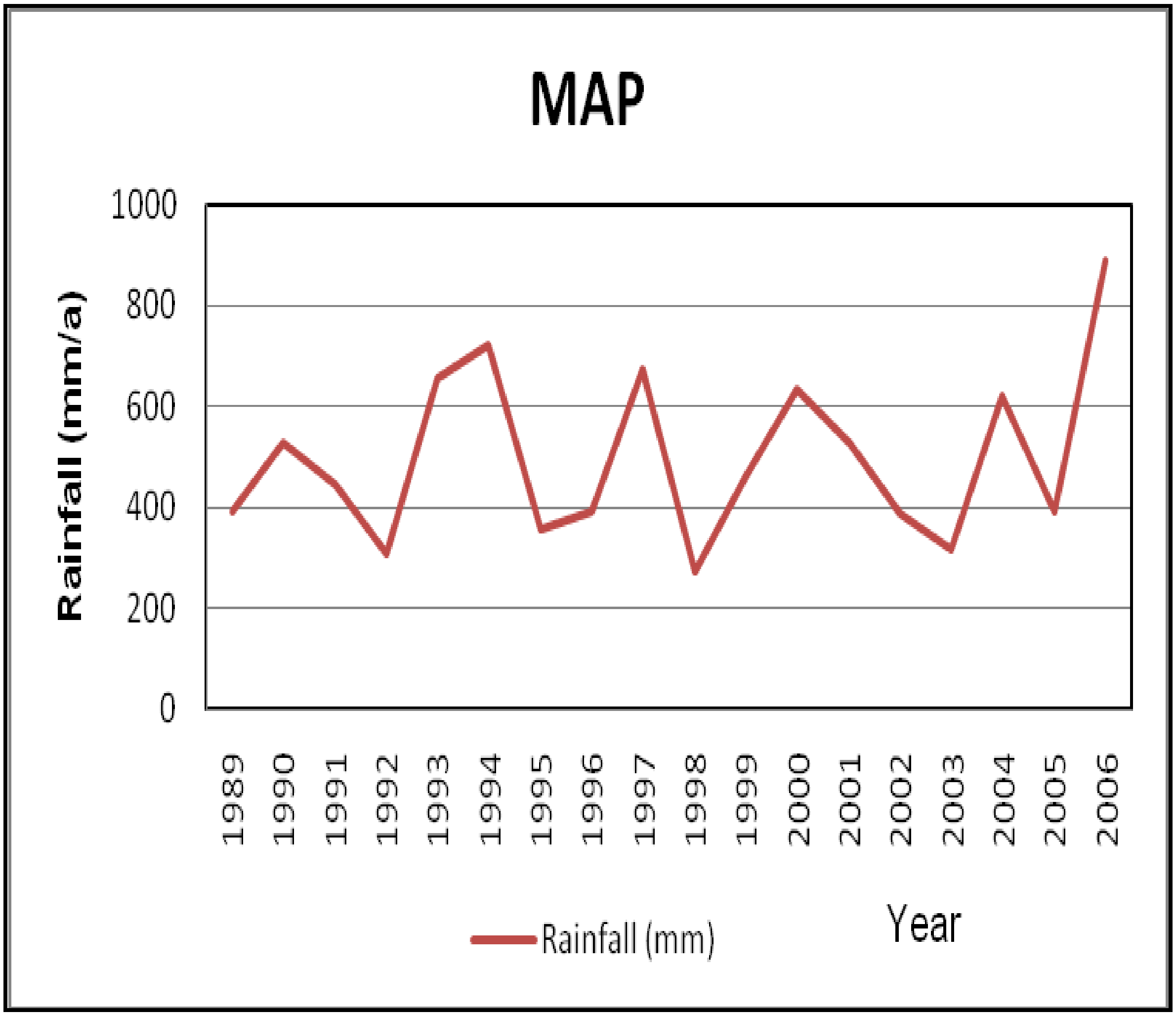

Figure 8: Mean annual precipitation of the study area

Rainfall statistics over the last 16 years (**Figure 8**), for which consistent data exist, reveal that about 8 years during this period showed below average rainfall, while only 6 years showed rainfall above the established visible precipitation-recharge threshold of 600mm/a.

The statistics translate to a statistical maximum of 4 years of potential recharge in every 10 years. According to this information, and the fact that recharge in the study area occurs only during exceptionally wet rainfall seasons (Ploethner, 1997), it can be said that the replenishment rate of the Kombat Aquifer is climatically compounded. If the rainfall-recharge threshold advanced by Ploethner (1997) to be 600 mm/a is valid, then the Kombat Aquifer is recharged once every four years.

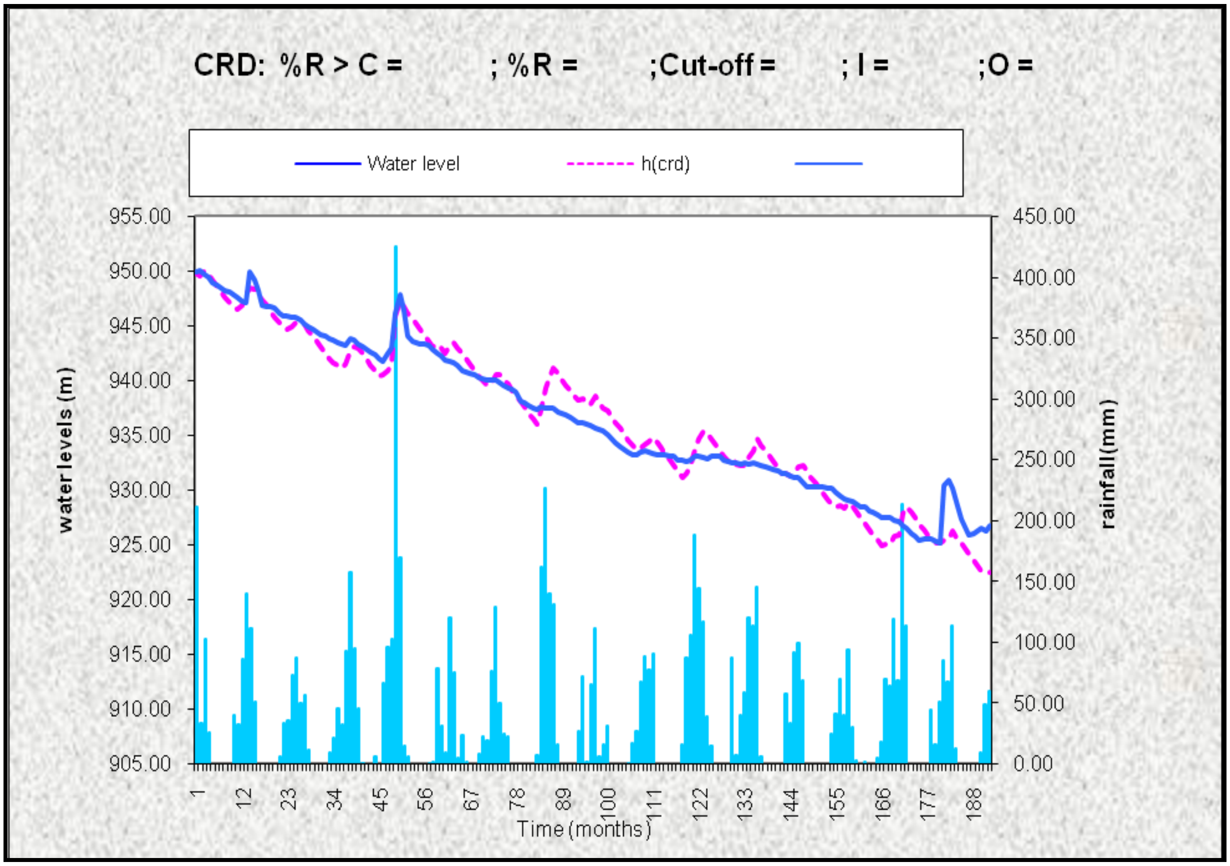

Figure 9: The amount of rainfall producing noticeable recharge

Figure 9 shows a hydrograph of a borehole drilled on the slope of the northern limb of the Otavi Valley, along a northeast trending stream channel. Theoretically, Borehole WW27001 represents boreholes that are preferentially situated to benefit from local recharge; it is therefore best suited to reflect every recharge event in the study area. The borehole hydrograph is therefore considered a good reflection of the comparison between rainfall and recharge events in the study area.

A comparison of the hydrograph and rainfall trends in Figure 9 shows that only monthly rainfall of 200 mm can initiate visible recharge to the aquifer (boreholes) This observation is in agreement with Ploethner's (1997) findings, which associate recharge with exceptionally wet seasons, and might translate to the observed persistent water level decline of the Kombat Aquifer flow system.

In view of the second objective of this study, the rainfall dataset informs the study of the frequency at which water is added to the Kombat Aquifer. This temporal data component therefore addresses the question of how often fresh water is added to the Kombat groundwater flow system, and provides insight into the balance between the recharge and discharge of the Kombat Aquifer. The low ratio of 4 out of 10 years potential groundwater system recharge cycle has implications for the distribution of long-term groundwater storage within the aquifer domain. By implication, long-term groundwater storage would be more reliable towards the discharge zone compared to the recharge zones of the aquifer. There is therefore a need for detailed recharge estimations if the aquifer is to be considered for long-term sustainable bulk water supply.

3.3.2 Topographic Relief and Surface Drainage

At a national level, Namibia is divided into four broad geomorphological units, namely the Namib Desert (**ND**), the Escarpment (**E**), the Central Plateau (**CP**) and the Kalahari Sandveld (**KS**), with the study area situated on the northeastern edge of the central plateau (**Figure 10**). This geomorphic setting makes the study area a raised landmass, which abuts 500 m above its surroundings to a maximum peak of 2093mamsl (Ploethner, 1997). Therefore the study area represents the peak of a watershed draining westward into the Ugab River, northward into the Etosha Pan and Okavango River, and southward into the Omatako River catchment, thereby forming a poorly drained island (**Figure 11**)-Kombat.

As mentioned earlier, in karstic geological settings like the study area, drainage influences both the recharge and permeability of the underlying fracture networks due to the dissolving nature of fractured carbonate surfaces.

The argument is that, in the study area, geological structure (fractures) controls drainage patterns, and in return, drainage collects surface water that infiltrates via fractured stream beds as focused recharge. The reasoning is that geological structures in the form of lithologic contacts, faults and fracture zones prepare the ground for stream channel incision through the inherent decrease in the structural cohesion of rocks along fractured surfaces. The cohesion inferiority of structurally weaker zones makes them preferential stream channel incision zones.

Despite the absence of well-defined drainage at a national level, the study area maintains local north-south and west-east trending streams, ranging from one to three kilometres in length. According to Seeger (1990), the study area is characterised by an absence of well-defined surface drainage system, a phenomenon ascribed to karst topography, where drainage is predominantly underground. With this, Seeger (1990) contends that the streamlets of the study area facilitate groundwater replenishment by collecting surface water and rerouting run-off.

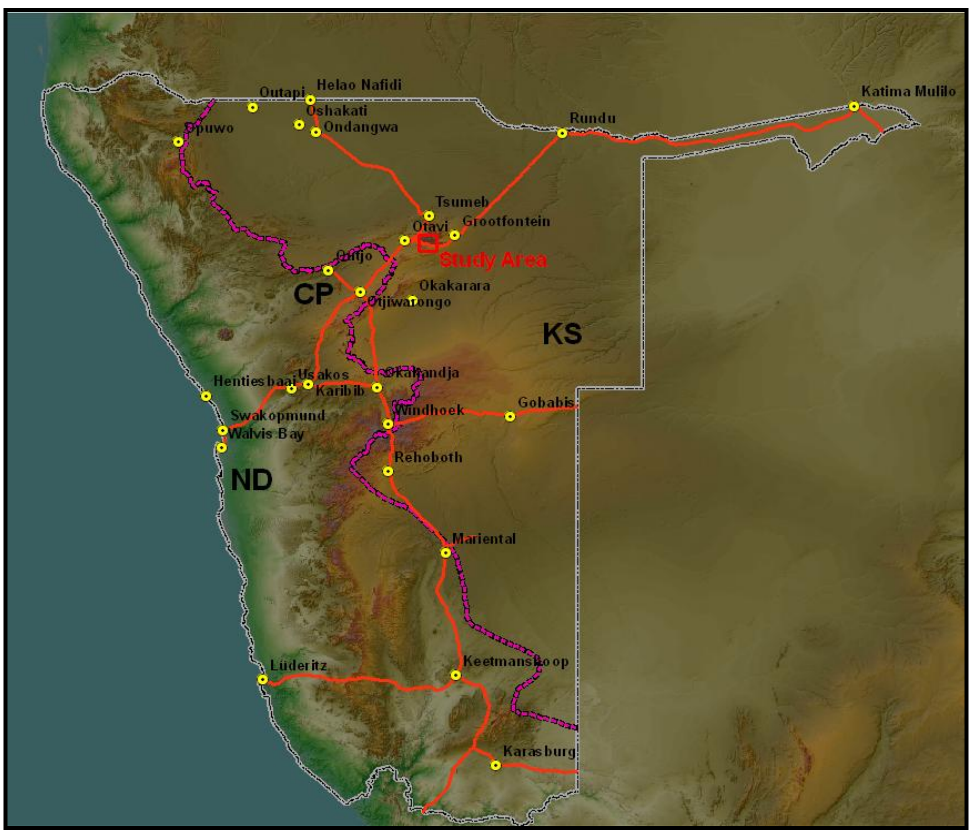

Figure 10: The distribution of geomorphic units in Namibia

At a national level, the study area is characterised by a complete lack of drainage (**Figure 11**).

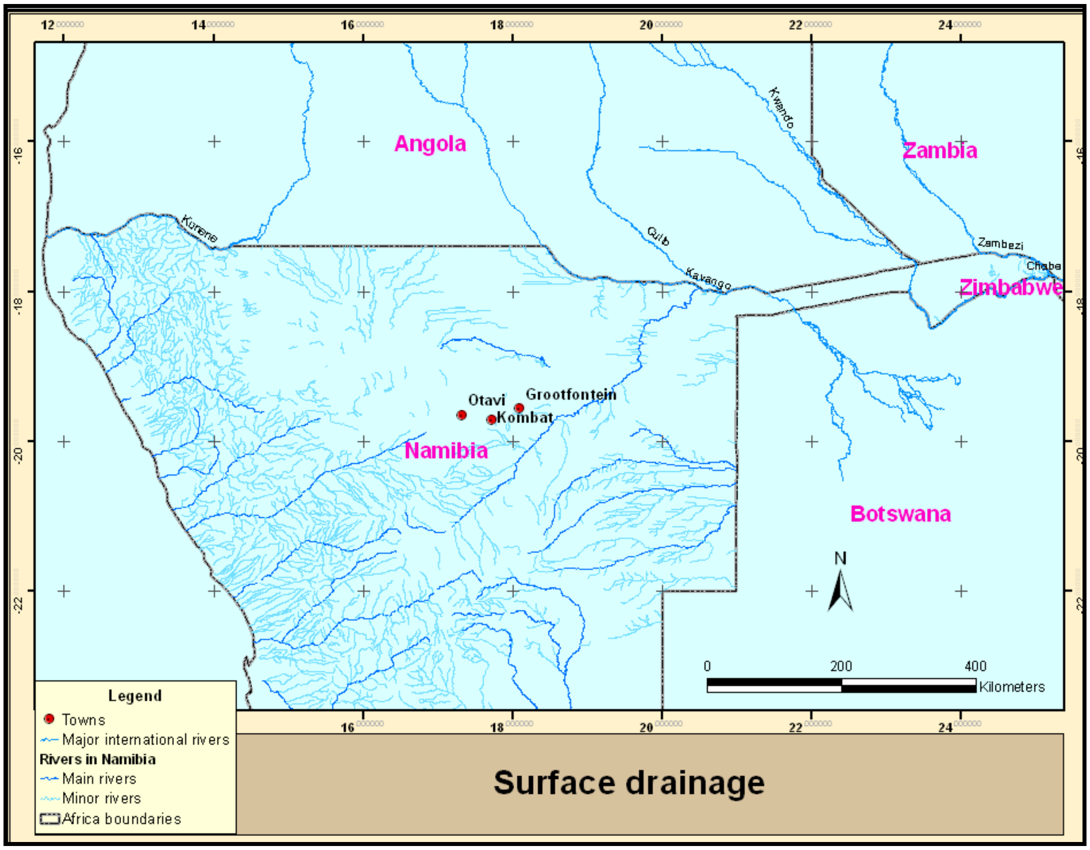

Figure 11: The rivers used for unit run-off estimations

An analysis of the surface drainage pattern in Figure 11 reveals that surface drainage mimics aquifer scale structural elements, i.e. tilting of the rocks in response to folding provides the general direction of stream development over the dip slopes. Streams that have developed on the northern Karstic Plateau and on the southern Otaviberg are parallel to the bedding parallel fracture set. Stream patterns on the dip slope of the northern limb of the Otavi Valley copy the northeast faulting and jointing observed during fieldwork. The influence of the north-south faults to the northwest of Kombat mine is seen in the north-south adaption of streams in that area (**Figure 12**).

A combinatorial study of geomorphology, topography and drainage in geological settings like the study area therefore augments insight into the association of surface drainage, infiltration and groundwater recharge. The emphasis is placed on discerning the nature of recharge in recognition of the fact that groundwater modelling and the sustainable use of groundwater resources partly depend on the understanding of groundwater recharge mechanisms.

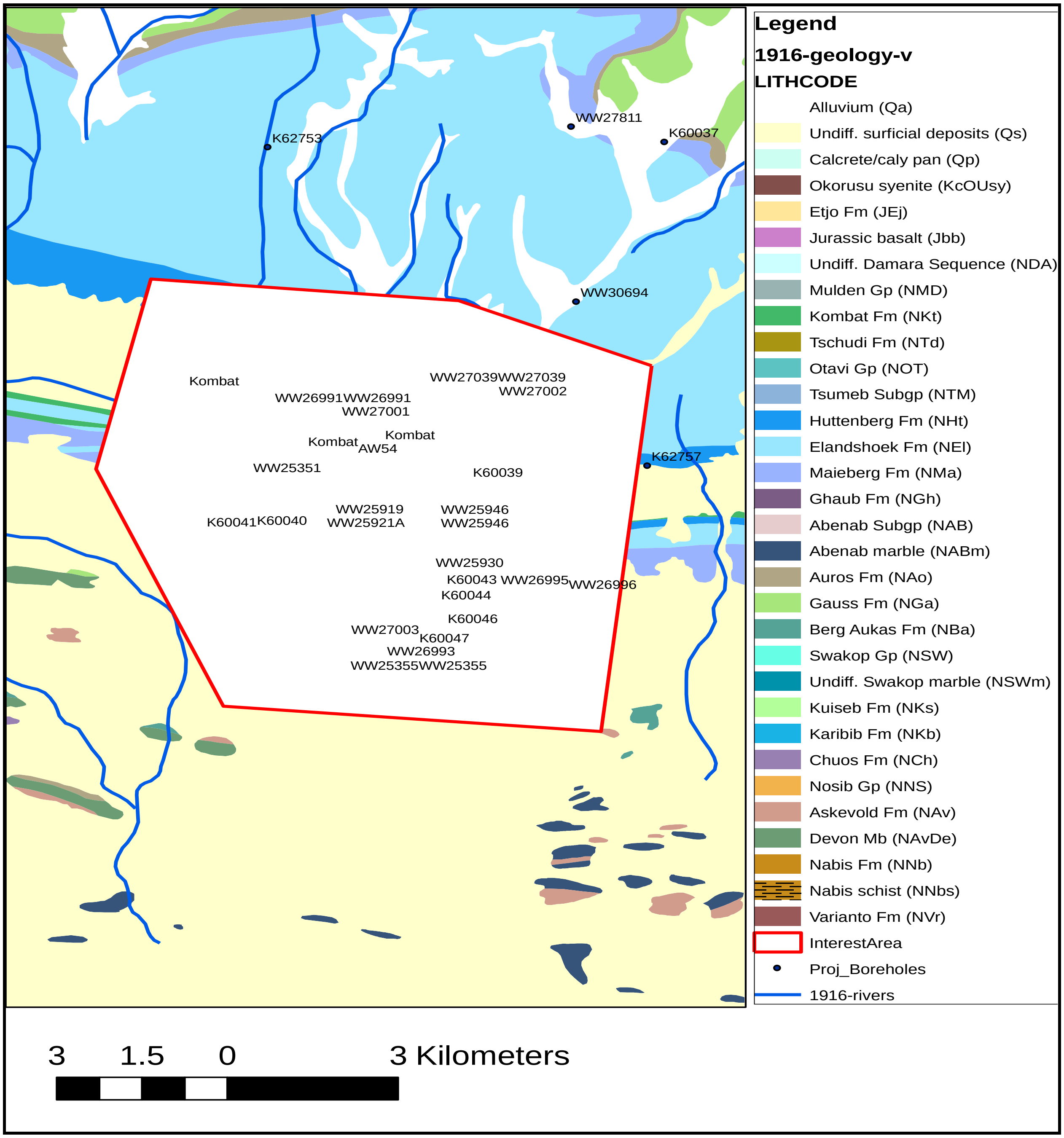

Figure 12: The local drainage within the study area

Local drainage within the study area is relief subdued; it therefore essentially flows north to south.

3.4 Geology

Regional Geology

The study area is located on the northern shelf of the Damara Sequence, which consists of the upper clastic Mulden Group, comprising of the Kombat Formation, the Middle Carbonate, Otavi Group and the lower clastic Nosib Group of rocks (Innes and Chaplin, 1986).

The rocks of the Damara Sequence are folded into a number of east-west trending synclines and anticlines. The Mulden Group is not well-developed; therefore it is only preserved in the cores of synclines, including the Otavi Valley Synclinorium at Kombat.

The dolomite and limestone of the Otavi Group rest unconformably on the floor of quartzite and lava of the Nosib Group and the granite gneiss of the GBC (Seeger, 1990)

The lower clastic unit, the Nosib Group, is exposed on the margins of basement highs in the central and southern portions of the Otavi Mountain Land (Innes and Chaplin, 1986).

On the basis of fold structures, the Otavi Mountain Land has been subdivided into four sub-areas (Seeger, 1990), designated as follows:

Area I: Eastern half of the Otavi Valley Uitkomst Synclinorium, part of which is the study area

Area II: The Grootfontein-Berg Aukas Syncline

Area III: The Harasib-Olifantsfontein Syncline

Area IV: The southern portion of the Tsumeb – Abenab Synclinorium

Local Geology

The study area is situated in the Otavi Valley Synclinorium, which is a west-east trending doubly plunging, canoe-shaped structure.

In the Kombat area, there is a cross-warp accentuated by displacement along several northeast trending dip and strike slip faults (**Figure 13**).

The synclinal structure is asymmetrical, with the northern limb dipping south at angles of between 20° and 75°, and the southern limb being steep in altitude, overtuned to the north or locally recumbent.

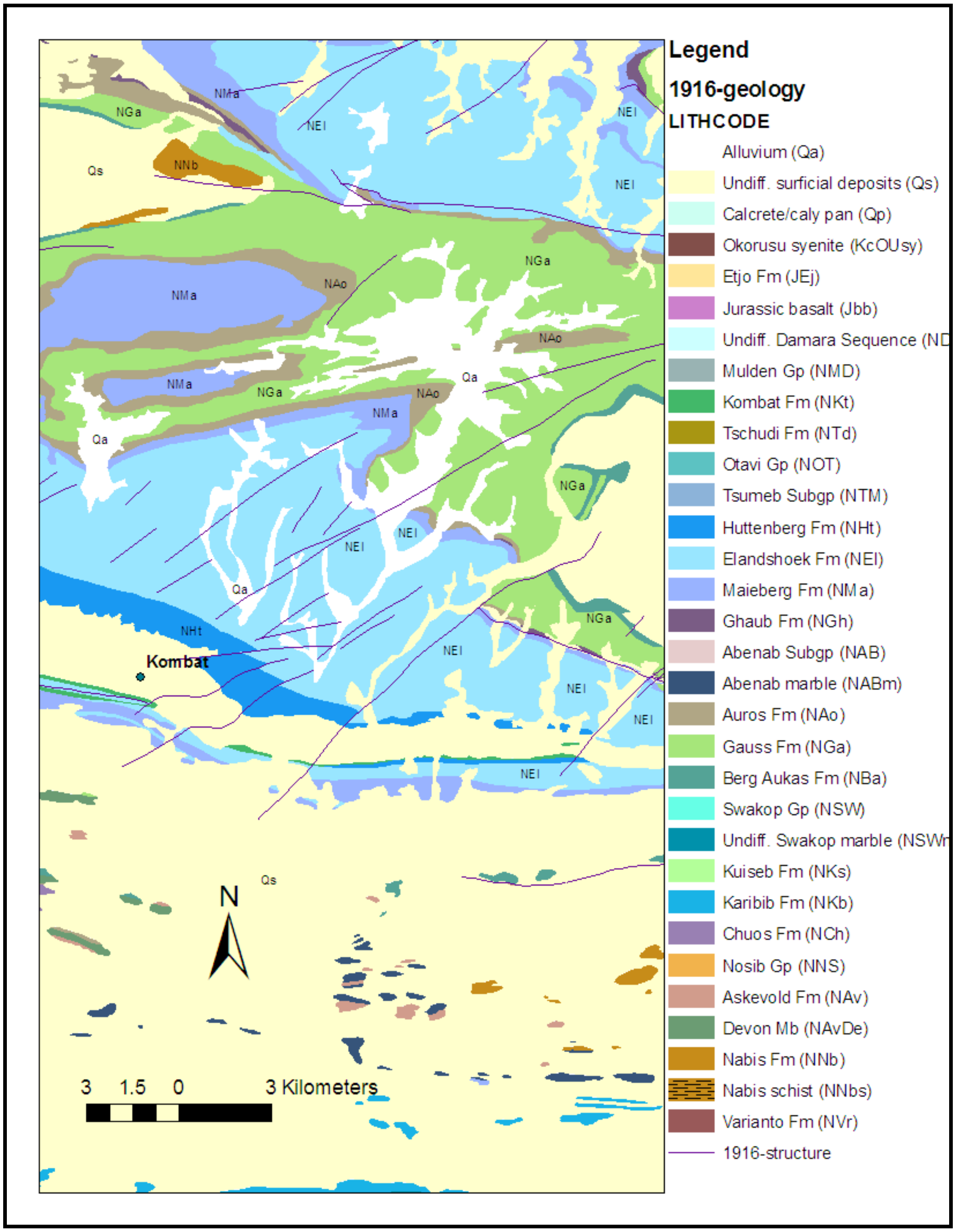

Figure 13: The local surface geology of the study area

Both limbs of the Otavi Syncline are composed of massive and bedded dolomite, thin bedded limestone and subordinate phyllite, thus giving rise to west-east trending prominent mountain range and hills. The core of the syncline consists of phyllite of the Kombat Formation, which forms the flat floor of the Otavi Valley (SRK, 1992).

Two major and numerous minor normal and reverse faults trend northeast-southwest across the Kombat area, and have been exposed during mining and mine development (Deane, 1995). The faults vary in width, alignment and degree of infilling. In places there is a fault breccia with unconsolidated material of all sizes. Dips vary from vertical to high oblique (85^o) with either an easterly or westerly bias (Seeger, 1990). Shear zones are associated with the faults, extending for several metres either side of the Central Otavi valley (SRK, 1992).

3.4.1 Stratigraphy

Detailed stratigraphic descriptions fall outside the scope of this study; hence a summary of the stratigraphy of the study area follows from that given by Hedberg (1979).

The rock formations of the study area belong to the Otavi Group of the Damara Sequence. The Otavi Group (**Figure 13** and **Table 3**) consists of thick carbonate rocks deposited under stable platform conditions on the northern platform of the Damara Provenance.

The stratigraphy of the Otavi Group is divided into the lower Abenab Subgroup and the upper Tsumeb Subgroup by a fluvio-glacial deposit known as the Chuos Formation (Hedberg, 1979). In hydrogeology, stratigraphic boundaries provide natural planes of weakness that act as preferential pathways to bedding parallel groundwater movement (Shapiro, 2000). Furthermore, in geological formations of poor primary porosity like the study area, stratigraphic units act as groundwater flow barriers to bedding plane perpendicular groundwater flow components.

3.4.1.1 The Abenab Subgroup

The Abenab Subgroup forms the base of the Otavi Group and consists of the Berg Aukas, the Gauss, and the Auros Formations.

The Berg Aukas Formation

The Berg Aukas Formation is a transitional deposit. It accumulated when depositional environments were changing from cold marine to a warm and shallow submarine environment. It comprises massive fine-grained dolostones, occasional arenites and shale.

The Gauss Formation

The Gauss Formation is well-developed and largely covers the northern hilly plateau of the study area; it consists of massive, fine-grained dolomite, limestone and minor chert.

The Auros Formation

The Auros Formation makes 230 m to 520 m wide stripes of platy limestone, shale, marl and massive whitish dolomite, marking the initial slope of the northern limb of the Otavi Valley Syncline, north of Kombat Mine.

3.4.1.2 The Tsumeb Subgroup

The Tsumeb Subgroup consists of the clastic Chuos Formation and the carbonate dominant Maieberg, Elandshoek as well as the Huttenberg Formations.

The Chuos Formation

The Chuos Formation, locally referred to as T_1 by Kombat Mine geologists, is a fluvio-glacial deposit. It consists of diamicties (conglomerate, shale, and quartzite) with lenses of dolomite and schist. It does not outcrop east of the Kombat Mine, meaning that the Abenab and the Maieberg Formations have a direct lithologic contact from the Kombat Mine eastwards.

The Maieberg Formation

The Maieberg Formation is a platform slope, deep water deposit. The lower Maieberg Formation consists of slump brecciated to laminated mixed carbonate and argillaceous sediments. The upper Maieberg Formation comprises bedded and finely laminated dolomite.

The Elandshoek Formation

The Elandshoek Formation conformably overlies the Maieberg Formation. It covers most of the northern limb of the Otavi Valley north of Kombat Mine, and it is responsible of the rugged geomorphologic terrain of the northern limb of the Otavi valley (Hedberg, 1979). The lower Elandshoek Formation comprises of massive dolomite, which hosts an extensive strata -bound zone of syn-depositional brecciation, especially at Farms Auros 595 and Sommorau 737, north of Kombat (Van der Merwe, 1986). The brecciation is regionally extensive and regarded as an important regional aquifer (Van der Merwe, 1986). The upper Elandshoek Formation is fairly thin and not easily distinguishable from the lower Elandshoek Formation.

The Huttenberg Formation

The Huttenberg Formation marks the change from the deep water environment observed in the Elandshoek Formation to shallow lagoon shelves. It consists of grey bedded basal dolomite overlain by two upper units (massive and bedded dolomite, chert) which are disrupted by a mineralised breccia body.

The Kombat Formation-Mulden Group

The Kombat Formation, which is the only formation of the Mulden Group in the study area, is a siliciclasitc molasse. It was deposited syntectonically during the early stages of the Damara Orogen; it consists of poorly graded Phyllite, slate, arkose, argillite and siltstone near base. In the study area, the Kombat Formation occupies the central basin of the Otavi Valley syncline, where it is separated from the Tsumeb Subgroup by an angular disconformity.

Table 3: Summary of the stratigraphy of the study area

Group	Subgroup	Formation	Lithology
Mulden		Kombat	Phyllite, slate, arkose, siltstone near base, argillite
		DISCONFORMITY	
Otavi	Tsumeb	Huttenberg	massive and bedded dolomite, chert
		Elandshoek	Massive, strata bound brecciated dolomite
		Maieberg	laminated limestones, marls, dolomite

		Chuos	Tillite (conglomerate, shale, and quartzite)
		DISCONFORMITY	
	Abenab	Auros	Massive dolomite, platy limestones, shales
		Gauss	Massive, fine-grained dolomite, limestone and minor chert
		Berg Aukas	Laminated dolomite, limestone and shale

A characteristic tight infold of the southern Otavi Valley at Kombat is out of character with the more common open fold style occurring elsewhere in the Otavi Mountain Land (Innes and Chaplin, 1986). According to Sohnge (1957), this style of folding persists south of the Otavi Valley, where folds become progressively tightly appressed with the southern limbs being overturned (**Figure 18**).

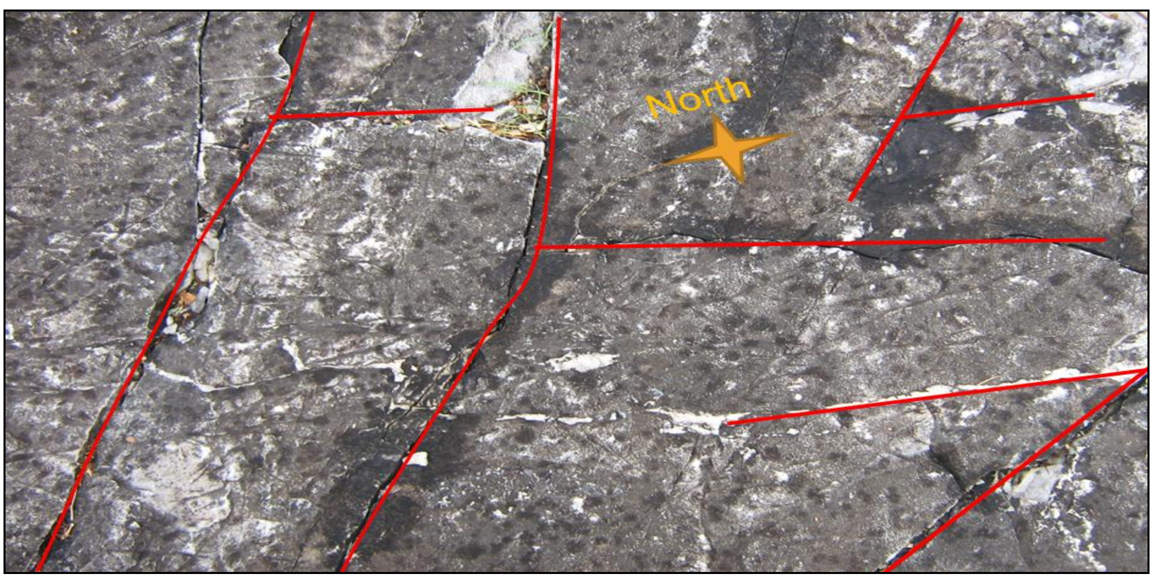

Figure 14: Cross-jointing on the northern dip slope (Fluviokarst).

3.4.2 Structural Geology

The structural geology (**Figures 14 and 15**) of the study area has been a subject of investigation by many geologists (Campbell, 1980, Innes and Chaplin, 1986; Geenway; 1994;

Deane, 1995) and later by hydrogeologists (Seeger, 1990; SRK, 1992; Ploether, 1997; GCS (pty) LTD, 2007). A common element in all the investigations is the verdict that three regional geological controls have been fundamental to structural development in the study area, namely basement highs, basinal deposition centres (*which surrounded the basement highs*) and the Damara Orogen.

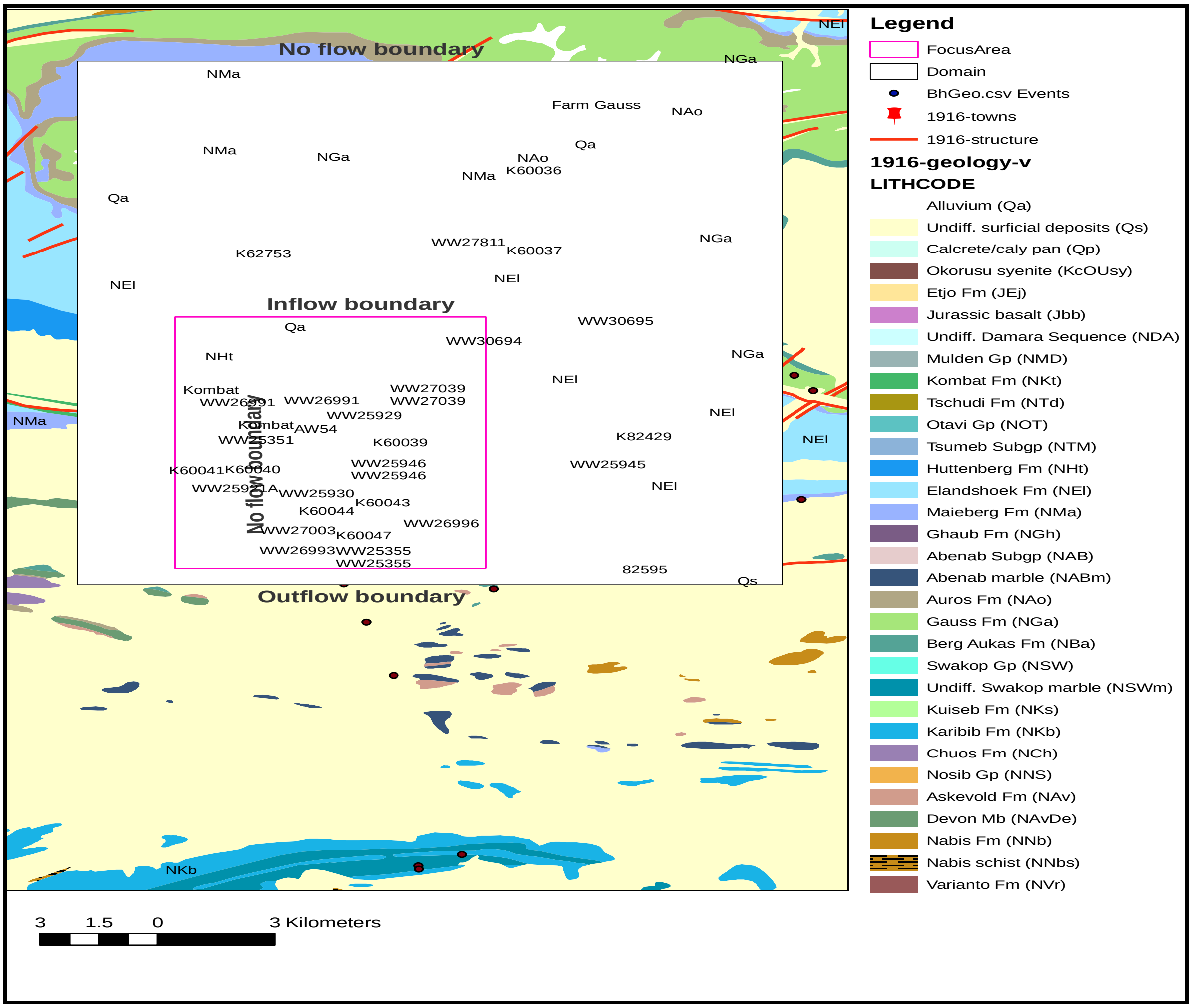

Figure 15: Faults and joints distribution in the study area

Combined with a platform margin depositional environment south of the study area, the basinal deposition centres of the Damara Geosyncline accumulated carbonate sediments ahead of an encroaching sea, whose deep water trough facies developed to the south of the study area (Miller, 1986).

With the initiation of the Damara Orogen, the land surface was folded into a series of east-west trending steep-sided synclines and anticlines. Further crustal stress induced several strike parallel, northeast and north-south faults, fracture zones and joints.

Drawing from field evidence and the findings of previous investigators (Campbell, 1980; Seeger, 1990; Ploethner, 1997), this study considers the Kombat Aquifer as a fractured and moderately karstified carbonate aquifer.

As inferred from Kombat Mine tunnel plans, detailed geological descriptions and field observations; the prominent geological structures (**Figure 16**) impacting on groundwater flow are faults, lithologic contacts and folds (Seeger, 1990). In his report, "The Visit to Kombat Mine," Campbell (1980) states that groundwater flow in the mine is confined to fractures and shears, while Kombat Mine geologists contend that massive dolomites are not worthy of the term aquifer. Combining the two statements, it can be deduced that geological structures (fractures, lithologic contacts, bedding planes) act as groundwater flow conductors. However, the same structures can act as groundwater flow barriers, i.e. in other places, the faults are only two metres in width, and completely occluded by calcite (Innes and Chaplin, 1986).

From a compilation of field maps by mine geologists, Greenway (1994) discovered that discrete faults bifurcate horizontally and vertically and then appear to join up again. In a fractured aquifer system it can be argued that geological structures rearrange and have the potential of compartmentalising groundwater flow within the study area.

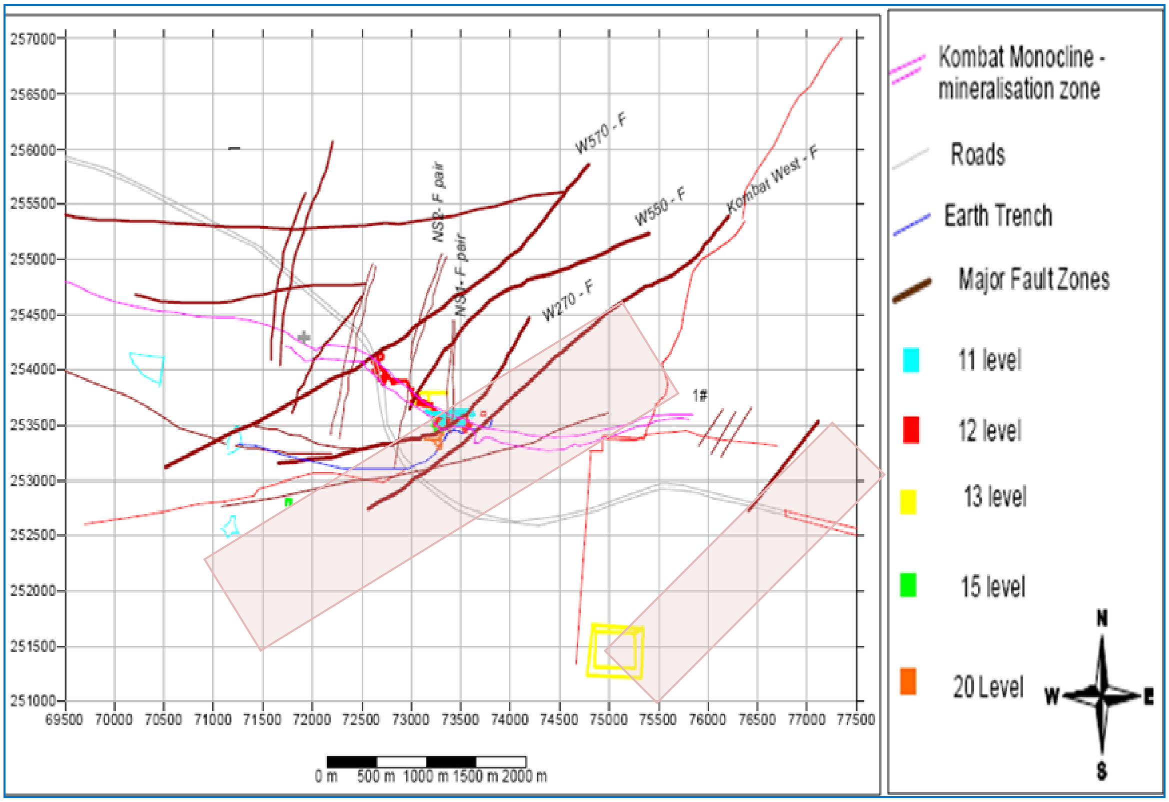

Figure 16: Major groundwater-carrying fracture zones around Kombat Mine (GCS, 2007)

Geological and mining activities by Kombat Mine geologists exposed two prominent north-east trending fault systems, namely the Kombat West (KWF) and the Asis Ost Fault Systems. According to Ploethner (1997), the Asis Ost is a deep-seated geofracture and displaces the northern flank of the Otavi Valley. Ploethner (1997) further contends that the Kombat West Fault might have a similar structural significance.

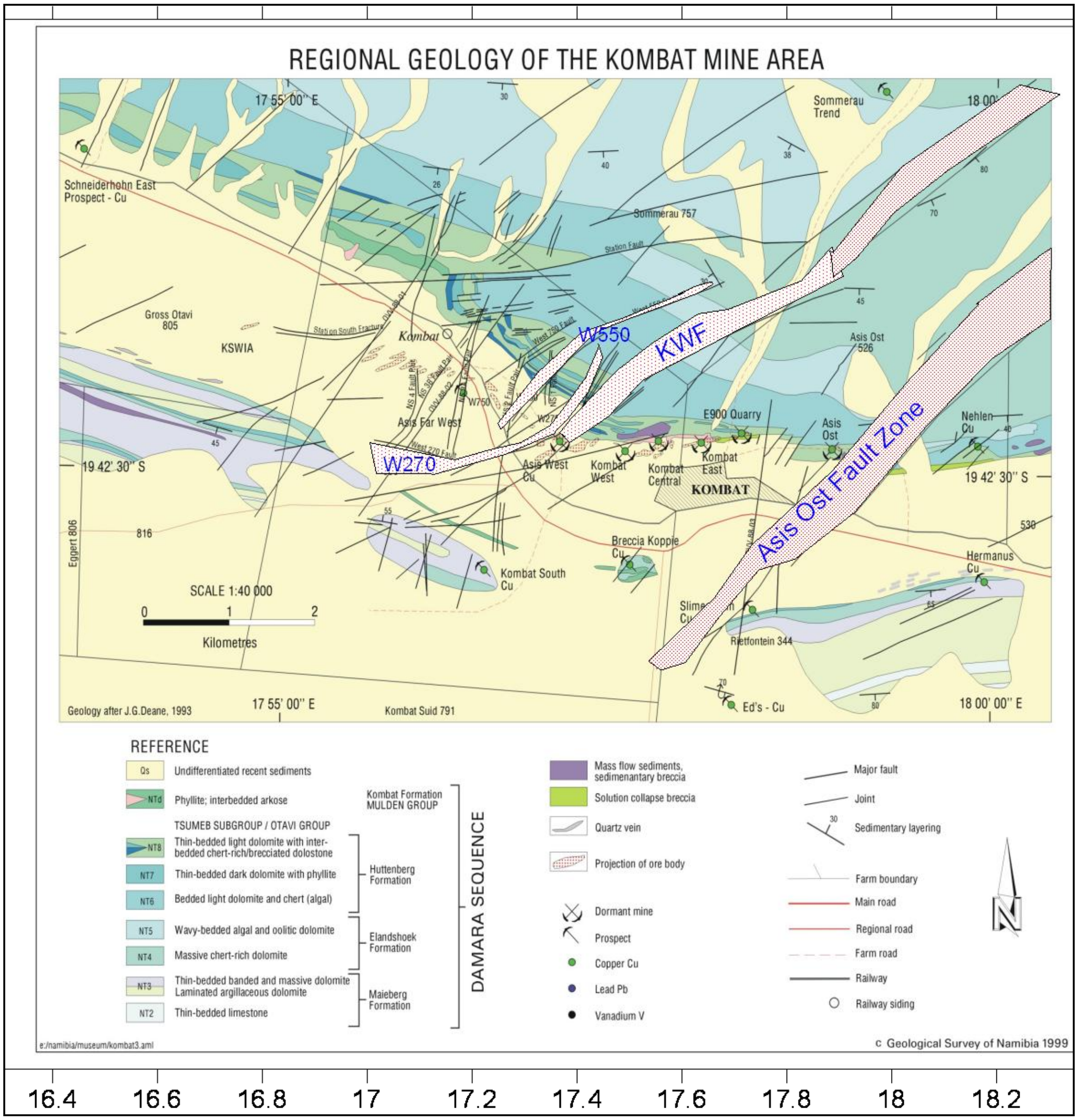

Figure 17: The locality of fracture zones (after Deane, 1995)

The Kombat West Fault System constitutes two subzones of intense faulting, which are separated by broad zones of relatively minimal fracturing (Greenway, 1994).

1. The KWF to KWF3 subzone
2. KWF4 to W270-1 Fault subzone.

Within the KWF System, three major "problem" faults carrying large volumes of water are identified as (Greenway, 1994):

1. The Kombat West Fault (KWF), with a 130 m fault zone width
2. W270, with a 70 m wide fault zone, and

3. W550, with a 10 m wide fault zone (**Figure 17**).

The hydraulic characteristics of the Asis Ost Fault zone are not well-documented, due to the fact that mining activities started east of the Asist Ost area and continued westward. Nevertheless, historic geology classifies the Asis Ost and the Kombat West Faults as related events with similar structural significance. Using the geofracture status and the 10 m to 30 m wide sinkholes which Seeger (1990) reports on the Asis Ost fault system, this study regards the Asis Ost Fault zone as a preferential groundwater flow zone equivalent to the KWF, especially within the context of conceptual groundwater flow modelling.

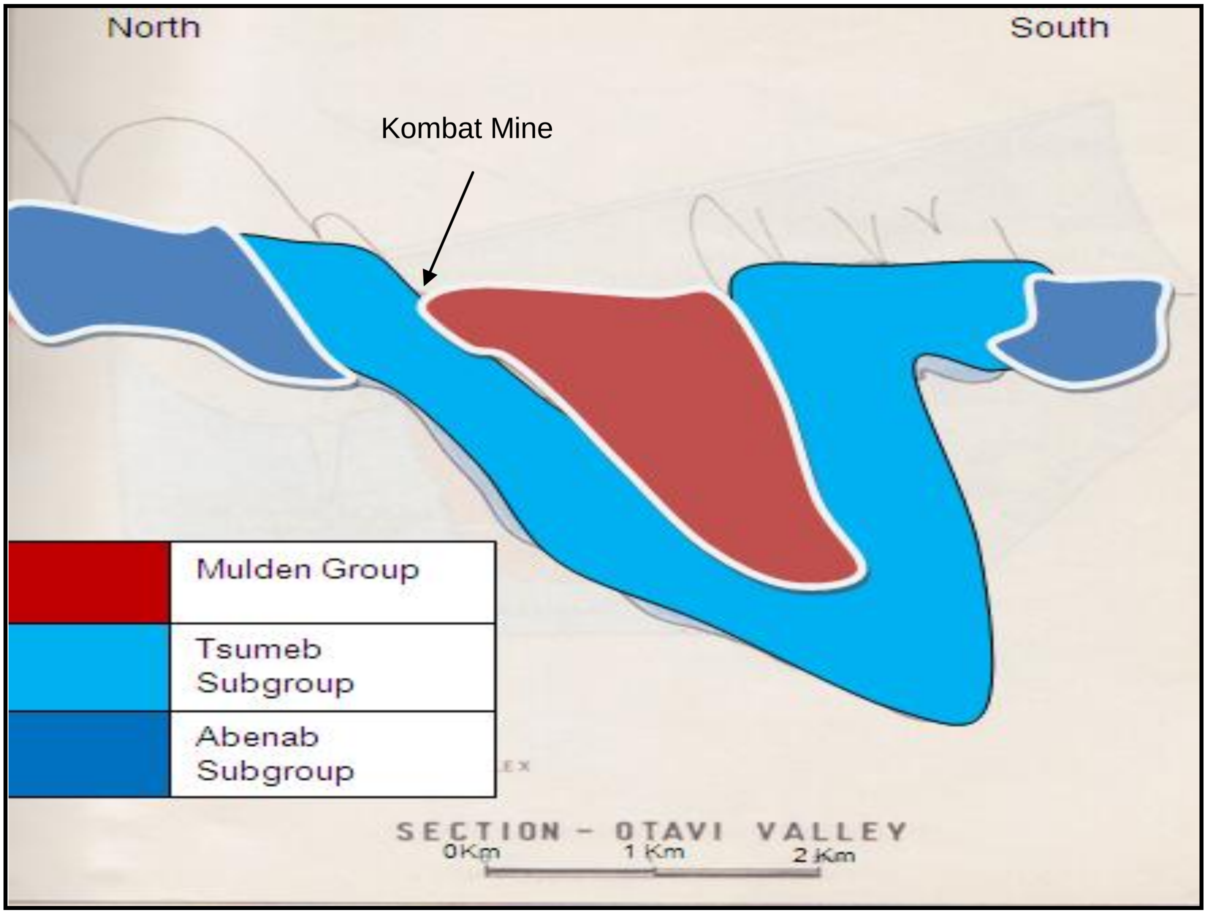

Figure 18: Over-folding of the southern limb of the Otavi Valley Syncline (Deane, 1995)

The regional folding in the Otavi Valley is divided into two phases (Deane, 1995).

Phase one: the eastwest folding that produced local northward-verging folds (**Figure 18**)

Phase two: the rupture of the Otavi Valley Syncline along its axis (**Figure 19**).

From a hydrogeological point of view, folding imposed two hydrogeological controls in the study area, the first being the north-south hydraulic gradient, which is the driving force for groundwater in the study area, and the second being the east-west bedding parallel shear fractures that act as the southern boundary groundwater flow capture structures. These shears redirect some of dominantly north-south flow components into the east-west flow direction.

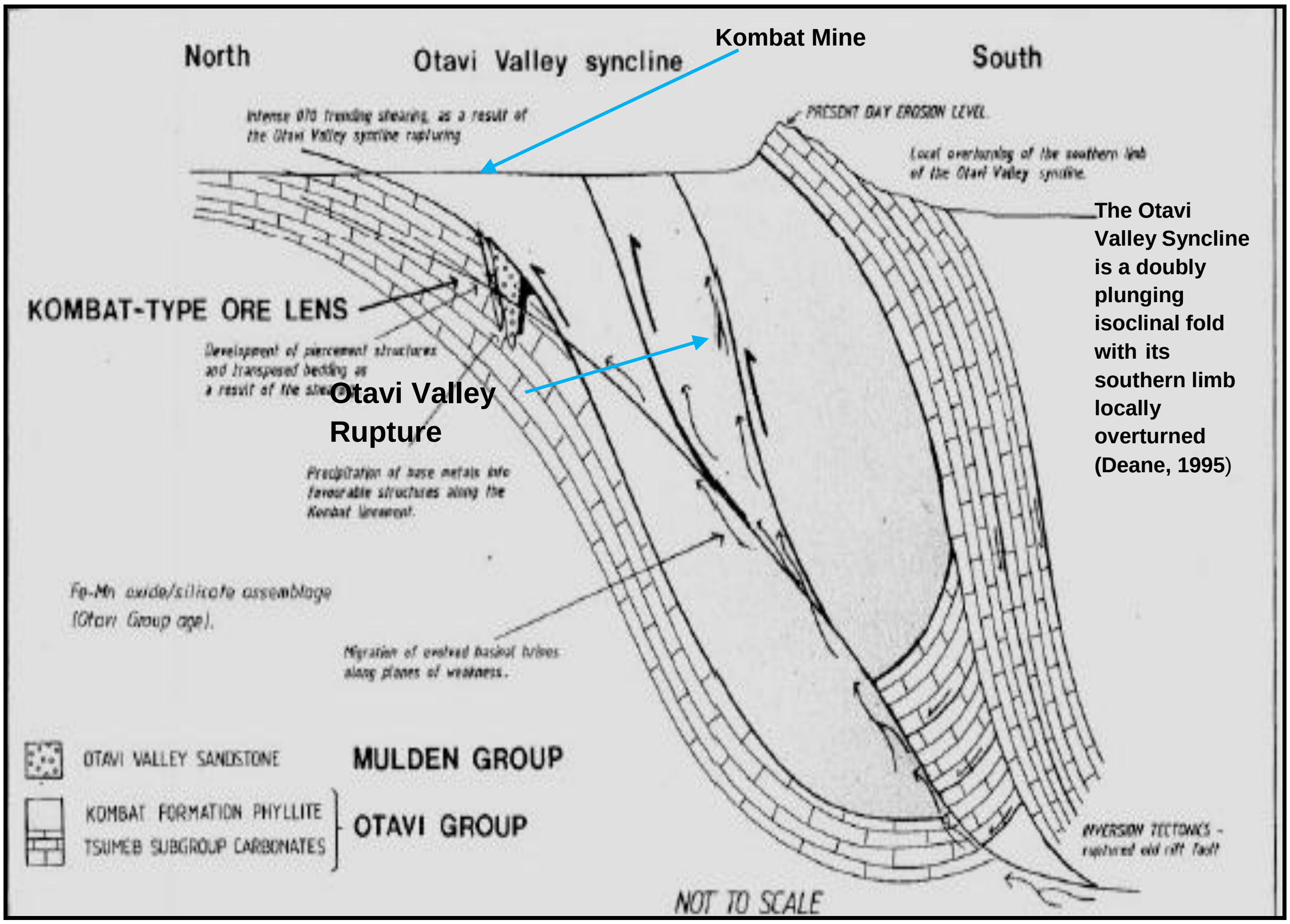

Figure 19: A north -south geological cross-section exemplifying the Otavi Valley rupture (Deane, 1995).

Cross-cutting the KWF are younger tensile north-south vertical faults that have given rise to horst and graben structures. Deane (1995) contends that the intersection of these younger north-south faults and the Kombat West Fault system produced compartment blocks within the Kombat ore body.

In his classification of contact zones as aquifers, Seeger (1990) did not recognise the Otavi Valley rupture (which runs parallel to the contact zone between the Huternberg and the Kombat Formations as an aquifer) as an aquifer. Whereas, Greenway (1994) states that the bedding plane (which is parallel to the Otavi Valley rupture (**Figure 19**) in the mining area is not a threat to mining, meaning that it does not carry much water. In the light of the cited observations, it is the conclusion of this study that the Otavi Valley rupture is not hydraulically developed to constitute a preferential groundwater flow fracture zone.

3.5 Hydrogeology

3.5.1 Hydrogeological Settings

The eastern half of the Otavi Valley Uitkomst Synclinorium, which hosts the study area is a complex, fractured and partly karstified aquifer. In the Kombat area, the aquifer is predominantly controlled by post-depositional folding and faulting of the Damara Orogen.

The natural boundaries of the study area are the peak of the Otaviberg in the north, which doubles as surface and groundwater flow divide, the local secondary folding flexure to the west, the geological contact between the carbonates of the lower Otavi Group, and the less permeable older rocks of the Nosib Group to the south.

The long-term recharge of the aquifer was estimated at 5.5 Mm^3/a by Seeger (1990); however, Ploethner (1997) contends that the groundwater-yielding potential of the study area could be much less than Seeger's (1990) estimate. He points to the infrequent recharge events and the paucity of potential recharge to the aquifer as the basis of his conclusions.

The mine dewatering activities, starting at Kombat Mine in 1989, marks the major abstraction point of the aquifer. Abstractions of between1000 to 2500 m^3/hr have been reported by Seeger (1990) and GCS pty Ltd (2007).

In summary, the hydrogeological framework of the study area consists of interconnected weathered and fractured carbonate aquifers, a sinkhole plain on the northern peak of the study area, losing streams along the dip slope of the northern limb of the Otavi Valley, seasonal springs and fountains along the southern border of the study area. Non-carbonate rocks are restricted to a few shaly interbeds, intercalated horizons of diagenetic chert and local chert, and quartz in detrital carbonate units (Innes and Chaplin, 1986). These elements are interconnected and form a single aquifer that is characterised by steep hydraulic gradients, short flow pathways and concentrated discharge.

3.5.2 Aquifers

As stated earlier, the carbonate rocks of the Kombat area have no primary porosity or permeability, groundwater flow is therefore restricted to joints, faults and contact zones (Campbell, 1980; Seeger, 1990).

The regional aquifer system consists of an irregular network of cross-cutting structures. Local aquifer systems vary from shallow weathered, unconfined fractured aquifers to a deeper confined and predominantly fractured-rock aquifer (Seeger, 1990; Greenway1994).

After observing that the water level contours of the study area do not exhibit preferential flow zones, Ploethner (1990) describes the shallow aquifer of the study area as homogenously fractured and unconfined. However, Ploethner (1997) does not adequately qualify his position on the heterogeneity of the shallow aquifer, considering the fact that the fractures of the study area are not randomly orientated, the spatial scale at which Ploethner's homogeneity is averaged at has also not been given.

On the basis of the nature of geological structures hosting groundwater, Seeger (1990) identified two types of aquifers within the study area. The first one is the fractured and solution-enhanced bedding planes, which have been referred to as contact zones.

Due to steep groundwater flow components, these aquifers cannot be exploited in the elevated northern portion of the study area. The exploitation of contact zone aquifers is therefore restricted to the Central Valley and the SLLA, where they are intersected by boreholes at shallow depths of between 30 and 70 m below surface.

The second type of aquifer consists of faults and fault zones, which are surfaces along which rocks have been broken and relative movement of the rocks on either side of rupture has occurred. As mentioned earlier, two fault zones traverse the study area in a northeasterly direction, namely the Kombat West Fault and the Asis Ost Fault. Drilling for both water supply and mineral exploration purposes has shown that the permeability of the faults in the shallow aquifer (upper 180 m) is low (12 to 600 m^3/hr).

However, the intersection of the Kombat West Fault by underground tunneling at the depth of 450 m could deliver up to 5000 m^3/h, consequently flooding the mine in 1988 (Seeger, 1990).

The overlap between the water supply and mine dewatering sourced hydrogeological information appears to suggest the existence of a transition zone between 170 m to 240 m, within which the aquifer system changes from a shallow weathered, fractured and sheared unconfined aquifer to an exclusively fault-controlled, deep and confined flow system, which has thus far only been intersected by mining activities.

3.5.3 Hydrostratigraphy

The vertical segregation of groundwater flow by alternating horizons of permeable and impermeable stratigraphic units is referred to as hydrostratigraphy. This phenomenon occurs in the form of bedding contact zones of the study area.

From a hydrostratigraphy point of view, the contact zones of the study area can be divided into two categories; the intra- and interformational contact zones. Hydraulically active intraformational contacts are typically between bedded and massive dolomite or limestone, while the contacts between two different lithotypes are the most hydraulically favourable contact zones.

Seeger (1990) identified seven contact zones in the Otavi Mountain Land, two of which do not occur in the study area. Seeger (1990) further contends that dolomite, because of its massive property, tends to shear and fracture more intensely than the more elastic phyllite and well-bedded limestone along its contacts, and that the most extensive aquifer with the greatest potential is the contact between the basal dolomite of either the Berg Aukas or the Gauss Formations resting of older and less permeable rocks in Zone I.

The following contact zones were identified as potential aquifers in the study area (Seeger, 1990):

Zone I: Contact between the basal dolomite of either the Berg Aukas or the Gauss Formations resting on older and less permeable rocks.

Zone II: Contact between laminated dark shaly limestone and light dolomite belong to the Berg Aukas Formation.

Zone V: Contact between bedded light grey dolomite and thin-bedded pyllite of the upper Maieberg Formation.

Zone VI: Contact between massive dolomite of the Elandshoek and the underlying thin bedded limestone of the Maieberg Formation.

Zone VII: Contact between bedded dolomite and massive dolomite of the Elandshoek.

Table 4: Hydrostratigraphy of the study area (after Seeger, 1990)

Group or Subgroup	Group or Formation	Hydrogeological Unity
	Mulden (Kombat)	Aquiclude
Otavi (Tsumeb)	Hüttenberg	Unit 3c: Fractured/Karstfied Aquifer
	Elandshoek	Unit 3b: Fracture Aquifer
	Maieberg	
	Chuos	Unit 3a: Auitard
Otavi (Abenab)	Auros	Unit 2: Aquiclude
	Gauss	Unit 2: Fracture/Karstified Aquifer
	Berg Aukas	
Nosib Group	Varianto, Askevold, Nabis	Unit 1: Aquiclude
	Basement Complex	

The stratification and high pressure head in the north, combined with steep dipping relief and synclinal geometry makes the bedding parallel groundwater flow easily accessible in the central valley and southern zone of the aquifer, especially where the rocks are overturned.

The broader significance of this realisation is that, due the bedding fracture confinement and the near vertical geometrical attitude, the contact zones of the southern study area will most likely behave like bounded aquifers during abstraction. They will therefore have high initial yields that are unsustainable over longer periods, leading to the high drawdowns and collapsing abstraction boreholes that Ploethner (1997) reports. From the given hydrostratigraphic analysis, it becomes a possibility that groundwater outflow interception efforts should target the intersections of bedding contacts and the fracture/fault zone, in view of exploiting the joint storage and transport capabilities of both faults and the bedding planes.

3.5.4 Groundwater Levels

The Department of Water Affairs, as a custodian of groundwater resources, has monitored groundwater levels (**Figure 20**) in the study area and its surroundings since the mid-1970s, as confirmed from the borehole hydrographs of the study area.

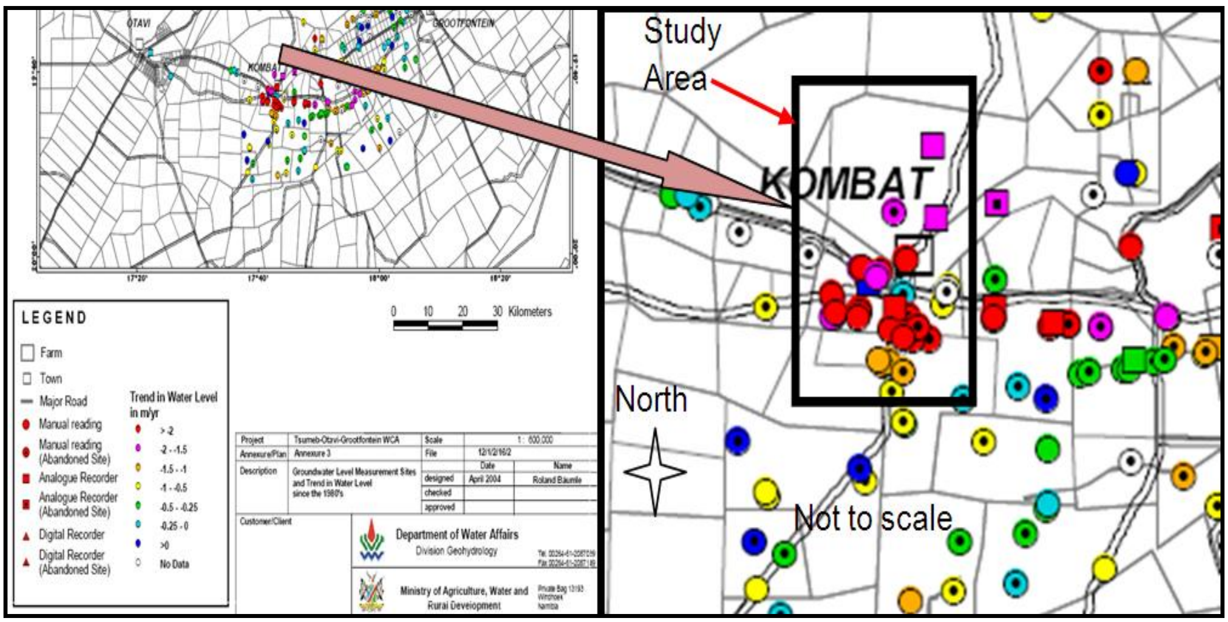

Figure 20: The distribution of monitoring boreholes around the study area

Noticeable in Figure 20, is the disparity in groundwater levels decline between the north and south of Kombat Mine, as indicated by the red dots denoting more than 2 m per year, the pink rectangles between 2 and 1.5 m per year, and the yellow dots for less than 1.5 m of water levels decline per year.

Due to the fact that the Kombat Aquifer consists of an irregular network of parallel and cross -cutting structures, the water table is not a continuous surface. Rather, it is a theoretical surface approximated by the elevation of water levels in boreholes that have penetrated into saturated zones (Seeger, 1990). The water table therefore appears parallel to the topography of the land surface, in a subdued manner.

In response to the high groundwater abstraction from Kombat Mine, the water levels recorded in the available monitoring boreholes indicate a well-established groundwater flow connectivity east of Kombat Mine, as opposed to the west, for instance the area affected by pumping from Kombat Mine Shaft no.1 extends only 5 km to the west, but more than 21 km to the east of Kombat (DWA, 2004).

In light of the observed strong correlation between the amount of annual rainfall and water level fluctuations, it can be stated that both short and long term groundwater level fluctuations of the Kombat Aquifer are dependent on and reflective of precipitation patterns, i.e. the 2006/2007 heavy rainfall event in Northern Namibia resulted in elevated recharge and subsequent mine dewatering problems (GCS (Pty) Ltd., 2007). The strong association between local rainfall and recharge tallies with Seeger (1990), who argues that, due to the study area's mountainous geomorphology, there is no surface or groundwater inflow from regions outside the study area.

Discrete preferential flow is evident from troughs in the groundwater level contours of the study area. The groundwater contours exhibit discrete groundwater outflow components from the regional recharge zone (Campbell, 1980; GCS (Pty) Ltd., 2007); therefore the groundwater flow directions point outwards from the highest parts of the mountains. From there, the groundwater splits into a western branch directed towards Otavi, and into three eastern branches along the Harasib–Olifantsfontein Syncline, the Grootfontein–Berg Aukas Syncline and the eastern portion of the Otavi Valley– Uitkomst Syncline. The eastern branches are formed by carbonate rocks and separated by aquitards composed of the basement rocks of the Nosib Group.

An assessment of borehole completion reports of the boreholes in the study area shows that the general depth to groundwater is between 30 m and 50 m below ground level in the central valley and the southern low lying areas, but can be as deep as 100 m in the elevated and hilly northern areas. However, the rest water levels can be as shallow as 11 m in the northern high lands and 8 m in central valley and southern low lying areas, this behaviour in groundwater levels is typical of semi-confined to confined aquifers.

3.5.5 Groundwater Flow

3.5.5.1 Regional groundwater flow

The topography and drainage, as discussed in Section 3.3.2, indicates that the regional groundwater flow control structures of OML consists of an elevated dome-shaped topography, synclinal valleys, anticlinal hills and ridges of stratified, fractured and karstified carbonate rocks. The elevated domed relief of the OML makes it a watershed peak from which both surface water and groundwater flows in all directions (Seeger, 1990); northward into the Etosha and Okavango catchments, and southwards and eastward into the Omatako catchments (**Figure 21**). Therefore the Etosha Pan, the Kavango and Omatako Rivers constitute the regional discharge zones of the carbonate aquifers of the OML, with the intensely fractured and karstified northern peak of the Otavi Valley's northern limb as the central and dominant recharge zone. The flow groups, as seen in Figure 21, are deduced from the hydrogeological map of Namibia (DWA, 2003)

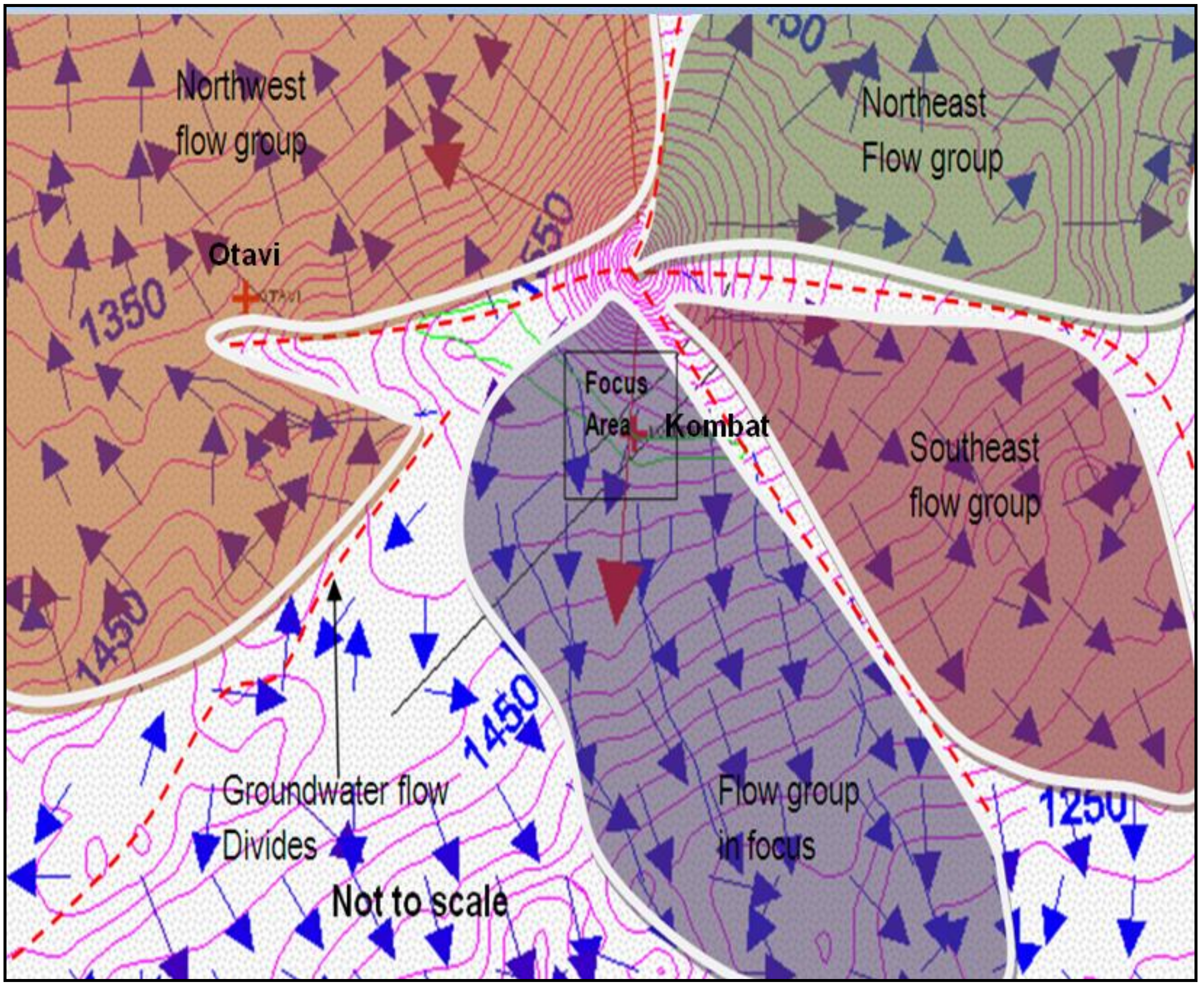

Figure 21: The regional outflow groundwater components of the OML

As previously stated, studies on the hydrogeology of the OML tend to insist that lithologies making up the carbonate massif of the OML have little or no primary porosity or permeability (Campbell, 1980; Seeger, 1990; Ploethner, 1997; GCS (Pty) Ltd, 2007). Therefore groundwater movement is through fractured rock and openings between bedding planes. Secondary porosity is created by faulting and fracturing and enhanced by chemical weathering (Seeger, 1990).

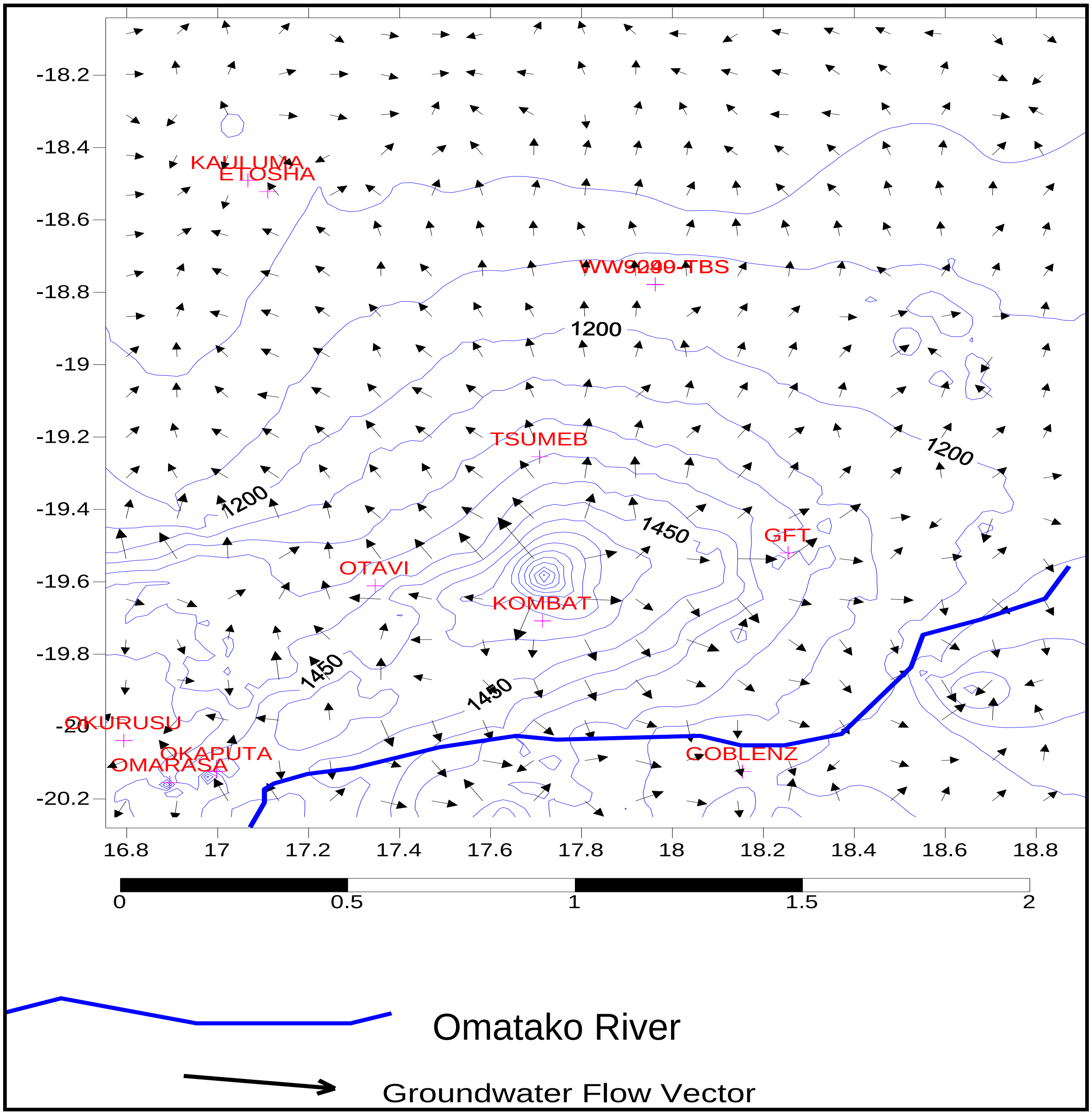

Figure 22: Regional groundwater level contours

3.5.5.2 Local groundwater flow

The local groundwater flow system of the study area stretches from the peak of the Northern Otaviberg southwards towards into the Central Valley and discharges into the less permeable rocks of the Nosib Group in the SLLA; it is therefore part of the regional groundwater flow component drained by the Omatako River Catchment (**Figure 21**).

The groundwater flow system of the Kombat Aquifer is marked by near-vertical recharge components under the northern ridge and upward-rising groundwater flow beneath the Otavi Valley. This flow configuration, according to the potential theory, is inherent of groundwater systems in ridge and valley topographic settings (Freeze and Cherry, 1979).

Assuming Darcian groundwater flow across the flow domain of the study area, a construction of theoretical equipotential surfaces and their corresponding set of orthogonal flow lines would produce a flow net with vertical groundwater divides beneath the karstic plateau (ridge) and the Otavi Valley. The peak of the anticline of the Otavi Valley Synclinoria therefore marks the northern no-flow boundary of the study. Ploethner (1997) cites lithologic constraints and locates this boundary five kilometres south of the ultimate peak of the anticline. As a result, strata-bound groundwater circulation of the study area would theoretically follow a concave flow path from the uplands through the central valley and discharge along the overturned bedding planes in the SLLA (**Figure 25**).

The combination of rugged topography in the recharge area and heterogeneous stratigraphy has divided the groundwater flow system of the study area into the upper aquifer, mainly consisting of the Tsumeb Subgroup and the aquifer that comprises the lower Abenab Subgroup. These two flow subsystems are divided by impermeable layers of the discordant and discontinuous diamictite of the Chuos Formation and the shaly limestone of the upper Auros Formation (**Table 4**).

Differential response to deformation has induced a high permeability basal dolomite aquifer unit, creating a direct link for recharge water from the uplands to the SLLA. From a groundwater supply point of view, Seeger (1990) refers to this aquifer unit as the most extensive, and that it has the greatest water supply potential. Viewed from a groundwater flow perspective, the basal bedding plane represents the regional groundwater flow medium of the southward regional groundwater flow component of the OML. It is therefore expected that the water levels of the boreholes accessing the deep aquifer are stable and would mimic steady state conditions, as opposed to the highly dynamic and seasonally variant water levels of the shallow fractured aquifers of the upper Tsumeb Subgroup.

While strata-bound groundwater movement essentially trends north-south along the regional hydraulic gradient, transverse fracturing has induced a northeast to southwest local groundwater flow pattern. Concordant to the fracture pattern, the fracture controlled groundwater flow pattern of the Kombat Aquifer is essentially parallel to the KWF along the northern dip slope, and tends to converge towards the Central Valley. The tendency of the groundwater to converge towards Otavi Valley might be explained by the relative converging spatial relationship of the two deep-seated fault zones traversing the entire flow system, as shown in Figures 16 and 17**.**

On both sides of the floor of the Otavi Valley, groundwater movement exploits bedding parallel shear fractures and adopts an easterly flow direction. This is due to the presence of the west-east trending, less permeable phyllite underlying the Central Otavi Valley. However, the north-south and southeast flow components are still maintained along faults and joints in the phyllite.

While the northern and southern groundwater flow boundaries are defined by geological settings, the eastern and western groundwater flow boundaries are essentially hypothetical, and are assumed to align themselves along the flow line, distinctions are made where fracturing enters or removes groundwater through the western and eastern groundwater flow boundaries.

In the absence a detailed studies on groundwater flow rate estimations; previous investigators describe the groundwater flow of the study area as rapid (Seeger, 1990; Ploethner, 1997). This position is supported by low EC values between 67 and 160 mg/l, as well as a persistent recent hydrochemical facie throughout the entire flow domain.

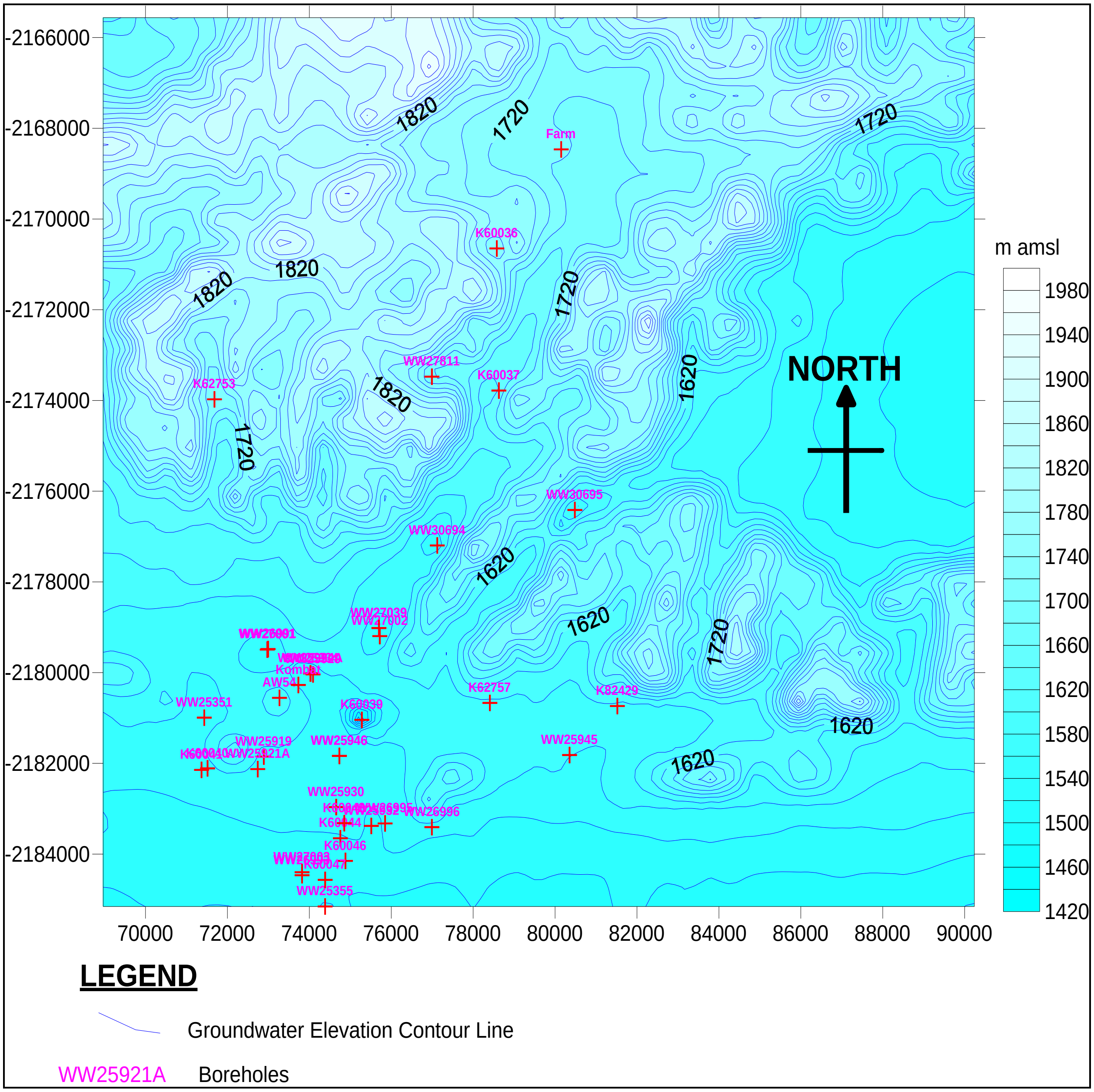

Figure 23: The distribution of local hydraulic head in the study area

Geological Sections

In order to facilitate the understanding of aquifer geometry, flow geometry, and the distribution of the hydraulic potential of the study area. Two geological sections are drawn along the groundwater flow line indicated in Figure 24. They present broad geological aspects of the Kombat Aquifer with respect to folding, lithology and faulting across the flow domain.

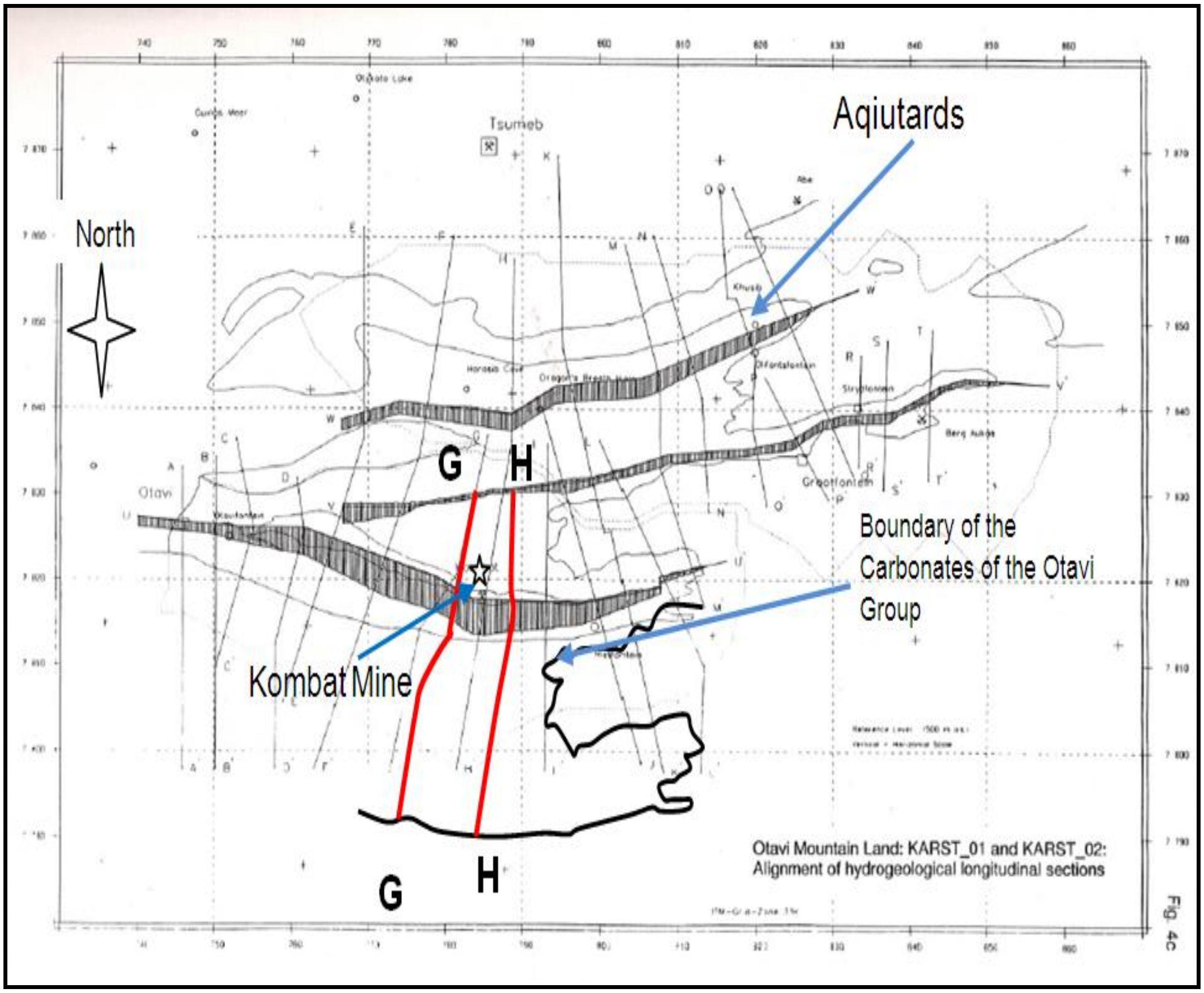

Figure 24: Site layout for the geological cross-section H-H and G-G (Seeger, 1990)

Geological sections H-H (**Figure 23**) is essentially a north-south trending traverse passing through Kombat Mine.

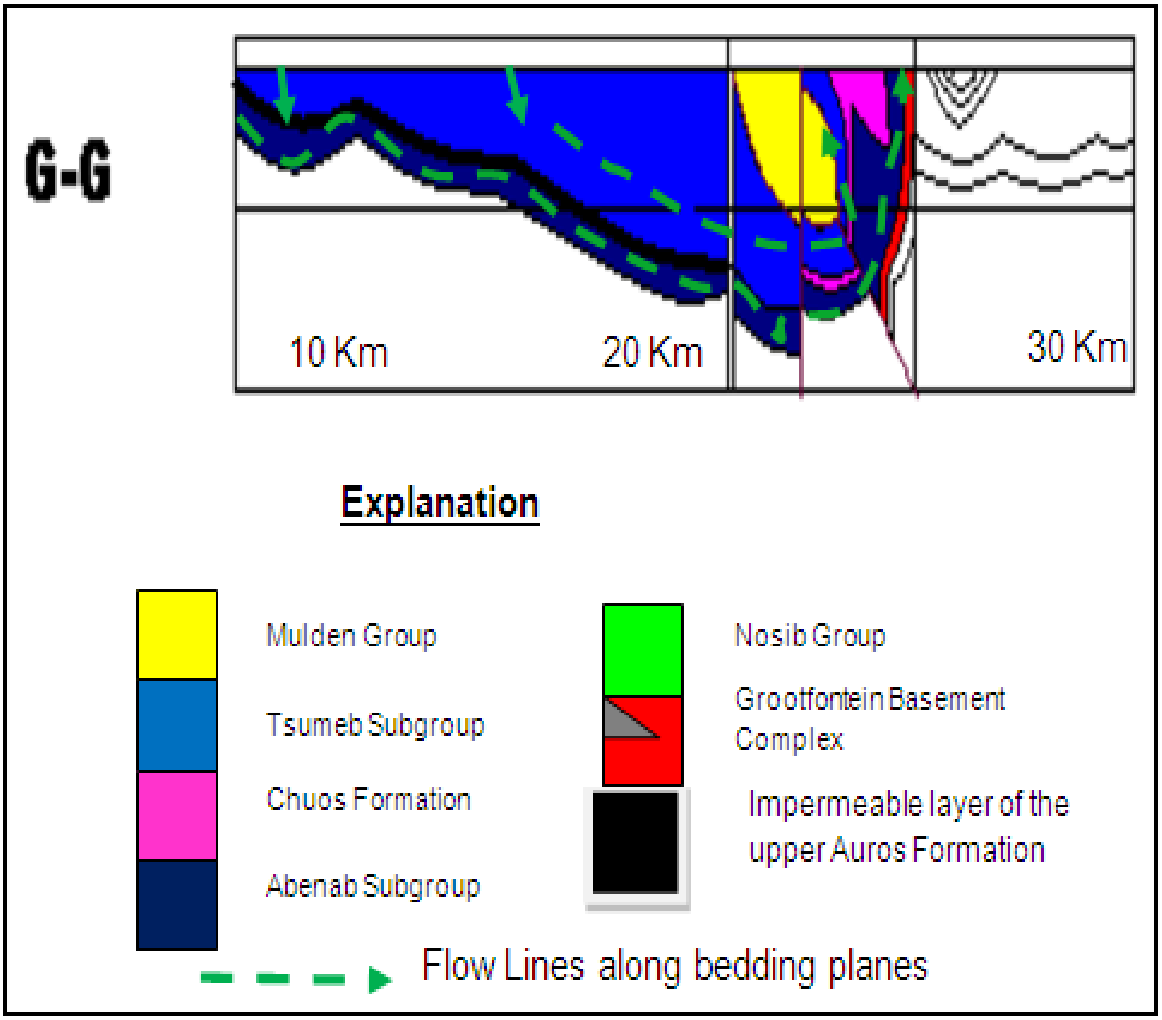

Figure 25: The geology along cross-section G-G

Geology

Sections G-G (**Figure 25**) and H-H are representative of a complete set of the subgroups of the Otavi Group, illustrating lithological and fault geometry in the immediate vicinity of Kombat Mine. However, Section H-H (**Figure 26)** constitutes all but the Chuos Formation, indicating that the Chuos Formation thins out eastwards from Kombat Mine. Both the Tsumeb and the Abenab Subgroups demonstrate a westward and uphill increasing loss of width.

This geologic setting imposes two groundwater flow constraints on the southern uphill flow component. Firstly, the progressive loss of width of the lithologic contact aquifer units builds up enormous hydraulic pressures in these sections of the flow system, thereby creating conditions conducive for spring flow. Secondly, the uphill groundwater flow component exposes this rather deep flow system to the surface, creating a shallow water table; thereby allowing seepage into the weathered upper portions of the rather impermeable meta-sediments of the Nosib Group and the GBC. The latter groundwater flow constraint facilitates the continuation of the southward flow component.

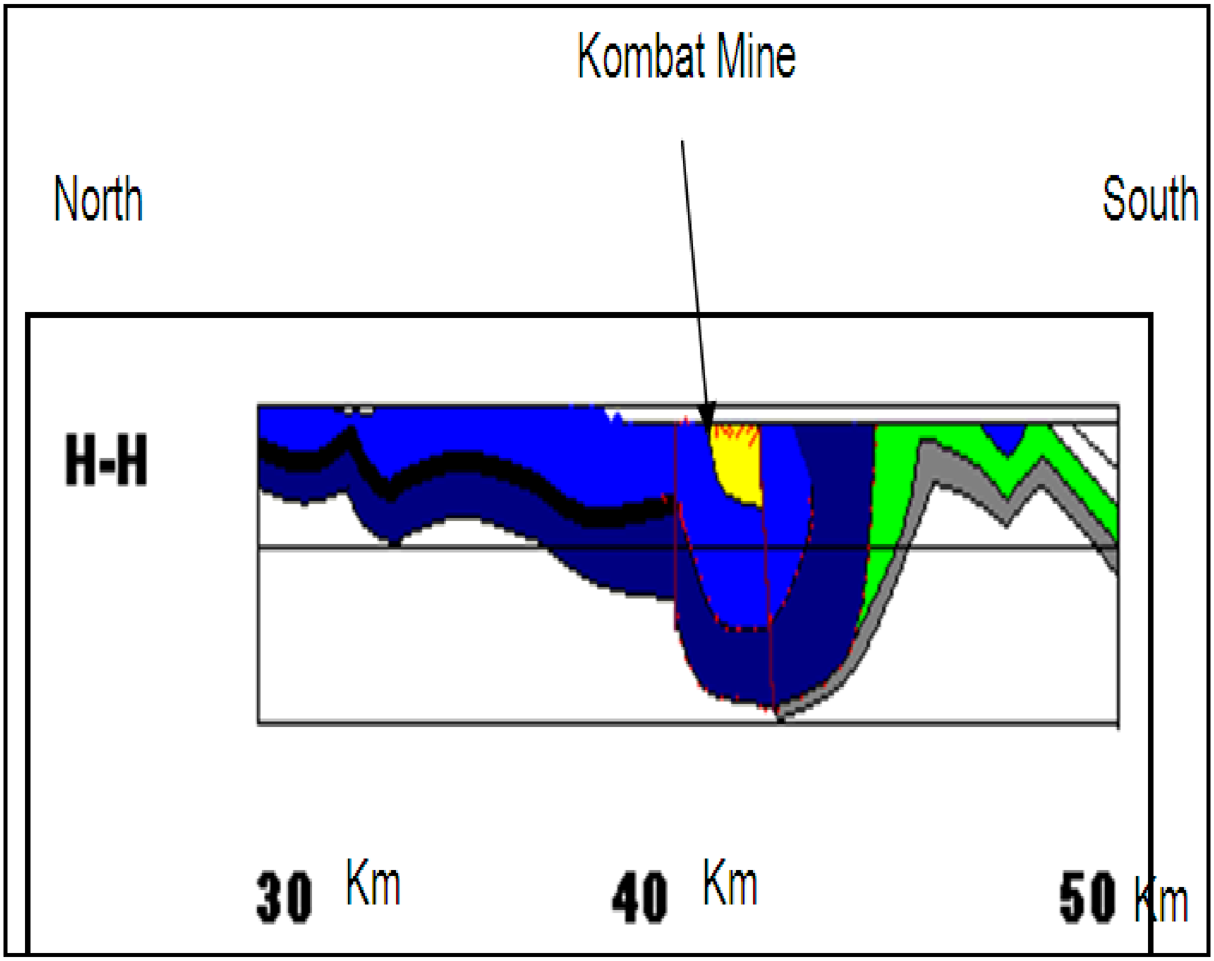

Figure 26: Geology along Section G-G

Groundwater Recharge

Groundwater recharge in the study area is rapid (no traces of evaporation in its isotopic signature), confined to the northern hilly area, and only occurs during exceptionally wet seasons (Ploethner, 1997).

A correlation between the amount of annual rainfall and water level fluctuations indicate that recharge to the Kombat Aquifer is predominantly dependent on precipitation (**Figure 27**).

Therefore the spikes on borehole hydrographs reflect years of above average rainfall, and thus substantial replenishment to the aquifer.

Quantitative estimations of the amount of recharge in the study area has revealed a high dependence on fluctuations in the frequency, intensity and duration of rainfall events; therefore such estimates are highly temporal and less useful in prediction exercises (Ploethner, 1997). Minor recharge takes place at localised residual hills and along the west east trending bedding parallel fracture south of Kombat Mine (Seeger, 1990).

Due to their wide range of predicates and unequivocal nature, current groundwater recharge methods have lured some researchers into the opinion that, of all aquifer parameters, the rate of groundwater recharge is the most difficult to derive with confidence (Simmers et al., 1997).

Recharge estimates are highly associated with the term aquifer safe yield, which is the basis for judicious management of groundwater. Therefore reliable groundwater recharge estimates provide the numerical frameworks for the understanding and analysis of safe yield of any groundwater flow system, especially in drought-prone arid to semi-arid areas like Namibia. Hence the quantification of the current rate of groundwater recharge is a basic prerequisite for efficient groundwater management.

Recharge is a major factor influencing the groundwater regime of the study area (Seeger, 1990). Viewed in the context of a typical fractured carbonate flow systems, and from a water supply point of view, Seeger's (1990) statement could have two implications;

- At an analytical level, it means that the volumes of water that remain in long-term storage and that which remains in active transport systems are dependent on the timing, amount, frequency and the nature of recharge. This emphasizes the functional value of recharge to groundwater analysts, especially in the concept of sustainable development of groundwater resources.

- At a management and policy front, it means that the understanding and knowledge of recharge rates and recharge dynamics should be central to the management and policy framework for evaluating the impact, cost, and effectiveness of policies and management strategies.

Considering the fact that Namibia is the driest country south of the equator, and given the gravity of recent droughts on the country's aquifers, the formulation of a rigorous strategy towards a coherent and cohesive groundwater management (recharge estimations) should be in the forefront of administrative efforts.

Recharge: Origin and age

Direct precipitation on dolomite outcrops is the major recharge component, as opposed to downward percolation of surface water (Seeger, 1990). Carbon-13 analysis of all the water samples from the OML and its surroundings reflects a strong carbonaceous environment (Ploethner, 1997). Although no specific age or time could be attributed to either the age or the residence time of the groundwater of the study area, both water quality and carbon-14 data have provided enough reason to classify the groundwater as recently recharged.

Conditions of infiltration and recharge

Based on patterns and horizons of isotopic data, Ploether (1997) concluded that groundwater abstracted from Kombat Mine and that emerging from the surrounding springs has been subjected to rapid infiltration.

The Kombat Aquifer receives recharge only in exceptionally wet periods (Nawrowski, 1983; Ploethner, 1997). Nawrowski (1983) found that precipitation in the study area is cyclic in nature, with minima and maxima cycles of 10 to 11 years.

Recharge Controls

Aquifer geometry, climate, topography, recent deposits (*soil cover, calcrete*), depth to the water table and aquifer parameters are identified as the major factors controlling recharge in the study area (Campbell, 1980; Seeger, 1990; Ploethner, 1997).

Regolith and calcrete greatly increase temporal storage of infiltration, Seeger (1990) differentiates between two types of calcrete; the highly porous calcrete overlying dolomite and limestone, and the impervious clayey calcrete overlying older granite gneiss. The later enhances overland run-off, while the former supports infiltration and recharge.

On the northern dip slope, overland run-off is further augmented by steep topographic relief and the fine-grained Aeolian red soils (Seeger, 1990).

The intensity and distribution of aquifer parameters (permeability and storativity) in a groundwater catchment area is fundamental to infiltration and recharge. Seimons (1990) contends that a well-developed vertical component enhances infiltration per unit area. Seimons's (1990) statement tallies with Ploethner's (1997) findings, which point to the predominantly vertical flexure fractured zone of the Northern Otaviberg as the major recharge zone.

Recharge estimates

On the basis of the extent to which Kombat Mine dewatering affects groundwater levels, Seeger (1990) identified two recharge areas; the first being the area affected by Kombat Mine dewatering, estimated at 120 km^2, and within which no outflow is expected, the second being unaffected by the dewatering activities at Kombat Mine .

Seeger (1990) found that the recharge rate in the dewatered area is enhanced by backflow from the rims of the area into the dewatered cone of depression via faults, and estimates a recharge rate of 4.8% of the annual rainfall for this area, compared to 3.7% of the area not influenced by mine dewatering. He further asserts that, with rainfalls of over 700 mm/a, recharge rates in the study area can be as high as 8%. However, long-term recharge numerical model-based estimates are significantly lower i.e. Ploethner's (1997) recharge model-based estimates are between 1% and 2% of the annual rainfall.

Groundwater Discharge

The southern boundary of the rocks of the Otavi Group, which forms a northerly facing arc constitutes the discharge area of the Kombat Aquifer. It is characterised by a west-east trending contact zone between overfolded basal dolomites of the Otavi Group and the less permeable meta- sediments of the Nosib Group. A prominent bedding parallel fracture acts as a north-south flow barrier, while north-south factures and faults act as west-east flow barriers. This hydrogeological setting splits the incoming, predominantly north-south flowing groundwater into west-east and southward flow components.

The west-east groundwater flow components escape from the aquifer as springs east of the study area, where the erosional contact of the basal dolomite and rocks of the GBC expose the water table to the surface.

Due to the permeability discrepancy between hydraulically well-developed carbonates and the less permeable rocks of the Nosib Group, the south to southwest groundwater flow component is released out of the aquifer into the less permeable rocks of the Nosib Group, and forms seasonal dams, fountains and springs during the rain seasons.

The Kombat Aquifer has experienced a net discharge during the past 20 years, as can be seen from the more than 20 year groundwater levels decline evident from downward trend in well hydrographs (**Figure 27**). Seeger (1990) estimates the annual groundwater decline in the study area at 0.3 to 0.6 m/annum in areas not affected by mine dewatering, and at between 1.5 m and 2 m/annum in areas affected by mine dewatering. As a consequence of the prolonged decline in groundwater levels, topographically controlled springs dried up. This is because the water table is now below the topographic surface on which they were issuing, e.g. the Rietfontein and the Otavifontein Springs.

CHAPTER 4 GROUNDWATER FLOW CONTROLS

4.1 Introduction

In groundwater studies, controls imply the existence of collaborative elements of a system of factors, with a distinct composite groundwater flow setting as the outcome.

In fractured carbonate groundwater flow settings like the study area, a combination of climate, relief, geology and geomorphology are recognised as the four major groundwater flow controls (White, 1988; Quinlan *et al.*, 1996; USGS, 2001).

With the support of control mechanisms (pressure regimes, hydraulic gradients, exchange flux coefficients), controls are ideally applied on processes (recharge, storage, release, throughflow, re-arrangement of flow, rerouting, discharge) to facilitate groundwater storage and transportation. A concise evaluation of groundwater flow controls is therefore crucial to the understanding and conceptualisation efforts of a groundwater flow system.

From a functional point of view, assessing groundwater flow controls entails the analysis of the contribution of individual control structures to groundwater flow as unitary entity. This section categories and discusses groundwater flow controls and the associated flow constraints imposed on the Kombat Aquifer.

4.2 Rainfall and Relief Controls

Climate has a profound influence on the frequency, amount and nature of groundwater replenishment. In semi arid zones like the study area, rainfall largely determines the amount of water an aquifer holds at any particular time, which is closely related to the rate at which the aquifer is replenished. In fractured carbonate aquifers with limited storage capacity like the Kombat Aquifer, the rate of groundwater replenishment tends to have some control on internal flow dynamics. This comes in form of a pressure re-equalisation mechanism between the high permeability fractured flow zones and the surrounding low permeability fissured matrix, especially during overdrawn and high groundwater stage periods.
Rainfall control on volumetric storage, especially after stormy summer rainfall, is evident in Figure 27.

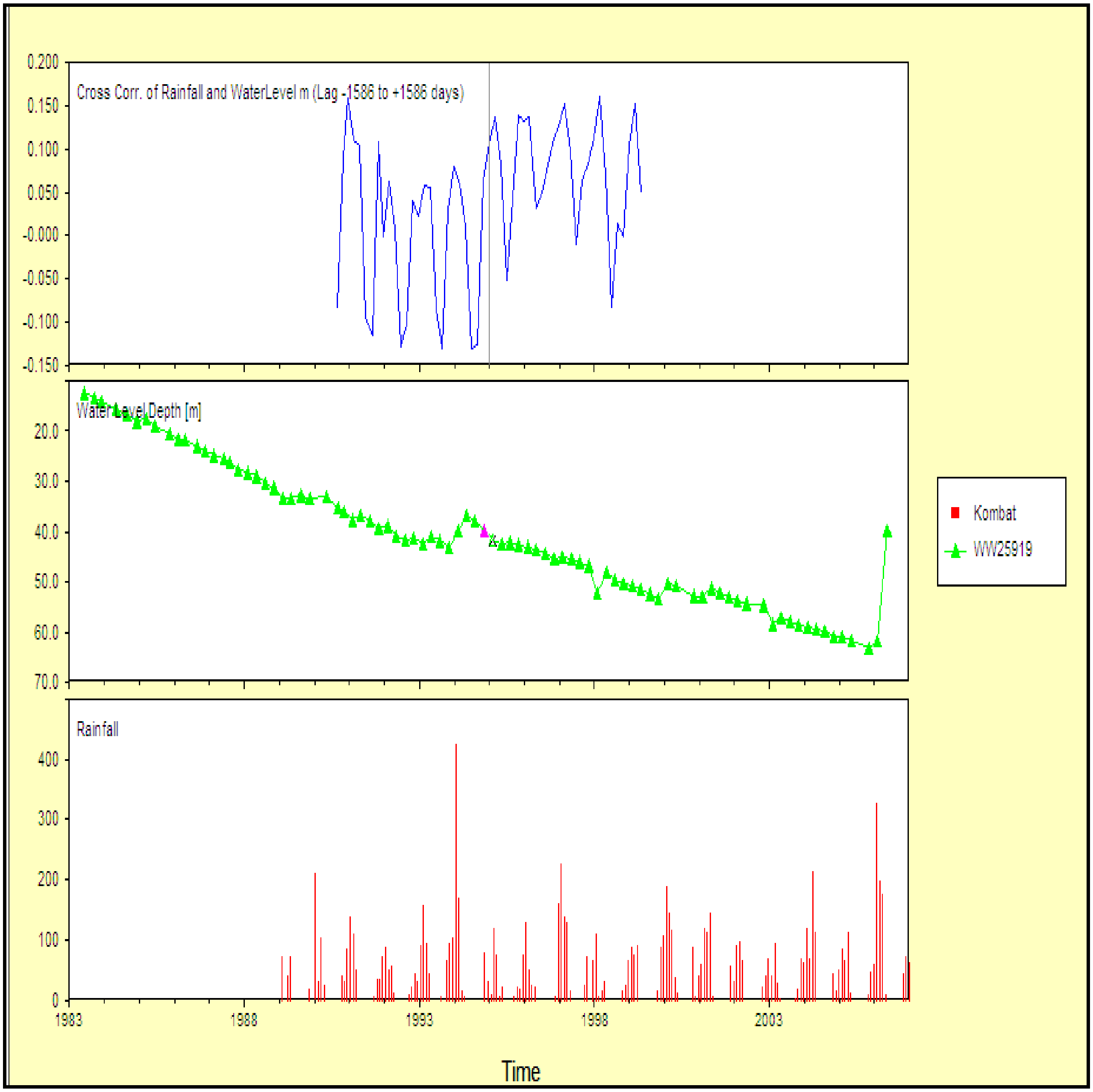

Figure 27: Cross-correlation between rainfall and groundwater recharge events

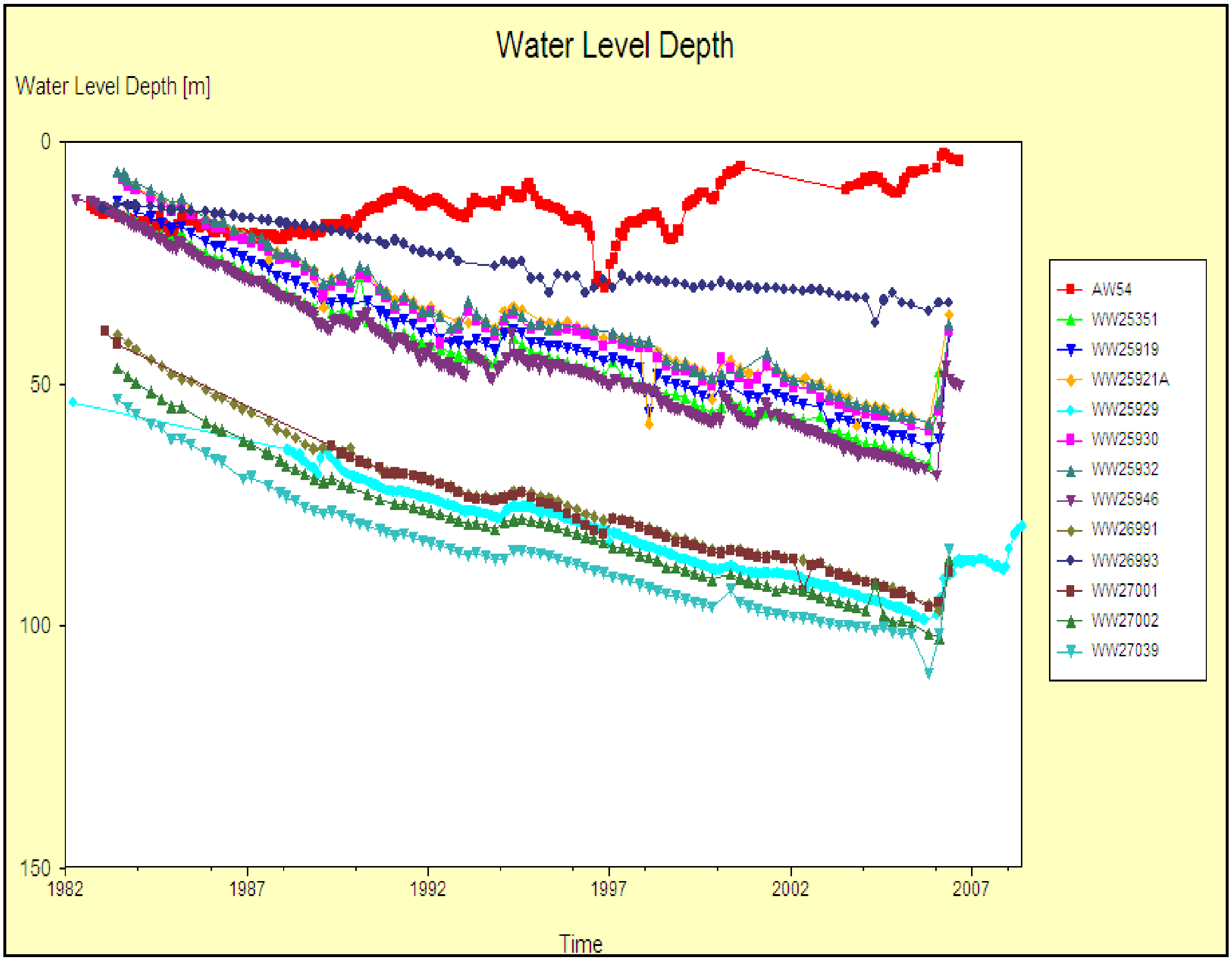

Figure 28: Borehole hydrographs of the study area

The frequency at which a groundwater flow system is replenished is central to the hydraulic balance between recharge and discharge. In a fractured aquifer with dual permeability like the study area, infrequent recharge events (**Figure 27**) translate into a highly temporal, higher permeability groundwater flow component. As a consequence, the lower permeability groundwater component becomes a long-term source of groundwater. This condition creates an overdrawn groundwater flow system due to the flow rate disparity between the source - lower permeability groundwater component and the sink (discharge), which belongs to the high permeability component.

This groundwater flow trend can be seen from the net decline in the groundwater levels of the study area (**Figure 28**). Furthermore, intermittent recharge, in a way of allowing longer periods between recharge events, tends to support pronounced troughs in the potentiometric surface by emptying the hydraulic-pressure sensitive high permeability flow component compared to its surrounding (the less hydraulic pressure-sensitive low permeability flow component). This situation forces most of the groundwater movement to be restricted to hydraulically well-developed zones of the flow domain (**Figure 29**).

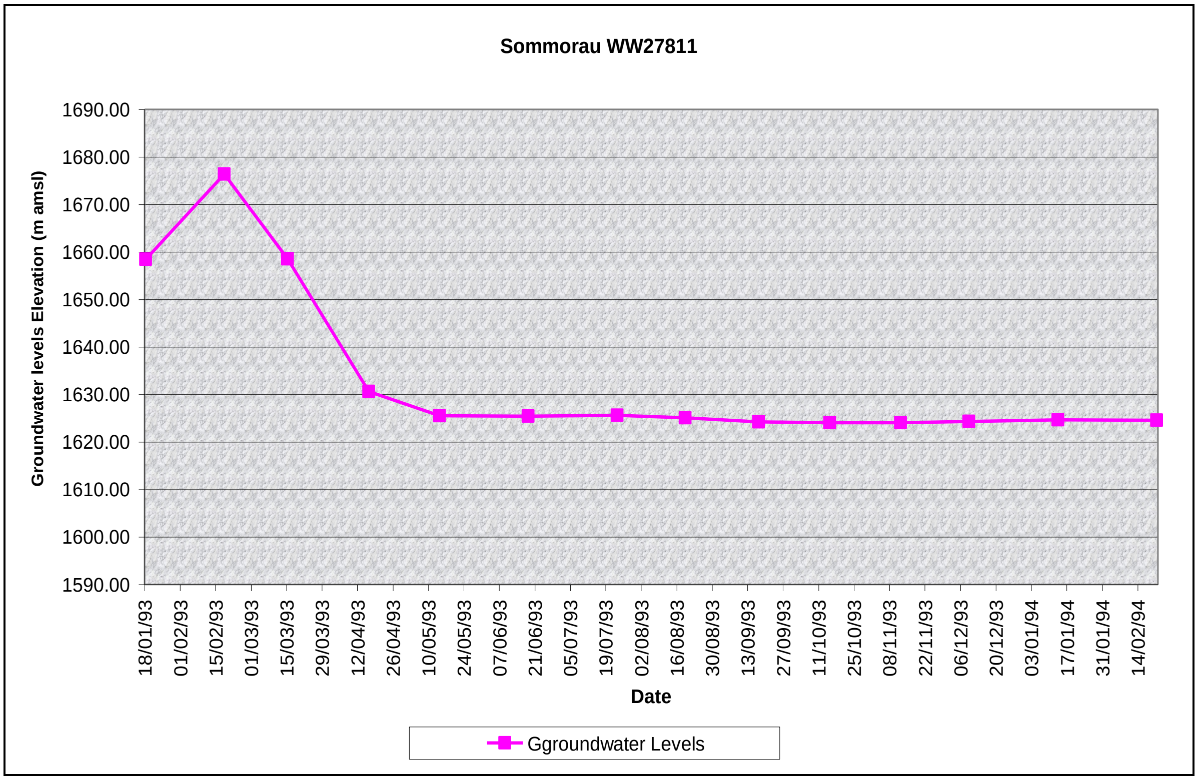

Figure 29: Changes in water levels following the January 1993 recharge event

Figure 29 presents a typical dual segmented recession hydrograph, illustrating the dual response of the aquifer to a stormy recharge event. The graph in Figure 29 does not only illustrate the nature of aquifer response, it also shades light on the centrality of climatic conditions on the groundwater flow mechanism in the Kombat Aquifer, especially the significance of the nature and temporality of precipitation events. Consequently, climatic groundwater flow control factors have some bearing on volumetric flow, internal groundwater flow mechanisms and the timing of dominant flow components in hydraulic groundwater flow settings similar to the study area. Although it might seem unrealistic, it is imperative that existing and future models should be equipped to account for such hydraulic dynamics.

4.3 Geological Controls

Geological controls on groundwater flow are often subdivided into lithology, geological structure and stratigraphy (Seeger, 1990; Nakhwa, 2005). With other factors assumed equal, the content of soluble mineral is a key catalyst of chemical weathering (karst development). Since karst structures in carbonate aquifers provide high permeability groundwater pathways, lithologic units depending on their soluble mineral content may act as either barriers or conduits to groundwater flow.

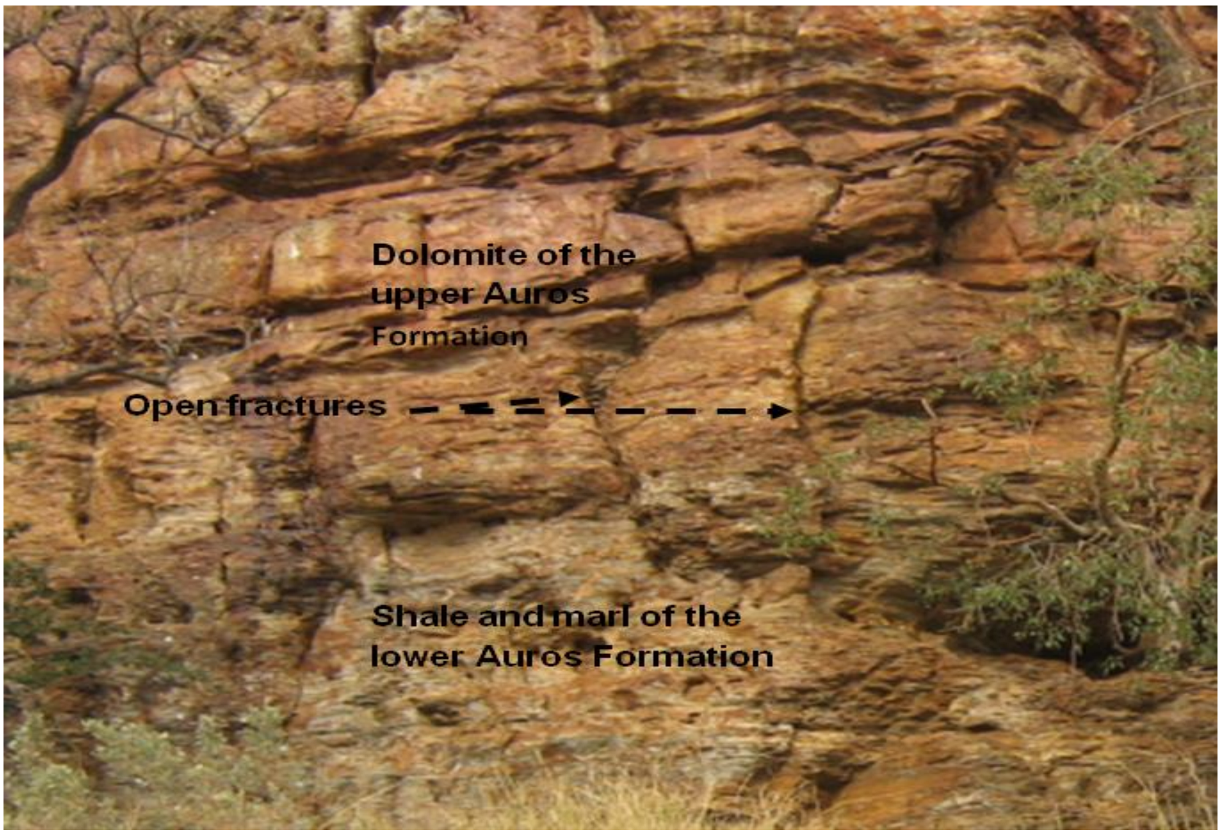

Figure 30: Changes in fracture openness across different lithologies.

Another important lithology dependent property of rocks that has direct bearing on groundwater flow is mechanical strength. The mechanical strength of a rock type (commonly referred to as competence) determines the mode of mechanical failure of the rock. During rupture, more competent lithologies tend to be brittle, thereby forming open fractures, whereas less competent lithologies tend to be ductile, giving rise to less open factures. This phenomenon can be seen in the loss of fracture width as fractures transit from more competent dolomite into the ductile shale (**Figure 30**) of the Auros Formation. In this way, lithology plays an important role in facilitating the development of groundwater flow pathways and/or barriers, especially in fractured aquifers like the study area.

The structural and stratigraphic component of geological groundwater flow controls determines the spatial arrangement of groundwater flow barriers and pathways. For instance, in the study area, regional folding constrains the flow direction of groundwater along the dip slope (**Figure 26**). Faults, joints and the bedding fracture allow hydraulic connectivity between stratigraphically separated aquifer units, reminiscent of the upper Tsumeb and the lower Abenab Subgroups, which are separated by the impermeable Chuos Formation, but hydraulically connected by the Kombat West and the Asis Ost deep-seated geo-fractures (Innes and Chaplin, 1986).

4.3.1 Evidence of Fault Controls

As a result of the fact that the groundwater table of the study area is subdued by topography, it logically follows that the local groundwater table would mimic local variations in topography. It has however been established that linearly persistent and profound local variation in topography like the Tiger Schlutch Valley correspond to the down-thrown blocks of major fault zones like the Kombat West Fault and the Asis Ost Fault zone (Deane, 1995)

As can be seen from Bayesian interpolated groundwater level contours (**Figure 31**), the troughs in the potentiometric surface of the Kombat Aquifer are adjacent and linearly aligned along the three known fault zones of the study area, namely the north-south faults locally mapped by Deane (1995), the Kombat West and Asis Ost Fault Zones.

The observation that geological controls largely influence the spatial arrangement of groundwater flow is also supported by theoretical hydrogeology; for instance, according to the cubic law and the principle of positive feedback, most groundwater transport is theoretically expected to occur in the open fracture sets like the northeast-southwest fracture set of the northern dip slope (fluviokarst).

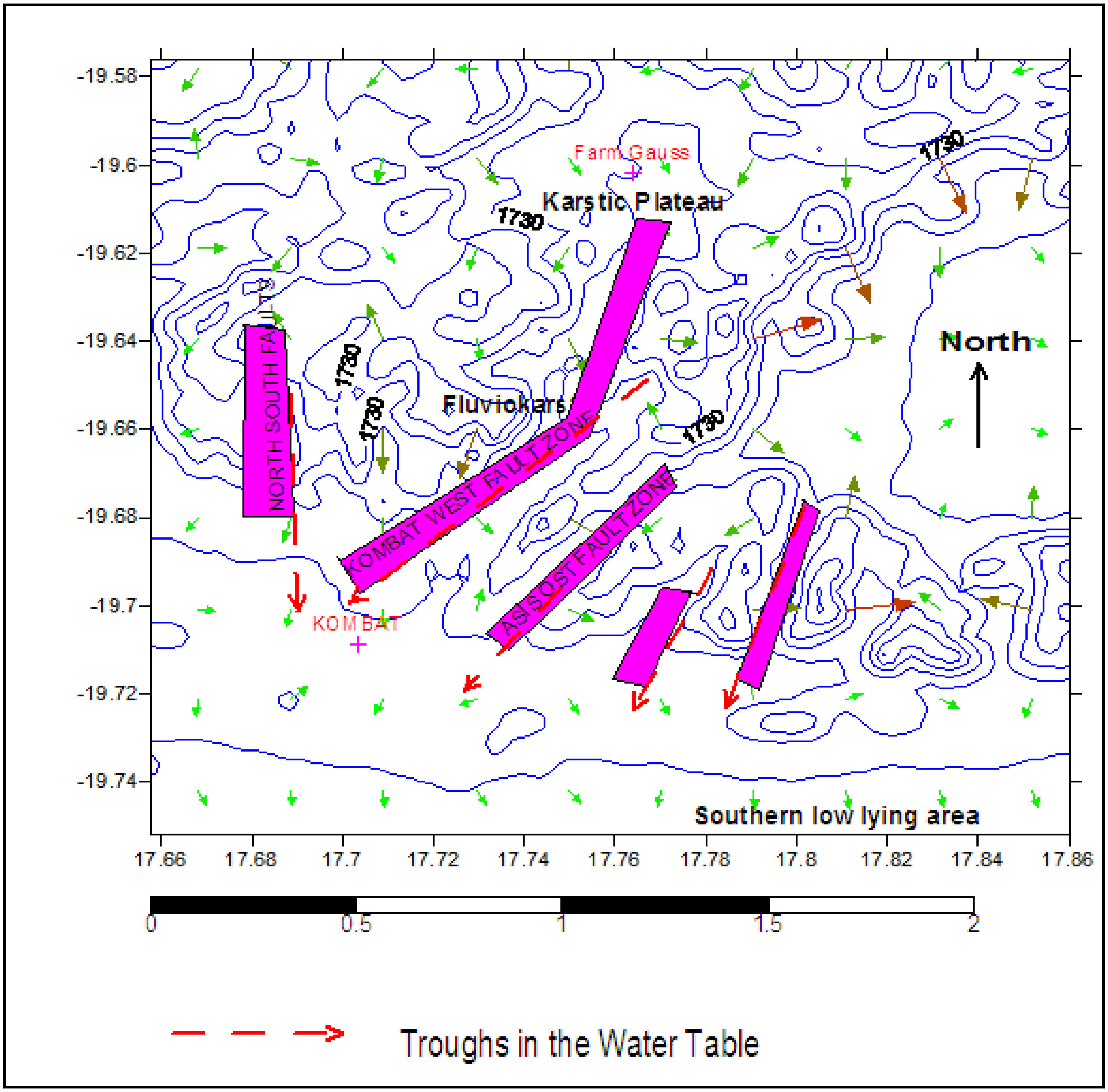

Figure 31: Shows the alignment of flow relative to fault zones

Figure 32: Iron staining in deep-seated joints

Figures 32 and 33 present diamond drill core logs of an exploration borehole drilled approximately one kilometer west of Kombat Mine Shaft _1. The borehole is drilled to a depth of about 400 m from surface. The objective behind drill core inspection to this depth was to assess aquitards, aquifer relationships, as well as the type of material filling in healed fractures.

Visual inspection of the core logs of Figure 32 above shows that, although there are joints and fractures throughout the borehole depth, intense fracturing is more visible in the first 70 m, and resumes at around 280 m below surface. It attains its peak at around 370 m below surface.

Figures 32 and 33 illustrate the evidence that support fracture confined preferential groundwater flow at depth. This observation is in agreement with mining activities around Kombat have intersected fault zone confined hydraulically active deep seated joints (**Figure 32),** and fracture zones (**Figure 33**) to depths beyond 800m. According to Ploethner (1997), these structures act as vertical groundwater flow and transfer conduits feeding areally extensive bedding planes like the basal dolomite contact. Therefore the hydraulic connectivity between the shallow and the deep flow systems is to a certain extent maintained.

Iron staining, as seen in Figure 32, is diagnostic of groundwater flow along the joint. There is a healed joint above the iron stained fracture, suggesting that the country rock around this joint is intact. This might indicate the existence of no-flow conditions in the country rock, as well as in the healed joint.

Figure 33: Fracture zone intersected by diamond drilling in the Huttenberg Formation

In order to determine the type of material in occluded fractures, a hydrochloric acid test was conducted on fracture infilling. The acid test showed that most of the healed fractures respond positively to the calcium carbonate acid test, thereby confirming that calcite is the dominant cementing material in healed fractures. Precipitation of calcite is suggestive of slow or stagnant groundwater flow conditions. Considering the results of the acid test and drawing from the principle of positive feedback, it can be inferred that healed or healing fractures in carbonate rocks do not support active groundwater circulation.

The above argument supports the notion that fractures of the study area play the role of pathways as well as barriers to groundwater flow. This observation positively highlights the groundwater flow constraints imposed by fractures on the flow system of study area.

The fact that the zones displaying intense facture healing follow just below the fracture zone is an indication that the facture zone in Figure 33 did not support vertical groundwater flow. Therefore not every fracture feeds the deep aquifer. In the absence of vertical leakage, such fractures would act like sealed bottom groundwater flow conduits across the flow domain.

Faults or fracture zones, especially in the absence of cross-fracturing, almost always play the dual roles of conduits in one direction and groundwater flow barriers in another (Nakhwa, 2005). For this reason, the essentially parallel faulting along the northern dip slope constitutes conduits to southwest groundwater flow and barriers to west-east groundwater movement. The broader significance in the healing, cross-fracturing, parallel fracturing, and solution enlargement of fractures in fractured aquifers is that they impose internal groundwater flow boundaries or flow groupings, which should be understood and where possible accounted for during modeling.

Figure 34: Thin bedding in the southern low lying areas, Kombat South

In the absence of fractures or thin bedding, the carbonate rocks in the mine workings cannot be referred to as an aquifer. This statement was expressed by Kombat Mine geologists to Campbell (1980) during a mine visit. Figure 34 supports the mine geologists' observation. It further shows how alternating thin bedded and massive dolomite disaggregates the Kombat

Aquifer into vertical successions of bedding parallel aquifer and aquitard units. The bedding planes in Figure 34 dip north and plunge eastwards, permitting a local west-east groundwater flow component that is confined to the southern discharge zone and central Valley. The point exemplified here is the extent to which static aquifer attributes arrange and re-arrange the groundwater flow pattern of the Kombat Aquifer.

4.3.3 Evidence of Fissured Matrix Controls

Table 5: Results of groundwater temperature logging

Borehole No.	Borehole Locality		Groundwater Temperature ^{o}C
	Discharge Zone	Recharge Zone	
Farm Gauss		X	22
WW25930	X		28.4
WW25932	X		28
Rietfontein BH	X		27
Neu Sommorau		X	23
WW30694		X	24
WW25945	X		26.7
K60035		X	23
K62753		X	22
WW27811		X	23
Average Temperature in the recharge zone			**23**
Average Temperature in the discharge zone			**28**
Temperature difference between recharge & discharge water			**5**

Table 5 presents the groundwater temperature difference between the recharge and discharge zones of the study area.

An explanation of the temperature difference in Table 5 can be offered by the dual permeability model. According to Mohrlock and Sauter (1999), the dual segmentation of the hydrograph recession curves suggests two groundwater storage sources in the study area; one with rapid and large hydraulic response associated with more open fractures, and the other slow and small hydraulic response associated with fissured matrix and/or the epikarst.

Assuming that groundwater in high permeable fractures does not have enough residence time to acclimatize to the temperature of the surrounding rock, then the temperature difference observed in Table 5 can be associated with possible groundwater temperature acclimatization in the fissure and/or epikarst groundwater storage component.

The above given inference informs this study's storage model and has been confirmed elsewhere by recharge models which assume that residence time within the epikarst and/or fissured matrix is sufficient for recharge water to adapt to the temperature of the rock (Mohrlock and Sauter, 1999).

In line with the conceptual approach of this study, and with specific reference to objective number one, it can be qualified that delineating the geological structure is fundamental not only to the understanding, but also to the location of specific groundwater processes like storage and transport.

However, at the resolution of the available data, this study cannot distinguish between groundwater that has been stored in the epikarst and that which might have been stored in the fissured matrix. Therefore, the storage of the groundwater exhibiting a high temperature will be referred to as intermediate storage.

4.4 Geomorphological Controls

With regard to groundwater flow controls, geomorphology had been functionally subdivided into two generic subdivisions, namely geomorphic landforms and topographic relief (Moon and Dardis, 1988; USGS, 2001).

Geomorphic units contribute to groundwater flow by providing the sites of groundwater infiltration and temporal groundwater storage. In a study with the title "A comprehensive strategy for understanding flow in carbonate aquifers," Worthington (2003) found that karst geomorphic landforms are input points to underlying channels or fracture networks. By virtue of their exposure to surface and near-surface weathering processes, geomorphic landforms (sinkholes, residual hills, blind valleys, disappearing streams, vertical shafts, cave openings, springs and seeps) inherently have well-developed porosity and permeability. Karst landforms are therefore critical factors in the temporal storage and routing of surface water, infiltration, recharge and discharge (White *et al.*, 1970; White, 1988 and 1997). The karst landforms observed in the study area are thus considered to be of similar significance.

With respect to those groundwater flow factors provided by geomorphic variations, geomorphic boundaries become groundwater flow boundaries, in that geomorphic landforms spatially constrain the hydraulic gradient, infiltration and recharge.

Figure 35: A sinkhole on the karstic plateau

As seen in Figure 35, Karst Landforms, especially sinkholes of the northern study area collect surface water and constrain the rate and direction of recharge. Furthermore, they do not only control the rate and direction of recharge, but depending on their areal extent and spatial distribution, they also have a direct bearing on the volume and chemistry of focused recharge of the study area. The latter is evident from the low electrical conductivity zone which encircles the sinkhole plane (in the form of a hashed contour) in the regional and local distribution of electrical conductivity of the Otavi Mountain Land (**Figures 36**).

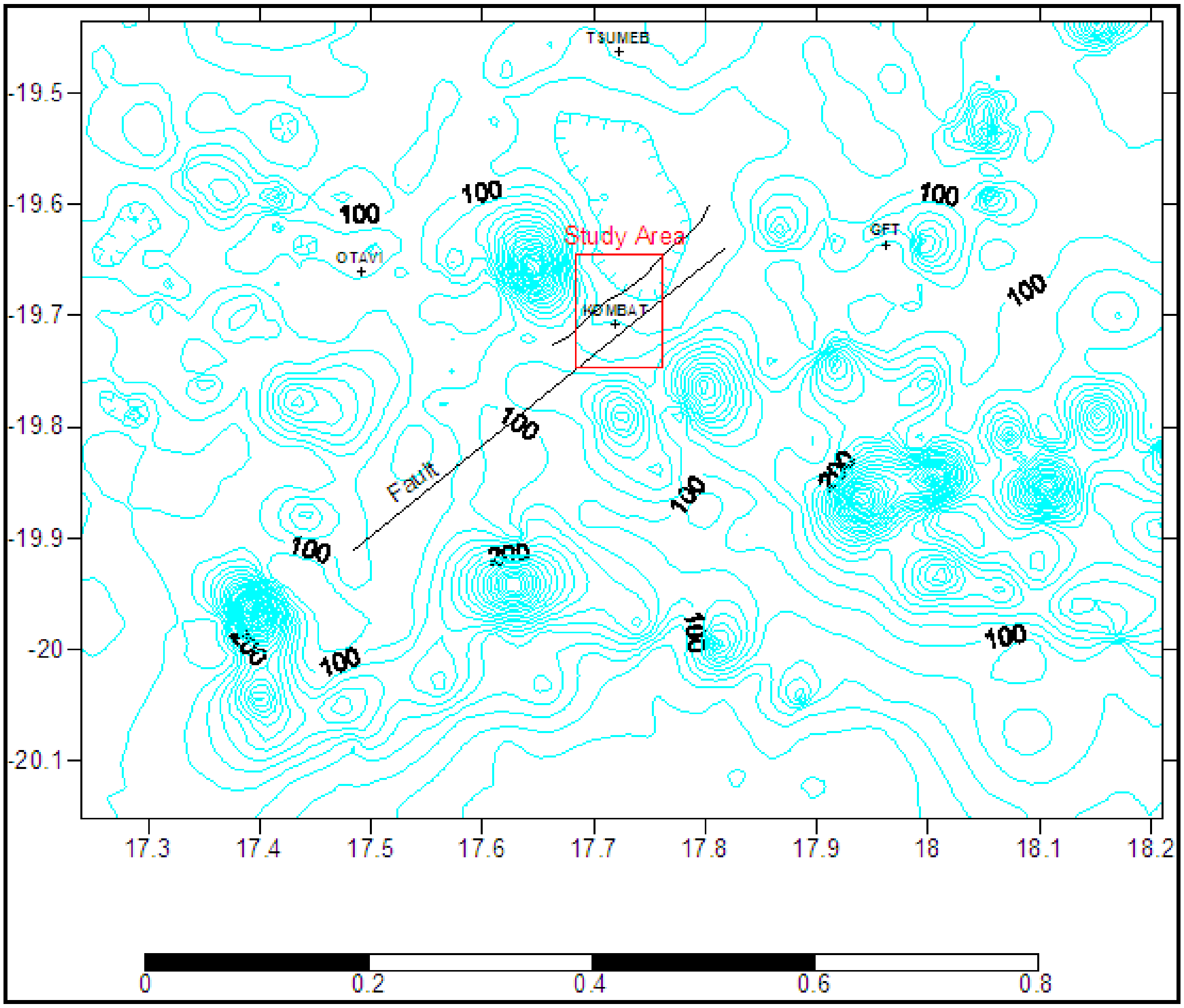

Figure 36: Regional distribution of electrical conductivity (EC)

It is assumed that some controls on groundwater flow can be engaged in their association with hydrochemical aspects of a groundwater flow system. Borehole chemical data was therefore compiled and analysed using Surfer and WISH. However, few boreholes have complete chemical datasets. The hashed contour represents the zone of lowest EC values (**Figure 36**), while the two black lines indicate the Kombat West and Kombat East Fault zones.

Figure 36 demonstrates that groundwater with the lowest dissolved solids enters the study area from the northern boundary. Since low EC is associated with either recharge or preferential flow, it can be inferred that both throughflow and groundwater recharge are restricted to the northern portion of the study area, thus during numerical modeling, the northern boundary will be assigned no flow boundary conditions.

Of broad significance to objective 3 of this study is that Chapter 4 brings out an understanding of how the Kombat Aquifer groundwater flow system is held together by patterns of external stimuli, hydraulic response, flow control relationships and the hidden laws of fluid flow.

4.5 Field Observations

Given the observation that groundwater flow in the study area is restricted to fractures (Seeger, 1990; Ploethner, 1997), a primary assessment aimed at delineating the most extensive and more open fracture set was conducted. This was done in form of a north-south traverse, mapping fractures on outcrops. The understanding behind the mapping of fractures is that the more extensive and most open fracture set would from the power (cubic) law sensitivity, be the dominant conductor of groundwater flow.

Field mapping of fractures in a given area is always a protracted exercise. Hence, it is useful to take into account all the likely factors that may influence the water-carrying potential of the fracture sets. Special attention was therefore given to the following geometrical aspects of fractures:

I. Orientation; dip and strike.
II. Consistence; length and density.
III. Aperture width.
IV. Type of infilling.
V. Any visible evidence of water flow, i.e. iron staining.

Field observation and mapping of fractures posed a number of challenges that may have some bearing on the completeness of the collected data dataset.

Reliable aperture width measurement, in particular, presents a dilemma, because most outcrops have in one way or another been affected by gravity release pressure, depending on how such surfaces have been exposed. The observed fracture apertures were in most cases not pristine.

Another important aspect is the type of infilling of the surface fractures, which is either washed out or not representative of the subsurface counterparts of the fracture sets. However, a diamond drill core inspection has shown that most fracture healing is filled with calcite.

The subsequent subsection presents the results of fracture mapping, as well as other field observations like sinkholes and epikarst. It ends with a hypothetical illustration of internal flow dynamics. The figures below provide extra results and evidence of probable groundwater flow controls; they are therefore annotated, and have detailed elaborations of their significance to groundwater flow.

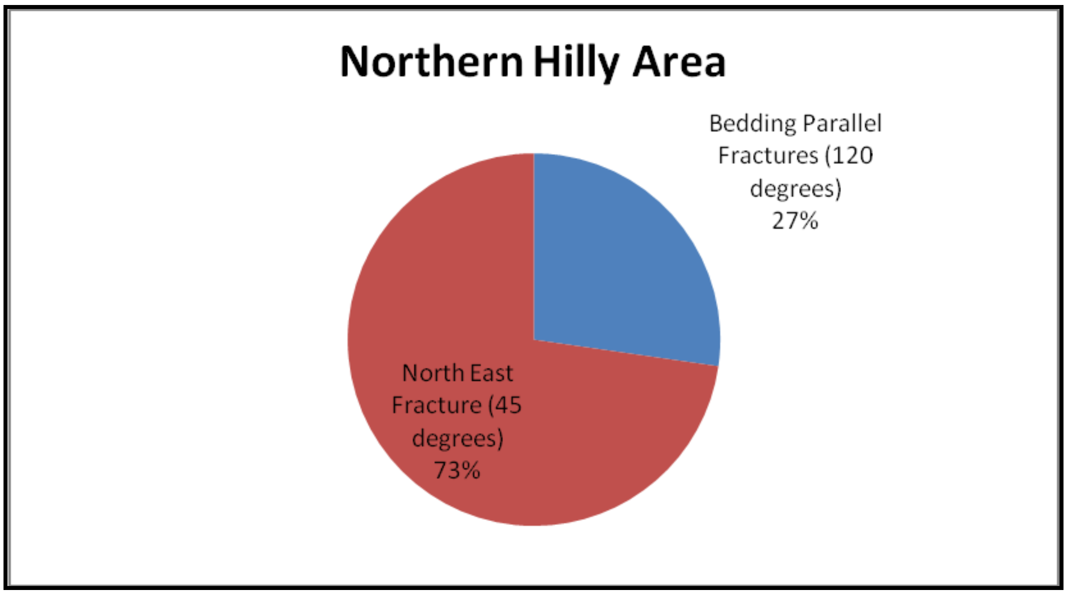

Figure 37: The relative distribution of fracture sets on the northern anticline (Karstic Plateau)

The Karstic Plateau

Although the northeast trending fracture set dominate the karstic Plateau zone, a rectangular dendritic fracture pattern around the northern anticline is the most representative form of presenting fracture distribution of that zone (**Figure 37**). The observed fracture pattern of the Karstic Plateau inherits from the intersection of a west-east trending folding-induced open-mode flexure fracture set and the northeast trending transform fracture set corresponding to the Kombat West Fault. The northeast fracture set is therefore the most consistent fracture set on the northern anticline (Karstic Plateau). It is worth noting that the northern anticline is also known to be the source of most of the recharge to the rest of the Kombat Aquifer

(Ploethner, 1997, Lowest regional EC). By implication, the northeast fracture set connects the rest of the aquifer to the recharge zone.

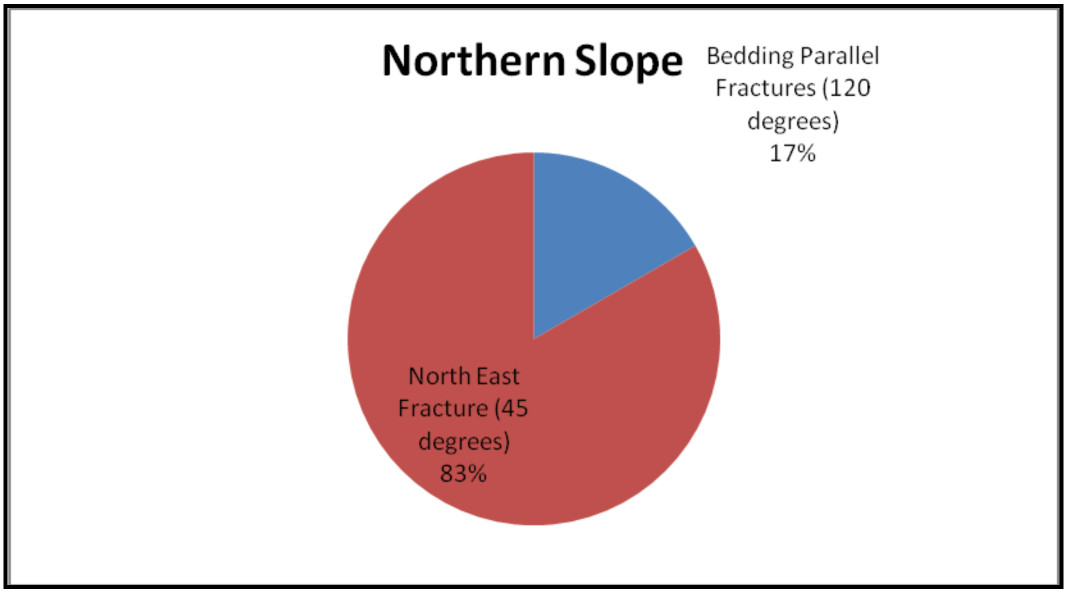

Figure 38: Relative distribution of fracture sets on the northern slope (Fluviokarst)

The Fluviokarst or the Northern Dip Slope

As seen in Figure 38, the northern dip slope consists of essentially parallel northeast trending fractures. Notable is the diminishing presence of the bedding parallel fracture set. The fact that the northeast fracture set is more consistent and intersects the axis of hydraulic gradient at a low angle (45^0), could enhance its capacity as a groundwater flow conductor.

In support of the latter inference, mining activities estimated flow volumes of up to 5000m^3/hr when mine tunneling intersected this fracture set - the Kombat West Fault - in 1988. It would therefore be logical that the northeast fracture set is the dominant groundwater flow conductor on both the Karstic Plateau and the northern dip slope.

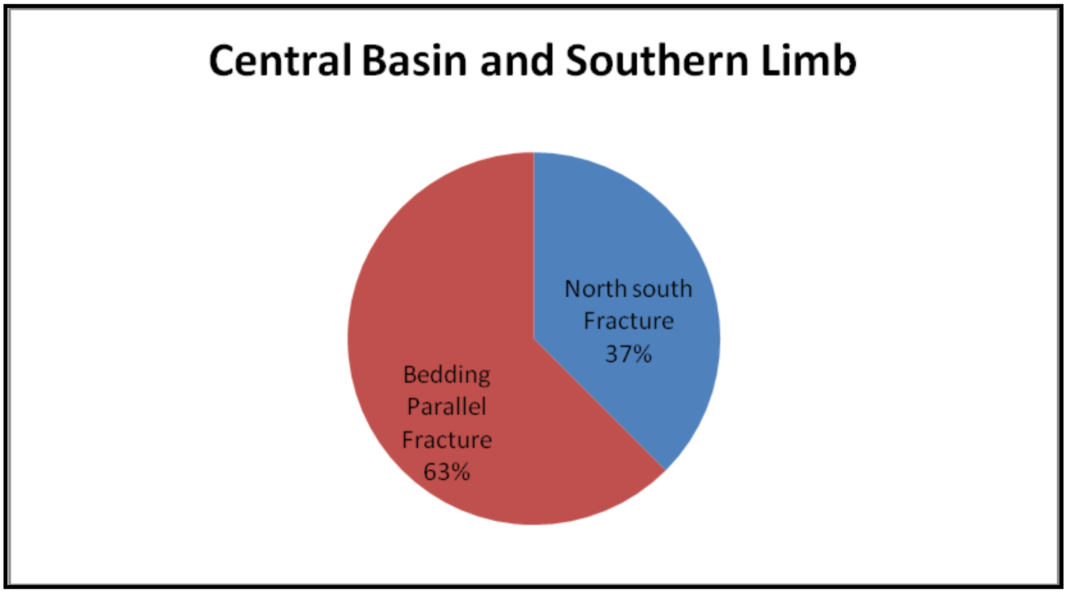

Figure 39: Distribution of fracture sets to the south of Kombat Mine

The Central Valley (CV) and the Southern Low Lying Area (SLLA)

Apart from major faults and fault zones, most joints and fractures observed on the northern dip slope terminate on reaching the core of the central valley. This is because the core of central valley is underlain by a less competent and ductile phyllite of the Kombat Formation.

Figure 39 illustrates the implications of the described geological reality of CV. The central valley exhibits total absence of the northeast fracture set, except where it is dissected by faults.

Although somewhat biased due to the lack of outcrop in the southeast of the the SLLA, Figure 38 is more representative of the CV as well as the southwest of the SLLA. The northeast fractures are therefore expected in the southeast of SLLA, because it is disrupted by the Asis Ost Fault Zone (Deane, 1995), with consequent high erosion activity and deep soil cover.

The groundwater flow domain covered by CV and the SLLA constitutes a highly fractured volume of rock, because, not only is it bounded on both sides by two west-east trending shear fractures, but it is also overturned and displaced over the northern portion (foot wall) to develop a thrust fault, making the CV and SLLA an unstable west-east trending volume of rock mass. With the north-south fracture set being highly local (Deane, 1995) and the CV covered by a less permeable lithotype, the bedding parallel fracture set becomes the most extensive and most open fracture set in the SLLA. Seeger (1990) used this geological reality to survey production boreholes on the contact between the dolomite and less permeable older rocks. One of the faults (Rietfontein Fault) exploiting the basal contact (bedding parallel fracture set), could in the past discharge to a permanent spring at a rate 150 m^3/h.

Figure 40: A collapse sinkhole along the west-east trending fracture set on the Karstic Plateau

The doline in Figure 40 elongates along the west-east bedding parallel fracture set on the Karstic Plateau. This study concludes that a bedding parallel fracture set is second to the northeast fracture set with regard to their groundwater carrying capacity.

Figure 41: Evidence of the existence of epikarst on the Karstic Plateau

The epikarst (**Figure 41**) is understood as the uppermost weathered zone of a carbonate aquifer with a larger degree of homogeneous porosity and permeability distribution compared to the underlying aquifer. It forms an important temporal storage of infiltration. The epikarst owes its high void volume to the preferential removal of calcium, magnesium and bicarbonate ions by slightly acidic fresh water, leaving it with a characteristic reddish white colour inherited from insoluble silica and iron oxide rich residue (Fleisher, 1981).

Figure 42, although hypothetical, illustrates the current understanding of the essential internal workings of the Kombat Aquifer, as inferred from the evidence presented in this chapter.

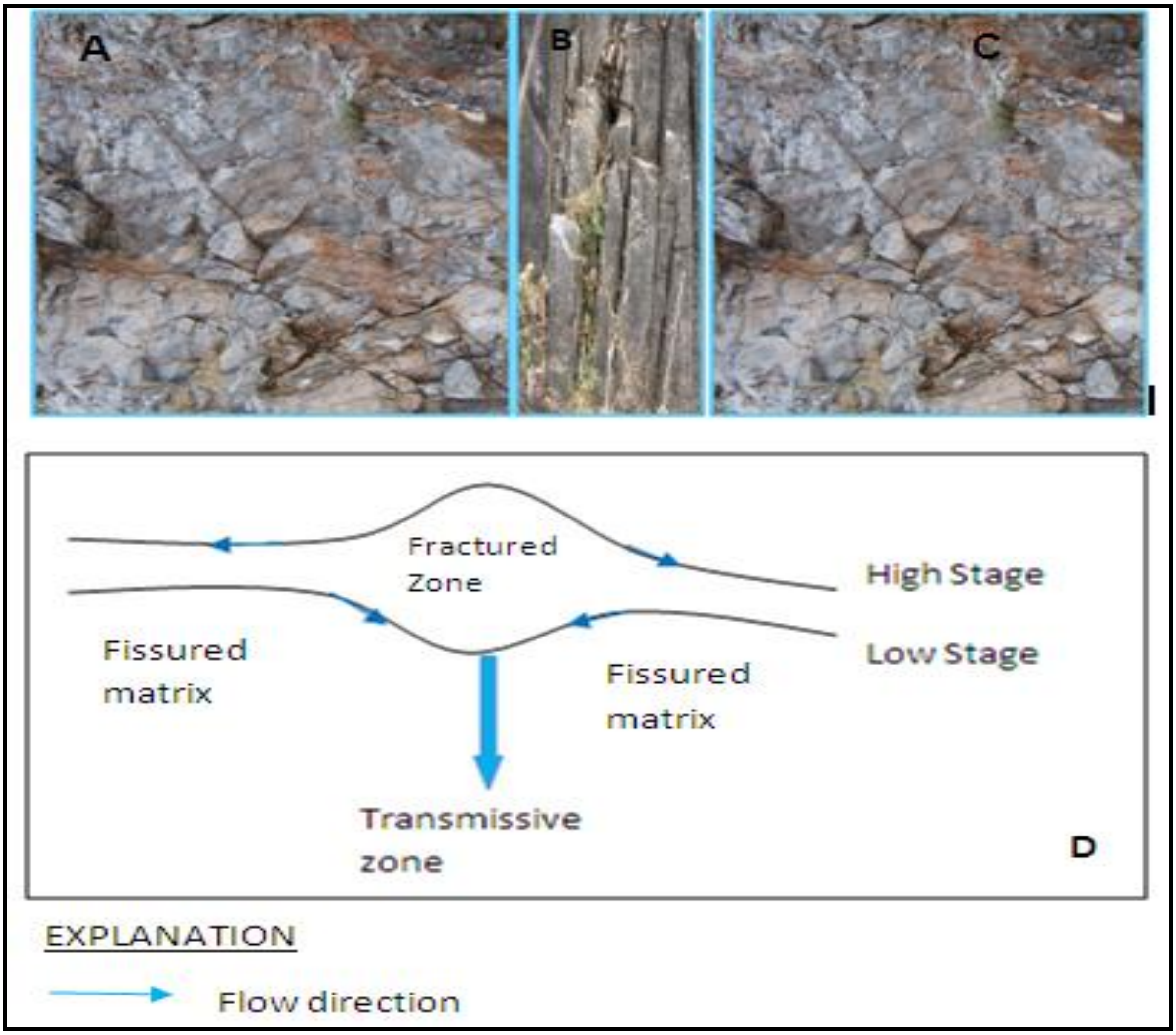

Figure 42: A hypothetical picture of the groundwater flow dynamics in the study area.

Figure 42 A and C represent the fissured aquifer, where as 42B illustrates the fractured aquifer system.

Figure 42 D illustrates the hypothetical groundwater flow dynamics between the fractured and fissured flow components during the high and low groundwater stage. In comparison to the fissured aquifer flow component, the fractured aquifer flow system is characterised by

a relatively high hydraulic head amplitude between the low and high groundwater stage. It should be noted however, that the inferences in this subsection depend on the validity of the observation that groundwater flow in the study area is restricted to fractures.

CHAPTER 5 CHARACTERISATION AND PARAMETER ESTIMATION

5.1 General

From a groundwater flow point of view, particularly in fractured hard rock environments, the knowledge of hydraulic parameters is crucial not only to the understanding of the nature of the aquifer, but also to the appreciation of the character of hydraulic head propagation.

It is therefore very important that the nature and conditions under which these parameters are derived would allow the highest accuracy that can be afforded. However, it should also be understood from a modeling point of view that hydraulic parameter estimates are meant to narrow the range of actual parameters of a groundwater system.

In normal practice, hydraulic parameters are obtained from evaluating pumping tests; similarly, parameter evaluation in this study used pumping test data from three sites. However some extra data from the 1988 mine flooding event, as well as some data from long-term mine dewatering were evaluated.

5.2 Hydraulic Response Characteristics

The hydraulic response characterisation of the Kombat Aquifer is engaged and assessed from four different sources of information, namely mine flooding, hydraulic tests, mine dewatering and borehole hydrographs.

5.2.2 Characteristics of the Kombat Aquifer from hydraulic pump tests

Monitoring of the recovery and decline of groundwater levels during the 1988 Kombat Mine flood event was well-recorded and documented by Campbell (1989). Even though this dataset exhibits recording time gaps, it is considered critical and satisfactory, especially in view of the fact that the gaps are statistically insignificant in comparison to the volume of data collected. Of all the monitored sites, Shaft_1 has the most consistent dataset. Thus the bulk response hydraulic characteristics of the Kombat Aquifer are inferred from this dataset.

From a response scale point of view, boreholes as far as 8 km to the south and 15km north of Shaft_1 were affected; therefore, the mine flood dataset from Shaft_1 represents the bulk hydraulic response of the Kombat Aquifer, especially when compared to hydraulic datasets from test pumping of individual boreholes. With this understanding, the results from the

Shaft_1 data will as the study progresses, be respectively compared and contrasted with that from pumping tests at macro- and micro-scales of the aquifer.

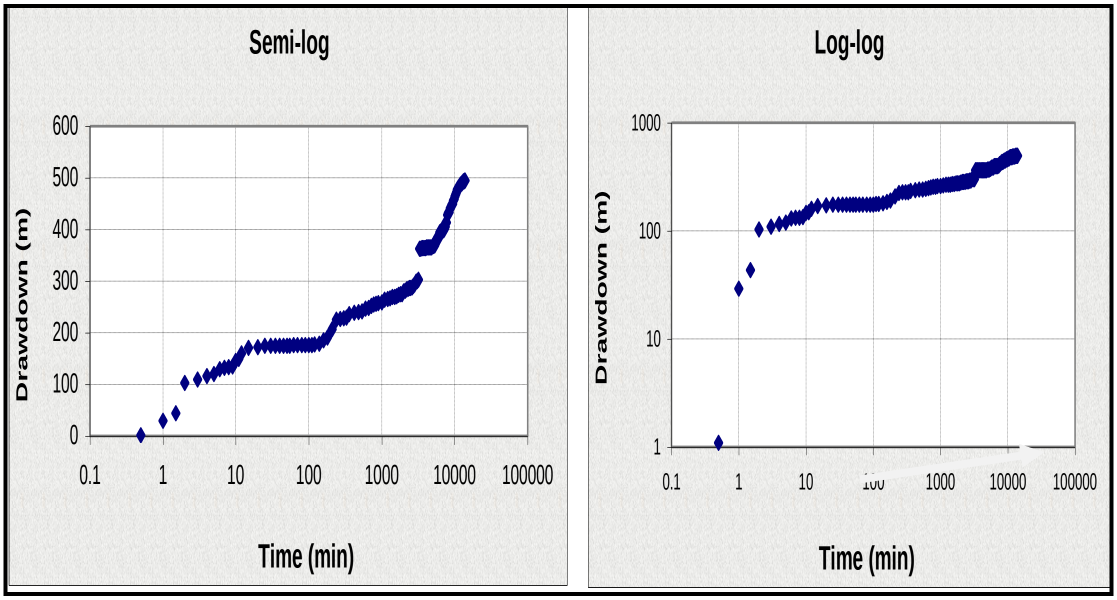

Figure 43: Diagnostic plots of Kombat Mine flood monitoring at Shaft_1.

Figure 43 presents the data collected by Kombat Mine personnel during the Kombat Mine flood event of October 1988.

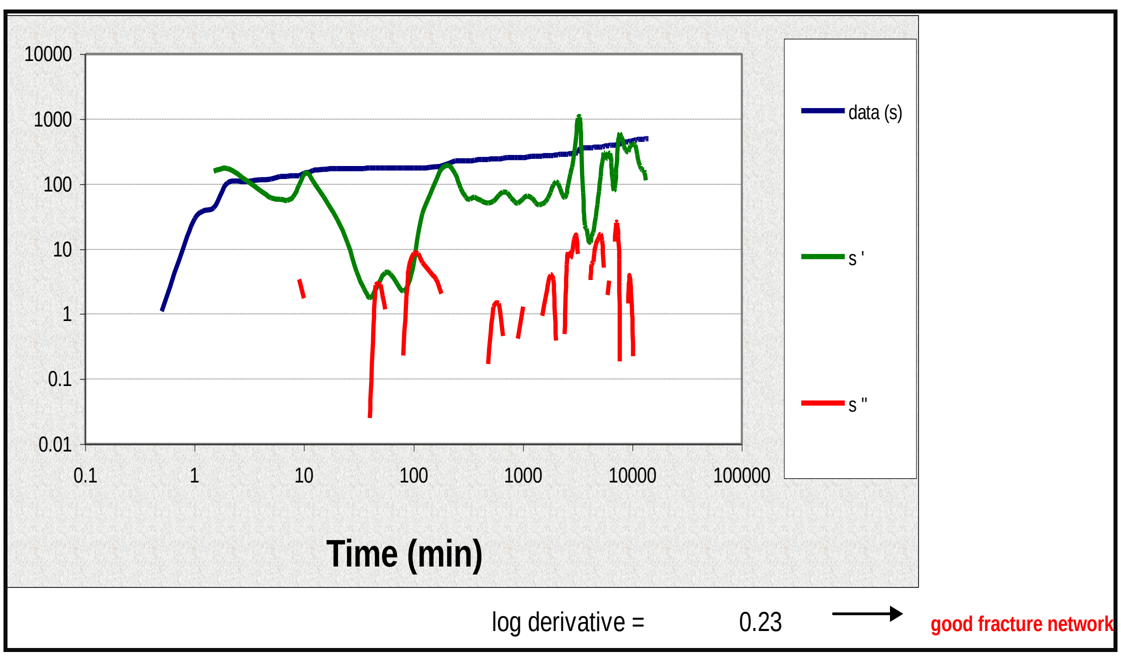

Figure 44: Derivative plots for the data of Kombat Mine flood monitoring.

Table 6: Flow characteristis from Kombat Mine flooding_Shaft_1

Curve/Method	Description
Semi-Log (**Figure 43**)	After the effects of wellbore storage, the slope of the semi-log curve flattens from the 15th minute up to 160 minutes, indicating either a storage and/or permeability increase. Between 160 and 270 minutes, the semi-log slope steepens with time by more than double, followed by a slight flattening and the steepening for the rest of the monitored time. The second flattening continued for 270 minutes, while the last steepening of the slope of the curve persisted to end of the monitoring.
Log-Log (**Figure 43**)	The slope of the log-log curve fluctuates between 0.5 during wellbore to less than 0.25 along flattening segments. This trend indicates alternating linear and bilinear flow. One interesting observation is that the wellbore storage slope does not repeat itself, indicating that there are no boundary conditions reached during this test. Therefore the segmentation observed in the log-log curve may be attributed to alternating zones of highly and low permeability parts of the flow system or alternatively zones of distinct storavity. However, it has been observed in this study that storativity values exhibits a better central tendency than transmissivity, creating an impression that transmissivity accounts for heterogeneities more than storativity. Thus there exist a high likelihood that alternating decrease and increase in the slope of the log-log curve observed is due to transmissivity variations. In view of the observed range of the slope of the log-log curve, it can be concluded that at the hydraulic response scale equivalent the Kombat Flooding event; boundary conditions have no significant influence on the Kombat Aquifer flow system. A statistical overview of the trend in the slope of log-log curve in Figure 43 shows that linear flow from the fracture is more dominant, about 60 %, compared to 40 % bilinear flow. This observation can lead to a deduction that, at a bulk response scale, the fracture system of the Kombat Aquifer is extensive and well connected.
First derivative (s’) (**Figure 44**)	Figure 44 presents the log derivative of data collected during mine flooding at Kombat Shaft_1. The early time downward and then upward trend in the slope of s’ (60 minutes) is often attributable to situations in which a fracture is dewatered which in this case implies that 1988 flooding event at Kombat Mine happen in fractured zone. This trend repeats itself at 250 and 3180 minutes, thus alluding to the existence of multiple fractures. From the alternating segmentation observed in semi-log plot (**Figure 43**), these fractures seem to vertically alternate with less fractured zones, and the fact that there is no evidence of closed boundary conditions, an effective hydraulic connectivity between the more and the less fractured parts of the aquifer can be assumed.
Second derivative (s’’) (**Figure 44**)	Brief instances of radial flow can be seen at the 420th and 10100th minutes, this is evident in the total absence of s’’.

Table 7 presents the aquifer parameters estimated from the drawdown curves in Figure 43.

Table 7: Aquifer parameter estimates from Shaft_1

Locality or Borehole number	Time	Fracture Transmissivity (m^2/day) FC-Method	Fracture Transmissivity (m^2/day) RPSOLV	Formation Storativity RPSOLV
Shaft_1	Early	4417	4147	
	Late	102	33	0.003
		314-Recovery		

The graphs in Figures 45, 46 and 47 are drawdown curves from a pumping test conducted at Borehole WW200451, north of Kombat Mine.

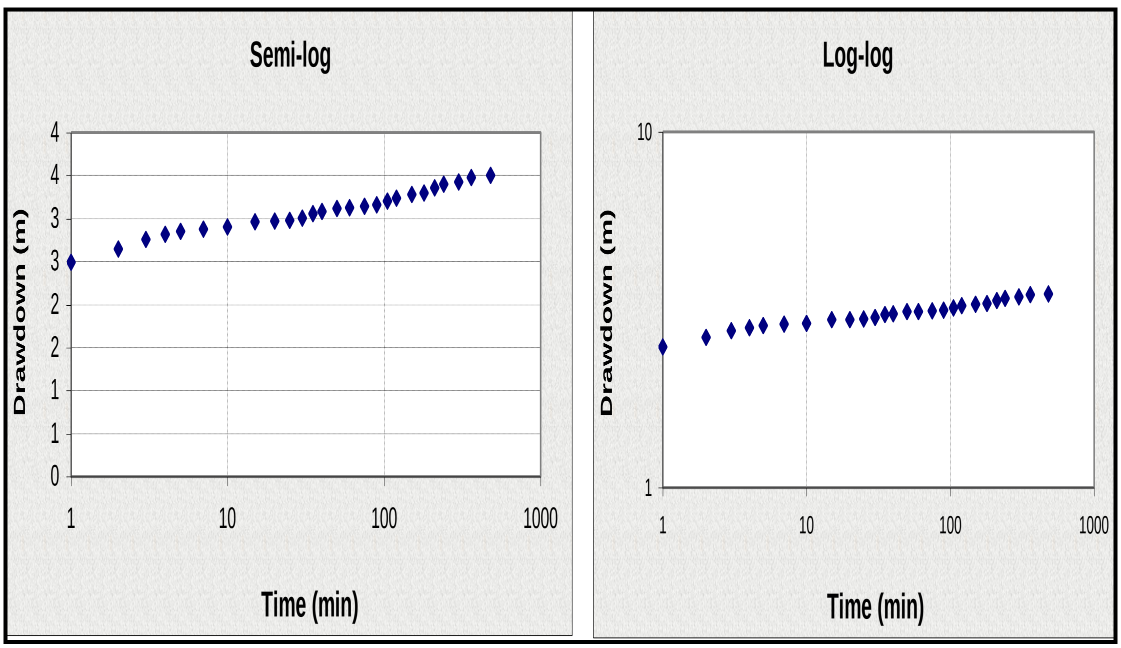

Figure 45: Diagnostic plots from constant discharge test data of Borehole WW200451

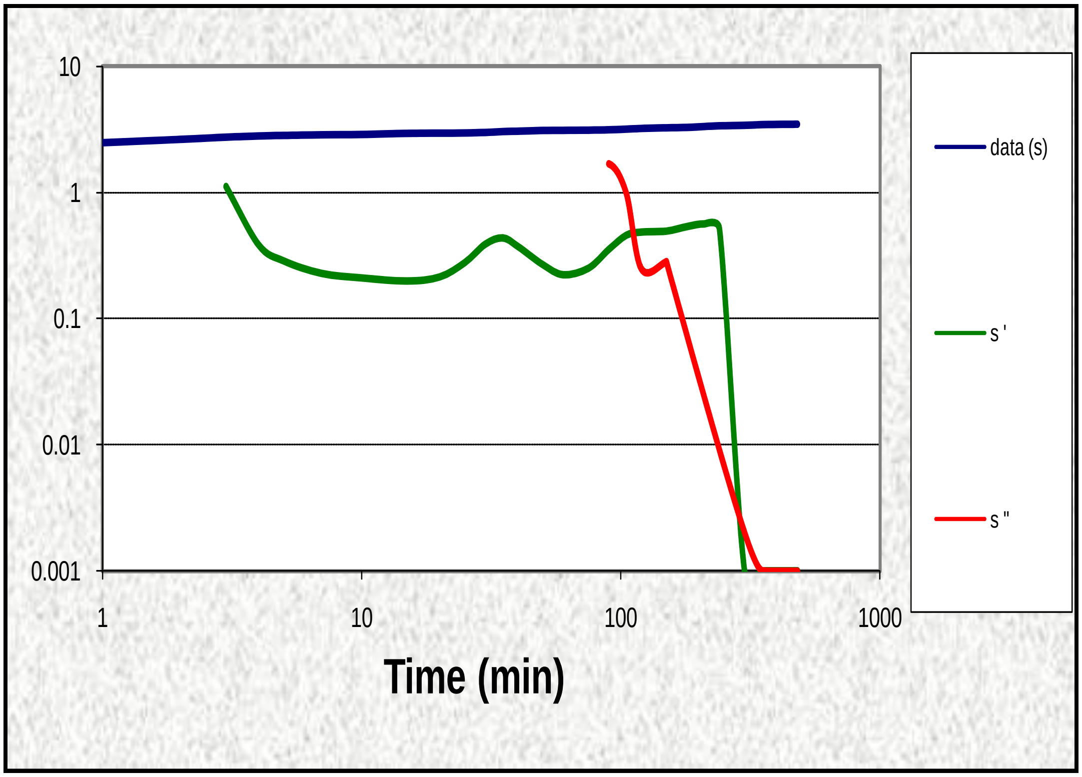

Figure 46: Derivative plots from constant discharge data for Borehole WW200451

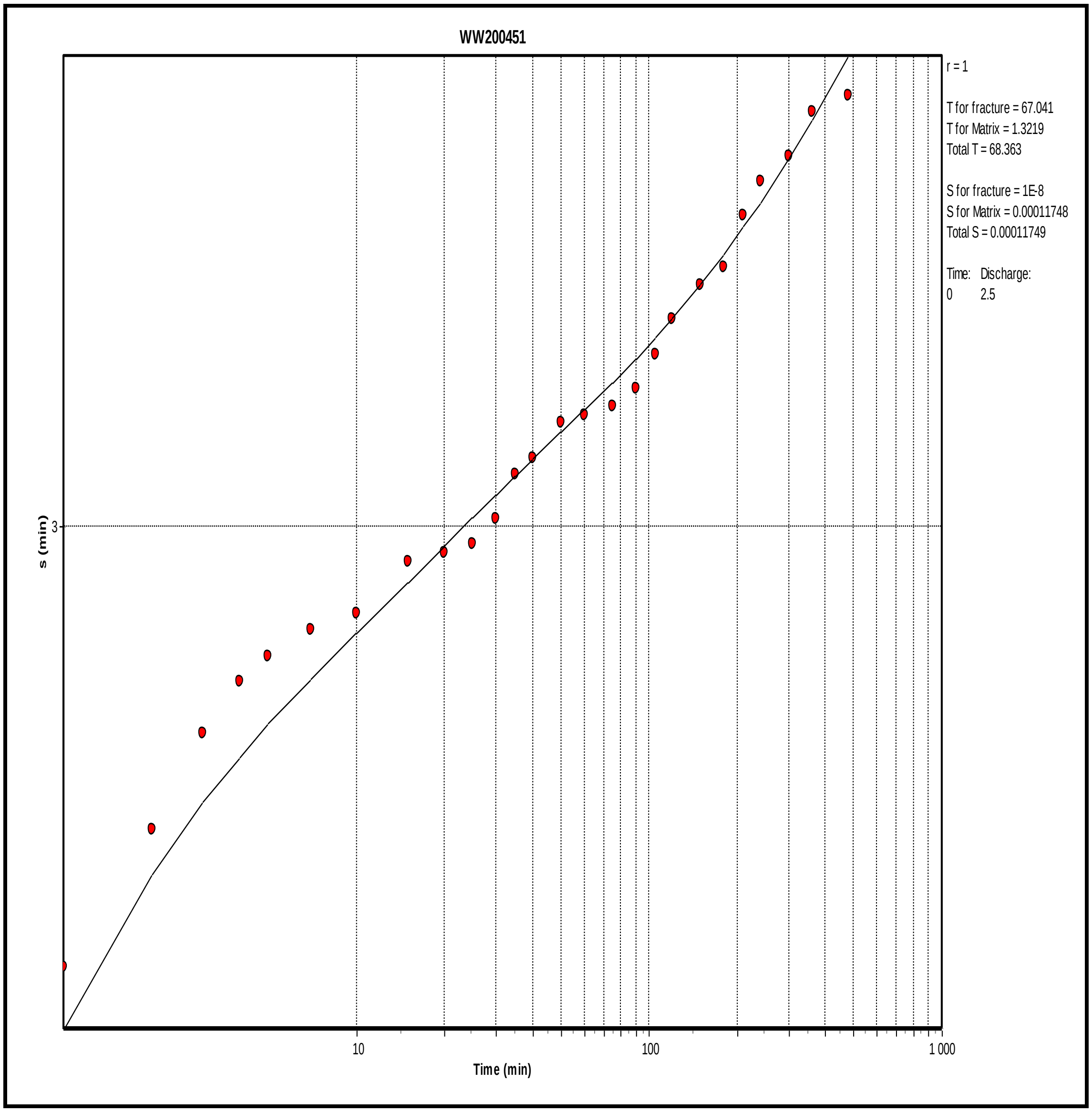

Figure 47: Hydraulic parameter estimate for Borehole WW200451

Table 8: Flow characteristics from Borehole WW200451

Curve/Method	Description
Semi-Log (**Figure 45**)	As seen in Figure 45, the slope of semi-log curve is essentially a straight line segment, even though it exhibits a slight increase at about 120 minutes.
Log-Log (**Figure 45**)	For the entire test, the slope of log-log curve of Borehole WW200451 is less than 0.25. The absence of linear flow (slope of 0.5) means that the storage of the fracture on which this borehole is drilled is insignificant. Therefore most of the water is coming from the formation
First derivative (s') (**Figure 46**)	The s' curve steepens and rises at early time (60 minutes), suggesting the presence of fractures, this observation does not repeat itself elsewhere during the test. Therefore this borehole may have intersected a single fracture with limited extent.
Second derivative (s'') (**Figure 46**)	The s'' curve is missing, except between 75 and 180 minutes, a trend which indicates existence of radial flow during periods where the s'' curve is missing, meaning that water is essentially coming from the formation. The strong downward trend towards the end of the test points to a potential situation where a recharge boundary or a high permeability zone has been reached. The fact that the curves exhibit total absence of linear flow, and that bilinear and radial flow dominated flow in this borehole; means that formational storativity and permeability is well developed to support the abstraction rate for the entire test. Of particular interest to the concept of fracture connectivity is the possibility that a recharge boundary might have been reached towards the end of the test. If that is valid, then connectivity between less permeable and the more permeable parts, as observed from the Kombat Mine flooding seems to confirm its existence. In this instance the connectivity is revealed at a scale of 8 hours constant discharge pump tests.

Table 9: Aquifer parameter estimates from Borehole WW200451

Locality or Borehole number	Time	Fracture transmissivity (m^2/day) FC-Method	Fracture transmissivity (m^2/day) RPSOLV	Storativity RPSOLV
Shaft_1	Early	104	62	
	Late	10		0.00026

Tables

Table 9 presents the hydraulic parameter estimates of fracture transmissivity and formation storativity at Borehole WW200451.

The following figures present drawdown curves of a constant discharge test conducted at Borehole WW200449 on Farm Sommorau, north of Kombat Mine.

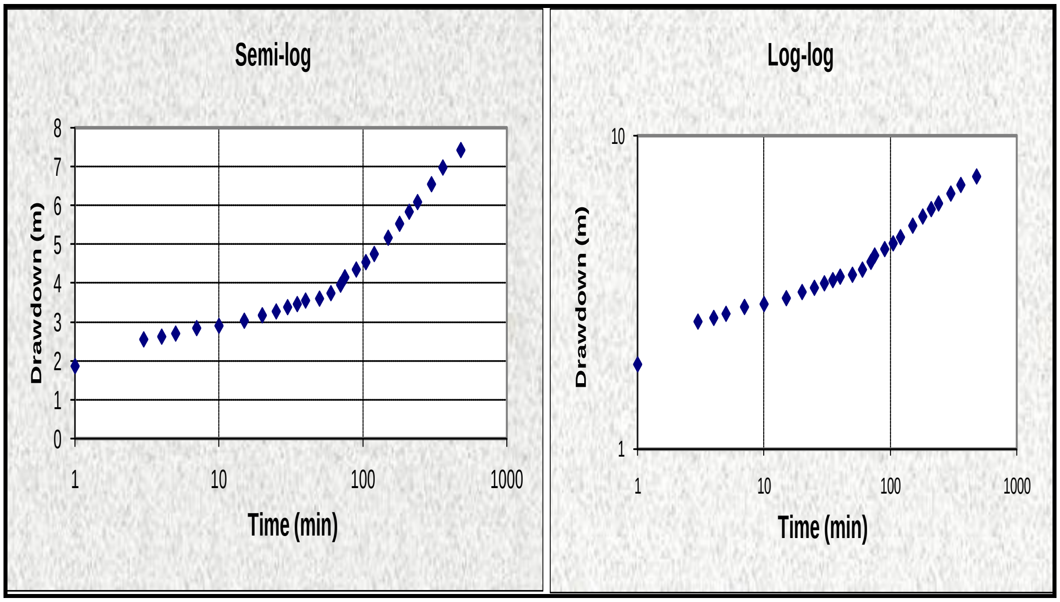

Figure 48: Diagnostic plots from constant discharge data for Borehole WW200449

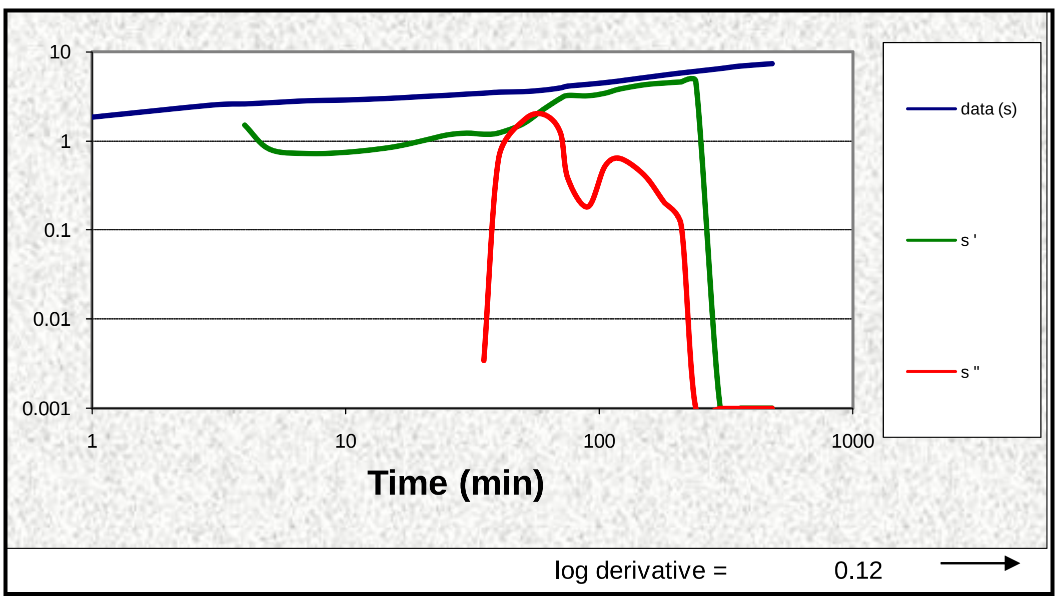

Figure 49: Derivative plots from constant discharge data for Borehole WW200449

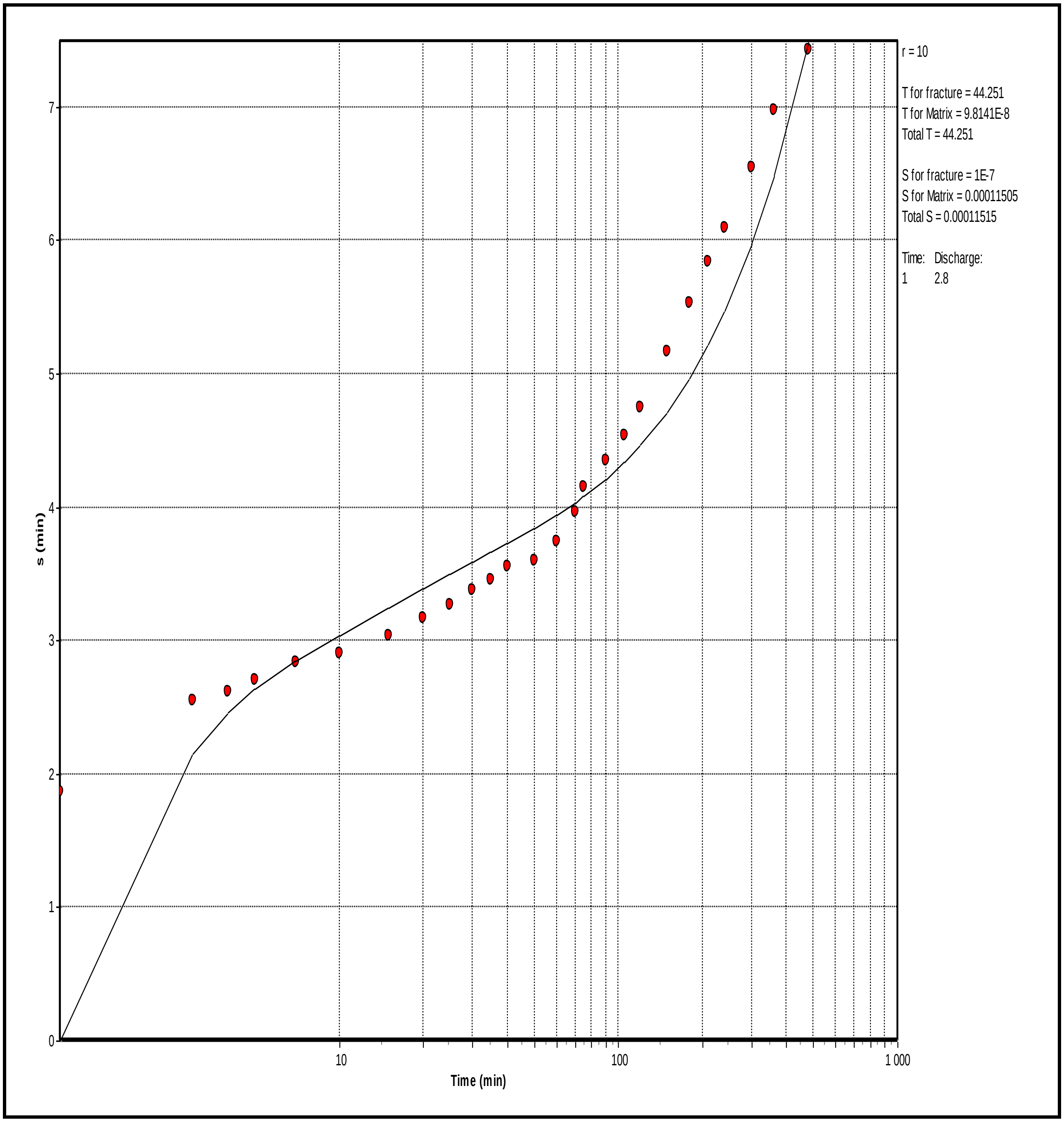

Figure 50: Hydraulic parameter estimates for Borehole WW200449

Table 10: Flow characteristics from Borehole WW200449

Curve/Method	Description
Semi-Log (**Figure 48**)	Displays two straight line segments, with the second straight line segment steepening till the end of the test. This trend as mentioned earlier on, is diagnostic of the presence of low permeability hydraulic boundary conditions.
Log-Log (**Figure 48**)	The intermediate to late time slope of 1 of the slope of the log-log curve; implies the presence of limited fracture extent or bounded reservoir. However, the fact that the slope of the drawdown curve doubles towards the end of the test supports the bounded reservoir alternative compared to the limited fracture one, although a co-existence of the two cannot be ruled put.
First derivative (s') (**Figure 49**)	The slope of s' is rising from the beginning of the test up until the 240th minute, It acquire a slope of 0.5 then decreases to 0.3 towards the end of the test. This trend in the slope of the s' suggests that formation flow dominates most of the flow up to the point when a recharge condition is reached. Therefore there is little fracture flow in the compartment hosting this borehole, however connectivity to well drained compartments seems to be maintained as can be seen in the recharge boundary towards the end of the test.
Second derivative (s'') (**Figure 49**)	The slope of s'' exhibits a strong downward trend towards the end of the test, this trend is strange because it does not appear in all the other diagnostic plots. However, it should be noted that the second derivative is very sensitive to small change in the drawdown, such small changes can sometimes reflect errors in data collection, recording and/or data capturing. If the trend is true, then it is typical of a pumping test cone of depression that has intersected a recharge boundary and/or a well drained compartment.

Parameter estimates of the aquifer at Borehole WW200449 are presented in Table 11.

Table 11: Aquifer parameter estimates from Borehole WW200449

Locality or Borehole number	Time	Fracture transmissivity (m^2/day) FC-Method	Fracture transmissivity (m^2/day) RPSOLV	Storativity RPSOLV
Shaft_1	Early Late	13 9	44	0.001154

Figures 51, 52 and 53 present drawdown curves of the constant discharge tests conducted at Borehole WW200450, also north of Kombat Mine

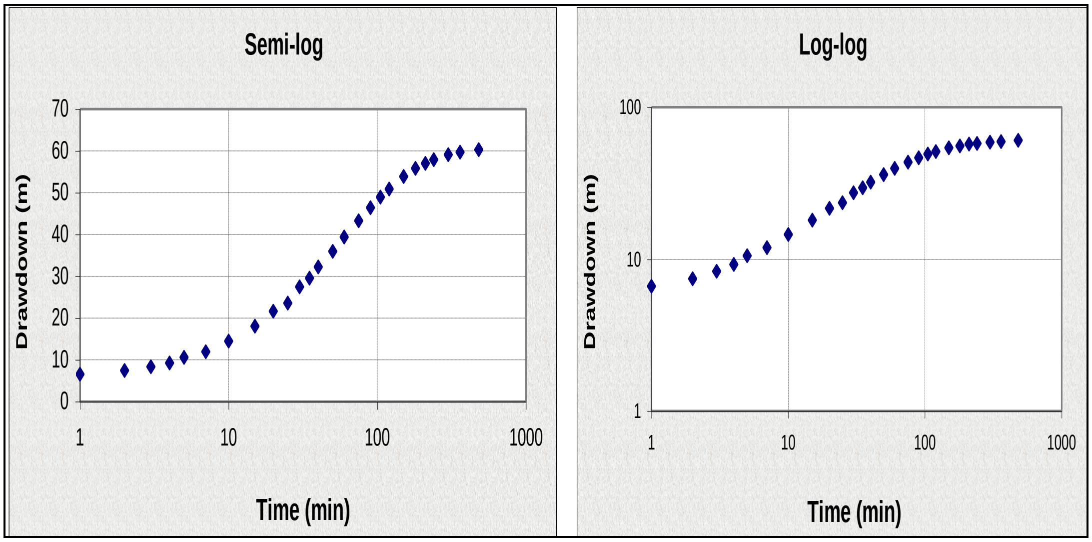

Figure 51: Diagnostic plots from constant discharge data for Borehole WW200450

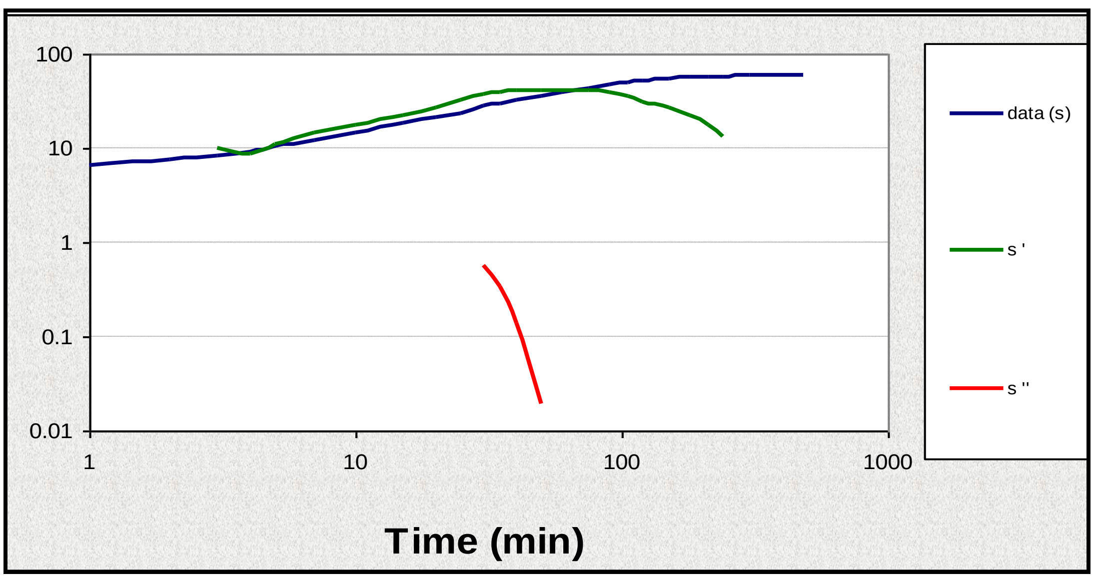

Figure 52: Derivative plots from constant discharge data for Borehole WW200450

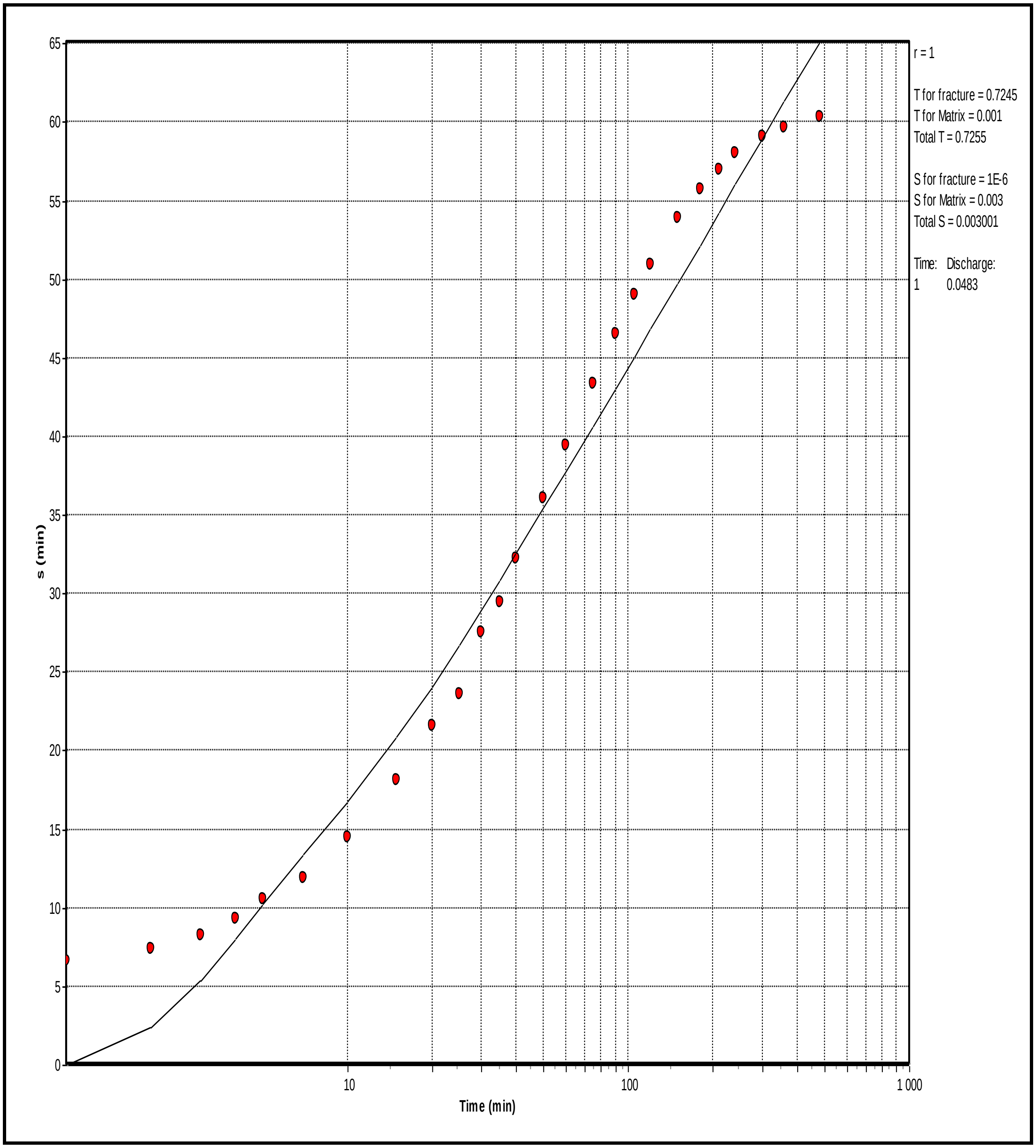

Figure 53: Hydraulic parameter estimates for Borehole WW200450

Table 12: Flow characteristics from Borehole WW200450

Curve/Method	Description
Semi-Log (**Figure 51**)	Two trends in the slope of the semi-log curve (**Figure 51**) can be seen, the first one is the steepening slope, which dominates most of the intermediate period from the 20th to the 100th minute. The send trend is the flattening of the semi-log curve from about 100 to the end of the test (480 minutes). The first trend implies that during the intermediate period, low permeability boundaries conditions might have been reached, while the late time flattening of the slope indicates that an improved permeability zone might have been reached. The alternating low and high permeability zones seem to be characteristic of the northern part of the Kombat Aquifer, because it is persistent in all the boreholes north of the Mine, including the Kombat Mine flood event. This observation can among others be interpreted as a consequence improving system connectivity as the area of influence increases.
Log-Log (**Figure 51**)	An intermediate slope of the log-log curve of 1, as stated earlier means an encounter of poor flow boundary conditions by the cone of depression.
First derivative (s') (**Figure 52**)	The s' slope is rising at a slope of 0.23 up to the 100th minute, from there it decreases and disappears shortly before the end of the test. The absence of downwards and then upwards trends in this curve implies that Borehole WW220450 is completed in less fractured rock, this inference is supported by hydraulic parameter estimates in Table 13. Table 13 shows that the transmissivity around Borehole WW200450 does not reflect those of fracture flow. However, the late time decrease in the slope of s', reflects that less permeable block in which this borehole is completed is connected to more permeable parts of the aquifer.
Second derivative (s'') (**Figure 52**)	The second derivative is essentially absent except for minor downward instance between 30 and 50 minutes, this implies radial flow conditions, thus most of the water pumped during this test came from the formation.

Table 13: Aquifer parameter estimates from Borehole WW200450

Locality or Borehole number	Time	Transmissivity (m^2/day) FC-Method	Transmissivity (m^2/day) RPSOLV	Storativity RPSOLV
Shaft_1	Early Late	0.2 0.2	0.73	0.003

Table 13 presents aquifer hydraulic parameters in the vicinity of Borehole WW200450.

Borehole 3 is drilled in the SLLA; it is therefore typical of boreholes exploiting the west-east bedding parallel shears, typical of the basal contact.

An outstanding feature of the drawdown curve in Figure 51 is the marked increase in drawdown after the 100th minute. This observation often typifies the hydraulic behaviour in a fractured aquifer when a borehole is subjected to a longer-term dewatering test. It is indicative of the aquifer's response locally when less favourable groundwater hydraulic conditions are encountered below a certain pump water level depth and so-called no flow boundary conditions.

The observed trend in Figure 51 and the discussion that follows tentatively support the notion that the bedding parallel shear zones of the SLLA largely behave like bounded aquifers. The bounded aquifer hydraulic behaviour of this part of the aquifer is logically expected, owing to the parallel plate geometry of the bedding parallel shear fracture of the SLLA.

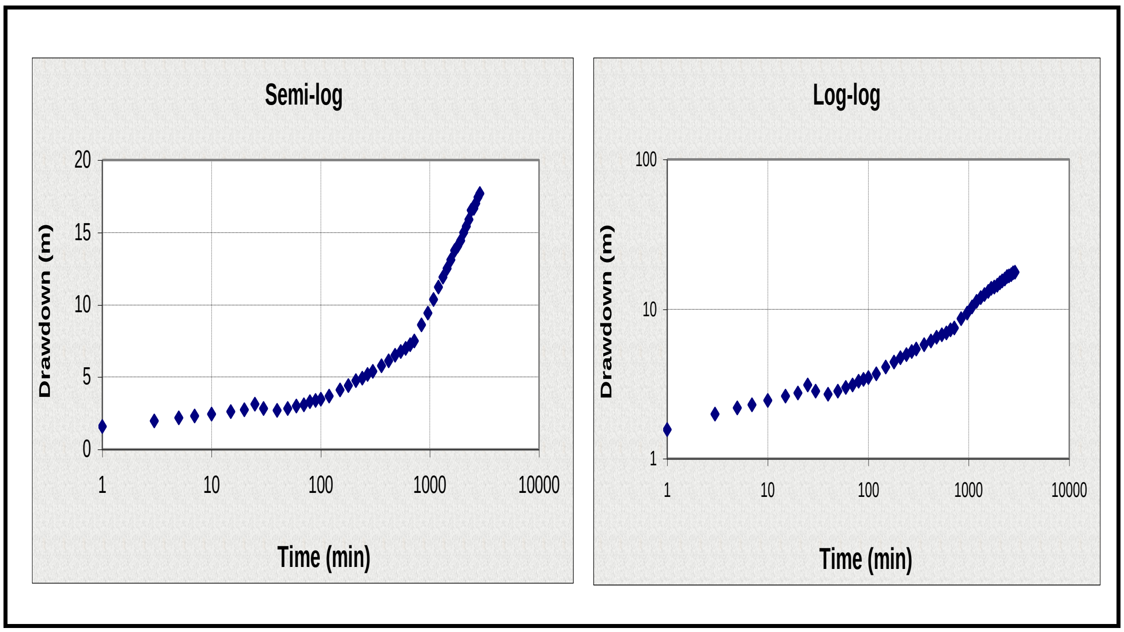

Figure 54: Diagnostic plots from constant discharge data for Borehole 3

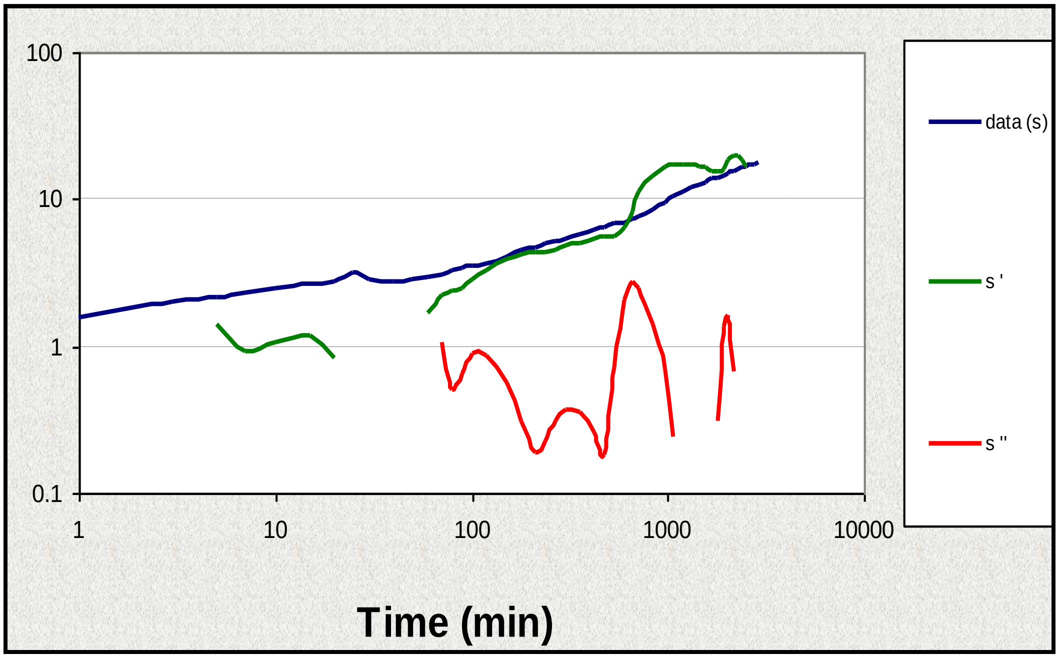

Figure 55: Derivative plots from constant discharge data for Borehole 3

Table 14: Flow characteristics from Borehole 3

Curve/Method	Description
Semi-Log (**Figure 54**)	Borehole 3 is of special interest to this study because it presents the hydraulic behaviour of the bedding parallel shears fractures of the SLLA. The borehole is completed in the Berg Aukas Formation (laminated dolomite, limestone and shale). Two trends in the slope (with slope of 0.5) of the semi-log curve (**Figure 54**) can be seen, the first one is the raising slope, which starts at 40 minutes and persists up to the 720th minute. The rise slope of 0.5 implies unfavourable hydraulic conditions like intersecting a low permeability. The second slope is even steeper (slope of 2), it starts at 720 minutes up to the end of the test. At late times, the quadruple of slope suggests that perpendicular no flow boundaries have been reached. Considering the fact that Borehole 3 exploits a near vertical to an over-tuned fractured bedding plane (**Figure 18**), the bounded aquifer behaviour it exhibits is logical.
Log-Log (**Figure 54**)	The slope of log-log curve shows a negative gradient (downwards trend) between the 25 and 40 minutes, thereafter it adapts to the two steepening segments observed on the semi-log curve. The first segment has a rising slope of 0.5, The second segment exhibits a rising slope of 0.8. On the log-log curve, a rising slope with a gradient of 0.5 is interpreted as a sign of linear flow (Van Tonder, 1999), meaning that at that stage during the pumping, most of the water was coming from fracture or cavity storage. The second segment with a slope of almost 1 suggests that the source of linear flow observed in the first segment is

	limited (Limited closed reservoir), which in a geological setting like the SLLA can be attributed to solution enhanced open fractures or cavities in dolomite. From the shape of the semi-log and log-log curves, it appears that the connectivity of this fracture or cavity to the rest of the aquifer is not good, and that stands in sharp contrast to what is displayed in boreholes drilled north of Kombat. Some of those boreholes are very low yielding (e.g.WW200450) compared to Borehole 3, but they still maintained some degree of connectivity to the well drained parts of the aquifer.
First derivative (s') (**Figure 55**)	The s' curve is not visible between 20 and 60 minutes, meaning that radial flow might have been reached during that period. From the 60th minute onwards, the s' slope increases with no sign of positions of fractures. At 600 minute the slope steepens and adapts a slope 1.3, which continued up to the 1200th minute, thereafter the slope decreases back to 0.5. These trends conform to those observed on the semi-log and the log-log curves, and are explained by a model that assumed closed no flow boundaries, which could possibly be solution cavities.
Second derivative (s'') (**Figure 55**)	Apart from the downward and then upward trend in the slope of s'' (300 minutes), the curve expresses what has already been observed on the other curves of Borehole 3. The downward and upward trend observed at 300 minutes indicates the position of fractures, but the fact that those fractures could not manifest themselves on the s' curve means that they are minor.

Table 15: Aquifer parameter estimates from Borehole 3

Locality or Borehole number	**Time**	**Transmissivity (m^2/day) FC-Method**	**Transmissivity (m^2/day) RPSOLV**	**Storativity RPSOLV**
Shaft_1	Early Late	178 35	200	0.00026

Table 15 presents aquifer hydraulic parameters estimated in the vicinity of Borehole 3.

5.2.2 Aquifer characteristics based on topography and water level correlation

The correlation of topography to static water levels of the Kombat Aquifer exhibits three to four distinct segments (as seen in Chapter 3 Section-3.3, **Figure 7**), identified on the basis of their steepness. Figures 56, 57 and 58 present the correlations on a north-south section along the flow system.

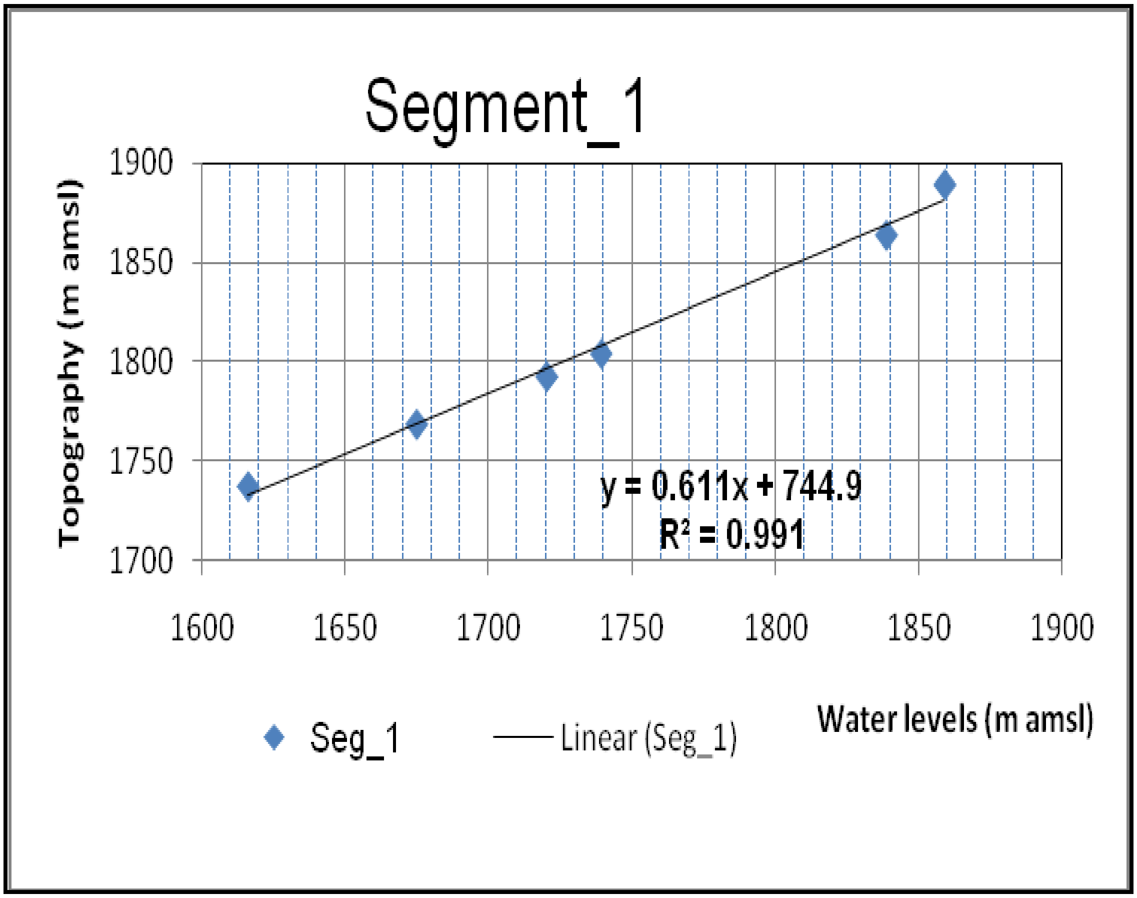

Figure 56: Topography-water level correlation of the elevated portion of the aquifer.

Figure 56 presents the correlation between topography and static water levels of the portion of highest elevation in the study area (Karstic Plateau). The correlation coefficient of 0.991, as seen in Figure 56, indicates that the water table of the Karstic Plateau is highly subdued by topography. High topography to static water level correlations are typical of unconfined aquifers. It can therefore be concluded the Karstic Plateau of the Kombat Aquifer is an unconfined aquifer.

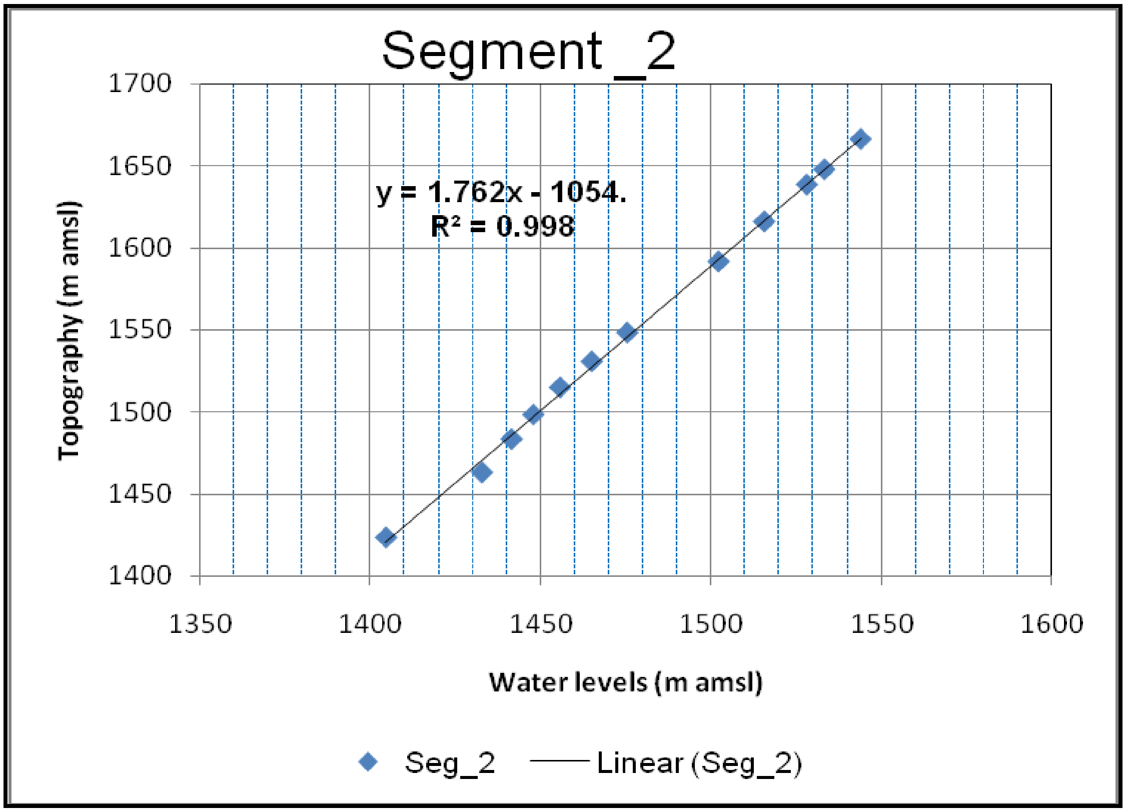

Figure 57: The second segment of the topography-water level correlation

The cross-correlation presented in Figure 57 represents the linear regression between topography and static water levels of the Northern Dip Slope (Fluviokarst). A comparison of the slope of the linear regression lines of the Karstic Plateau and the Fluviokarst shows that the groundwater flow component on the Fluviokarst is three times steeper than that of the Karstic Plateau. Assuming that a bulk transmissivity and hydraulic connectivity is applicable between the Karstic Plateau and the Fluviokarst; then the latter would flush groundwater three times faster than the Karstic Plateau.

The topographic setting of the Fluviokarst in relation to the other parts of the aquifer has implications on its hydraulic stability. Due to the high hydraulic gradient, the Fluviokarst responds to both recharge and discharge in a rapid and highly pronounced manner, in comparison to the other parts of the aquifer. This can be seen in the response of boreholes to recharge following the heavy rainfall of 2006 (**Figure 58**).

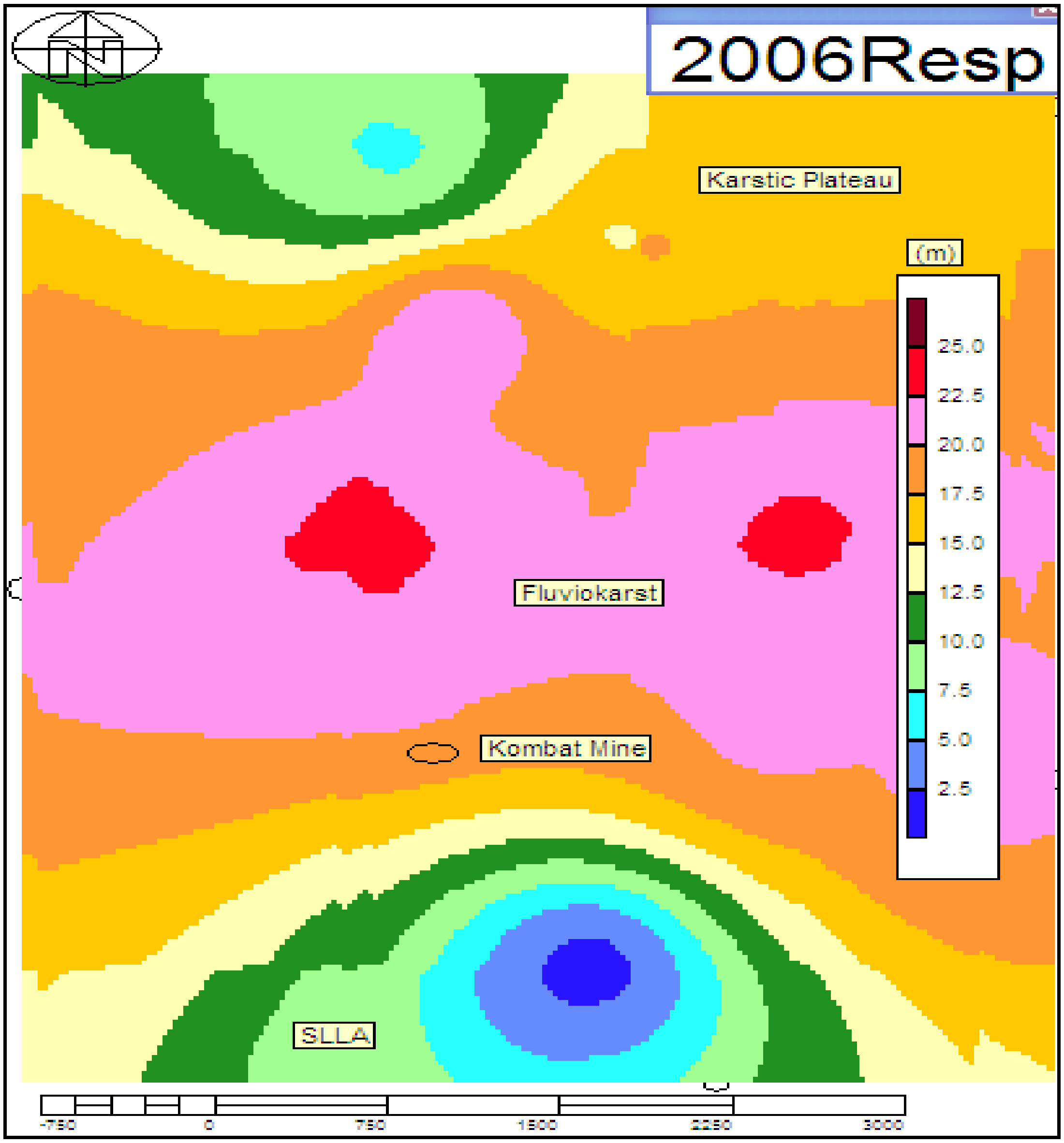

Figure 58: Hydraulic response of boreholes following the 2006 heavy rainfall

Figure 58 presents the recharge response of individual boreholes in the study area. This data set was collected and used by the Department of Water Affairs in determining groundwater allocation quarters to the farmers in the Karst area. Figure 58 shows that the most pronounced water level responses are restricted to the dip slope (Fluviokarst).

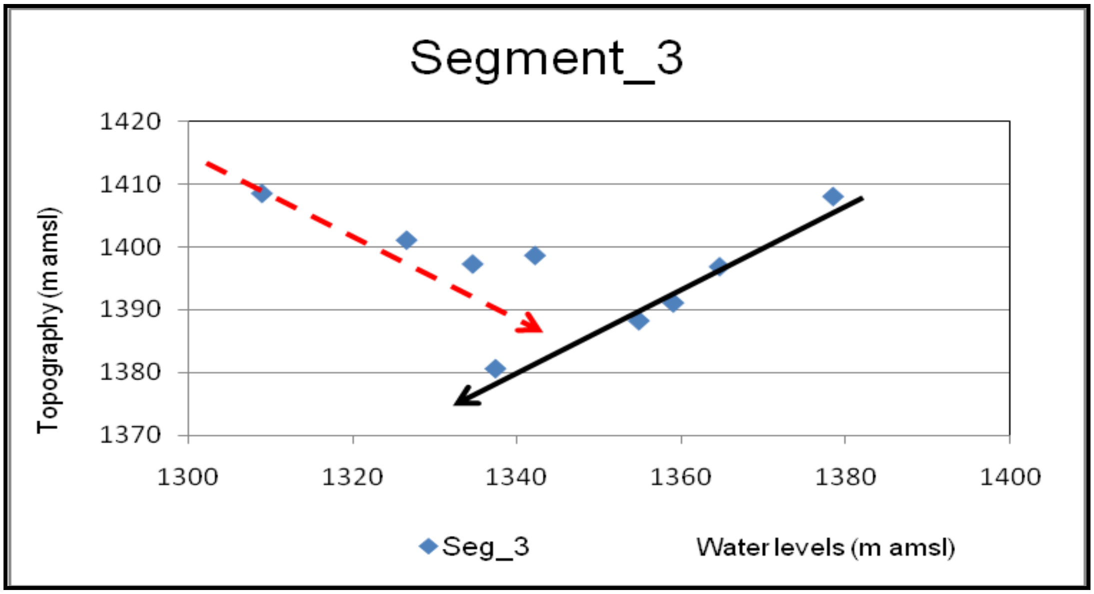

Figure 59: The third and low elevation segment of the topography-water level correlation

Figure 59 is the third and the southernmost segment of the topography-static water level correlation along the flow system of the Kombat Aquifer. It covers the CV and the SLLA.

Unlike the other segments, the CV and SLLA topography-static water level correlation shows a positive trend only up to the topographic elevation of 1409 mamls, below which the sense of correlation is reversed. It appears that, as topography decrease from 1409 to 1397 mmasl, the static water levels increase from 1309 to 1334 mamls. From there, the correlation becomes unclear (**Figure 59**).

In pursuing the explanation for the behaviour of the correlation, as observed in the CV and SLLA, the following aspects are worth noting:

I. The behaviour appears to correlate with the part of the aquifer occupied by the SLLA.

II. Directly south of Kombat Mine, the stratum of the SLLA is overturned; therefore the less permeable rocks of the Nosib Group overlie the dolomite.

III. The positive correlation between topography and static water levels is a property of unconfined aquifers.

It is therefore logical that the observed negative correlation between topography and static water levels, as observed in Figure 59, suggests that the SLLA is a confined aquifer.

5.2.3 Connectivity of the Kombat Aquifer, based on water levels reaction to flooding

The connectivity of the Kombat Aquifer can be examined from the time lag created when different parts of the aquifer respond to the effects of Kombat Mine flooding. Figures 60 and 61 respectively present the response of the northern and southern boreholes to the flooding.

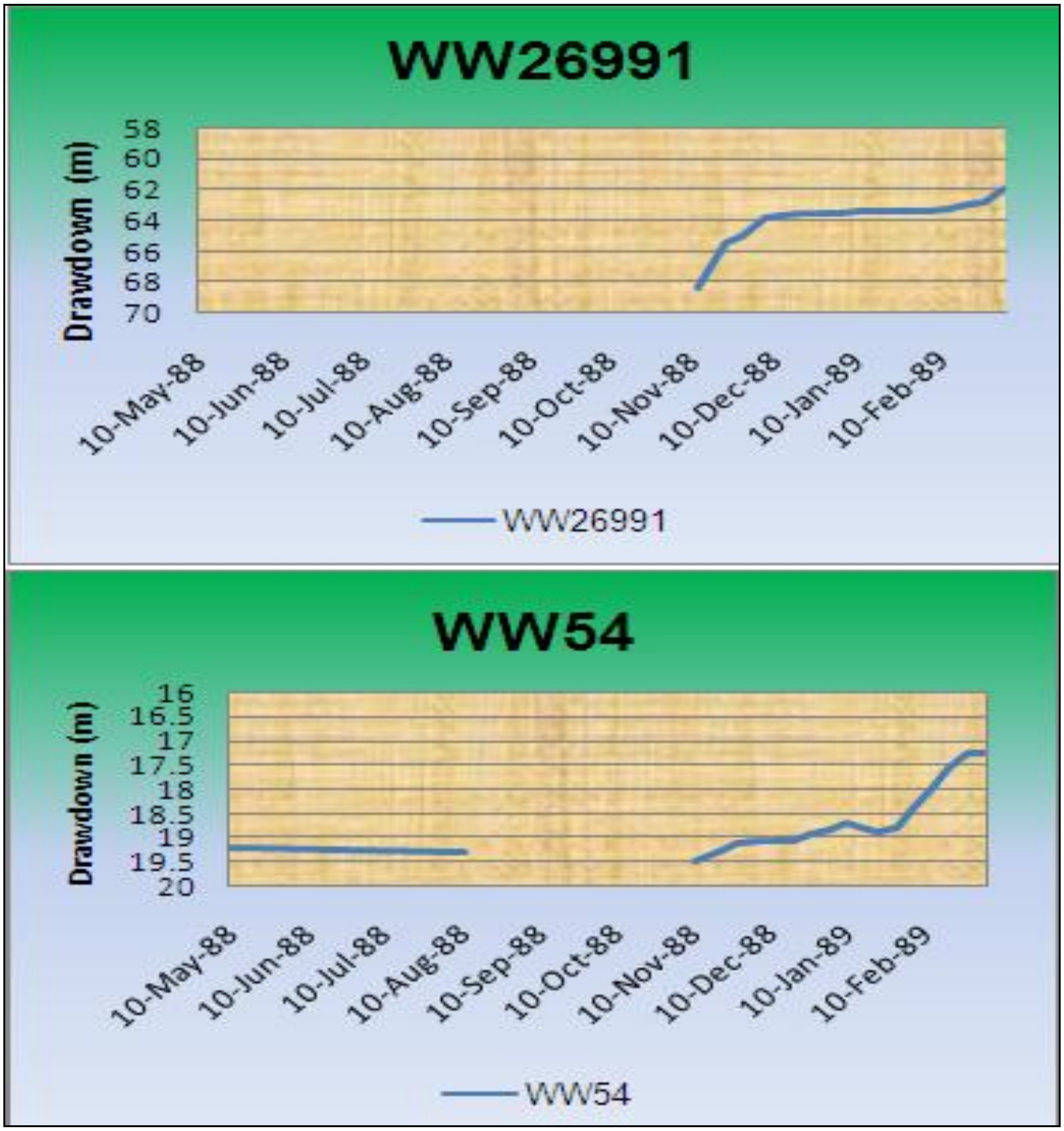

Figure 60: Hydraulic response of northern boreholes to Kombat Mine flooding

Boreholes WW26991 and AW54 are situated west and north of Kombat Mine Shaft_1. They represent the west and northeastern blocks of the flow system.

Figure 61: Hydraulic response of southern boreholes to Kombat Mine flooding

Borehole WW25921 and WW27002 are situated in SLLA of the study area; they therefore represent the part of the aquifer that exploits the bedding parallel shear fractures.

Despite the less permeable boundary presented by the phyllite of the Kombat Formation, there is both vertical and horizontal hydraulic connectivity between the northern and southern zones of the Kombat Aquifer. This is evident from hydraulic reactions observed in boreholes on both sides of the phyllite during the Kombat Mine flood event (**Figures 60 and 61**).

The fact that shallow boreholes (50 to 120 m below ground) reacted to the fault intersected at a depth of about 400 m within minutes, indicates that there is vertical connectivity between the shallow flow system (boreholes) and deep-seated fracture zones. However, the time lag in the reaction of the boreholes, as shown in Figures 60 and 61, reveals that the southern zones are poorly connected to the northern block. This observation can be explained by the presence of the already-mentioned phyllite between the two blocks.

5.2.4 Conclusions from Characterisation

- The hydraulic response of the boreholes from both pumping tests and Kombat Mine flooding indicates that there is widespread hydraulic connectivity in the Kombat Aquifer; this occurs in the form of hydraulic links between the shallow and deeper groundwater flow systems, the northern and southern blocks of the aquifer, and local connectivity between the low and the high permeability networks.

- The zone encompassing Shaft_1 and the intensely faulted block of the northern dip slope is efficiently interconnected. This is evident in the hydraulic response time lag disparity observed between the boreholes of this zone and those from elsewhere in the study area (i.e. the SLLA)-during Kombat Mine flooding.

- An audit of the flow characteristics from the log-log curve of most tests indicates that linear to bilinear flow is the Kombat Aquifer’s dominant hydraulic response to groundwater withdrawal (pumping), especially in the more open fractures.

- The aquifer is heterogeneous and locally compartmentalised. This is evident from the multiple segmentation and steepening character of most of the semi-log curves examined.

- There is strong evidence of perpendicular (vertica)l no-flow boundaries observed in the only borehole completed in the bedding shear facture-dominating the SLLA. This suggests that the bedding parallel shear fracture of the SLLA largely behaves like a bounded aquifer.

- The Kombat Aquifer is largely unconfined. This position is substantiated by the strong positive correlation between topography and static water levels observed along the flow line, except for the SLLA, where confined conditions seem to exist.

- The flow system of the Kombat Aquifer is interconnected on a large scale. This is evident from the log-log slope fluctuation of between 0.5 during wellbore to less than 0.25 along flattening segments; this trend indicates that boundary conditions have less effect of the flow system at the hydraulic response scale equivalent the Kombat flooding event.

On the basis of the shape of semi-log curve; two elementary drawdown type curves are identified, namely the S–Curve and the Arc–Curve.

The S–Curve is characteristic of boreholes completed in less permeable blocks, but are hydraulically linked to high permeability blocks, while the Arc–Curve is typical of boreholes completed in high permeability blocks.

The curves come in many forms, depending on the scale of pumping, the scale and permeability of the adjoining compartments; therefore a curve may be incomplete (**Figure 45**), complete and singular (**Figure 51**), and/or complete in series with other curves (**Figure 43**).

To realistically appreciate the significance of multiple segmentation of pump test curves, it is considered appropriate to draw from the Generalised Radial Fractured Flow Model (Barker, 1988). According to the GRFFM, the drawdown propagation of distinct flow zones is governed by changes in aquifer diffusivity and flow geometry. This relationship between distinct flow zones and aquifer parameters (also known as fractional flow) is mathematically represented by equation 1:

$S\ (r,t) \equiv F(K_f /S_f; K_f\ b^{3-n})$ …………………………………..Eq1

Where S (r,t) is the hydraulic head at time T since pumping started

F is the mathematic symbol for function
$\mathbf{K_f}$ is fracture hydraulic conductivity
$\mathbf{S_f}$ is fracture storativity
b is the extent of the cross-sectional area of flow.
n is the flow dimension which is characteristic of increase/decrease of the through flow area.
$\mathbf{K_f b^{3-n}}$ is the idealised fractured aquifer transmissivity.

Barker 's (1988) findings suggest that the straight line segments seen in the pump test curves can be viewed as pseudo-homogeneous compartments, whose distinct heterogeneities restrict the flow of groundwater such that the cross-sectional area of flow expands proportionally to their specific flow dimension.

The interpretive model provided by Barker (1988) allows this study to, on the basis of the observed shape drawdown curves, conceptualise aquifer geometry and assign hydraulic properties to distinct segments of the aquifer, especially those displaying known behavioural patterns (i.e.'s' and 'arc' type curves). With this understanding of the Kombat Aquifer flow system, the subsequent subsection attempts to generate extra aquifer properties from water-level monitoring during the recession or dewatering that followed the Kombat Mine flood.

5.2.5 Further parameter estimations based on water levels monitoring

The Department of Water Affairs, as the custodian of groundwater resources in Namibia, monitors groundwater levels of several boreholes in the study area, some of which are situated within the cone of depression of the Kombat Mine dewatering scheme. During periods of below average annual rainfall, the hydrographs of these boreholes largely reflect their response to dewatering; this data set can therefore be used in the same way as data from observation boreholes in constant discharge tests.

Even though this dataset is not very consistent, it is considered critical, especially in view of levels of available hydraulic data in the study area. This data set form the basis of the hydraulic parameters estimations presented in the Figures 62 to 66. Tables 16 and 17 present the summary of all derived transmissivities and storativities.

However, there are some shortcomings that might introduce inaccuracies in the parameter estimates presented below. The first is the lack of exact abstraction records from Kombat Mine; an estimate of the hourly abstraction of 1000 m3/h provided by GCS (2007) was therefore applied in generating the parameters presented in the figures that follow.

The second potential source of error is in the form of apparent backflow of pumped water that the mine used to dump on the phyllite of the Kombat Formation in the CV.

As a precaution, care was exercised to sample the parts of the hydrograph displaying minimal external interference. The relative distances of the borehole localities were estimated using ArcGIS. On the basis of known geological boundaries and response time lags, the boreholes (Figure 62) where divided into five groups (see Comments, **Table16**).

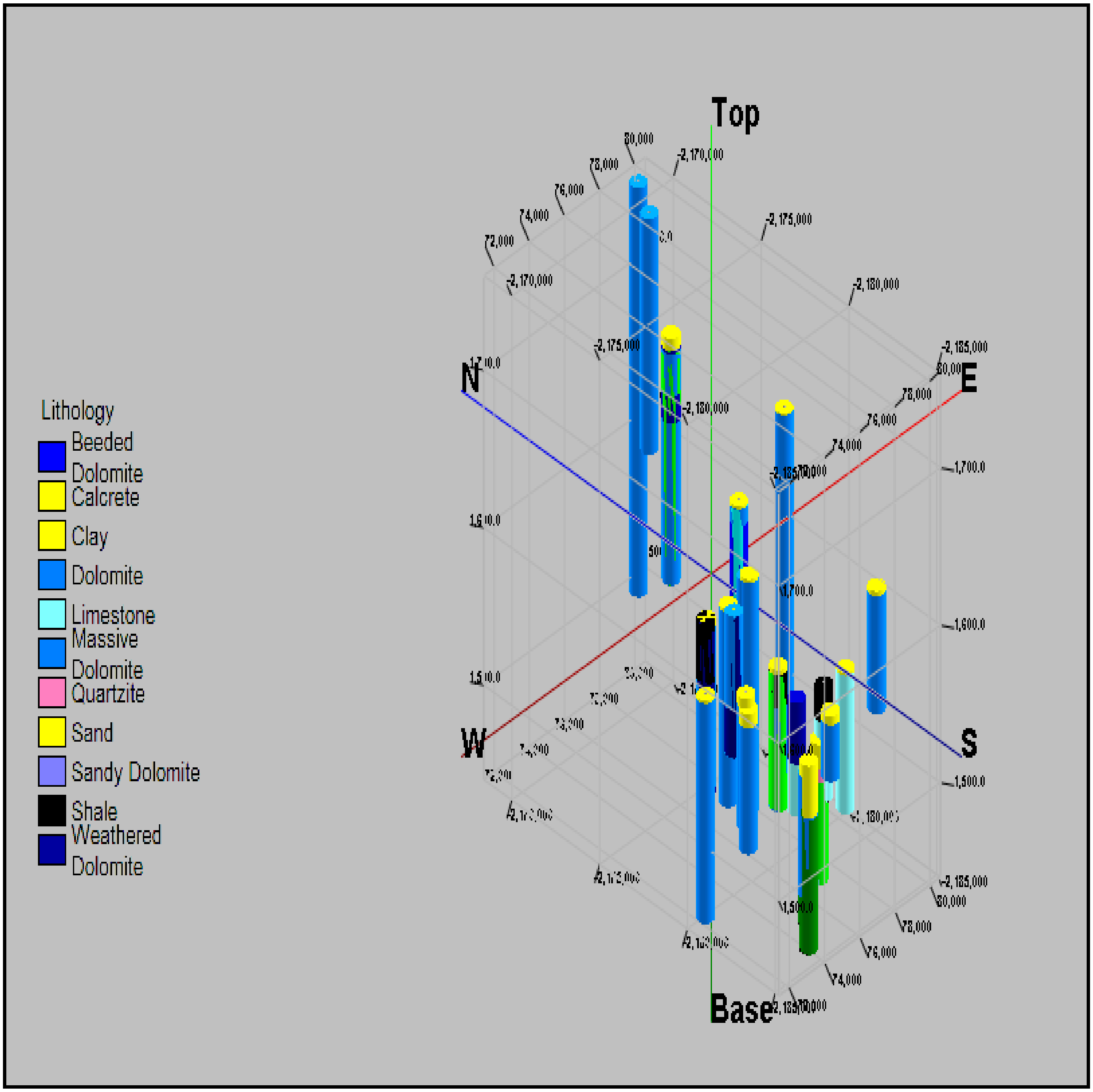

Figure 62: Locality of group boreholes

Figure 62 shows distribution of boreholes with complete geological logs, these boreholes form part of the entire set of 36 boreholes upon which the parameterization and response groups are based.

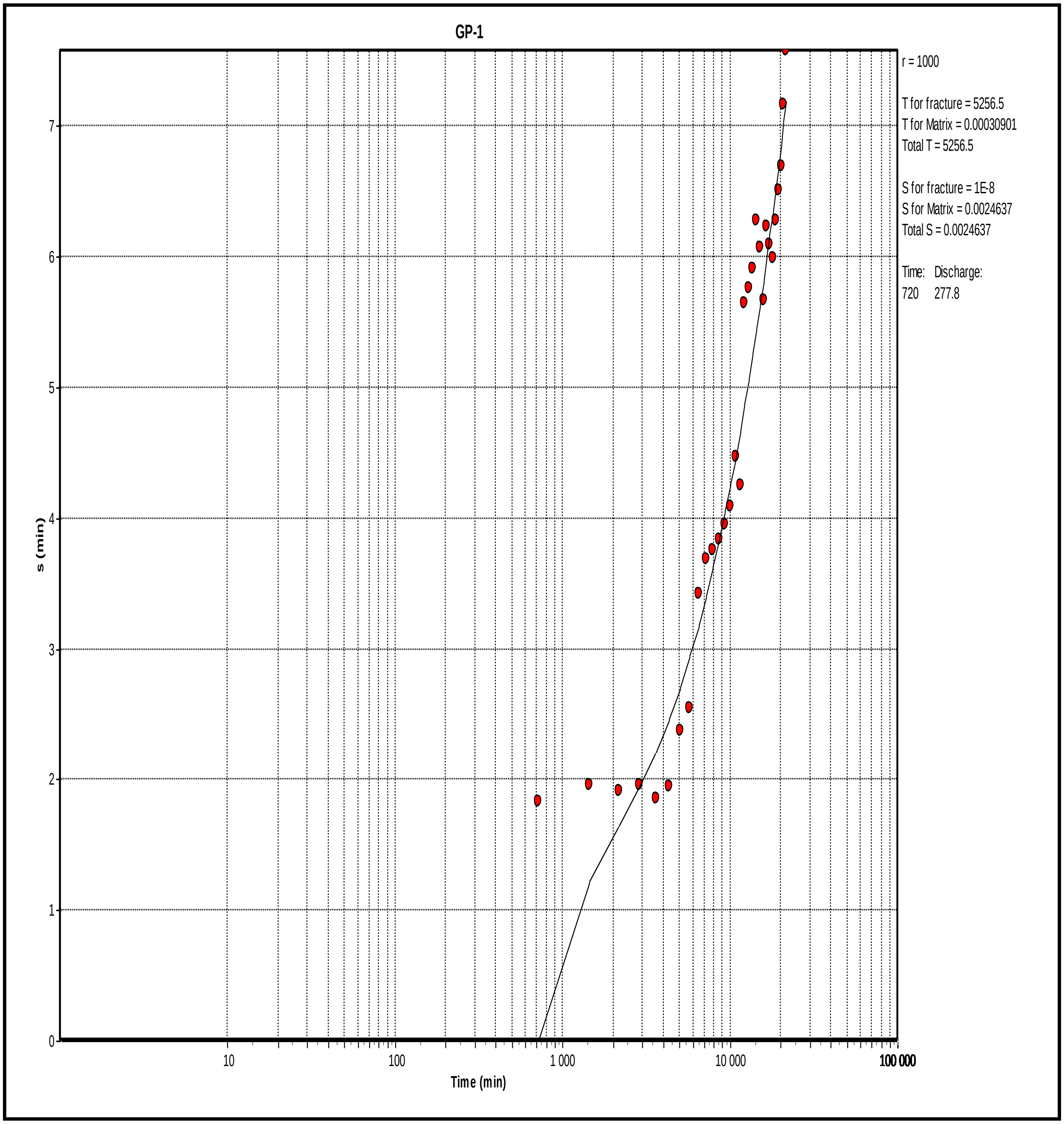

Figure 63: Hydraulic parameter estimation for Group 1 Boreholes

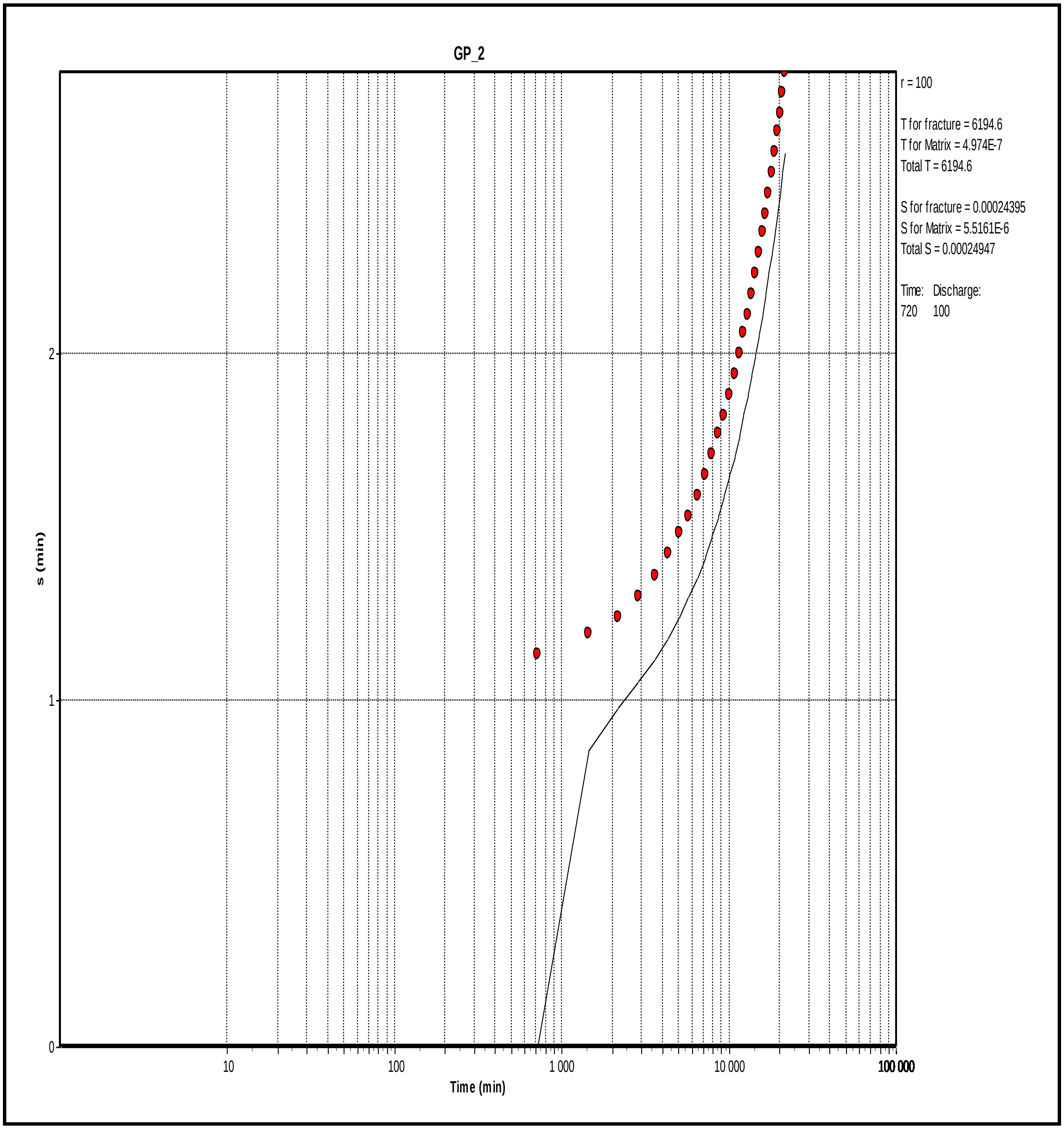

Figure 64: Hydraulic parameter estimation for Group 2 Boreholes

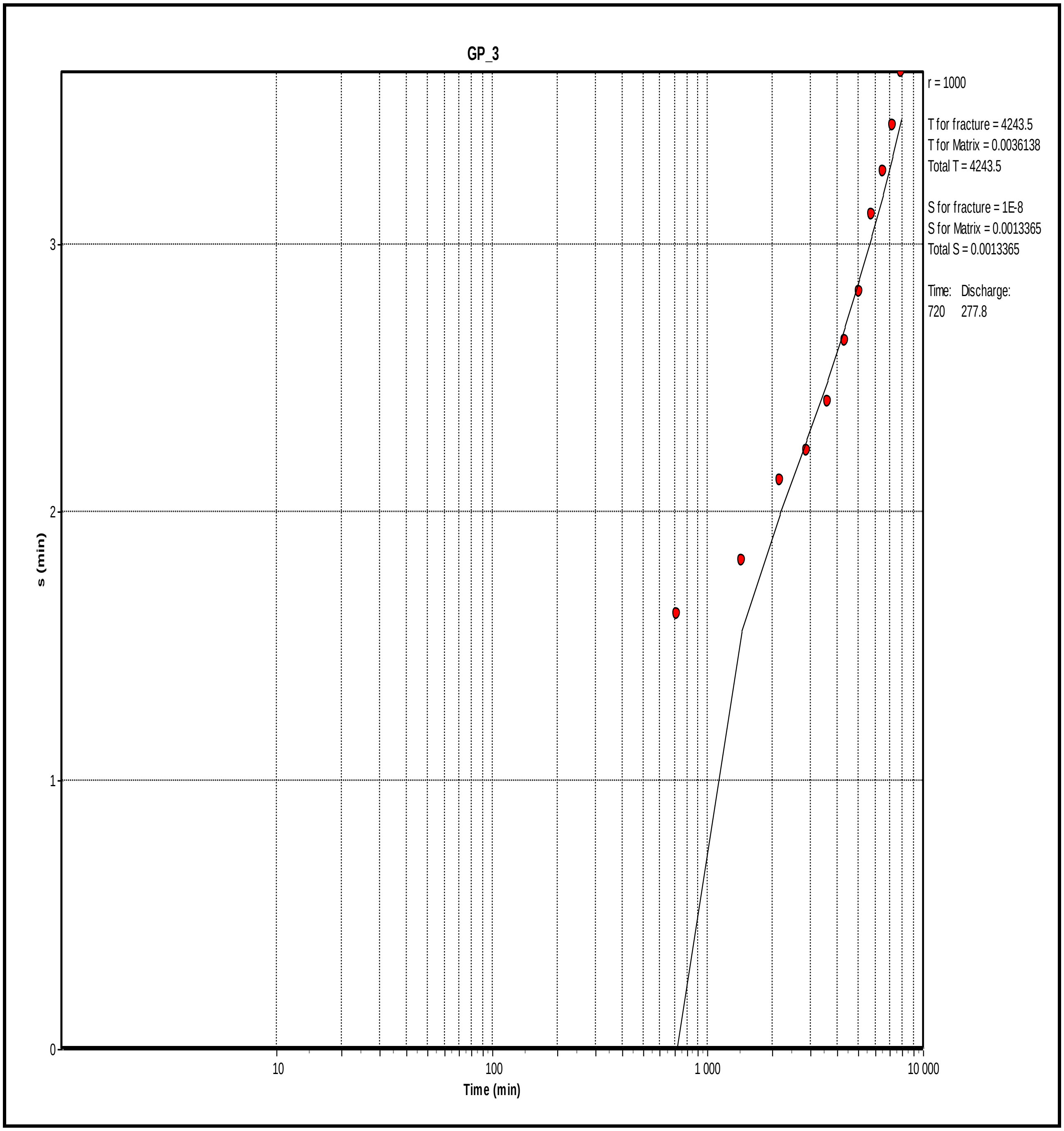

Figure 65: Hydraulic parameter estimation for Group 3 Boreholes

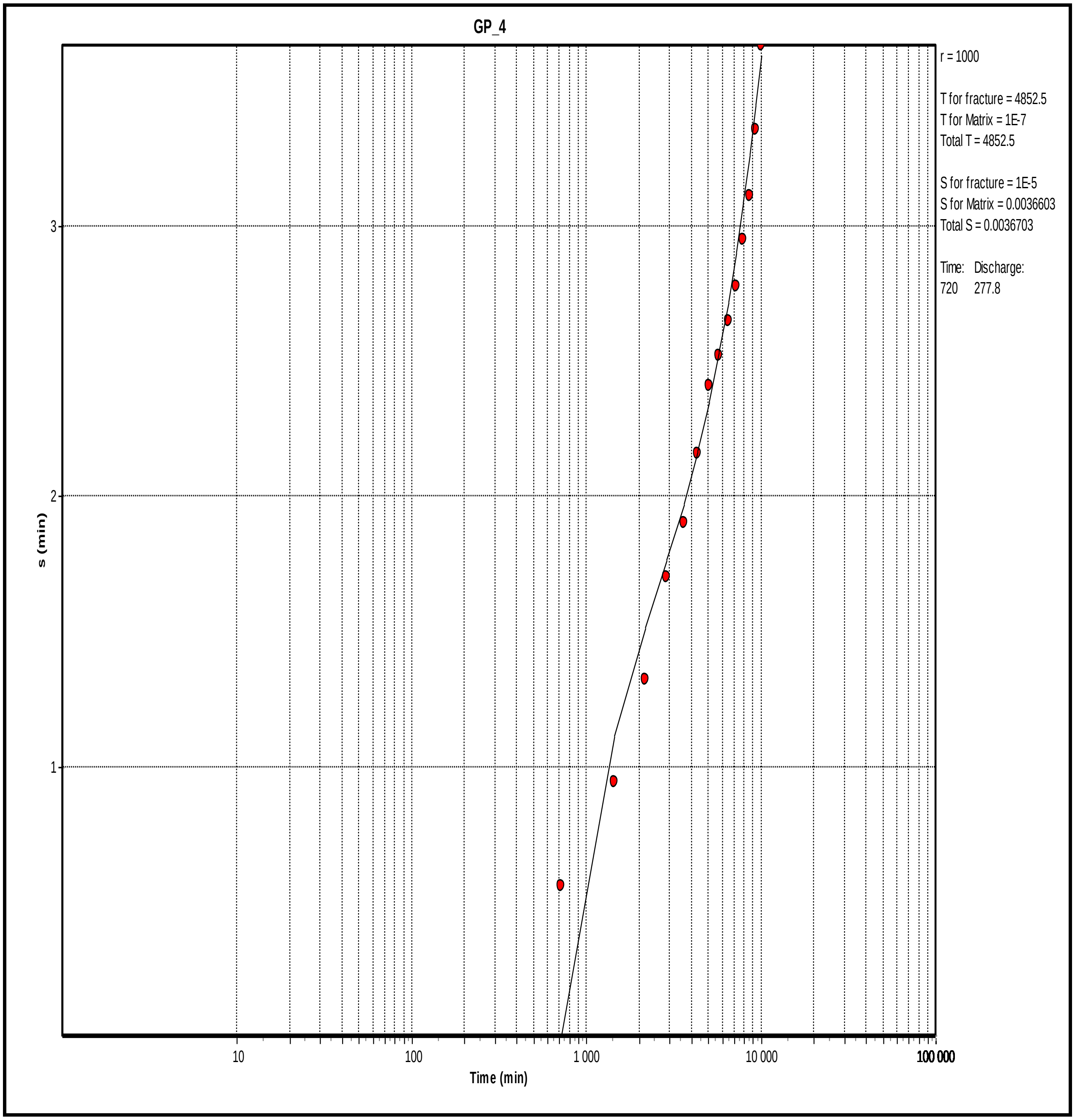

Figure 66: Hydraulic parameter estimation for Group 4 Boreholes

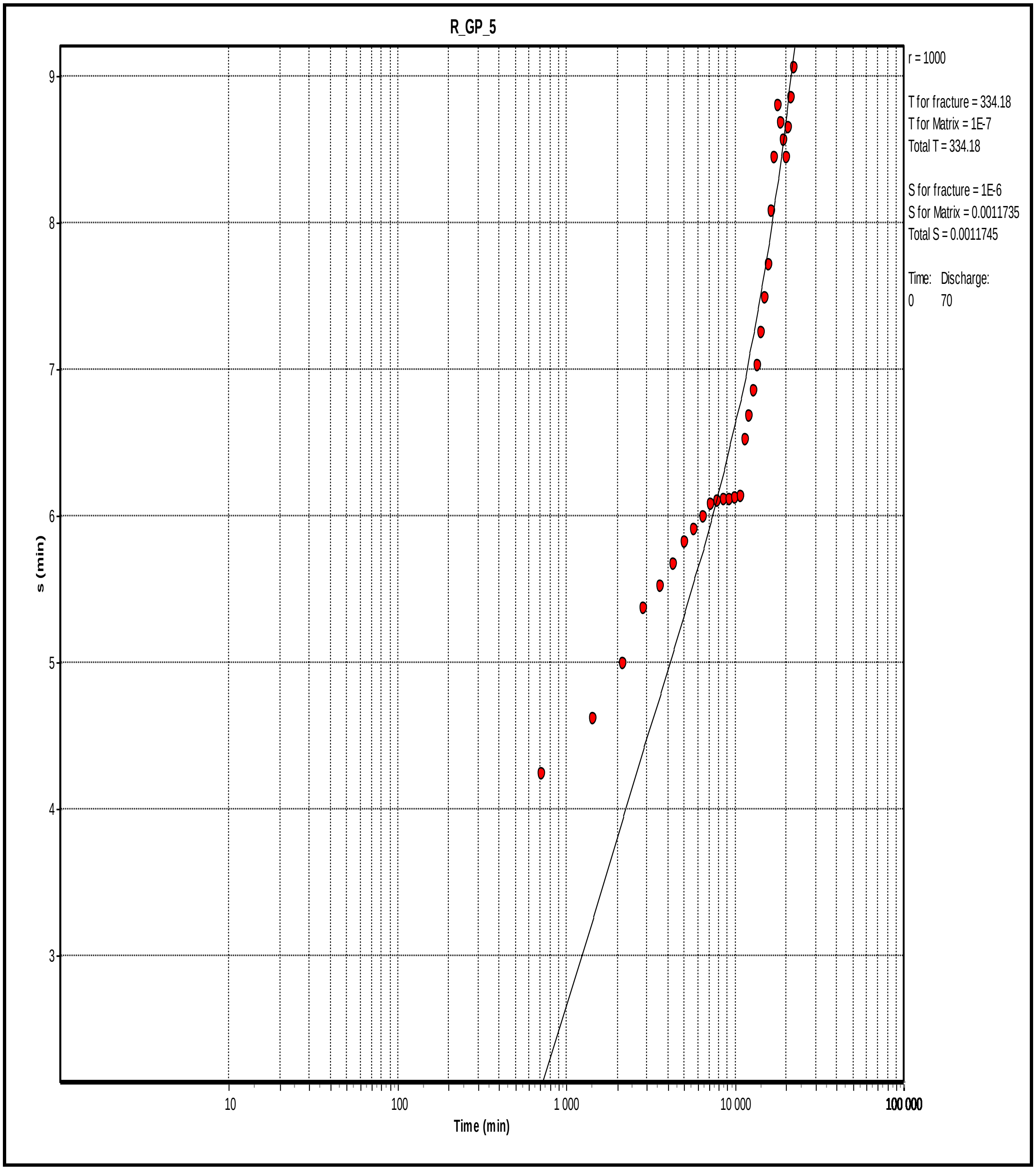

Figure 67: Hydraulic parameter estimation for Group_5 Boreholes

Aquifer Parameter

Table 16: Summary of all aquifer parameters

DEWATERING Bh_Group	T_f (m^2/day)	T_m (m^2/day)	S_c [ ]	COMMENT
1	5266	0.00031	0.0025	North of Shaft_1
2	6195	0.00025	0.00116	Basal Contact
3	4244	0.00036	0.00134	NE of Shaft_1
4	4853	1.00E-07	0.0037	SE of Shaft_1
5	334	0.000117	0.0023	South of Kombat Mine-NMa
STATISTICS				
AVERAGE	4528.4	0.000254	0.0022	At Aquifer Scale
MAX	6195	0.00036	0.0037	At Aquifer Scale
MIN	2084	0.0000001	0.00116	At Aquifer Scale
STDEV	1539.72	0.0001484	0.00102	At Aquifer Scale

Parameter estimates from Kombat Mine flooding and test pumping data

Table 17: RPSOLV hydraulic parameter statistics

PUMP TESTS	T_f (m^2/day)	T_m (m^2/day)	S_c [ ]	COMMENT
WW200449	44	9.80E-08	1.15E-04	North of Shaft_1
WW200450	0.725	7.26E-01	0.003	North of Shaft_1
WW200451	62	1.00E+00	5.30E-04	North of Shaft_1
BH_3	200	0.1	0.00026	Basal Contact Type Fracture
AVERAGE	76.6813	0.4565	0.00098	At a local scale
MAX	200	1	0.003	At a local scale
MIN	0.725	9.8E-08	0.00012	At a local scale
STDEV	86.1403	0.4842544	0.00136	At a local scale

5.3 Recharge processes and estimates

5.3.1 Rainfall recharge relationship

This section builds a conceptual understanding of recharge processes, initially by attempting to gain an understanding of the relation between local recharge and rainfall, secondly by analysing borehole hydrographs, and finally by applying quantitative methods as tools to estimate the range of groundwater recharge rates of the study area, and by linking both recharge rainfall relation and hydrograph behaviour to the storage and response dynamics of the Kombat Aquifer. Synoptic water level contour maps will also be used to infer potential recharge boundaries.

In semi-arid regions like the study area, almost all groundwater recharge originates from rainfall. Therefore the hydrological regime of aquifers in these areas are controlled by the long-term balance established between rainfall and the characteristics of the aquifer (Bredenkamp et al,. 1995).

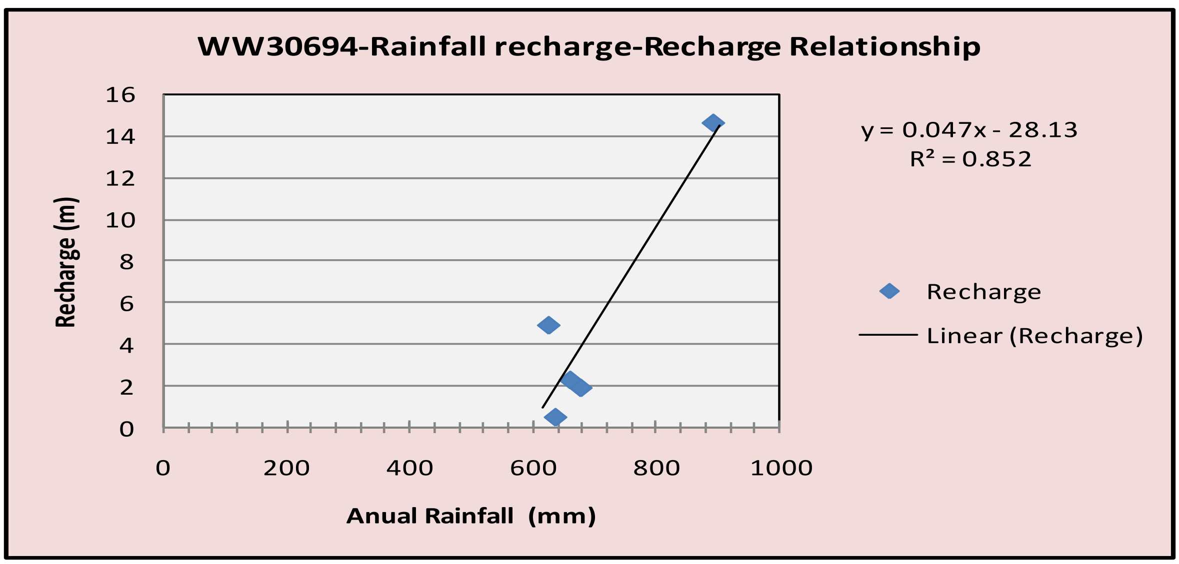

Figure 68: Rainfall-recharge relation of the study area

Figure 68 presents the amount of groundwater level recovery associated with the four highest rainfall events of the last 10 years, as estimated from borehole hydrographs within the study area. From the rainfall-recharge relationship graph in Figure 68, it is clear that a threshold of 592 mm/a is required for visible recharge to the Kombat Aquifer. However, this finding should not be misconstrued as the amount of rainfall needed for the onset of the recharge process in the Kombat area, but should be understood as the amount of rainfall needed to equilibrate the outflow and inflow of groundwater flow components and effect net recharge of the groundwater flow system. The onset of the recharge process should be much lower than 592 mm/a, considering the abundance of outcrops, thin soil cover and the fractured nature of the rocks underlying study area.

Historically, recharge studies have shown that the reliable determination of recharge of a groundwater body, in terms of the timing, spatial distribution and magnitude are fundamental to the sustainable management of groundwater resources (Simmers et al, 1997). However, there is a common understanding among reputable scientists in support of the notion that the reliable estimation of aquifer recharge is the most elusive undertaking of groundwater resource investigation (Simmers et al, 1997).

5.3.2 Recharge Mechanisms

As stated earlier, the recharge mechanism in the study area is characterised by two components; the instantaneous and highly temporal, and the gradual and sluggish (**Figure 69**).

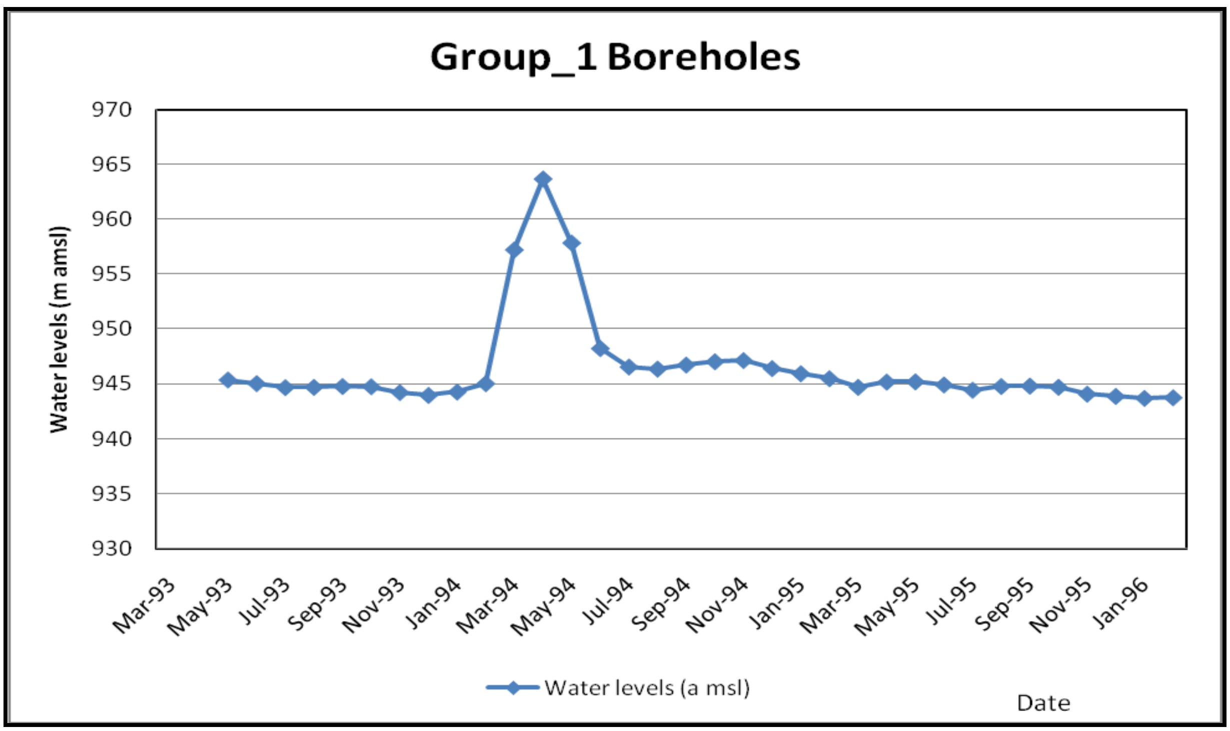

Figure 69: Typical hydraulic response of the study area's water levels to recharge

Figure 69 presents the composite response of groundwater levels of the borehole to the immediate north of Shaft_1. A close examination of the hydrograph presented in Figure 69 reveals a drastic increase in water levels between January and March 1994, reaching a peak of 963.69 m from a background of 943.9 m. This constitutes a 19.79 m rise in water levels; yet by June of the same year, 17.17 m (946.52 m) of the original 19.79 m had receded, demonstrating the temporality of the instantaneous recharge component. In August of the same year, another recharge event caused the water levels to recover slightly, by a metre. This recharge component reaches its peak in five months (November of the same year), but empties slowly until it is mixed with minor recharge of the following year in March.

The instantaneous recharge component is often associated with infiltration via fractured outcrops. It would therefore be prevalent on the northern dip slope (Fluviokarst) and the Southern Otaviberg of the study area. Although the depth to the water table may be another control factor, the second and gradual recharge component is associated with the weathered and soil-covered parts of the aquifer.

The relative significance of the two recharge mechanisms is not well-investigated, but it is assumed that boreholes that are drilled in preferential groundwater pathways benefit from the rapid recharge component, while those drilled in tight blocks would benefit from the distributed gradual recharge component.

From a long-term water supply point of view, the gradual recharge component will be the main source of water during dry and drought periods; it therefore becomes more important than its rapid counter part.

As discussed in the earlier chapters of this study, the link of the discussed components of recharge to geomorphology and discharge mechanisms is well-established and documented (Moon and Dardis, 1988; USGS, 2001; Petric, 2002).

In summary, two replenishment mechanisms are delineated and linked to the geology and geomorphology of the study area, thereby facilitating the processes and parameter distribution within the flow domain.

With this understanding, the results of the recharge rates derived from the EARTH model, as applied to the four identified borehole groupings, are presented in the subsequent subsection.

5.3.3 Recharge Estimates Based on the EARTH Model

Detailed descriptions and discussions of the inner workings of the EARTH model are not part of the scope of this study; moreover, its applicability is important. Three aspects of the EARTH model underpin its suitability as a model for simulating recharge in the study area; firstly, its ability to incorporate abstraction, secondly, its aptitude to redistribute concentrated recharge so as to spread it over time, and thirdly, the EARTH model is designed to simulate recharge in semi-arid areas like the study area.

Fundamental to estimating groundwater recharge using the EARTH model is prior knowledge and reliable transmissivity and storativity values. For this reason, an estimation of the recharge rate of the study area follows after the estimation of transmissivities and storativities.

RESULTS FROM EARTH MODEL

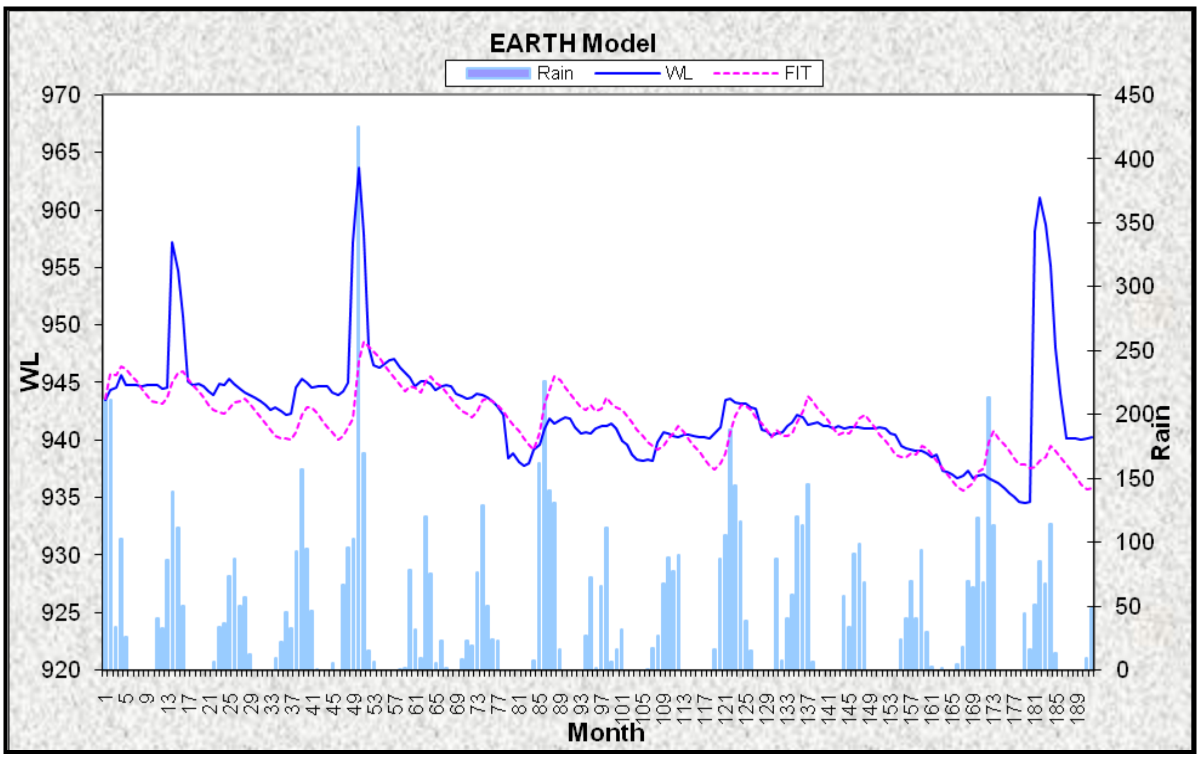

Figure 70: EARTH Model recharge estimate for Group 1 Boreholes

An estimated recharge value of 4.7 % of mean annual rainfall was arrived at for the Group 1 Boreholes (**Figure 70**), situated north of Shaft_1.

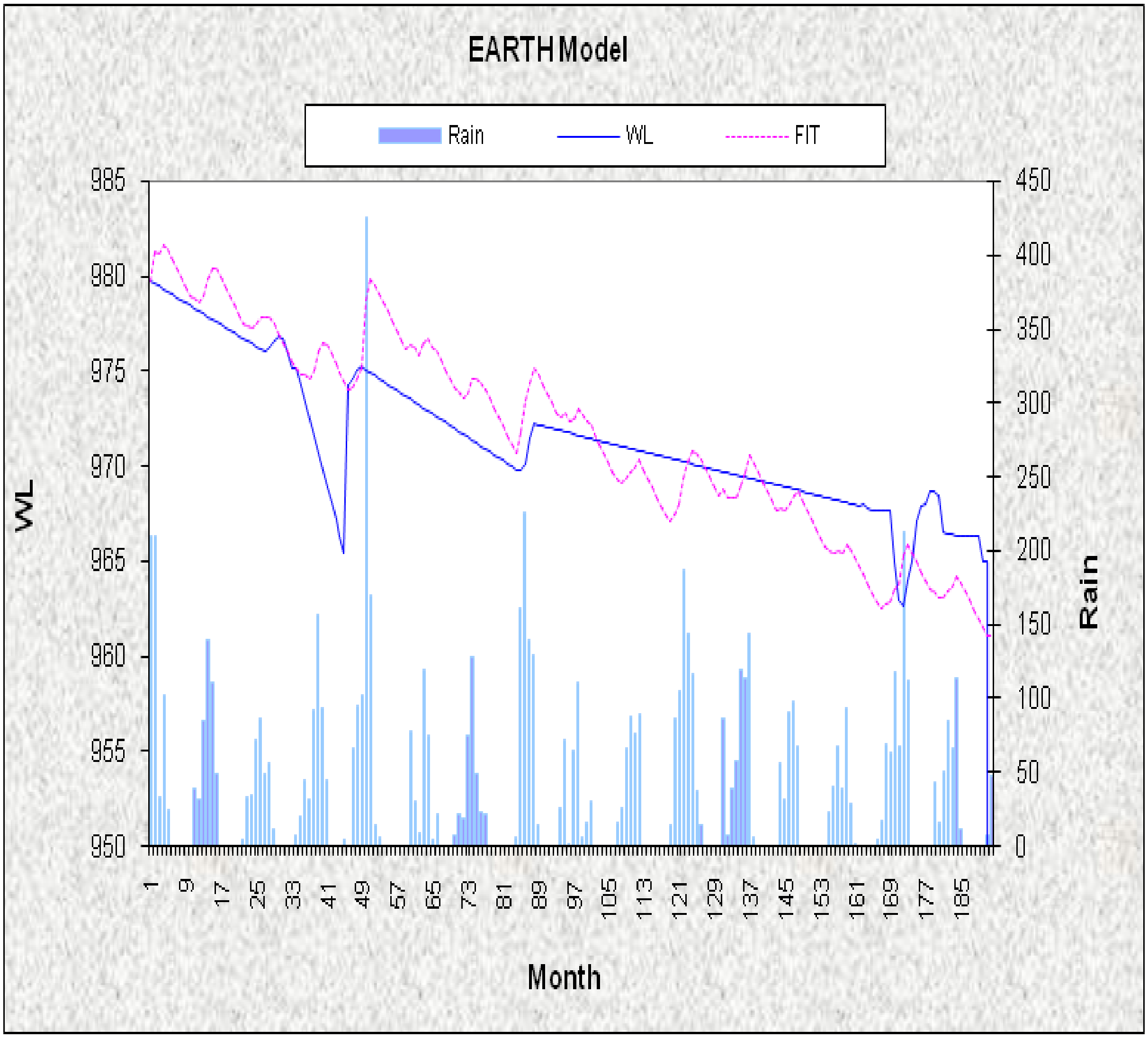

Figure 71: EARTH Model recharge estimate for Group 2 Boreholes

An estimated recharge value of 3 % of mean annual rainfall was established for the Group 2 Boreholes (**Figure 71**), situated south of Shaft_1.

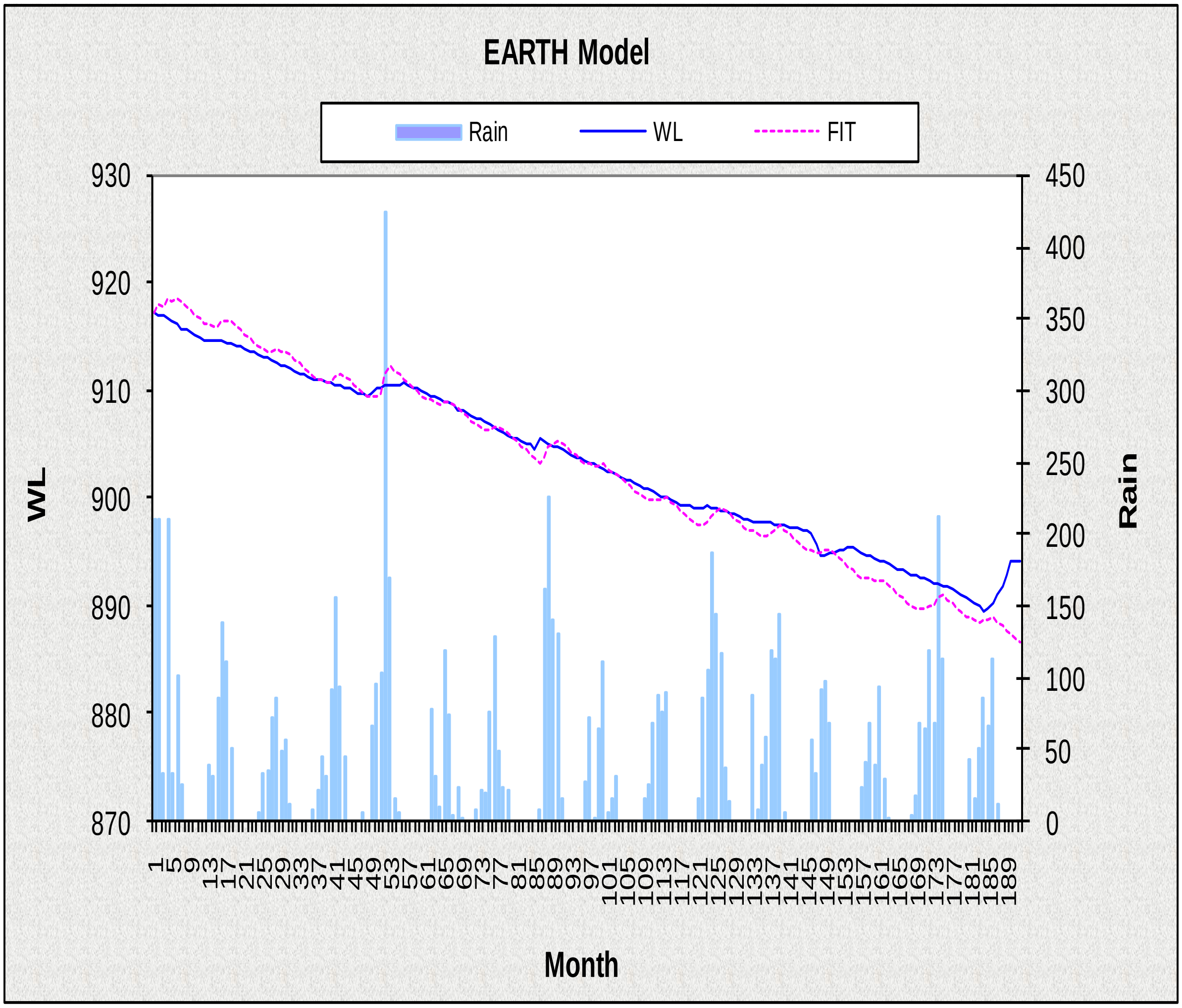

Figure 72: EARTH Model recharge estimate for Group 3 Boreholes

An estimated recharge value of 3.1 % of mean annual rainfall was found for Group 3 Boreholes (**Figure 72**), situated northeast of Shaft_1

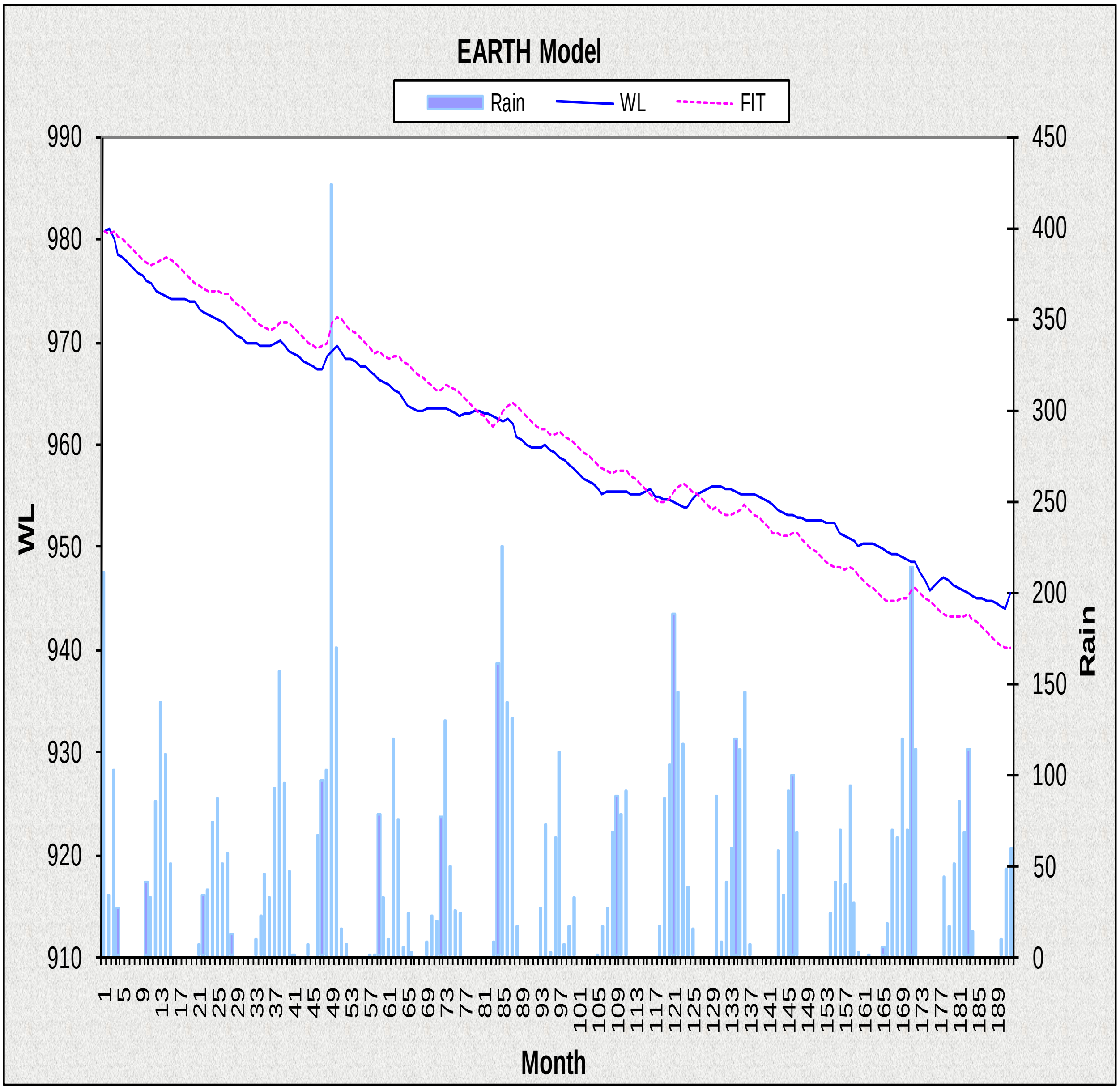

Figure 73: EARTH Model recharge estimate for Group 4 Boreholes

An estimated recharge value of 3.6 % of mean annual rainfall was found for Group 4 Boreholes (**Figure 73**), situated southeast of Shaft_1.

Table 18 is a composite estimate of the recharge rate in the study area, based on the harmonic mean of the chloride content of water from boreholes.

Table 18: Recharge estimate from water chemistry

Borehole Number	**Chloride Data (mg/l)**
WW25930	17
WW25355	6
WW25932	12
WW26996	35
K62753	14
K62757	4
K60036	4
K60037	13
WW26991	2
WW25919	1
WW25934	14
WW26993	16
WW27002	8
WW27039	5
WW27003	10
K60036	9
K60037	3.0
K60039	8.0
K60041	6
HARMEAN	**5.02541**

A recharge rate of 5 % of mean annual rainfall is slightly higher than the average recharge estimates from the EARTH model. However, it relates closely to the 4.7 % EARTH model recharge estimate of boreholes located north and northeast of Kombat Mine.

Table 19: A summary of all recharge estimates

Recharge Zones			m/day	m/a
Borehole groups	% MAP(500mm/a)	mm/a		
1	4.7	24	6.6 E-05	0.024
2	3	15	4.1 E-05	0.015
3	3.1	15.5	4.2E-05	0.0155
4	3.6	18	4.9 E-05	0.018

A 200 m by 106 cells north to south and 99 cells by 200 m west to east model grid has been constructed over the whole study area; on the basis of this model grid, and taking the (Table 19) recharge estimates into consideration, the study area receives an apparent average recharge of **7.6 Mm^3/a**, of which about **3.4 Mm^3/**a falls within the cone of depression of the Kombat dewatering scheme.

CHAPTER 6 THE CONCEPTUAL FLOW MODEL

6.1 General

The dolomites of the study area are heterogeneous rocks. A good understanding of the physical framework of these dolomites with respect to groundwater storage and transport is fundamental to the conceptual hydrogeology of the study area. On the basis of depositional heterogeneities, two types of dolomite/limestone occur; the upper and predominantly massive facie, and the lower, thin bedded to laminar facie. Compared to the laminar and thin bedded lower facie, the massive facie tends to be more competent and develops better fracture networks; thus it inherently hosts high permeability.

This chapter conceptualizes the flow system of the Kombat Aquifer by building on the above mentioned heterogeneity. In an effort to clarify observed hydraulic behaviour, established interpretive conceptual frameworks like dual permeability, fractional flow models and fractional flow dimensions, will be evoked.

6.2 Flow dynamics

The movement of groundwater, whether natural or artificially induced, can best be inferred from trends of water level contours across the groundwater flow system. For this reason, Figure 74 will be used to make inferences about macro-scale groundwater flow dynamics of the Kombat Aquifer.

The Bayesian interpolation logarithm was used to generate the groundwater levels presented in Figure 74, while the contours and flow vectors are created in Surfer. Due to a steep slope north of Kombat Mine, a 50 m contour interval is used to enhance visual spacing between adjacent contour lines. Although the flow vectors in the hilly northern dip slope tend to verge towards local troughs, some flow patterns can be discerned with relative clarity, especially in the southern lower half of the study area.

The three prominent faults, as seen in Figure 74, are from east to west; the Asis-Ost Fault, the Kombat East Fault and the Kombat West Fault. From the groundwater level contours (**Figure 74**), it can be seen that the groundwater flow direction tends to align itself parallel to faults, especially above the 1660 m contour line and to the east of Shaft_1, where flow is essentially southwest, whereas to the west of Shaft_1, the flow line trends north-south.

In fact, an artificial north-south line through Kombat Mine shows the entire flow system within the study area on the basis of flow direction being divided into two components; one to the east of the artificial line, which is essentially southwest up to the -2182500 m southing, from where the flow component changes its direction from southwest to southeast and continues in that direction beyond the southern discharge contour line. The other, to the west of the artificial line, is north-south, from the northern boundary up to the southern discharge contour.

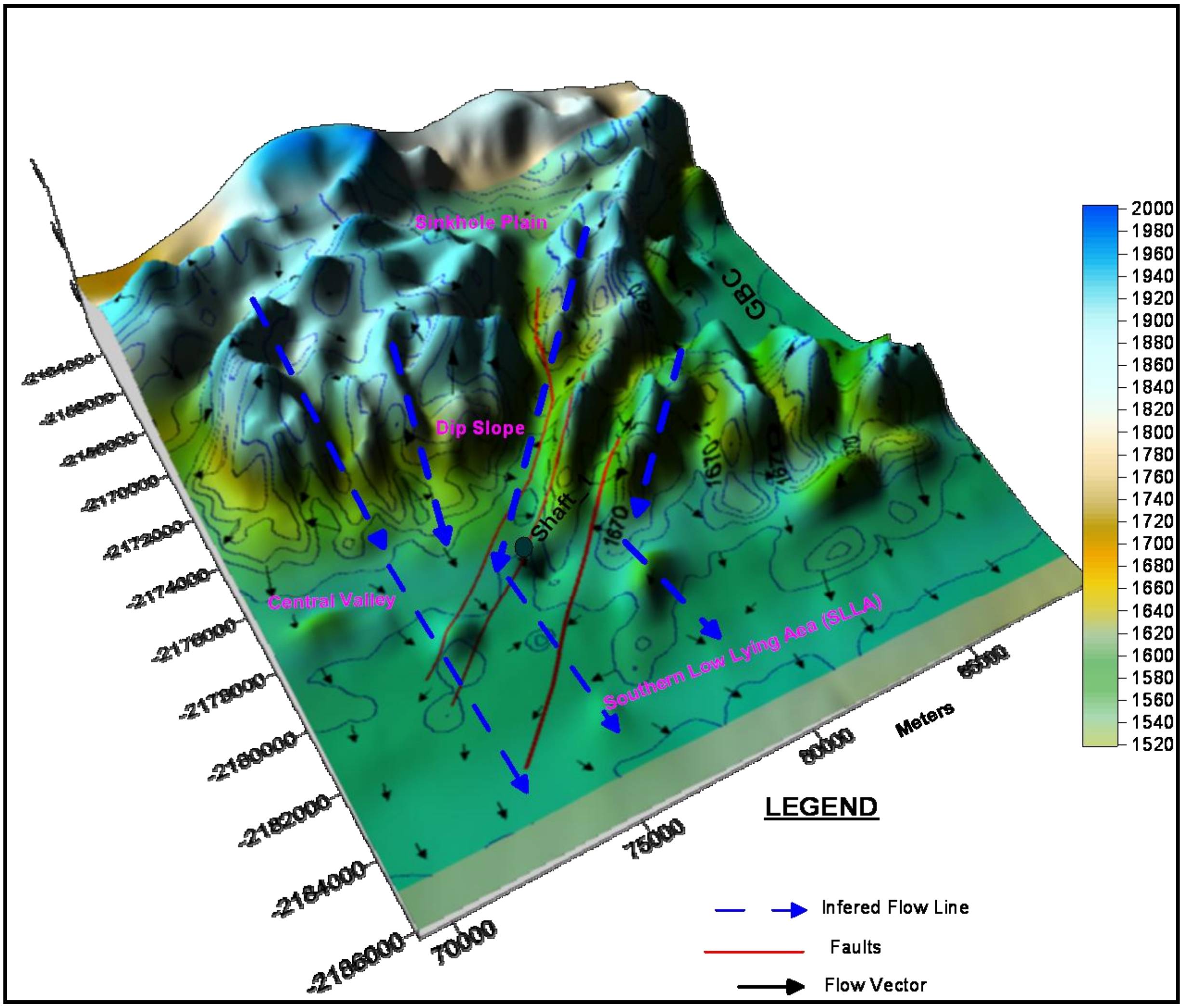

Figure 74: Flow patterns in the Kombat Aquifer

At a macro-scale, the groundwater flow direction of the study area is essentially north-south, but appears to have been locally controlled to a southwest direction in the highly faulted zones of the Kombat West and Asis Ost Fault Zones. The southeast preferential discharge flow component has been alluded to by hydrochemistry, but cannot be explained at this stage.

Figure 75 attempts to explain the micro-scale hydrodynamics of the Kombat Aquifer.

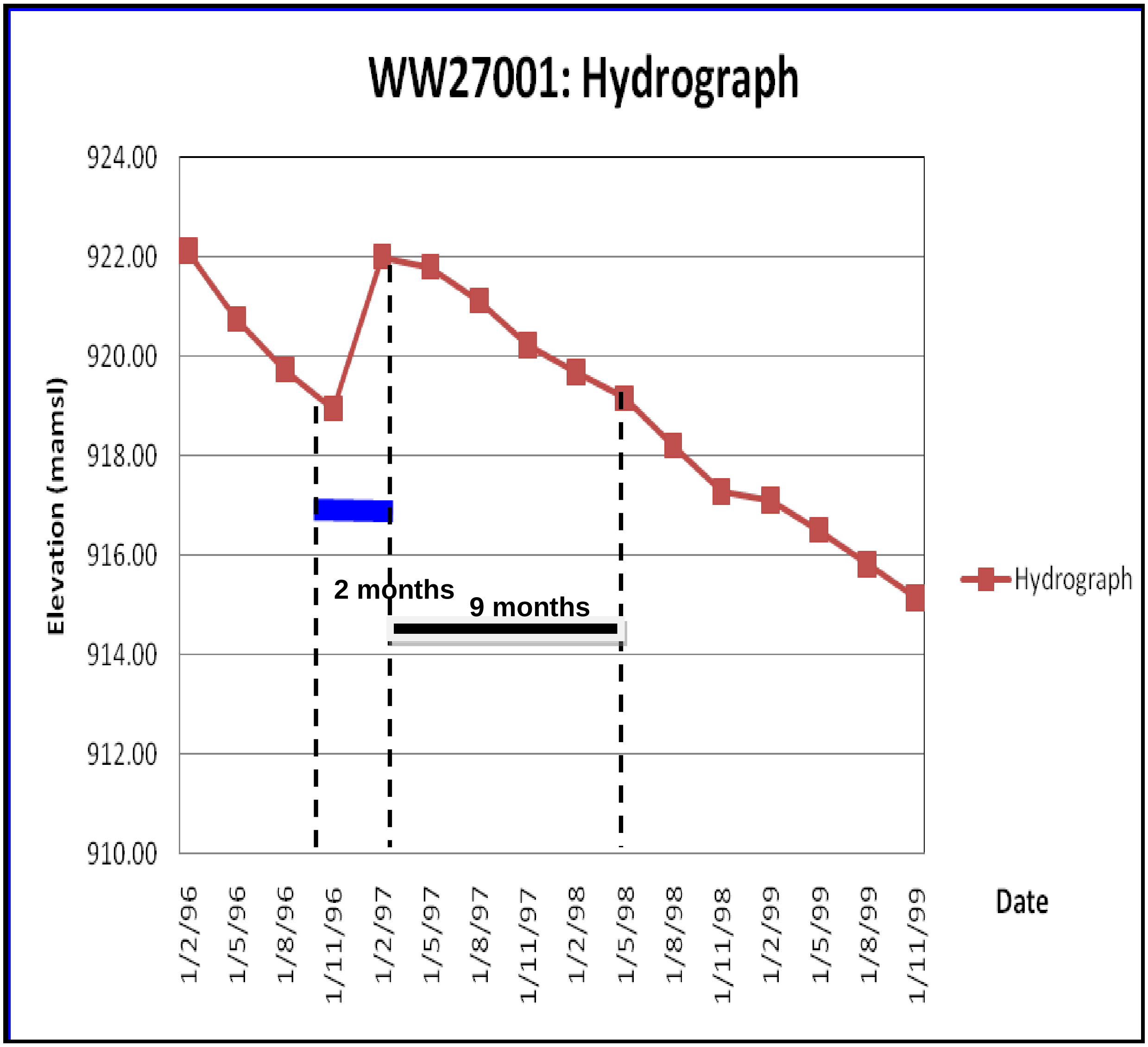

Figure 75: A typical hydrograph of the study area

At a micro-scale, the groundwater flow dynamics of the study area can probably be inferred from the typical hydrograph behaviour, as illustrated in Figure 75, and is explained within the dual permeability groundwater flow framework. As a consequence of hydraulic pressure re-equalisation between the fractured and fissured matrix flow components, the high permeability and channelled fast flow regime become low hydraulic pressure zones during the low water stage, into which groundwater from the fissured, slow flow regime flows. During the high groundwater stage, brought on by stormy recharge events, for example, the fast flow zones become potentially high hydraulic pressure zones, from which groundwater moves into the surrounding slow flow regime.

This subsection highlights three fundamental aspects of the groundwater flow dynamics of the study area; the aerial view of the flow system; the association of flow components with faults, and the positioning of that flow component within the high permeability context of the dual permeability conceptual framework; and the internally hidden flow mechanisms which are responsible for the observed hydraulic response of the system. The three aspects combine to enhance current knowledge, especially the ability to predict the character of future occurrences.

Citing similar depositional environments and post-depositional stress fields, hydraulic test results from a study conducted in the same stratigraphic lothologies to the north of the study area are presented (**Table 20**) and used to supplement the available data (**Bayesian approach**) in the qualitative and quantitative association of lithologies to permeability trends of the Kombat Aquifer.

In an effort to attain a fair distribution of hydraulic parameters across the flow domain, a distinction is made between the permeability of major faults and that of joints and fractured zones. It is further recognised that the data from the Kombat Mine flooding event predominantly engaged the permeability of faults rather than local joints and fractures. With this understanding, the various hydrogeological units, their geometry and hydraulic parameters, are assigned to the Kombat Aquifer (**Figure 76**).

Higher transmissivity values are correlated with massive lithologic units of the Huttenberg and Abenab Formations, while high storativity values are found in thin bedded and laminated lithologies (**Figure 76**), i.e. the Maieberg and Auros Formations. The lowest transmissivity values are those of the Kombat Formation (phyllite) and the GBC (meta sediments, volcanic and granite gneiss).

Table 20: Results of the hydraulic test evaluations during the TGWS, Phase 1 and Phase 2

Formation	T [m^2/d]	S [-]	Characterisation
Basement Complex	n = 1 $T < 5 \cdot 10^{-3}$ m^2/d	n = 0	Aquiclude
Nosib	n = 3 T ~ 3 m^2/d along fault zones T = 0.2 m^2/d non-faulted zones	n = 3 $1.0 \cdot 10^{-3} < S < 1.3 \cdot 10^{-3}$	Aquitard
Abenab	n = 5 14 m^2/d < T < 466 m^2/d T = 0.08 m^2/d at depth > ~200m	n = 1 $S = 6 \cdot 10^{-4}$	Aquifer
Chuos	n = 1 T = 2.4 m^2/d	n = 1 $S = 6 \cdot 10^{-6}$	Aquitard
Maieberg	n = 4 87 m^2/d < T < 123 m^2/d T = 0.4 m^2/d within Disturbed Zone	n = 2 $3.0 \cdot 10^{-5} < S < 8.0 \cdot 10^{-4}$	Aquitard (South) or Aquifer (North)
Elandshoek.	n = 8 15 m^2/d < T < 1260 m^2/d average T = 309 m^2/d	n = 1 $S = 7 \cdot 10^{-4}$	Aquifer
Hüttenberg	n = 8 121 m^2/d < T < 5565 m^2/d average T = 1725 m^2/d T = 4 m^2/d at depth > ~300m	n = 5 $4.0 \cdot 10^{-4} < S < 1.6 \cdot 10^{-2}$ $S = 2.0 \cdot 10^{-4}$ at depth > ~300m	Aquifer
Kombat	n = 1 T = 3.2 m^2/d	n = 1 $S = 3 \cdot 10^{-4}$	Aquitard
Unit 5 (Karoo)	n = 4 1.1 m^2/d < T < 11 m^2/d	n = 4 $7.0 \cdot 10^{-5} < S < 3.0 \cdot 10^{-3}$	Aquitard
Unit 6 (Kalahari)	n = 3 434 m^2/d < T < 10367 m^2/d	n = 0	Aquifer

(Source: GWK & Bicon 2001)

It is therefore logical that dominant groundwater flow would be restricted to more open fractures in the massive lithology of the Huttenberg, Elandshoek and Abenab Formations.

As is expected, lithology imposes boundaries on the continuity of hydraulic properties, as well as on the flow geometry of the Kombat Aquifer, thereby creating large-scale compartments. The same applies to regional faults such as the KFT and Asis Ost fault.

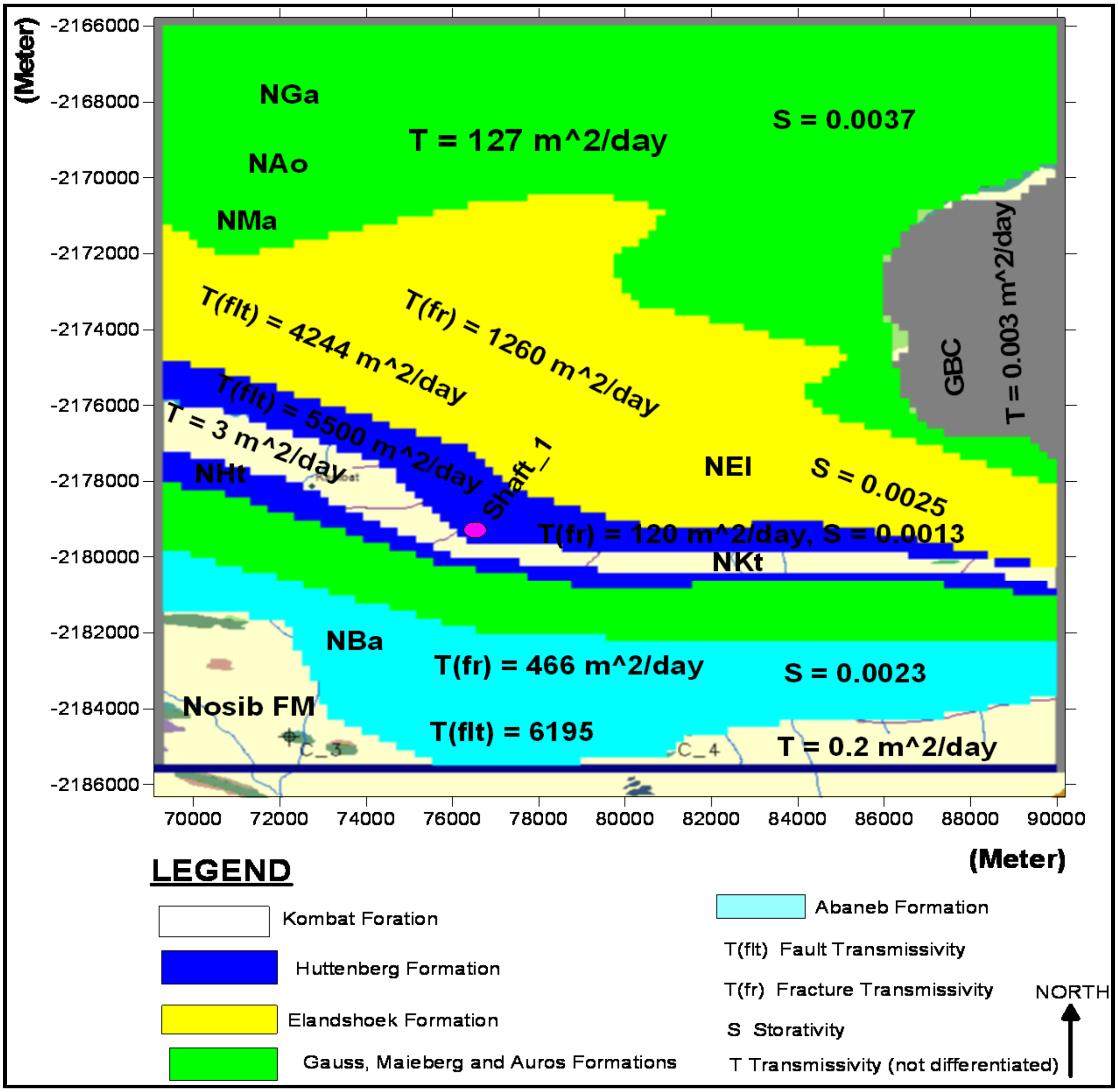

Figure 76: Distribution of hydraulic parameters, based of lithology

Based on the collected and generated data from this study, Figure 76 illustrates the distribution of hydraulic parameters over the Kombat Aquifer flow domain.

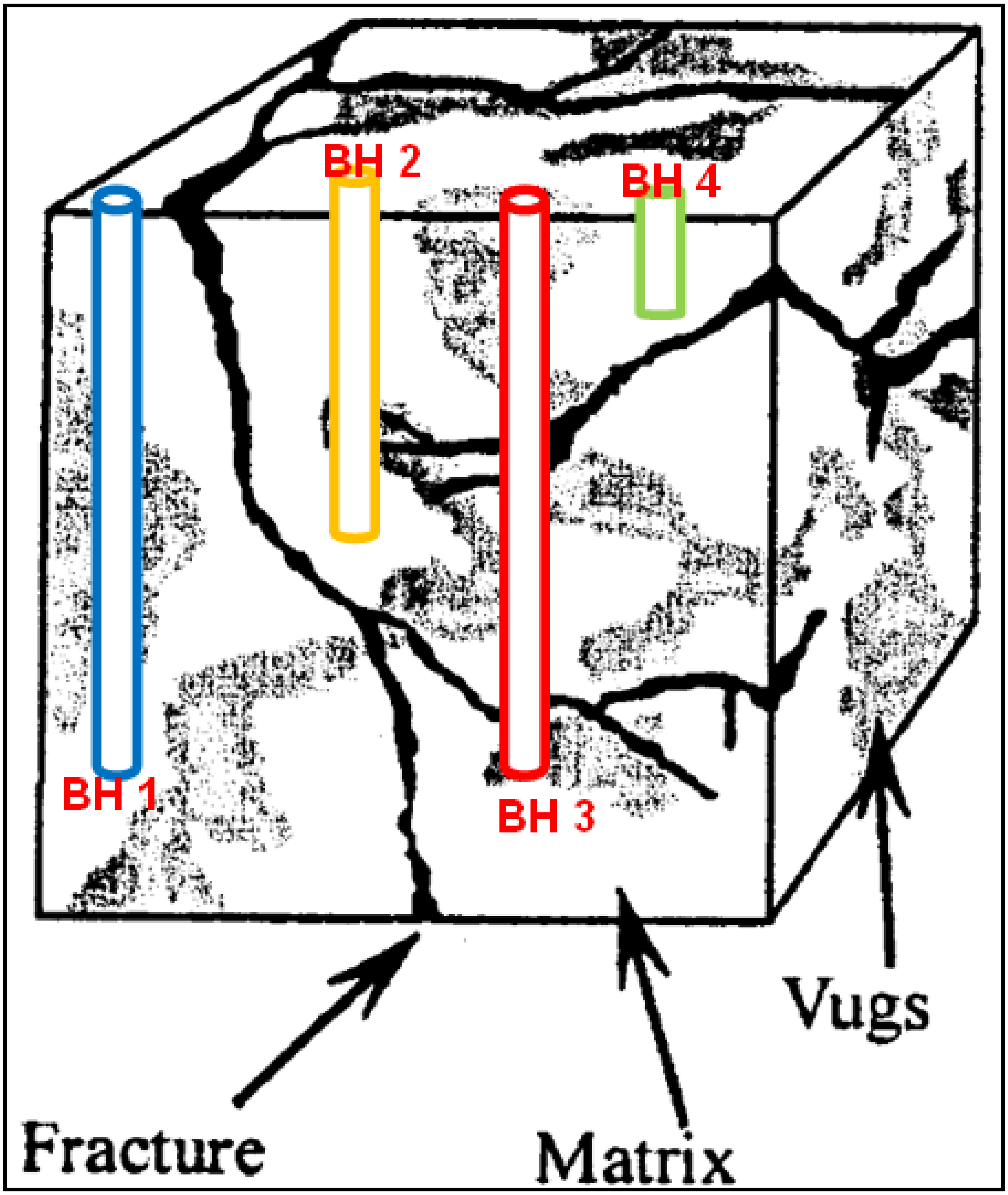

Figure 77: The hypothetical permeability distribution (modified after Warren and Root, 1963)

Results from hydraulic tests indicate that the Kombat Aquifer flow system consists of two permeability networks, the low permeability high storage permeability network associated with vugs and fissures, and the high permeability low storativity permeability-network associated with faults and fracture zones.

The extent and connectivity of the two permeability networks define the hydraulic response character of the entire flow domain.

In order to appreciate the flow constraints imposed by the co-existence of the above-mentioned permeability networks of the Kombat Aquifer, it would probably be appropriate to draw from the generalised radial fractured aquifer flow model (GRFAFM). The GRFAFM proposes that, in fractured aquifers, flow properties are controlled by the fracture distribution, which results from the distribution and connectivity of the conductive fractures (**Figure 77**). This theory is a generalisation of the Theis model, taking into consideration the radial flow and the flow dimension (n) into a homogeneous, confined and isotropic fractured medium, which is characterized by a hydraulic conductivity Kf and specific storage Ss_f. This generalized flow model introduces the fractional dimension of flow, n, which characterises the variation law of the cross sectional area of flow according to distance from the pumping well. Values of n vary from 0 to 3; the flow is spherical when n = 3 (Figure 6), cylindrical when n = 2 (corresponding to the Theis model) and linear when n = 1 (Barker, 1988)

The log-log slope of the drawdown curve from the Kombat Mine flooding event exhibits gradients in the range of 0.5 and 0.25, indicating a linear to bilinear hydraulic response to groundwater withdrawal.

Extending the GRFAFM to the hydraulic response of the Kombat Aquifer, the power by which the cross-sectional area available for flow will expand would be 2 or 1, depending on the spatial arrangement or a combination of the permeability network of the aquifer. The point emphasised here is that the distribution of the fractures, fissure or vugs characterises the hydraulic response of a fractured aquifer system to groundwater withdrawal.

Figure 77 attempts to convey the current understanding of the physical framework within which the groundwater of the study area resides and moves.

By associating drawdown curves to the permeability networks or fracture combination, this subsection highlights the flow and hydraulic response constraints imposed by the aquifer's physical framework on the flow system.

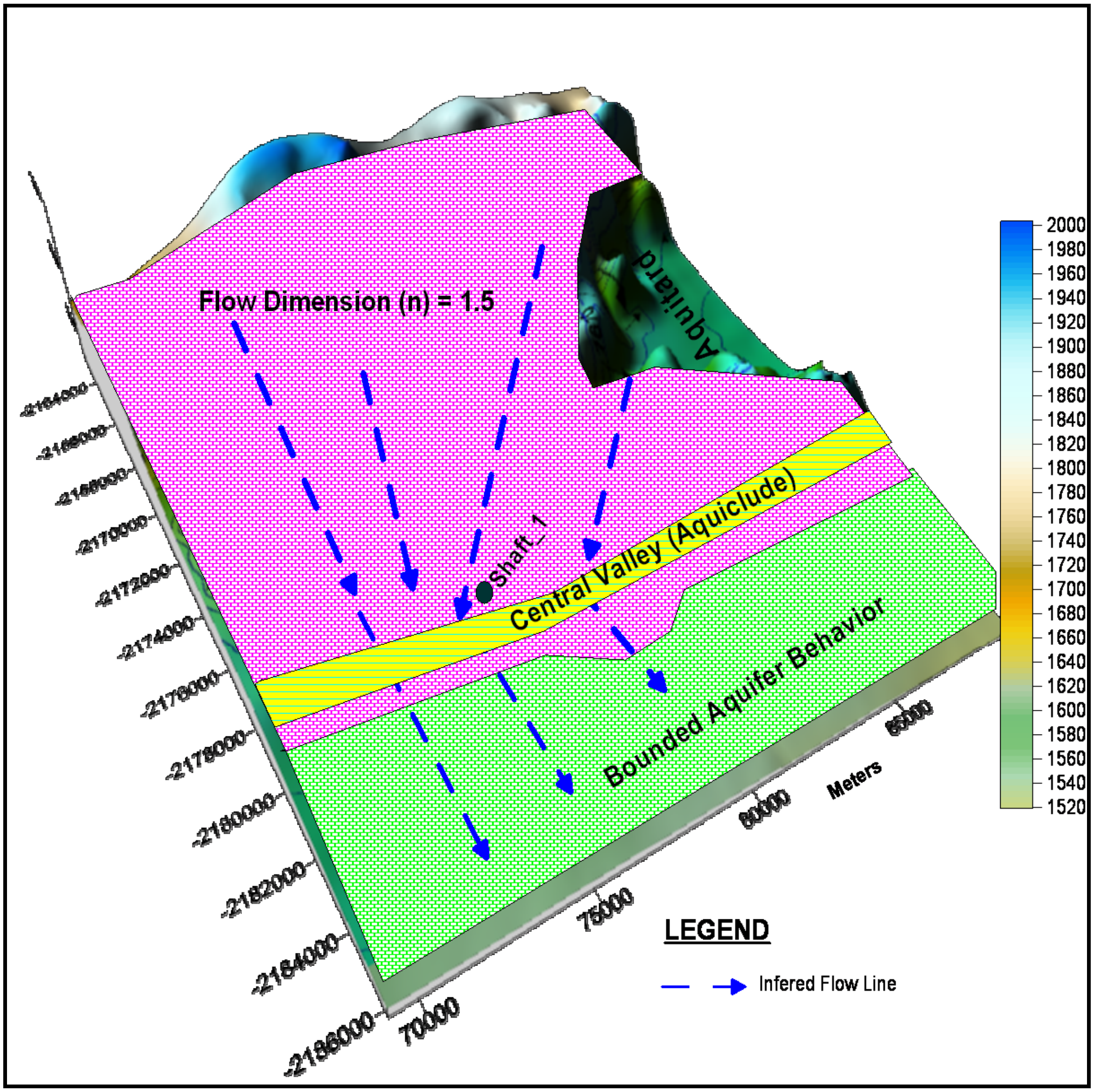

Figure 78: The inferred distribution of flow dimension distribution in the Kombat Aquifer.

Based on the flow system results from hydraulic tests, although the data is not sufficient to validate the inference; there appears to be some bias towards the flow dimension distribution in Figure 78.

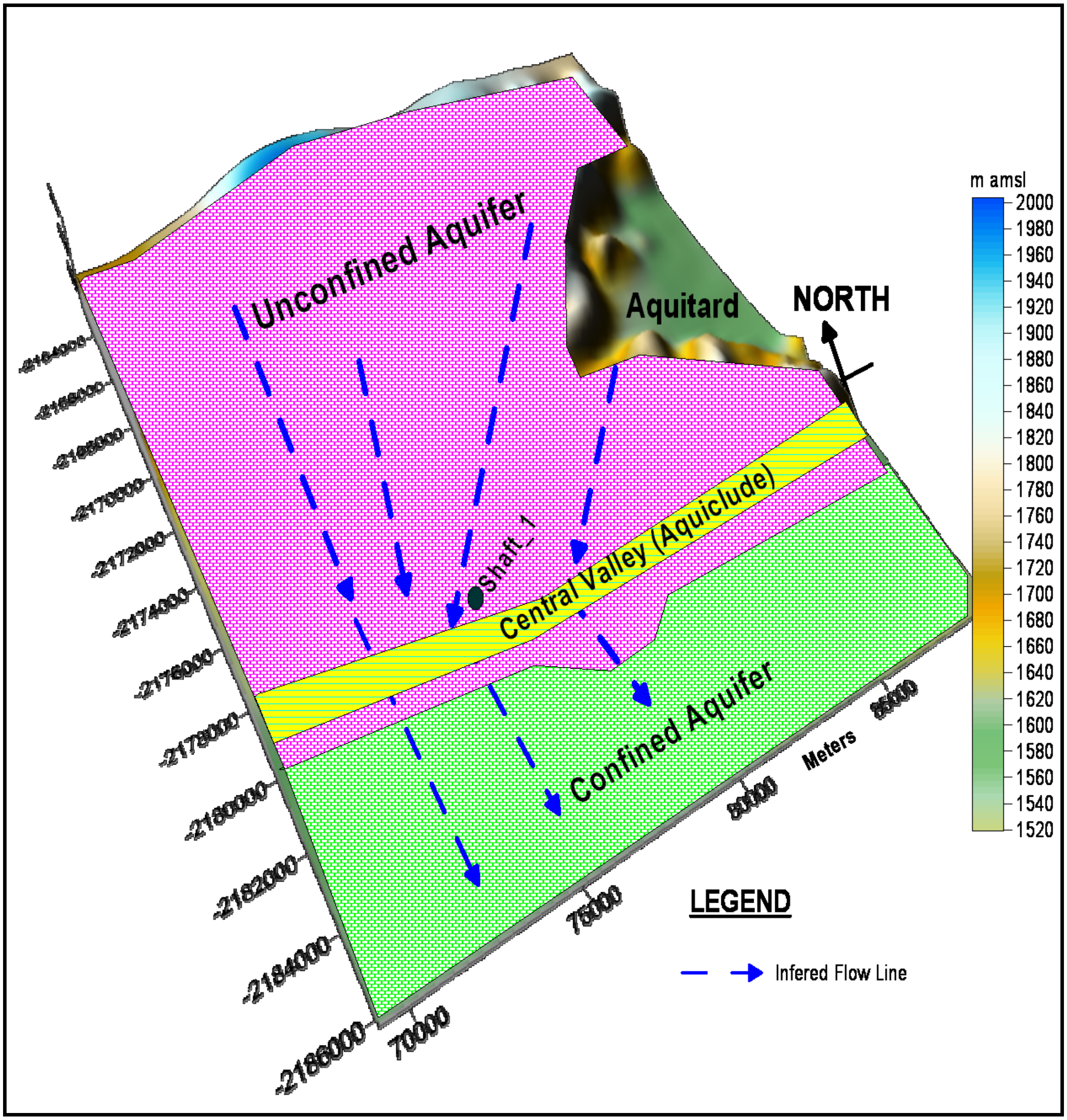

Figure 79: Types of aquifers

The Kombat Aquifer flow system consists of two types of aquifers; one confined and the other unconfined. The confined aquifer extends from the foot of the Southern Otaviberg to the southern discharge boundary, while the unconfined one starts south of the CV, and extends northwards to the northern border of the study area. This position is supported by evidence from hydraulic tests as well as from the correlation between topograpgy and static water levels.

6.3 The Recharge Model

After observing similar hydrograph patterns to those of the study area, Mohrlock and Sauter (1999) linked the hydrograph behaviour to water storage processes, and assumed two typical recharge models;

(a) The Epikarst Recharge and Storage Model, in which infiltration is via the epikarst and groundwater is temporarily stored in the epikarst and then slowly released into the aquifer via fissures into the fractured zones, and

(b) The Aquifer Recharge and Storage Model, in which the bulk of the water is conveyed via vertical shafts to the phreatic zone, where, due to the difference in hydraulic gradient, water flows from the open fractures into the fissured system. The latter then slowly releases the water back into the fractured system.

In support of the hydraulic response, isotopic and hydrochemical data show that groundwater abstracted from the study area and that emerging from springs and fountains have low electrical conductivity (EC), and is not affected by evaporation (Ploethner, 1990).

The nature of the hydrograph response described, the low EC and absence of evaporation effects in the groundwater chemistry jointly support the existence of a mechanism that enables rapid infiltration. It can therefore be stated that a recharge model postulating rapid multifaceted recharge is appropriate for the Kombat Aquifer. Such a recharge model should be able to account for both preferential and diffuse infiltration recharge mechanisms.

From the given arguments, and in the absence of any specific information that may lead to the exclusion of fissured matrix storage, this study adopts a hybrid recharge model (**Figure 80**), in which temporarily stored diffuse and preferentially routed infiltration components co-exist.

The description of the Kombat Aquifer Recharge Model combines the dualistic views presented by Mohrlock and Sauter (1991) and Petric (2006), but falls short of using the term conduit in its description of the high permeability component of the flow regime. This is in line with the absence of unequivocal evidence that confirms the conduit flow status in the study area.

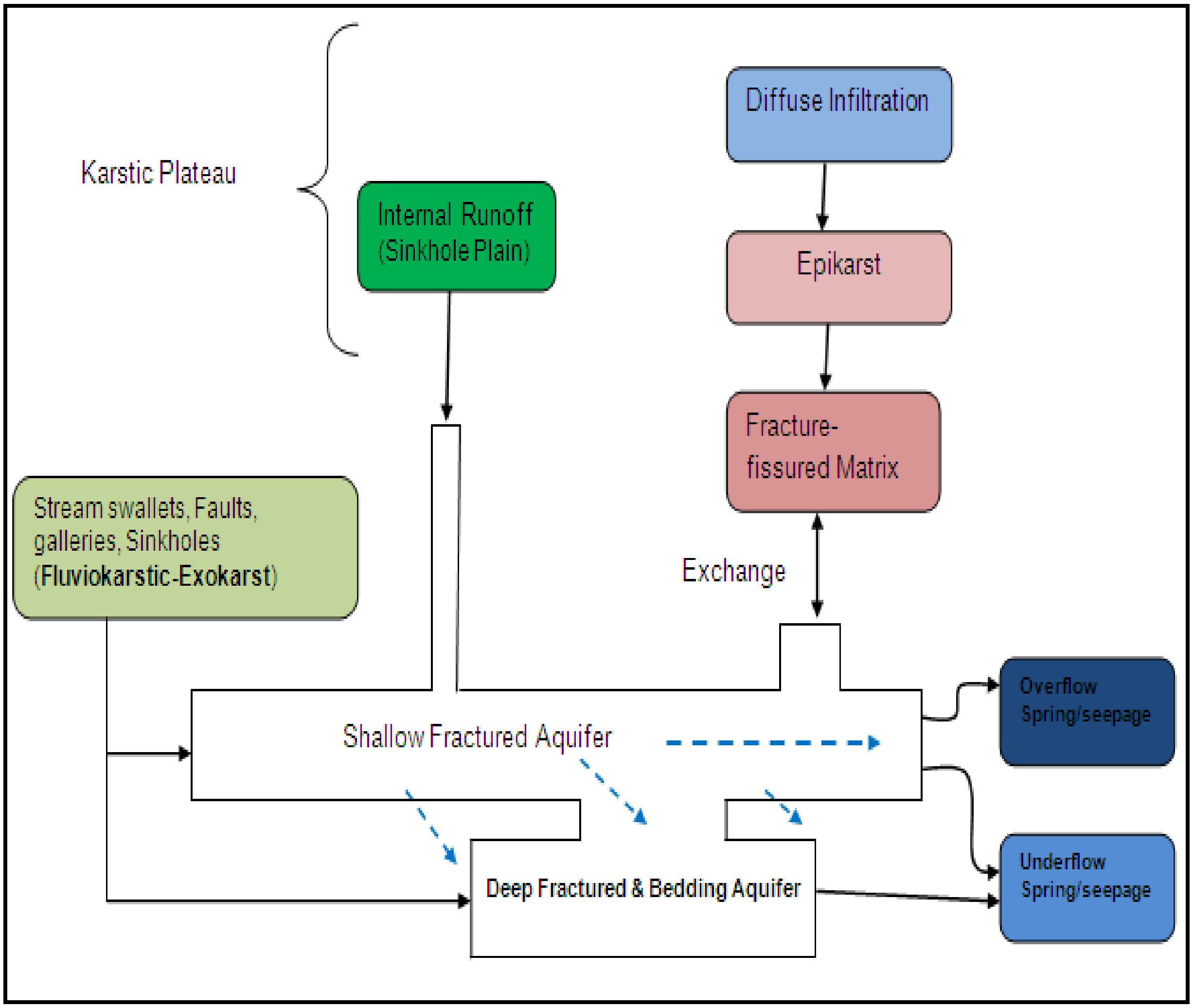

Figure 80: A schematic recharge model of the Kombat Aquifer (modified after White, 2003)

The Kombat Aquifer Recharge Model (KARM) identifies the open mode west-east local flexure fracture set located on the northern anticline as the geological structure facilitating the existence of a mechanism that enables rapid entrance of the infiltrated rainwater into the underlying fracture drainage networks, and is therefore responsible for the majority of the stormy recharge component observed in borehole hydrographs of the study area.

The KARM further recognizes the epikarst and the fissured matrix as the geological forms responsible for temporal storage, redistribution, and the slow release of groundwater to boreholes or/and into fractured zones. The latter would then sustain the base flow of the aquifer over long. Considering the geomorphology and the tectonic settings of the Kombat Aquifer, the major component of the epikarst would be located on the Karstic Plateau, while the fissured matrix makes the majority of the vadose and the saturated volume.

After studying groundwater movements in similar geological setting, Shapiro (2000) discovered that surface water entered the groundwater system through an interconnected network of near-vertical fractures and through sub-horizontal bedding parallel shears. Once in the aquifer, the sub-horizontal groundwater flow component moves laterally through conductive bedding planes. This model can be extended to this study in view of the geological settings of the study area. Figure 81 shows the distribution of recharge, based on EARTH model estimates.

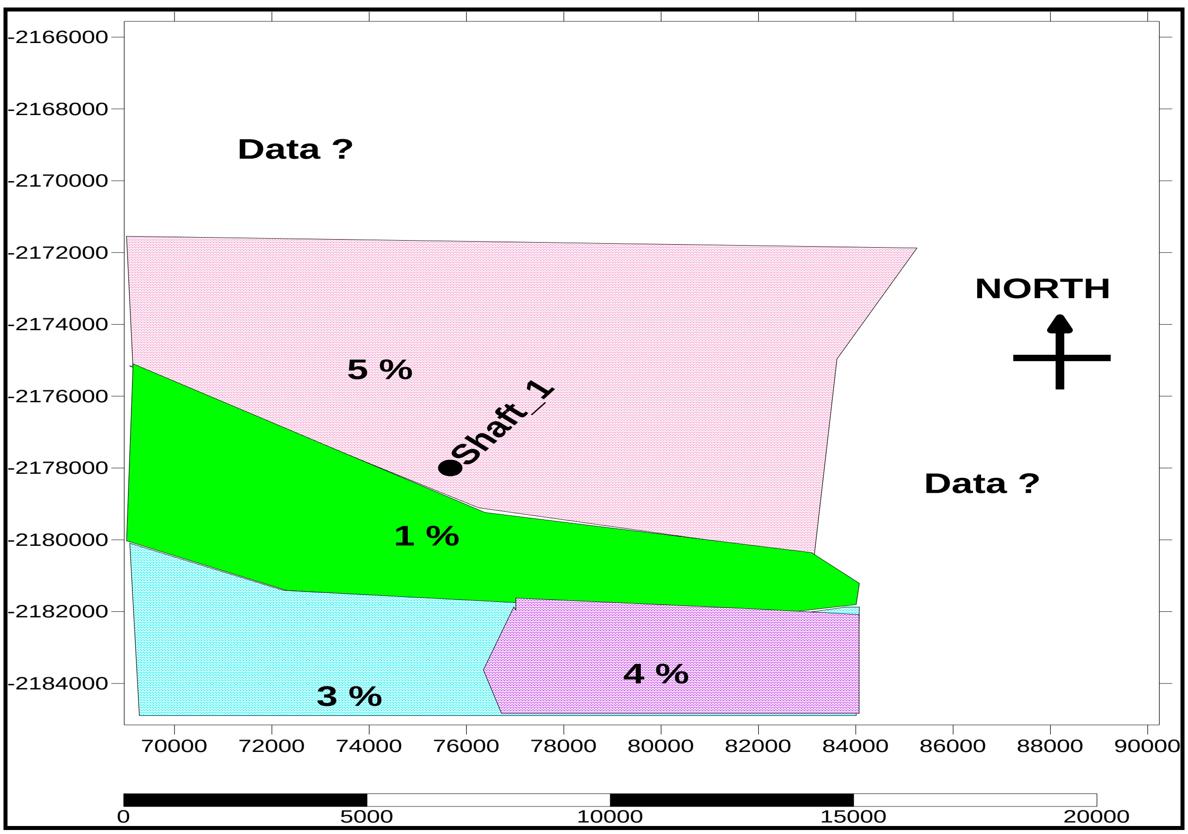

Figure 81: The distribution of recharge as a percent of mean annual rainfall.

6.4 The Storage Model

The storage model attempts to describe and locate the aquifer elements that are predominantly responsible for the storage function.

As stated earlier, two storage models are identified; the epikarst storage model and the fissured matrix model. Epikarst storage is spatially restricted to northern anticline. It is unconfined and situated above the fissured matrix storage.

In support of the position on the storage model of the study area, some carbonate hydrogeology scholars regard the presence of epikarst as a given in any carbonate aquifer, unless evidence is provided for its absence (Quinlan et al, 1996), implying that temporal storage and the subsequent rerouting of infiltrating water are also a given in the Kombat Aquifer, since epikarst is widespread on both the northern and southern anticlines of the Otavi Valley, especially on Karstic Plateau of the northern anticline.

In support of the epikarst storage model, the regional and local EC distribution of the study area encircles the Karstic Plateau of the northern anticline as the zone with the lowest EC values, while the groundwater temperature difference between recharge and discharge zones supports the fissured matrix storage model.

This study therefore proposes a hybrid storage model, which consists of both epikarst and fissured matrix storage components. The fissured matrix storage model would be located outwardly from fracture zones and/or intensely jointed zones.

6.5 Discharge Model

The Kombat Aquifer Discharge Model (KADM) is based on the behaviour patterns of the recession curves of hydrographs observed during this study and spring discharge observed by Ploethner (1997). The KADM is conceptualised according to the dual permeability analytical framework, in which the hydraulic pressure-sensitive high permeability flow component drains the less sensitive fissured flow component to create concentrated discharge points along the southern discharge boundary of the study area.

A combination of all the evidence from water levels, hydrochemistry, hydrographs and spring discharge indicates that the Kombat Aquifer discharges groundwater from both its low and high permeability flow components via the high permeability groundwater flow component;

hence the concentrated discharge around specific zones of the southern boundary, as observed by Campbell (1980). The exact zones of concentrated discharge would need further investigation, but the current data appear biased towards either position. For instance, structural orientation is biased towards the southwestern region of the southern flow boundary, while hydrochemistry is biased towards the southeastern region of the same flow boundary.

6.6 Boundary and Boundary Conditions

The conceptualisation of how and where water originates and leaves the system is critical to the development of responsive models. For this reason, the boundary and boundary conditions of the Kombat Aquifer are inferred, conceptualised and discussed in this section.

The northern and southern boundaries of the study area are defined by well known geological structures; the geological contact between the basal dolomite of the Otavi Group and the old impervious meta-lava and granite gneiss of the Nosib Group defines the southern boundary, whereas the peak of the northern anticline of the Otavi Valley Syncline marks the northern boundary.

The western and eastern boundaries are defined by the limits of the study area, while their corresponding boundary conditions are inferred from groundwater flow patterns. Internal boundaries and boundary conditions are loosely deduced from known geological contacts.

In hydrogeology, the boundary conditions most encountered are linked to either the hydraulic head or groundwater flux conditions at the borders of aquifers; they are generally of two types:

1. Prescribed head or ‘Dirichlet’ boundary conditions, and the

2. Prescribed flux or ‘Neumann’ boundary conditions

The prescribed flux boundary (Neumann) conditions entail the specification of a prescribed flux across the boundary of the region of interest, and are most commonly encountered where a river cuts across the aquifer (Muller, 1984). In the absence of permanent surface water bodies in the study area, none of the boundaries or boundary conditions of the Kombat Aquifer will conform to the prescribed flux boundary.

The Dirichlet boundary condition (prescribed head) requires that the water levels along a boundary are kept at a prescribed level during the actual process of groundwater flow simulation.

The prescribed head boundary condition is to a certain extent, applicable to the boundaries of the study area. However, the application of the Dirichlet boundary condition to the boundaries of the study area should be considered in terms of several factors which could introduce inaccuracies. The first source of inaccuracy would be the lack of a proper network of observation boreholes in the northern part of the study area, the second and most potent source of inaccuracy is the fact that the water levels of the study area are highly transient, as can be seen in borehole hydrographs (**Figure 75**).

6.7 Integrated Groundwater Flow Model

The integrated groundwater flow model of the study area attempts to describe the groundwater flow regime of the Kombat Aquifer. The conceptualisation of the Kombat Aquifer groundwater flow regime follows from the definitions of a typical fractured karst aquifer conceptual model, which is viewed as an interconnected sequence of recharge areas, permeability distributions, and the geological substrates that provide a visualisation of the way in which water is added to the system, stored in the system, transmitted through the system, and discharged from the system (Bradbury, 2003; White, 2003).

On the basis of observed tectonic facies, geomorphology, lithology and stratigraphy, the groundwater flow system of the Kombat Aquifer is divided into and conceptualised within the following subsystems:

6.7.1 The Epikarst–Endokarst subsystem

This groundwater flow subsystem covers the Karstic Plateau and the Fluvokarst. It is characterised by deep weathering, a flexure and transverse fracture tectonic facie. It is therefore a weathered, fissured and fractured subsystem, which comprises rapid, near-vertical infiltration and a recharge flow component. The epikarst–endokarst subsystem supports both the vertical allogenic and autogenic recharge mechanism. Its deep weathering profile performs an important temporal storage function. Beyond the temporal storage function, the epikarst – endokarst subsystem collects and concentrates surface water via dissolution-induced depressions, thereby redistributing infiltration into the underlying collector networks.

6.7.2 The throughflow subsystem

The throughflow subsystem of the Kombat Aquifer is inferred to be spatially confined to the region between the northern contact of the Hutternberg and the Mulden Group-Kombat Formation at the southern foot of the southern Otaviberg. It is a predominantly fractured and fissured flow subsystem, characterised by an east-west trending bedding plane and a north-south trending parallel fracture tectonic facie. From a groundwater flow point of view, the throughflow subsystem comprises a convergent horizontal and concave vertical preferential groundwater flow zone. It plays host to the co-existing low and high permeability storage and transport components of the Kombat Aquifer. It also plays the predominant role of transmitting groundwater into the discharge subsystem.

6.7.3 The discharge flow subsystem

The discharge flow subsystem is confined to the southern low-lying areas. It is characterised by the intersection of south-west trending fault set, and the bedding parallel west-east trending thrust fault set. It comprises of highly sheared and partially karstified, steeply dipping to overturned strata-bound bedding planes.

6.8 Summary: The flow regime of the Kombat Aquifer

It is inherent in groundwater modeling to report complex hydrogeological systems by making general statements. The integrated simplified groundwater flow system of the Kombat Aquifer is presented here.

Descriptions and evidence from geomorphology, fractures, hydraulic response, relief and hydostratigraphy have allowed this study to make certain generalisations on the classification and groundwater flow pattern and dynamics of the Kombat Aquifer.

Based on the models described earlier in this chapter, the following generalisations about groundwater flow in the Kombat Aquifer can be made:

I. The flow system exhibits localised recharge and discharge areas that are connected by bedding planes and transverse faults. Evidence from EC and the isotopic study conducted by Ploethner (1997) supports this deduction.

II. Drawing from the power law sensitivity, as well as from the observed lack of central tendency in the statistics of transport parameters, the extremities of these properties (transmissivity and fracture geometry) are significant to the groundwater flow regime of the aquifer, as opposed to their average values.

III. The hydraulic response of the groundwater regime exhibits two flow components at both the macro- and micro-groundwater flow scales, the macro-subdivision of flow components are based on the flow direction aspect, while the micro-subdivision of flow components is based on a distinctive hydraulic response to stimuli.

IV. In view of point III, the groundwater flow regime of the Kombat Aquifer can be conceptualised within the dual permeability framework.

V. The flow regime receives noticeable recharge at a threshold of 590 mm/a, translating to an equivalent recharge periodicity of once every four years.

VI. The long-term storage of the flow regime tends to adapt to the temperature of the host rock, a phenomenon suggestive of fissured matrix and/or epikarst storage, as opposed to fracture storage.

VII. The transmissivity of the rock matrix in the absence of fractures is insignificant for all practical purposes.

VIII. The transport parameters are scale-dependent. They increase with the scale of investigation and seem to be tied to the level of fracture connectivity at different scales.

In summary, this study conceptualises the groundwater flow regime of the Kombat Aquifer from three fundamental aspects of any groundwater flow system, namely the groundwater flow controls, the positions or localities of dominant groundwater flow, and finally from the groundwater dynamics aspect.

From a flow pattern point of view, the study focused on the variety of lithologic, tectonic and geomorphic settings and their influence on groundwater flow geometry. The argument advanced is that hydraulic characterisation of geological groundwater controls enables the mapping and assigning of properties to sites of groundwater flow. Within this framework, the types and nature of hydro-dynamics were inferred.

Literature reviews, supplemented by a fracture survey, enabled some inferences on potential dominant conductors of groundwater flow, in combination with hydraulic response, this developed into the basis of the division of the flow regime into two permeability networks.

The evaluation of rainfall and hydraulic test data allowed the conceptualisation of the replenishment periodicity and enhanced the understanding of the centrality of fracture geometry to hydraulic response of fractured groundwater flow system, like the Kombat Aquifer.

From the Kombat Mine flooding data, the fracture distribution and geometry allow a continuum of hydraulic response of the Kombat Aquifer Flow regime only at response scales of about 11 km in radial distance from the point of abstraction. This inference poses scale constraints on effective modelling and the development of the aquifer system.

The summary attempts to provide insight into key aspects of the Kombat Aquifer's flow regime, especially on how these aspects relate to each other and to the observed hydraulic response behaviour of the aquifer.

6.9 Model Summary

The conceptual flow model of Kombat Aquifer subdivides the flow system into:

I. The shallow and the deeper flow regimes; the shallow flow system is weathered, fractured and highly transient. The deeper flow regime has only been intersected by mining activities. It is associated with deep-seated geo-fractures like the Kombat West and the Asis Ost Fault systems. This flow component probably approximates steady state conditions, especially under the CV and SLLA where it is confined.

II. The multiple permeability, which is dichotomized into the lower and higher permeability networks for the sake of simplicity. The lower permeability network is associated with high storavity and linked to the development of vugs and fissures within dolomite and limestone, whereas the higher permeability network is associated with major faults, joints and fracture zones. The connectivity between these permeability networks largely defines the hydraulic response of the Kombat Aquifer to hydraulic tests. Information from hydraulic tests have shown that the extent and the connectivity of the two permeability networks govern the propagation of the cross-sectional area available for flow to abstraction boreholes, consequently compartmentalising the aquifer into pseudo-homogeneous blocks.

III. The northern unconfined and southern confined aquifers, this became evident after a negative correlation of topography to static water levels was discovered south of the southern Otaviberg. From the scarce hydraulic data available, it appears that the bedding parallel shear fractures of the SLLA hydraulically behave like bound aquifers, while data from the north of Kombat Mine seem to confirm widespread connectivity among poorly yielding compartments.

CHAPTER 7 ABSTRACTION SCENARIOS AND MANAGEMENT

7.1 General

A convenient starting point in addressing issues of groundwater development and management, would be an assessment of whether existing hydrogeological data document flow system behaviour adequately to allow the potential effects of future developments to be adequately evaluated and understood.

A primary concern to groundwater managers and users should be that groundwater pumping may result in substantial storage changes and water level declines near the centre of pumping. Depletion of groundwater storage is often associated with increased costs, due to:

I. Progressive drawdowns

II. Borehole deepening and reconstruction

III. Abandonment of land due to losses in livestock carrying capacity, or losses in crop yield

In addition to the knowledge of the current hydrogeological conditions of the system, part of the answer to groundwater development and management issues is the availability of agreed-upon standards, as well as resource management approaches. While it is acknowledged that there are existing groundwater resource management approaches by DWA and the Karst Water Management Board, it is impossible to deny that the current groundwater development and management instruments have not managed to stop the Kombat Aquifer from over-utilisation.

Practical solutions are urgently needed. Although there is no simple blueprint for action, it is considered appropriate to first identify areas that can be developed. This can be achieved through deliberately synthesising results from various comprehensive studies conducted in the area.

Secondly, is to move away from approaches where each individual abstracts from his or her own source to managed approaches, involving established wellfields supplying a variety of users. Underpinning the second measure is the revelation that the Kombat Aquifer seems to respond to abstraction more efficiently at a bulky scale than at a micro-scale. An integrated approach would include the development of a pool of resources and knowledge and that could improve groundwater aquifer management.

7.2 Feasible abstraction scenarios for the study area and the Kombat Wellfield

Feasible abstraction scenarios of the Kombat Aquifer are based on the following stationary and non-stationary aspects:

- An average natural net outflow of 1085 m^3/day or roughly 1100 m^3/day, which is equivalent to 1.5 m annual loss in hydraulic head, which DWA attributes to the boreholes least affected by mine dewatering.
- An average storativity of 0.0022 is applied across the entire flow domain; this value is based on data from the bulk response of the aquifer during the Kombat Mine flooding event.
- An area of 314 km^2 for the Kombat Wellfield; based on this study's estimate of the area affected by mine flooding in 1988, and an area of 420 km^2 for the entire study area, based on the grid of the study area model as set up in this study.
- A recharge rate of 3.5 % of the mean annual rainfall (500 mm); based on the average recharge rates from the EARTH model and water chemistry chloride content derived in this study.
- An aquifer replenishment cycle of once every four years, as established in this study. Meaningful recharge is expected every fourth year, with an average water levels recovery of 8.4 m assumed.
- An average rainfall variation of 30% is applied to the rainfall data in the years of the simulations. The 30 % rainfall variation is based on a 17-year annual rainfall record obtained from the Grootfontein Weather Station in 2008.

During the simulation of the water level drawdowns (**Figure 82, 83, 84, 85 and 86**) of the study area, the Saturated Volume Fluctuations Method is applied to the described aquifer.

The surface elevation coordinate of Shaft_1 is 1612 m amsl. Following the temporal closure of Kombat Mine in December 2007, the static water level at Shaft_1 has been at 87 m below ground; therefore the initial hydraulic head (simulation starting water level) is at 1546 m amsl.

7.2.1 Scenario I: Namwater abstracts 4.38 Mm^3/a

In order to restore its water supply capacity to the Waterberg Water supply Area, Namwater aims to source 4.38 Mm^3/a from Kombat Mine at Shaft_1. Figure 82 presents the simulated groundwater levels under Scenario I conditions.

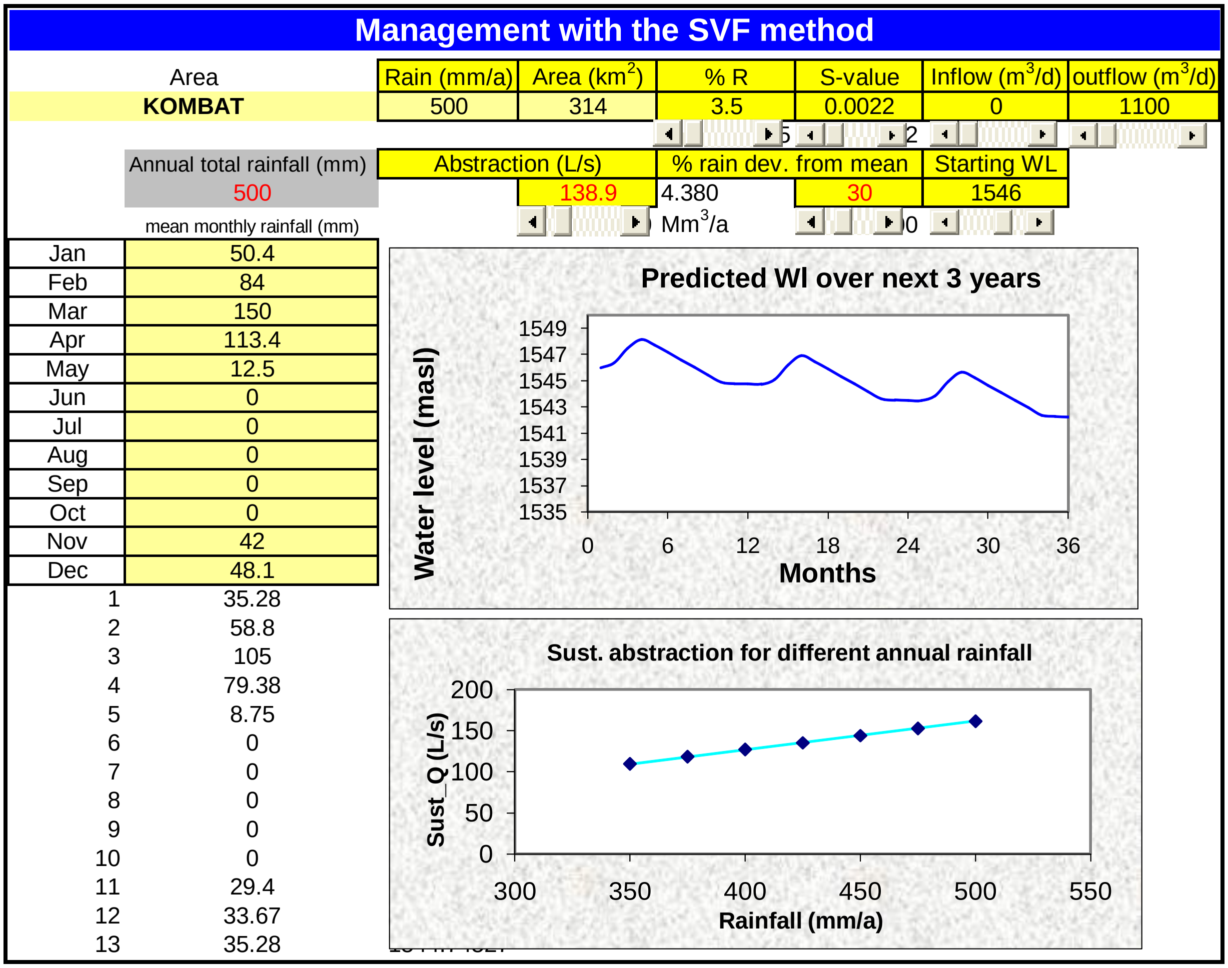

Figure 82: A three-year drawdown simulation at Shaft_1 at an abstraction rate of 4.38 Mm^3/a

Under these conditions, abstracting 4.38 Mm^3/a (**Figure 82** from the Kombat Wellfield has the potential of inducing a drawdown of 4 m by the end of the third year. Considering the 8.4 m expected water level recovery in the fourth year, the aquifer is expected to recuperate over 3 m; that is equivalent to 16 % overdraft of the available reserves of the Kombat Well field by the end of the third year of below average rainfall.

7.2.2 Scenario II: Namwater and the new mine owner of Kombat Mine

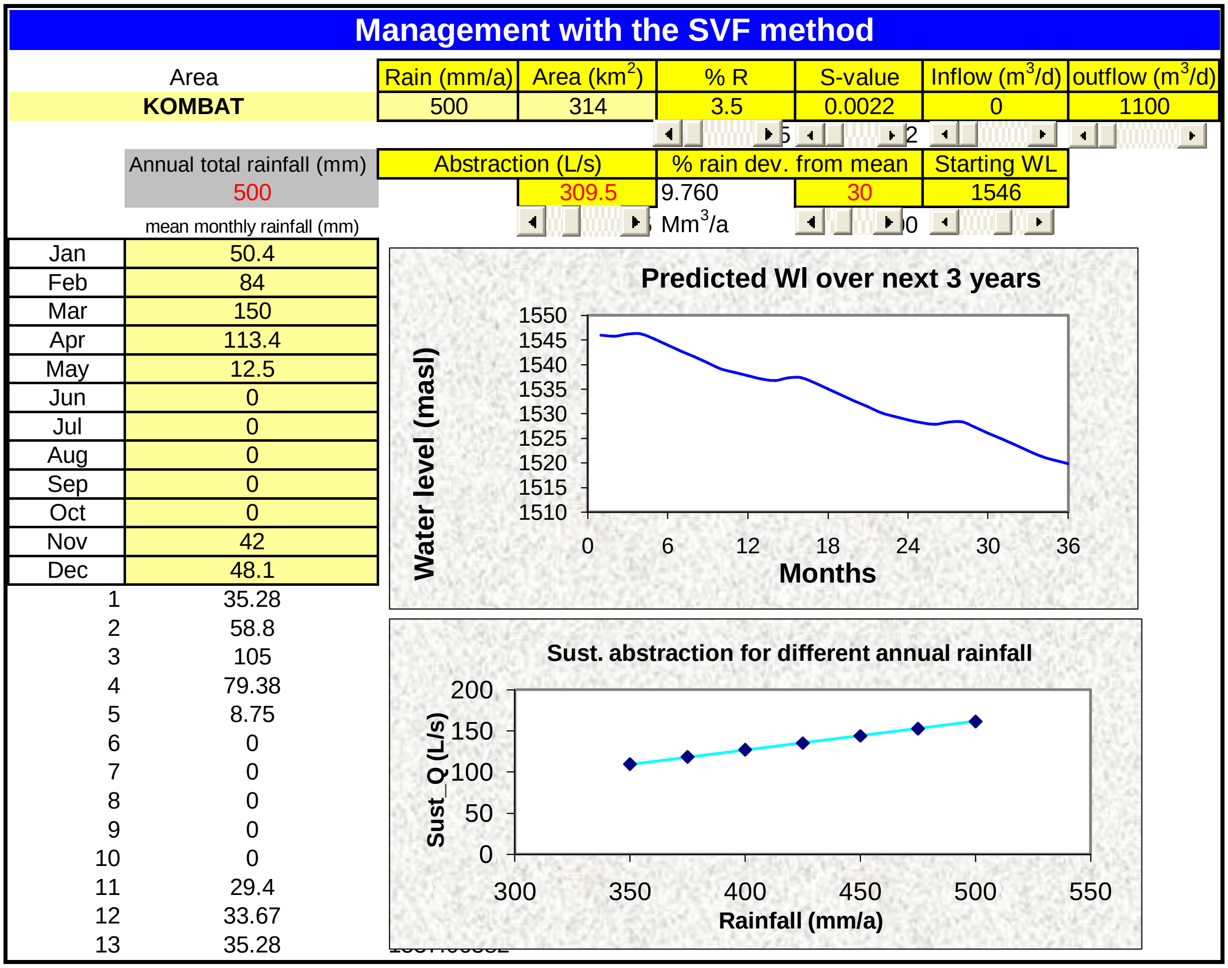

Figure 83: A three-year drawdown simulation at Shaft_1, at an abstraction rate of 9.76 Mm^3/a

With regard to the envisaged developments in the area, the new owner of Kombat Mine intends to rework the tailings. It is expected that he will need about 5 Mm^3/a, which he intends to source from Kombat Mine Shaft_1. Abstraction scenario II simulates the expected drawdown at the end of the third year at a combined abstraction rate of 9.76 Mm^3/a (**Figure 83**).

Under these conditions, scenario II will induce a drawdown of about 25 m by the end of the third year. This is equivalent to 17 m of residual drawdown, which considering the static water level of 87 m, translates to water levels of 104 m below ground with a corresponding groundwater reserves withdrawal overdraft of approximately 160 %.

7.2.3 Scenario III: Safe Yield - transient state

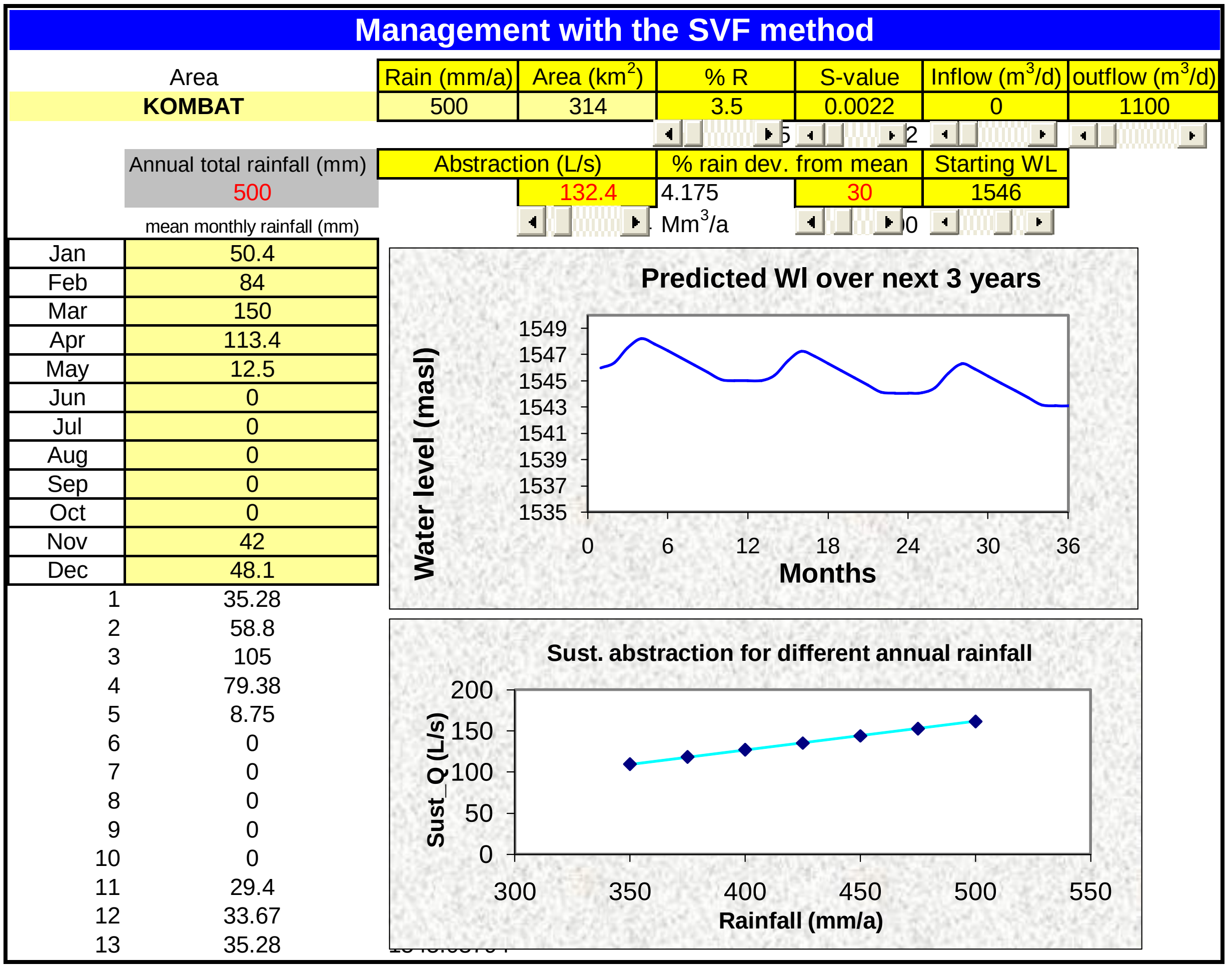

Figure 84: A three-year drawdown simulation at Shaft_1 at safe yield

Under current conditions, the Saturated Volume Fluctuations Method estimates the safe yield of the Kombat well field at 4.2 Mm^3/a (400 m^3/h). The water levels will potentially fluctuate between 1546.3 m and 1544 m. At that abstraction rate, the drawdown at the end of three years would be 2 m; envisaging recovery of 8.4 m in the fourth year would allow water levels recovery of about 6 m (**Figure 84**). Scenario III is expected to induce a minimal stress on the reserves, equivalent to an overdraft of 11 % by the end of the third year of continuous pumping. Assuming a rainfall event of above 600 mm at the end of the third year of continuous abstraction, much if not all the 11 % overdraft is expected be recovered.

7.2.4 Scenario IV: Optimal Use

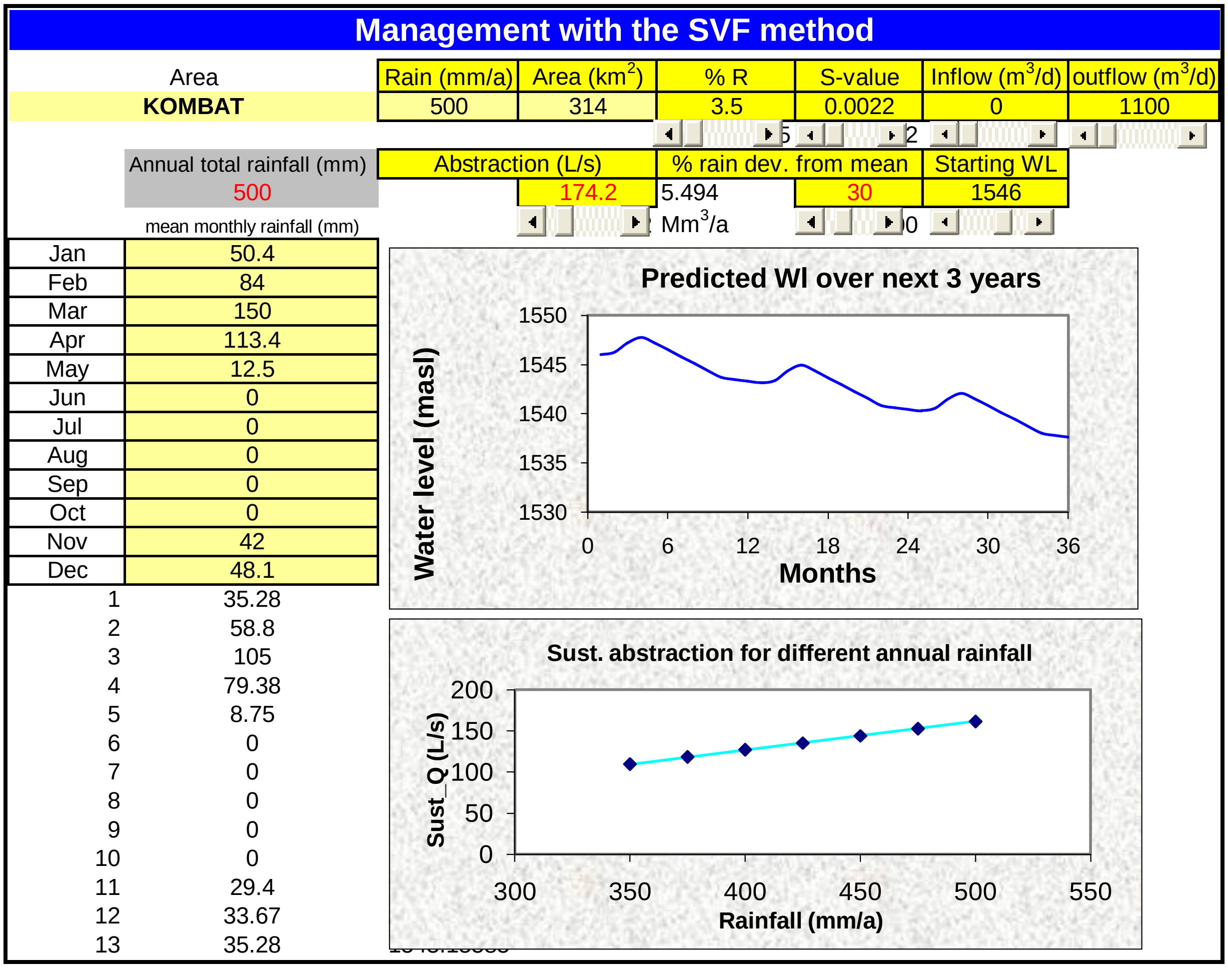

Figure 85: A three-year drawdown simulation at Shaft_1 at the optimal use

At optimal use, it is expected that only the effective water level recovery (8.4 m) will be consumed in the three-year period. Figure 85 presents the simulation of the 8.4 m drawdown consumption over three years, and the results indicate that, for 8.4 m drawdown to be consumed in that period, an abstraction rate of 5.5 Mm^3/a will be needed. The optimal abstraction rate of the Kombat well field is therefore 627 m^3/h. The optimal use of the Kombat well field is expected to induce a reserve overdraft of 46 % by the end of the three years production period of below average annual rainfall.

7.2.5 The safe yield of the study area

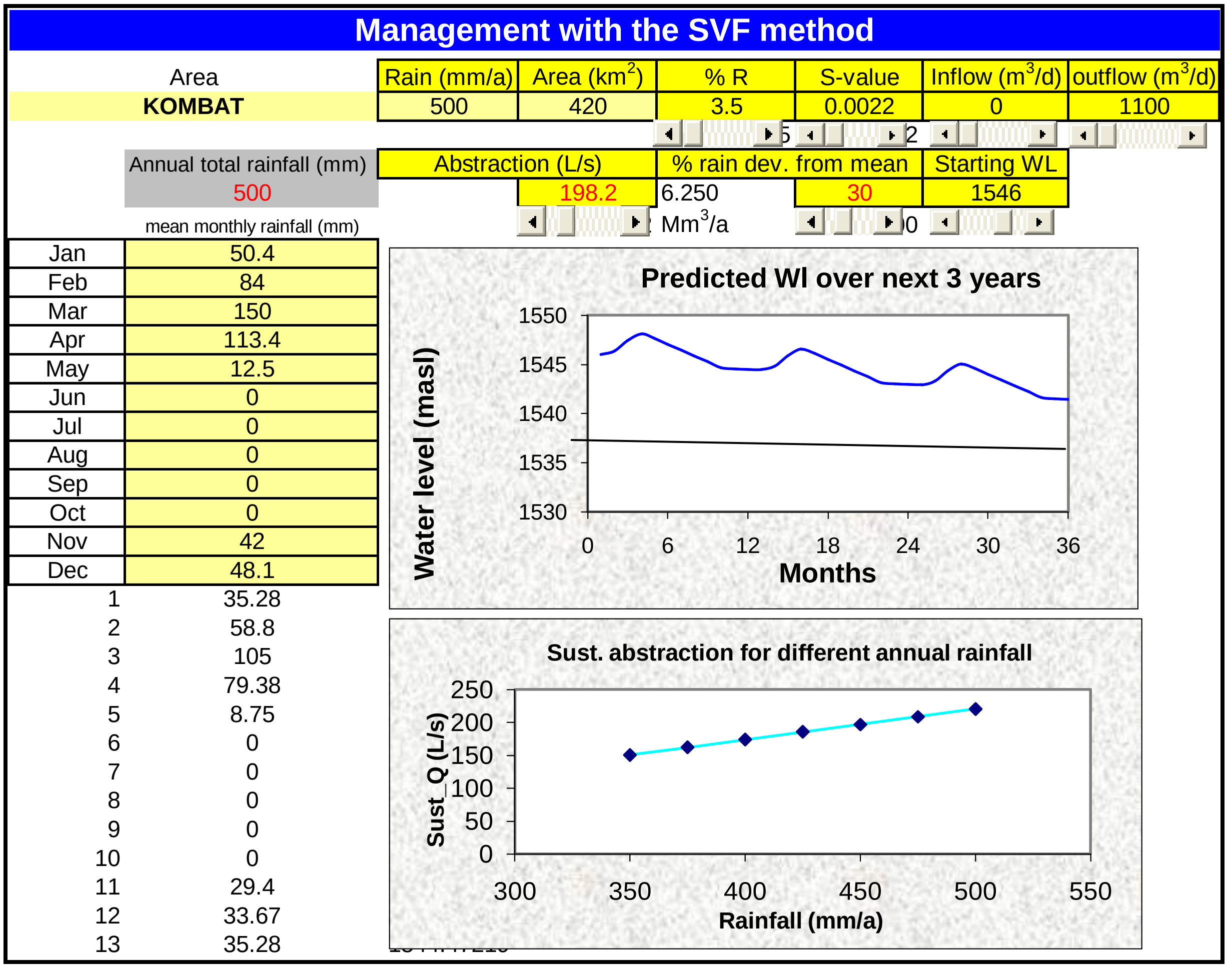

Figure 86: A three-year drawdown simulation at Shaft_1 at aquifer safe yield

The estimation of the safe yield of the whole study is graphically presented in Figure 86. Keeping all the other parameters the same, except the area, the Saturated Volume Fluctuations Method estimates the safe yield of the Kombat Aquifer at **6.2 Mm^3/a**, with an associated effective drawdown of 8.4 m at the end of the third year (below average annual rainfall).

It should be acknowledged that the data, as well as the processes that form the basis of the abstraction and drawdown estimates, bear inherent potential errors, the first being the applicability of the storativity value over the entire flow system, especially to the north and northwest of the study area, where data is scarce.

The second potential source of inaccuracy is the 8.4 m of water level recovery, which assumes that, in every fourth year, at least 600 mm of rain would fall. The other compounding factor is fact the most of that 8.4 m is usually lost through fractures and faults in the first three months of recharge inception (high permeability flow component), even though it is assumed that pumping at Shaft_1 would create a cone of depression that should be able to capture all the recharge within its rims. It should also be acknowledged that the drawdown estimates assume that mine tunnel boundaries (walls) would be reached within hours from the onset of pumping. The validity of this assumption depends on the size and connectivity of the mine tunnels, as well as their connectivity to the rest of the aquifer.

Given the context within which the abstraction scenarios are formulated, it is considered that close monitoring and further calibration of the above given predictions will be needed when some of the envisaged activities commence. The results should then be considered as guiding values towards the actualisation of the appropriate platform upon which the management of the Kombat Aquifer will be based.

The idea is to move towards achieving and maintaining a long-term balance between the annual amount of groundwater withdrawal and the annual amount of natural recharge in the active area of the Kombat Aquifer. With a focus on managing water levels, especially in areas of localised depletion, the Kombat Wellfield, as opposed to the whole basin (aquifer) water balancing of groundwater pumping and recharge.

The optimisation of economic benefits across the Kombat Aquifer flow system will require efficient inter-linkages between the knowledge of the physical system and the replenishment periodicity of the flow system. These linkages are critically important to resource development and the management of the source. For this reason, it is advised that abstraction scenarios and their appropriateness serve as agreed-upon rules of engagement between regulators and users.

CHAPTER 8 CONCLUSIONS and RECOMMENDATIONS

8.1 Conclusions

- The dominance of relatively competent massive dolomite and less competent thin bedded limestone tends to induce large-scale variability in fracture permeability. That makes the comparison and integration of results easier, because even though there are local anomalies like the basal contact, which is associated with a thin bedded lithology. The reasons for such local anomalies are attributable to the same differential.

- The Kombat Mine flooding and pump test data made it possible to investigate the significance of heterogeneities at different scales of the aquifer. A comparison of transmissivities obtained from pumping tests to those obtained from Kombat Mine floods, indicate that transmissivity increases with the scale of investigation. The higher permeability measured at large-scale hydraulic tests are often attributed to larger impacted aquifer volumes, which are more likely to intersect interconnected zones with intense fracturing and preferential groundwater pathways. This increases the hydraulic conductivity of the tested volume. However, this observation might be limited to situations where there is widespread connectivity, which allows the migration of the cone of depression to distant parts of the aquifer. If the reverse is prevalent, it is likely that small-scale tests would yield similar results.

- The geologic, climatic and geomorphic aspects of the study area control the flow pattern, the replenishment rate and periodicity of the Kombat Aquifer's flow regime. The two types of faults observed partition the flow pattern of the Kombat Aquifer into two; one conforms to the localised north-south faults, which are more prevalent to the northwest of Kombat Mine, while the other aligns itself with the northeast to southwest-trending regional fault zone. From the CV southward, the flow pattern is in conformity with regional faulting, thereafter is changes direction and adapts to a southeast flow direction. No explanation has been found for this abrupt change.

- The intensity of tectonic deformation and the degree of chemical weathering controls the permeability and its associated hydraulic response. Information from hydraulic tests at different scales indicates that most boreholes intersect isolated or well-connected fractures or cavities with limited area extent. The size and connectivity of such cavities or fractures characterise the way in which the aquifer responds to pumping. If the fracture or cavity is large enough, linear flow would dominate most of the tested period; if not, then bilinear flow would dominate. In cases where there is good connectivity to other parts of the aquifer, alternating segments reflecting different permeability networks will characterise the drawdown curves.

- The Kombat Aquifer flow regime comprises a karstic recharge area characteriszed by sinkholes and fractured outcrops. The recharge area connects to the discharge zone via efficient fracture networks, coupled with fissure and cavity permeability. Sheared bedding planes and faults constitute the most extensive and dominant groundwater conductors; they funnel groundwater across the flow domain of the Kombat Aquifer and concentrate discharge. Even though this study holds no evidence of concentrated discharge, studies conducted about 20 to 30 years ago, when the water table of the study area was shallow, confirmed concentrated discharge zones. This might however have changed following prolonged periods of declining water levels.

- Hydraulic response of the boreholes from both pump tests and Kombat Mine flooding indicate that there is widespread hydraulic connectivity in the Kombat Aquifer; this occurs in the form of hydraulic links between the shallow and deeper groundwater flow systems, the northern and southern blocks of the aquifer, to local connectivity between low and high permeability networks. This observation should be internalised in the context within which the boreholes of this area are drilled. Most, if not all, of the boreholes in the study area are drilled for water supply and not research; they therefore tend to exploit local fractures if they have been drilled by a farmer, or regional structures if they have been drilled by authorities like bulk water suppliers. They are therefore biased towards connectivity, because they are not drilled randomly. Even in this context, there are still boreholes completed in isolated compartments, such as WW200450.

- The zone encompassing Shaft_1 and the intensely faulted block of the northern dip slope is efficiently interconnected. This is evident in the hydraulic response time-lag disparity observed between the boreholes of this zone and those from elsewhere in the study area (i.e. the SLLA)-during Kombat Mine flooding.

- Shallow boreholes and the results of the Tsumeb Groundwater Study indicate that there is a decreasing trend in transmissivity with depth. This trend seems to continue and reaches an asymptote at about 200 m below ground, below which transmissivities become insignificant. This lower boundary, however, is not easily correlated with any lithological or structural discontinuity. In contrast to this observation, is the fact that mining activities report increasing water problems from the depth of about 300 m (8 level) up to the point where mining stopped (800 m). Thus it is believed that there is a shallow and deeper flow system in the Kombat Aquifer. Although the supposed deep flow system has only been intersected by mining activities, it appears that it comprises fracture zones and faults. The transmissivities associated with the deep flow system, as assessed from the Kombat Mine flood, are three to four orders of magnitude in comparison to those of the shallow flow system.

- There is strong evidence of vertical heterogeneities and flow boundaries observed from diamond core drilling. Besides the known lithological discontinuities, the calcitisation of fractures, together with intercalations of shale and marl, especially in limestone, impose sharp vertical boundaries on the flow system. This situation becomes worse in the SLLA, where it is complemented by thin bedding. In response to tectonic stress, black shale often migrates into the space between thin beds. This and the overturned nature of the stratum of the SLLA causes the bedding parallel shear fracture set of the SLLA to behave largely like a bounded aquifer.

- The Kombat Aquifer is largely unconfined. This position is substantiated by the strong positive correlation between the topography and static water levels observed along the flow line, except for the SLLA, where confined conditions seem to exist.

- The flow system of the Kombat Aquifer is interconnected at a large scale. This is evident from the log-log slope fluctuation of between 0.5 during wellbore, to less than 0.25 along flattening segments; a trend indicating that, at the hydraulic response scale equivalent to the Kombat Flooding event, boundary conditions have less effect on the flow system of the study area.

8.2 Recommendations

In order to improve the current understanding of the Kombat Aquifer, and especially if distributed parameter numerical modeling is to be realised, the following is recommended:

- A more detailed mapping, hydraulic evaluation and classification of the geological discontinuities (faults, joints, fracture zones, bedding parallel shears), so as to a enable deterministic modeling approaches, improve hydrodynamic simulations and enhance judicious management of the groundwater resources.

- Conducting targeted tracer tests to establish the connectivity between the sinkholes of the recharge zone and concentrated discharge of the southern zone.

- In order to improve data distribution as well as reliability of hydraulic information, at least three boreholes should be drilled in the north and northwestern parts of the study area.

- To enable the development of high resolution 3D or 2D conceptual and/or numerical models of the area, it would be appropriate to embark on a programme aimed at establishing a physio-chemical database of selected; if not all, boreholes of the study area.

- As a short term measure and prior to any further groundwater investigations, groundwater development efforts should target the central and southern Otavi Valley. That will facilitate easy and cheap access to the groundwater of the study area, but should not be considered as long term reliable sources of groundwater.

- To maintain a hydraulic balance between recharge and abstraction, a study focusing specifically on recharge rate estimations should be conducted before any long-term bulk water supply schemes area established in the Kombat Aquifer.

- In order to relieve pressure on the Kombat Wellfield, the elevated zone between the Kombat West Fault and the Asis Ost fault could be a feasible to target for potential exploitation of the deep groundwater flow system. This is in light of a possible shallow water table on the downthrown side of Asis Ost fault. Alternatively, the system could be conceptualised to identify areas where the depth of ordinary boreholes can penetrate both aquifers.

- To avoid a localised area of groundwater depletion, the envisaged development in the Kombat Wellfield should be contained within Kombat well field's safe yield capacity.

- Due to their sensitivity to groundwater withdrawal, the boreholes exploiting the SLLA should be closely monitored to avoid possible fracture dewatering and the associated collapse of boreholes.

- Due to sharp variations in transmissivity over short distances, i.e. between the matrix and the fracture system, groundwater flow at a local scale is mostly controlled by the fracture system. It is therefore considered appropriate to use the discrete fracture modeling approach if the aim is to simulate hydrodynamics, whereas a continuum approach would be appropriate for modeling changes in available resources.

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