HYDROGEOLOGICAL CONCEPTUAL MODELING OF THE KOSI BAY LAKES SYSTEM, NORTH EASTERN SOUTH AFRICA

By

MBALI NDLOVU

Submitted in fulfilment of the academic requirements for the degree of

Master of Science

In Hydrogeology

Discipline of Geological Science

College of Agriculture, Engineering and Science

University of KwaZulu-Natal

Durban

South Africa

December 2015

As the candidate's supervisor I have/have not approved this thesis/dissertation for submission.

Signed: ________________ Name: __________________ Date: ________________

PREFACE

The research reported in this dissertation was completed by the candidate while based in the Discipline of Geological Science, School of Agricultural, Earth and Environmental Sciences of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Westville Campus, South Africa. The research was partially supported by the Water Research Commission and the University of KwaZulu-Natal.

The contents of this work have not been submitted in any form to another University. Except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

DECLARATION 1: PLAGIARISM

I, Mbali Ndlovu, declare that:

i. The research reported in this dissertation, except where otherwise indicated or acknowledged, is my own original work;

ii. This dissertation has not been submitted in full or in part for any degree or examination to any other university;

iii. This dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;

iv. This dissertation does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

   a. Their words have been re-written but the general information attributed to them has been referenced;
   b. Where their exact words have been used, their writing has been placed inside quotation marks, and referenced;

v. Where I have used material for which publications followed, I have indicated in detail my role in the work;

vi. This dissertation is primarily a collection of material, prepared by myself, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;

vii. This dissertation does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the dissertation and in the References sections.

____

Signed: Mbali Ndlovu

Date: December 2015

ABSTRACT

This M.Sc. Thesis focuses on the hydrogeological study of the Kosi Bay Lakes system, located in the north-eastern KwaZulu-Natal (KZN) Province of South Africa. The research catchment covers an area of about 659 km^2. It is characterised by four interconnected lakes, two isolated lakes and an estuary with a combined area of about 48 km^2. Two fresh water streams; namely, Sihadhla and Gezisa drain into the lakes. The study was initiated due to information gaps and the importance of the area with respect to conservation, ecology and water resources. The main objectives of the research was to characterize the groundwater and surface systems, in terms of their interconnection, flow and hydrochemistry; conduct a water balance study and develop a conceptual hydrogeological model on the occurrence and interaction of groundwater and surface water within the study area. The study has been undertaken by collecting primary data through a series of field campaigns in April 2013, May 2013 (onsite measurements and water, and water sampling) and October to December 2014 (geophysical data collection and supervision of borehole drilling). Original data generated in this study was complimented with data from KZN Groundwater Resource Information Project (GRIP), the National Groundwater Archives (NGA) and geophysical data, borehole logs, chemistry, and borehole yield data from consultant reports. Geophysical sounding data were calibrated using borehole logs and aquifer pumping tests, which indicate the presence of three hydrostratigraphic units in the study area, namely; the unconfined Holocene cover sands, the Kosi Bay and Port Durnford Formations, and the leaky-confined aquifer made up of the Umkhwelane and Uloa Formations, from top to bottom, respectively. The mean annual precipitation (MAP) for the study area based on data collected at Ingwavuma Kosi Bay and Ingwavuma Manguzi meteorological stations is 939 mm/year. The mean annual groundwater recharge estimated using the chloride mass balance method is 13% of the MAP. Surface water runoff from the catchment to the lakes derived using the Runoff Curve Number method is 14% of the MAP. Evaporation rate from the lakes and evapotranspiration from the catchment area estimated using the Penman and FAO Penman-Monteith approach are 1341 mm/a and 1135 mm/a, respectively. The water balance parameters indicate that inputs into the lakes are greater than the output as indicated by the positive change in storage (ΔS). The lake water balance result was supported by long-term lake level records that show an increasing trend over time. The measured electrical conductivity (EC) for the Kosi Bay Lakes range from 1024 µS/cm (Amanzamnyama) to 24600 (Makhawulani) µS/cm, for the groundwater from 86 to 400 µS/cm and for the streams, it ranges from 227 to 341 µS/cm. The high EC and TDS values of some of the Kosi Bay Lakes are attributed to the high evaporation and connection to the sea through the estuary. The shallow aquifers are characterized by Na-HCO_3-Cl, whereas the deep aquifers have a Na-Ca-Cl hydrochemical facies. All groundwater, stream and lake water samples have $\delta^{18}O$ and $\delta^{2}H$ values that plot on the local and global meteoric water lines indicating recharge from meteoric sources. Groundwater in the shallow Holocene aquifer and streams has similar hydrochemical and isotopic signature, indicating strong interconnection. On the other hand, the lakes are characterized by Na-Cl hydrochemical water type and an enriched stable isotopic signal (positive δD and $\delta^{18}O$ signals) indicating evaporation and terminations of the local surface and groundwater flow system. The detectable tritium signal along with the low salinity of groundwater in the shallow aquifer reflect recent (< 50 years) recharge.

ACKNOWLEDGMENTS

Firstly I would like to extend my sincere thanks to my supervisor Dr. Molla Demlie, thank you for the opportunity, for your guidance and for always pushing me throughout the research.

I wish to thank Mark Schapers, words could never describe how grateful I am for the field experience that I gained at Jeffares & Green (Pty) Ltd, thank you for the long and passionate talks about the coastal flats. Your kindness, patience and guidance is appreciated.

I wish to thank Jan Weitz, my fellow colleague. It has been a huge pleasure sharing an office with you. Thank you for our long talks and the time we spent venting, it kept me sane throughout the two years. I wish to thank Zesizwe Ngubane, for being a supportive and for making everything easy for me. It has been awesome getting to know you.

I wish to thank my family and friends, I can never thank you enough for your prayers, love, support and unconditional love throughout the years. To Vikani Funda, my pillar of strength, my blessing from day one. Thank you for standing right beside me always, for believing in me when I did not believe in myself and for being a best friend.

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

C	Runoff coefficient
Clp	Chloride concentration in precipitation [mg/l]
Clgw	Chloride concentration in groundwater [mg/l]
CMB	Chloride mass balance
CN	Curve Number
DEM	Digital elevation model
R	Recharge [mm/year]
DO	Dissolved oxygen [ppm]
DWA	Department of Water Affairs
DTWL	Depth to water-level [m.bgl]
EC	Electrical conductivity [m*S*/m]
Eh	Reduction potential [mV]
FAO	Food and agriculture organisation
GMWL	Global meteoric water-line
IC	Ion chromatograph
ICP-MS	Inductively coupled mass spectrometry
LMWL	Local meteoric water-line
m^3/a	Cubic meter per annum
MAP	Mean annual precipitation
MCM/a	Million cubic meter per annum
ORP	Oxygen reduction potential [mV]
P	Precipitation [mm/month]
RH	Relative humidity [%]
SAR	Sodium adsorption ratio
SAWS	South African weather service
TDEM	Time domain electromagnetic
TAL	Total alkalinity [mg/l]
TDS	Total dissolved solids [ppm]
TU	Tritium unit
UNESCO	United Nations Educational, Scientific and Cultural Organization
WMA	Water Management Area

CHAPTER 1- INTRODUCTION

1.1 Background and Rationale

South Africa is a semi-arid country characterized by low average rainfall with a growing population which may pose a great challenge in the provision of water supply for domestic, agricultural and industrial purposes. In this regard, water in South Africa should be treated as a very important natural resource that needs to be preserved and protected for the current and future generations. Surface water has been the main focus in both development and exploitation in most parts of South Africa over the years with the exception of rural areas such as northern KwaZulu-Natal where groundwater remains the main source of water for the rural communities (Bredenkamp *et al.,* 1995, Mayer and Godfrey, 1995, Kelbe *et al*., 2001). The Kosi Bay Lake System, which is the focus of this study, is one of the most pristine Lake systems on the South African coast and has been used for recreational fishing since the 1950s (James *et al*., 2001). It is an ecologically important wetland system that falls within the ISimangaliso Wetland Park and has been designated as one of the registered RAMSAR Convention Wetlands of International Importance (RAMSAR Site no.527; UNESCO, 2015). The Kosi Bay Lakes system is a complex, interconnected and dynamic hydrological system made up of interconnected groundwater, stream, lakes, wetlands and estuary system. These interconnections mean that a change in one element of the system may have serious implications on the entire hydro-ecosystem. Local communities that reside in the western part of the catchment are largely dependent on groundwater for their water supply.

Historically, there have been several studies conducted along the coastal plain. Significant to the current research includes works done by Worthington, 1978; Mayer *et al*., 1982; Mayer and Godfrey, 1995; Wright *et al.,* 2000; Kelbe *et al*.,2001; Mayer *et al.,* 2001; Wright, 2002; Porat and Botha, 2008; Kelbe and Germishuyse, 2010 and Weitz and Demlie, 2014. A review of these and other literature in the area revealed that detailed information regarding the hydrogeology, hydrochemistry, the rate of groundwater abstraction in the catchment and its impact on the lakes, the overall water balance of the Lakes system and the interaction of the various hydrological elements within the Lakes Kosi Bay catchment remain poorly understood. Thus, in order to overcome this information gap on one of the most pristine Lake system on the South

African Coast, it is vital that the hydrogeological characteristics of both groundwater and surface water is understood, all the water balance components of the Lake system be quantified and interaction of lake–groundwater understood and available to the decision makers.

1.2 Research aims and objectives

This dissertation aims to contribute towards improved understanding of the hydrological functioning of the Kosi Bay Lakes catchment including the interaction of surface water and groundwater by collecting and integrating hydrogeological data.

The main objectives of the research are:

a) To characterize groundwater and surface water in terms of interconnection, flow and hydrochemistry.
b) To undertake a water balance analysis of the Lakes system including its catchment.
c) To develop a conceptual hydrogeological model for the Kosi Bay Lakes catchment that explains among others the interaction between surface water and groundwater.

1.3 Thesis structure

- Chapter one set out the background and rational to the research and introduces to the scope, aim and objective of the research.
- Chapter two presents a systematic description of the study area by providing the most important salient features such as the geology in terms of stratigraphy and, lithology general hydrology and hydrogeology, climate, land use - land cover, coastal evolution and the likes.
- Chapter three provides a literature review which outlines and discusses the state of the science of the catchment and lake water balances, and conceptual modelling of the interaction of surface water and groundwater
- Chapter four outlines the methods and the material used in the study to collect, analyse and interpret the data generated.
- Chapter five focusses on the results obtained, outlining and discussing the

hydrogeological unit, groundwater recharge and flow direction, lake and catchment water balance, hydrochemical and environmental isotope results, water quality, the conceptual modelling of the Kosi Bay lakes system.

- Chapter six draws conclusions and provides recommendations for future research.
- References used and cited within the text and appendices are presented after the conclusion.

CHAPTER 2 –DISCRIPTION OF THE STUDY AREA

2.1 Location

The Kosi Bay Lakes system is made up of four interconnected lakes, two isolated lakes and an estuary (Figure 2.1). The Lakes system is located along the northeastern coastal region of South Africa which is part of the largest primary aquifer system that stretches from Mtunzini in the south up to the Mozambique border in the north (Mayer *et al.,* 2001). The catchment area is estimated to be about 659 km^2 of which 48 km^2 is covered by the lakes and estuary. These Lakes are Makhawulani (0.117 km^2), Mpungwini (3.299 km^2), Nhlange (38.853 km^2) and Amanzamnyama (1.860 km^2), from north to the south, respectively and are connected to the Indian Ocean through the Kosi mouth (estuary). Gezisa and Sihadhla are the two main perennial streams that drain into the lakes.

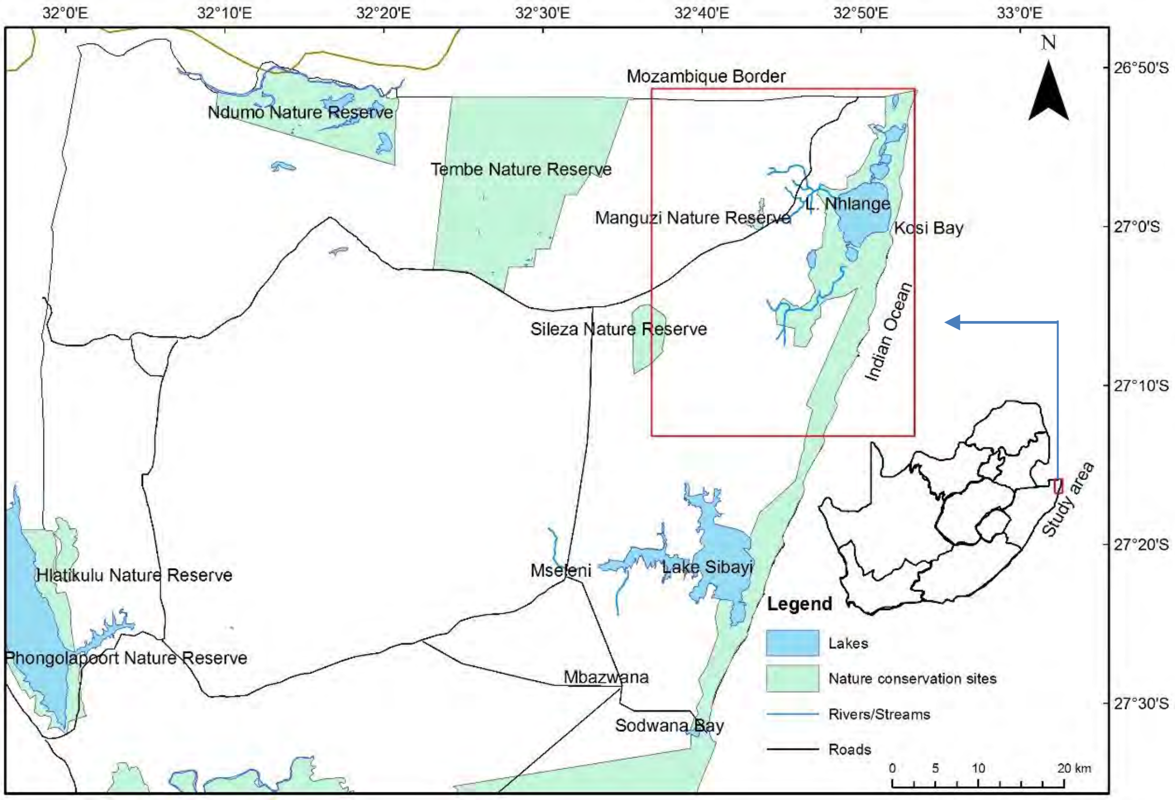


Figure 2.1: Location map of Kosi Bay lakes system.

2.2 Drainage and Physiography

The Kosi Bay Lakes System is situated on the Zululand coastal plain. It is made up of 4 interconnected lakes that are linked to the sea by a single outlet called the Kosi mouth (estuary). The Kosi Bay Lakes system has a north-south orientation and drains to the Indian Ocean. The limit of the lake's catchment was defined using a Digital elevation model (DEM) and it is constrained by the coastal dune cordon in the east and the older dunes in the west. The deepest lake is Nhlange (32 m), followed by Mpungwini (21 m), Makhawulani (8 m) and Amanzamnyama (2 m) (Wright, 2001). It is through the Kosi mouth that the salt water inters the system, while the fresh water is thought to enter through groundwater and small streams around the Lakes. Hence, the existence of a salinity gradient from fresh conditions at Lake Amanzamnyama in the south to saline conditions in the Kosi mouth (Mayer *et al*., 2001; Ndlovu and Demlie, 2015). The Lakes system except the Kosi mouth is secluded from the ocean by densely forested sand dunes that are as high as 130 m a.m.s.l (Wright, 2002). While on the western side, it is bound by paleodune cordons, which demarcates the western catchment boundary of the lakes (Figure 2.2). The coastal parabolic dunes are important features of the Kosi Bay area and are described in detail in Porat and Botha (2008). These coastal dunes are made up of the Sibayi Formation and are known to trend in an approximate north-south direction along the coast.

The area characterized by flat topography, permeable sands, wetlands and flood plains of Gezisa and Sihadhla streams flowing towards Lake Nhlange and Lake Amanzamnyama, respectively (Figure 2.2). The elevation of the area varies from zero meters above mean sea level (a.m.s.l) to about 102 m a.m.s.l further inland. The two streams are perennial and drain across the wetlands, which is typical of coastal water bodies. The Sihadhla stream is associated with peat soils from the swamp forest vegetation and is very nutrient poor (Begg, 1978; Grobler *et al*., 2004), hence the association of Lake Amanzamnyama with the dark colored organic material.

The swamp forest wetland is a major feature of the Kosi Bay area. It is part of the ISimangaliso wetland park, which has been designated as a Ramsar site (Site No.527) of international importance. The wetlands found in the Maputaland coastal plain are situated in low lying interdune, valley bottom areas and underlain by low permeability sediments and cover most of the Kosi Bay area and extends further on the western side (SANBI, 2014). Worthington (1978) reported that the underlying aquifers are fully saturated from the surface of Cretaceous basement up to the shallow water table. According to Rawlins and Kelbe (1998) and Grundling *et al.* (2013), there has been a decrease in the water levels around the area over the past years. This is evident through drying of hand operated shallow boreholes and pans. Since the wetlands within the area are directly linked to groundwater and surface water, and are highly dependent on climatic changes and land use, this becomes a challenge. Rawlins and Kelbe (1998) established that the increased agricultural activities together with forestry and rural water supply schemes on the Maputaland coastal plain are the main reasons behind the decrease in the level of groundwater resources. Wetlands are nutrient rich and water saturated in nature, therefore, are used by the local community for subsistence farming, plantation and forestry.

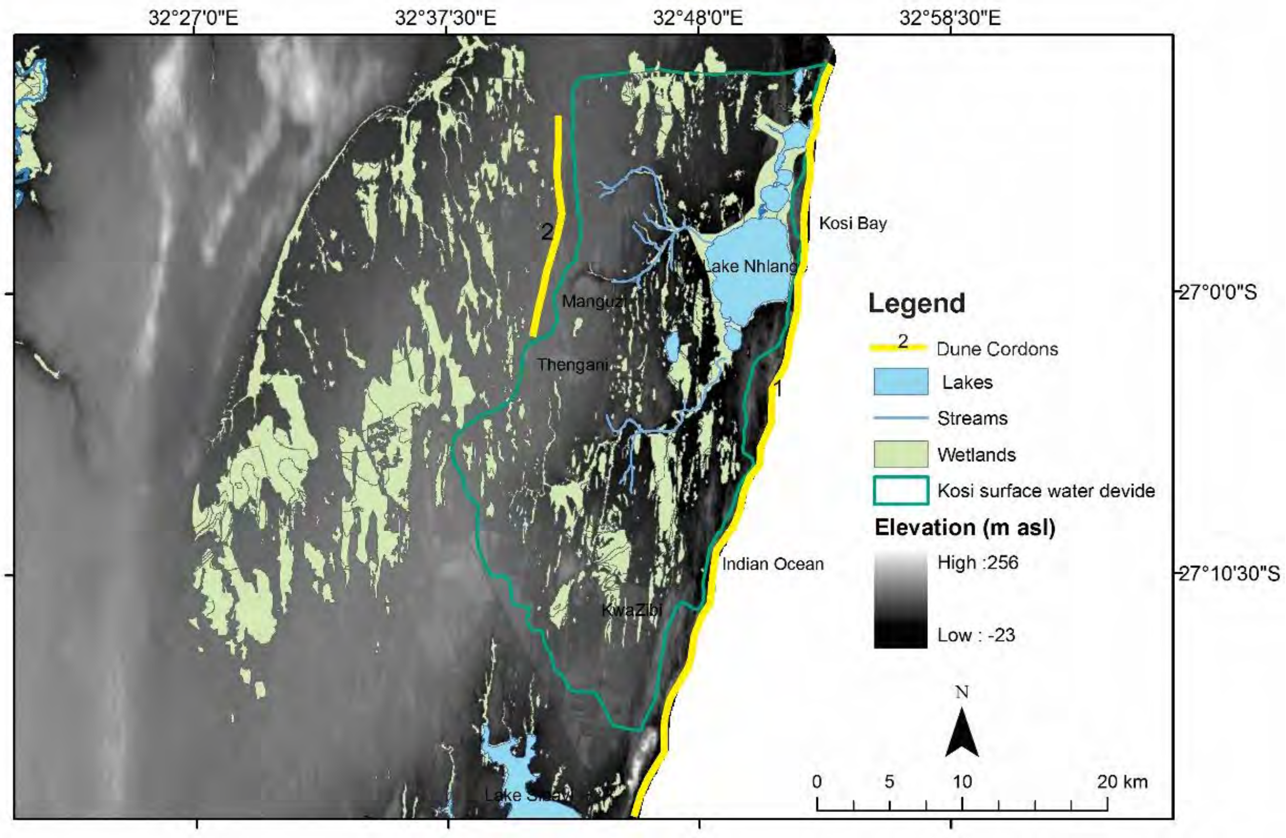


Figure 2.2: Local surface water drainage and physiography of the Kosi Bay area.

2.3 Hydrometeorology and Climate

The general climate of the area can be described as humid subtropical with warm summers, dominated by southern subtropical high pressure belt (Hunter, 1988, Wright, 2002). Pan evaporation data retrieved from the Department of Water Affairs and Sanitation (DWA, 2014) for the Kosi Bay Lakes catchment is about 1450 mm/a. Rainfall occurs throughout the year along the coast, but a large portion of it is experienced mostly in the summer months (Figure 2.3).

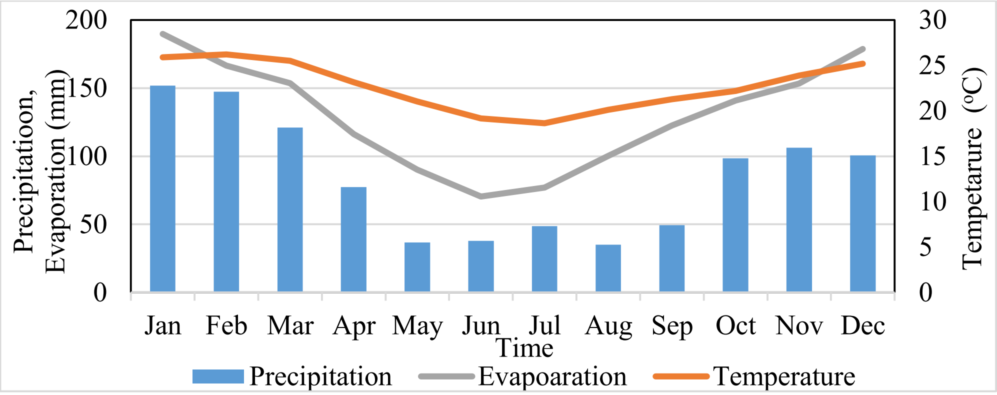


Figure 2.3: Mean monthly rainfall data from Ingwavuma Kosi Bay station, mean monthly temperature data from Mbazwana station and W7 catchment S pan evaporation (SAWS, 2014).

The rainfall varies from 1100 mm/year along the coast and decreases towards the west to less than 600 mm/year at the base of the Lebombo Mountain range (Figure 2.4). Kelbe *et al.* (2001) reported that the rate of groundwater recharge and surface runoff in northeastern region of KwaZulu-Natal is controlled directly by rainfall more than any other catchment factors. January experiences the highest evaporation rate. Temperature records from the Mbazwana Airfield meteorological station indicates a mean temperature of 22.6 °C (varying from 18.6 °C in July to 26.2 °C in February). Relative humidity ranges between 80.4 % in December to 91.2 % in July (Table 2.1).

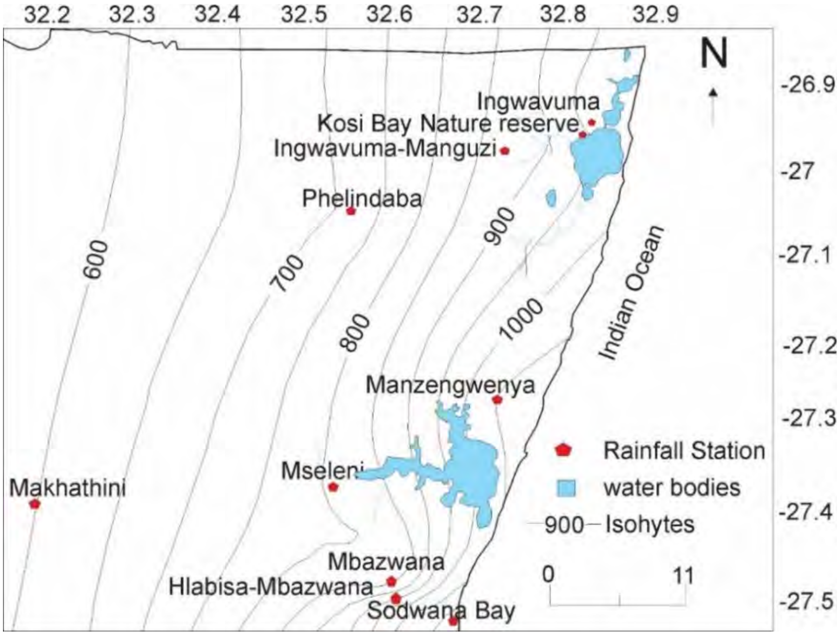


Figure 2.4 Spatial distribution of annual rainfall for the area around the Kosi Bay Lakes system (rainfall data from SAWS).

Table 2.1: Meteorological data from various stations (SAWS, 2014).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall	135.96	132.29	113.78	68.48	28.30	38.25	34.89	28.42	45.54	86.90	109.46	107.02
Temperature (°C)	25.88	26.21	25.49	23.15	21.04	19.15	18.64	20.11	21.28	22.19	23.87	25.19
Humidity (%)	82.80	84.63	87.27	89.64	89.33	91.13	91.20	87.27	83.00	81.67	80.53	80.40
Wind speed (m/s)	2.55	2.55	2.55	2.55	2.55	1.52	1.76	2.16	2.67	2.94	3.03	2.85
Pan evaporation	189.76	166.54	153.48	116.23	90.16	70.47	76.90	100.35	122.52	140.78	153.30	178.72
Sunshine duration (hours)	6.63	6.96	7.17	7.19	7.61	6.71	7.26	7.63	6.65	5.66	5.68	6.14

2.4 Land use and vegetation

Because of the limited occurrence of mineral deposits, the study area can be classed as underdeveloped as far as mining activities are concerned. The same is true for agricultural activities. These resulted in limited infrastructure development (Watkeys *et al*., 1993). Hence the Kosi Bay Lakes system still remains by far the most pristine lake system on the South African coast. The extensive redistribution of the nutrient poor sandy soil limits the utilization of the readily available land for agricultural purposes. This has also contributed to the preservation of the area’s ecosystem. Looking at the land cover map (Figure 2.5), greater than 10 percent of the land is covered by water bodies and wetlands. Grassland and cultivated land are the most dominant land covers, while the urban areas cover a small proportion of the catchment.

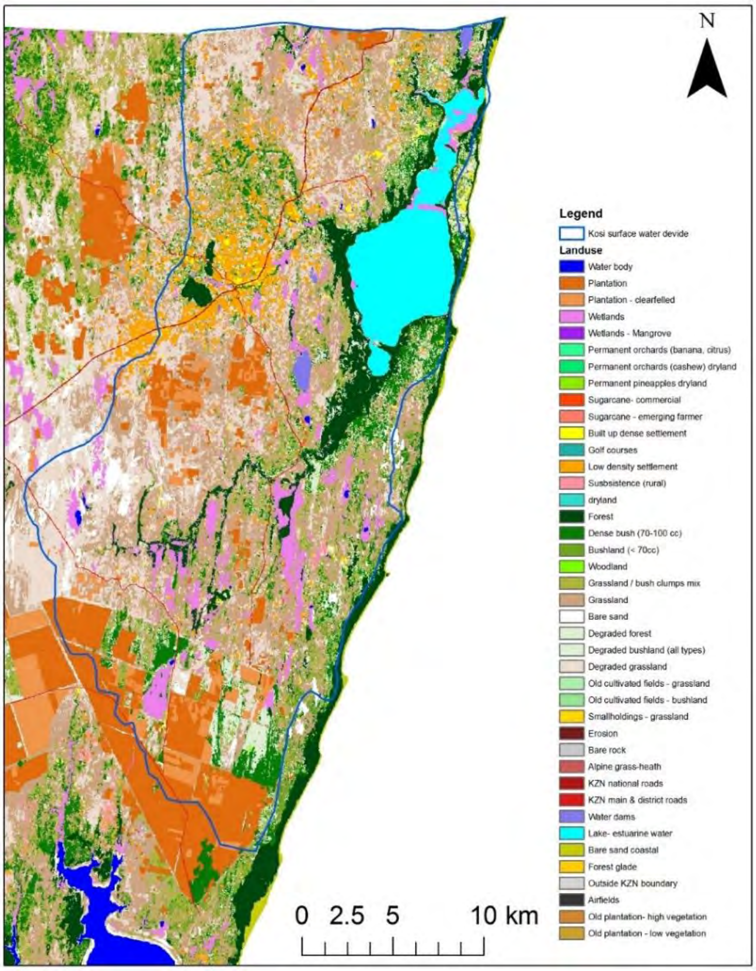


Figure 2.5: Land cover map of the north eastern KZN (modified) (SANBI, 2016).

2.5 Demography and economic activities

The Kosi Bay Catchment falls within uMhlabuyalingana local Municipality which is one of the five municipalities under uMkhanyakude District. The towns within the catchment are Manguzi and Thengani. UMhlabuyalingana Municipality has a population of about 156 736 people and the majority resides in deep rural, traditional authority areas (Stats SA, 2012). Kosi Bay is under the W70A Quaternary catchment which falls under the

Usuthu-Mhlatuze Water Management Area (WMA), and the local communities depend on groundwater for their supply (DWAF, 2008).

Apart from private groundwater abstraction through hand operated boreholes by the local community, the Inkanyezini and Kwangwanase water supply schemes pump and supplies water from more than 10 production boreholes to the local communities in and around Manguzi to meet the water demand. The two schemes were implemented in the 1990's and have since been in operation until present. The scheme supplies water to an estimated population of about 73 000 people at 60 liters per person per day, and the number is expected to increase (Holliday, 2012). Additional raw surface water is abstracted from Gezisa and Nkanini streams, and Shengeza Lake (Jeffares & Green, 2008). In addition to the Kwangwanase and Inkanyezini schemes, the Mbazwana, Mpophomeni-Mseleni, Phelindaba, Shemula, Mbila, Qondele-Gujini and KwaZibi water supply schemes supply the north eastern part of the UMkhanyakude District Municipality (Stats SA, 2012).

2.6 General geological and hydrogeological settings

2.6.1 Geology

Geologically, North-eastern KwaZulu-Natal Province is underlain by Mesozoic and Cenozoic sediments (Figure 2.6 & 2.7). The Cretaceous age deposits of the Zululand Group comprising of the Makhathini, Mzinene and St Lucia Formations from bottom to top, respectively, are the lower most layers underlying the north KwaZulu-Natal, at least from a hydrogeological perspective. These Zululand Group sediments are overlain by the Maputaland group sediments, these sediments are mostly infertile, wind-blown distributed sands. The Maputaland comprises of the late Miocene Uloa Formation, which in turn overlain by the early Pliocene cross-bedded calcarenites of the Umkhwelane Formation (Mayer *et al.,* 2001).

The Umkhwelane Formation is overlain by the loosely consolidated sands, silts and clays of the Pleistocene age Port Durnford and Kosi Bay Formations. Overlying the Kosi Bay Formation are the redistributed dune sands of the KwaMbonambi Formation, which are in turn overlain by the Holocene age sediments of the Sibayi Formation forming the cover sands and active dunes (Wright, 2002; Porat and Botha, 2008).

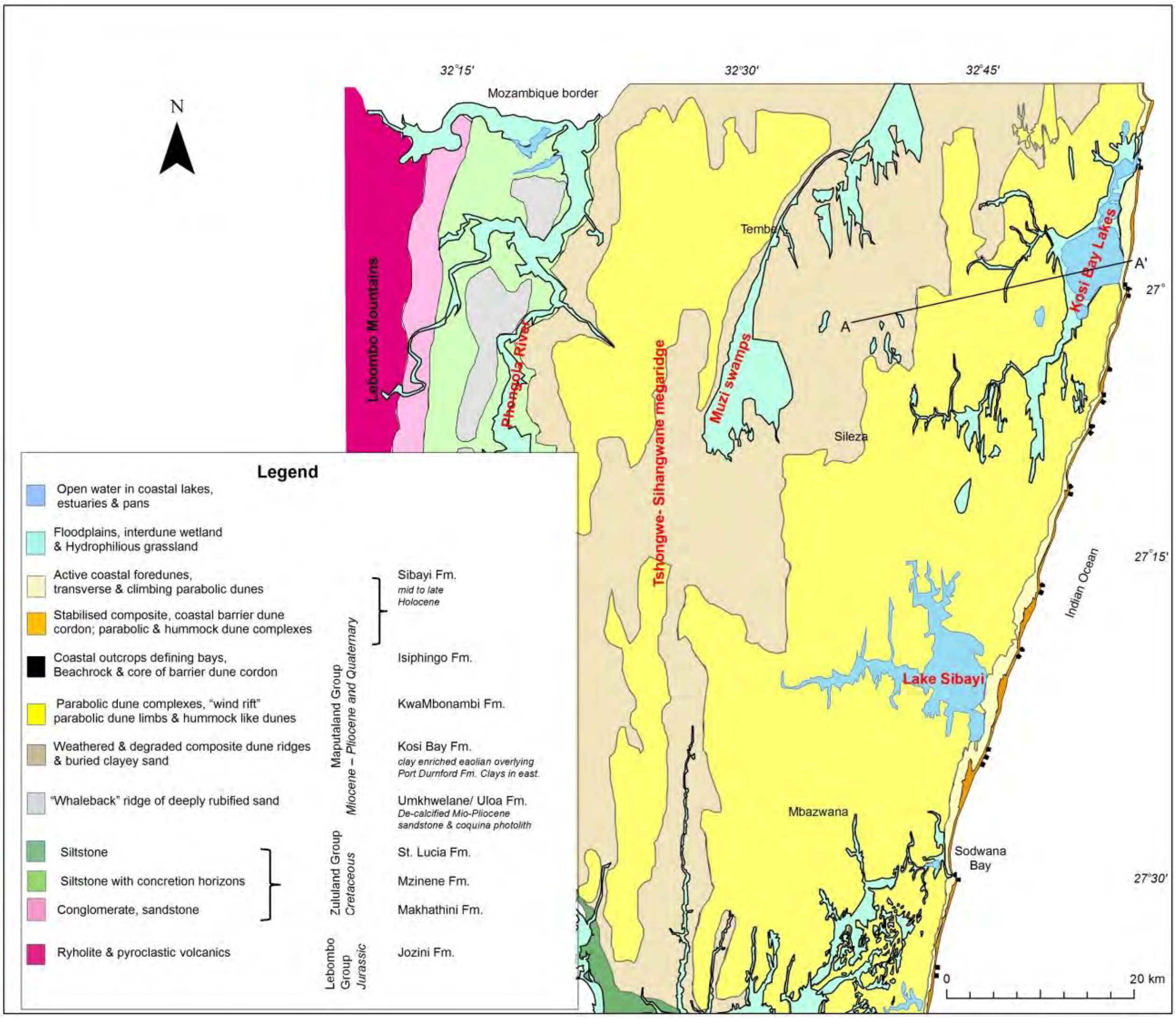


Figure 2.6: Geological Map of the north eastern KwaZulu-Natal (modified Porat and Botha, 2008).

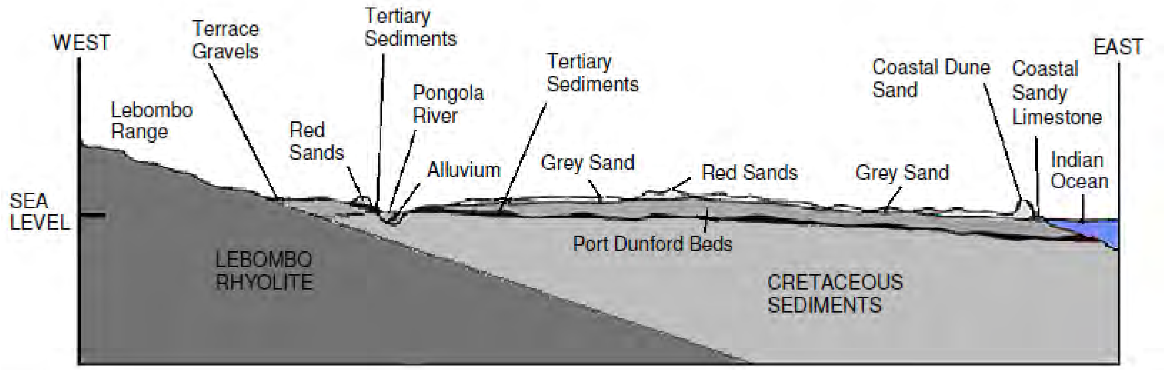


Figure 2.7: A schematic geological cross section across the northern KwaZulu-Natal Coastal plain (Bruton and Cooper, 1980).

2.6.2 Hydrogeology

The north eastern region of KwaZulu-Natal is primarily underlain by Quaternary sand deposits making up the largest primary aquifer in the Southern Africa (Mayer *et al.*, 2001). Governing the primary aquifer are geological features and hydrogeological boundaries. The Kosi Bay Lakes catchment is complex and sensitive to anthropogenic stresses and the primary aquifer is directly linked to the water bodies within the system (Kelbe *et al.*, 2001; Weitz and Demlie, 2014; Ndlovu and Demlie, 2015).

The hydrogeological classification of the area described by the DWAF (1998) in the published 1:500 000 "Hydrogeological Map Series of the Republic of South Africa, is "a3", which indicates that the principal groundwater occurrence is within intergranular aquifers that have yield range between 0.5 and 2.0 l/s. Groundwater quality contoured in the hydrogeological map suggests that the Electrical Conductivity (EC) to be in the range of 0 to 70 mS/m. Generally, drilling experience in the unconsolidated sands indicate that they are good aquifers as long as medium to coarse grained sands are encountered below the water table.

The St Lucia Formation is considered as the "hydrogeological basement" in north-eastern KwaZulu-Natal, dominated by a uniform fine siltstone with thin bands of hard sandy limestone and sandstone in some areas. This unit is considered as having low permeability, poor quality and quantity of groundwater with TDS > 8 000 mg/l (Mayer *et* *al.,* 2001). The coquina layer is yellowish brown, hard, coarse and characterized by shell fragments, while the Umkhwelane Formation is made up of coarse light grey sandy limestone.

The Uloa Formation is very important in hydrogeology as it can be regarded as one of the main aquifers in the stratigraphic sequence (Worthington, 1978). According to Mayer *et al.* (2001), it is possible that the upper layer of this coquina has been exposed to karst solution or chemical weathering before the deposition of the overlying layer.

The Port Durnford Formation overlies the Uloa Formation. It is relatively thick and made up of loosely consolidated sand, clays, silts and lignite. According to Mayer *et al.* (2001), the Port Durnford Formation is found along the entire coastal dune cordon; reaching 25-30 m in thickness at the coast (Worthington, 1978) and is the most promising aquifer (Mayer *et al.*, 2001). The layer is then divided into the lower argillaceous member, characterized by blue–grey sand and mudstones, overlain by thin yellowish brown sand and reddish shelly fragmented sandstone.

The upper arenaceous member of the Port Durnford Formation is the Kosi Bay Formation, it is about 15 m thick and predominated by aeolian facies with large scale cross-bedding and these are generally white, yellow or yellowish–orange in colour and are mostly fine grained (Worthington, 1978). Discontinuous thin beds of carbonaceous sand and lignite occur at various levels (Jeffares & Green, 2012).

The upper most part of Port Durnford Formation and the overlying Holocene sands are extremely difficult to distinguish because of the westward grading of the units and for this reason the western limit of the Formation could not properly be defined (Mayer *et al.,* 2001).

The overlying aeolian and fluvial sands of middle to upper Pleistocene and Holocene age are dominated by fine grained sand and about 5% silt and clay (Mayer *et al.,* 2001) and are largely unconsolidated. Inland, these sands are exposed and are called the Berea type red sands. The vulnerability of the primary aquifer is high, mainly due to the unconsolidated and shallow nature of the aquifers in the coastal flats.

2.7 Coastal evolution

Coastal evolution as described by Wright (2002) is the product of the morphodynamic processes that arise in response to changes in external conditions. Studying coastal evolution helps to understand how the coastal plain and all its features were formed. It is an inevitable fact that human growth and existence always had and will continue to have an effect on the natural settings as a result, over the past 50 years, human activities have had an influence on the evolution of the coast.

The Northern KwaZulu-Natal coastal plain is associated with dune cordons from the Tertiary age in the west and progressively become younger toward the coast. These linear relic cordons are believed to have been formed adjacent to old coastlines, and dating them can reveal the past climate and sea levels influence on the evolution of the coast (Wright *et al.*, 2000).

According to Wright *et al.* (2000), the areas best to observe the modern evolution of the coast along the Northern KwaZulu-Natal are areas such as the Lake Sibayi, Lake St Lucia and Kosi Bay Lakes system where all the historical data are repositioned. However, the lack of outcrops and fossil remains and the reworking of older sand that forms the cover still present a problem in understanding the Cenozoic evolution of the Northern KwaZulu-Natal coastal plain.

The Kosi Bay Lake system is one of the three large coastal water bodies in the northern KwaZulu-Natal formed as a result of the Mio-Pliocene low sea-level still stands (Wright, 2002). According to Wright *et al.* (2000), the still stands allowed the rivers to scour the channels into the underlying sedimentary sequence. In the quest for unravelling the historical settings of the area, Cooper *et.al.* (1989) reported Molluscan assemblages around Lake Nhlange, which are indications of tidal flats that had been in place a number of times where the lake is currently situated. The oldest tidal flat owes its existence to the last interglacial. The 6-8 m terraces preserved west of the lake is evidence that the Last Glacial Maximum (sea level dropped to -130 m) had no effect on the terraces through river incision (Wright, 2002).

CHAPTER 3- LITERATURE REVIEW

Groundwater exploitation in the past decade has been heavily debated, mainly because of the increasing scarce water resources and the need to optimise its use in the African continent (Robin *et al*., 2006). Over and above, the basic principles are all available to the hydrogeological sector when it comes to predicting or anticipating the likely outcome of groundwater exploitation. Conventional hydrogeological studies and groundwater flow modelling are the principal tools that aid in groundwater investigations. However these methods are limited by information gaps in the geometry and hydraulic properties of the underlying aquifers and related data. Methods of determining aquifer properties include the analysis of borehole logs, the assessment of the aquifers response to pumping, hydrochemical and isotope data. This information and data assist in the development of conceptual hydrogeological model of the study area which can be used for various purposes independently or converted to a numerical groundwater flow model.

3.1 Conceptual modelling

A conceptual model is a simple method of representing why and how a hydrological system behaves in a particular way and is an effective way of representing the interaction between groundwater and surface across all landscapes. It is mainly based on the present situation of a system and cannot fully represent and describe the tiniest details of the flow system (Fetter, 2001). It serves as the most simplified way of representing field problems so that they can be analyzed. A hydrogeological conceptual model incorporates geological, hydrogeological and hydrochemical data into a model. A model depending on the purpose can be either of the following categories (Anderson and Woessner, 1992):

- Predictive models: - these are models that can be used to predict what might occur or result in the long run.
- Interpretative models: - these are models used for evaluating dynamics within the system.
- Generic models: - these are models used to analyze hypothetical hydrogeological systems.

Conceptual models are often used to build numerical models for predictions, and are used mostly by managers for more informed decision making on groundwater use and management. The accuracy of conceptual models influence the quality of the result of a numerical model.

Conceptual models need a lot of data; the more the data used, the more reliable the model will be. The data needs to be updated as new data are available for the purpose of improving and increasing the confidence level on the proposed model. Data can be in the form of field maps, borehole logs, geophysical investigation results, pumping test, hydrochemical, and environmental isotope data. The resulting conceptual model is then used to define hydrological boundaries, aquifer units, water level and flow direction and hydrochemical evolution process of the system.

Defining hydrostratigraphic units is mostly challenging, especially in areas where the geology is very difficult to distinguish. Yet it still remains one of the most important tasks to do when constructing a conceptual model. Hydrostratigraphic units are defined and differentiated based on their geological properties on geological maps, borehole log and geophysical data. Borehole logs are a true reflection of what the layers on the ground look like, adding certainty to what is portrayed on geological maps, whilst geophysical results add to meaningful results, as it provides an estimate of the resistivity, depth and thickness of a geological layers, which in most cases must correspond to the borehole logs.

The Kosi Bay area is mainly composed of sands of different composition and age. Hydrologically, they are defined based on their hydraulic properties such as storativity, transmissivity, hydraulic conductivity and specific yield that are obtained from pump test data. Hydrochemical data also aids in distinguishing between the hydrochemical characteristics of aquifer units.

Hydrostratigraphic unit boundaries are defined and spatially represented using maps. This is where the use of numerical interpolation and extrapolation methods are mostly needed. The common interpolation techniques such as kriging, spline, and nearest neighborhood interpolation are nowadays easily available in most computer programs and software such as GIS and Surfer. Kriging interpolation interpolates a probability surface that fits best to a scattered set of point values in two-dimensional space, it can be used in small area where sampling is systematic and assumes a uniform pattern of distribution of point values (Esri, 2016). Spline interpolation estimates values using a mathematical function that minimizes overall surface curvature, therefore, used to smooth out the effects on data. This method is best for gradually varying surfaces such as elevations, water-table depths, or pollution concentrations. It is not appropriate when there are large changes within a short horizontal Distance because it can overshoot estimated values (Esri, 2016). Nearest neighbourhood interpolation delaunay triangulation of the input points and selects the closest nodes that form a convex hull around the interpolation point, then weights their values by proportionate area (Esri, 2016), it is good for random sampling. Sometimes, areas where a large portion has limited data or there is no datum at all, the above techniques are applicable together with relevant assumptions.

In the current study area for instance, a map of the aquifer basement was created by adding the modified bathymetric surface of deep lakes and rivers in the area and assumed the depth for the areas with no data using the known geological data from surface contours, borehole logs and cross sectional transects done for the region (Kelbe and Germishuyse, 2010).

There are other approaches that can be used to create these maps, which include using literature in the form of scientific journals and reports, using deep coastal lake bathymetry and information about the palaeochennels and other geological features that can define the upper and the lower limits on the elevation of the surfaces. For the Maputaland basement, various literatures such as King (1972) and Meyer *et al.* (2001) described the basement surface as dipping at an angle of 3-5 degrees. Kelbe and Germishuyse (2010) used the palaeochennels proposed by Worthington (1978), Maud (1968) and Davies Lynn and Partners (1992) to develop a conceptual model and maps of the subsurface layers.\

3.2 Application of geophysical methods in hydrogeology

There are a number of geophysical methods used for a broad spectrum of purposes. For the purpose of mapping and investigating the occurrence of groundwater in an area covered by unconsolidated material, the electrical resistivity technique is the most suitable and cost effective geophysical technique, and allows a relatively rapid survey of the geological succession (Worthington, 1978). In the Zululand coastal plain, the electrical resistivity technique has shown that the contrast in resistivity and low resistance, depth of penetration capabilities and the speed of operation (Van Zilj, 1971; Australian Groundwater Consultants, 1975; Worthington, 1978; Meyer and De Beer, 1981; Meyer *et al.,* 1983; Meyer *et al.*, 1987; Coetsee, 1991). The two techniques that have been successfully used in the coastal flats are direct current and the electromagnetic sounding techniques. The gravity method has been applied without success by the Directorate Geohydrology, DWAF in order to locate palaeo-channels in the area around St Lucia that are believed to have been infilled by the younger sediments. Two profiles were investigated and none of them showed the paleo-channels that were identified by the drilling operation, resulting in the abandonment of the technique.

Worthington (1978) and Meyer *et al.* (2001) conducted a detailed geophysical work in the Zululand coastal plain using the Schlumberger technique. Despite the fact that the sounding curves were calibrated using existing nearby boreholes, the interpretation proved to be very difficult especially because of the homogenous nature of the coastal sands. Worthington (1978) analysed 900 sounding curves to establish the geological succession above the impermeable Cretaceous and Palaeocene siltstones, whilst Meyer *et al.* (2001) reported the analysis of 408 sounding curves.

Worthington (1978) concluded that the Miocene Uloa Formation overlying the siltstone, is the major aquifer and has thicknesses in the excess of 20 m in places. The younger overlying Pleistocene sequence which is made up of fine-grained sand, clay and lignite layer is a leaky confined aquifer. The interpretation of the borehole logs and the geoelectrical sounding data aided to conclude the fact that the Miocene Uloa Formation has been deposited irregularly in the southern part of the Zululand coastal plain. Worthington (1978) created a histogram of surface measured Formation resistivities and divided the geological succession into four geo-electric units (Figure 3.1). Meyer *et al.* (2001) extended the geological succession to five units. Table 3.1 is the extended biostratigraphic, Lithostratigraphic and geoelectric subdivision of the Cenozoic and Mesozoic succession as reported by Meyer *et al.* (2001). The list of the variation in the apparent resistivity of the geological Formation were obtained from borehole information and direct current sounding done on the outcrops of the various geological Formations (Worthington, 1978; Meyer *et al.*, 2001).

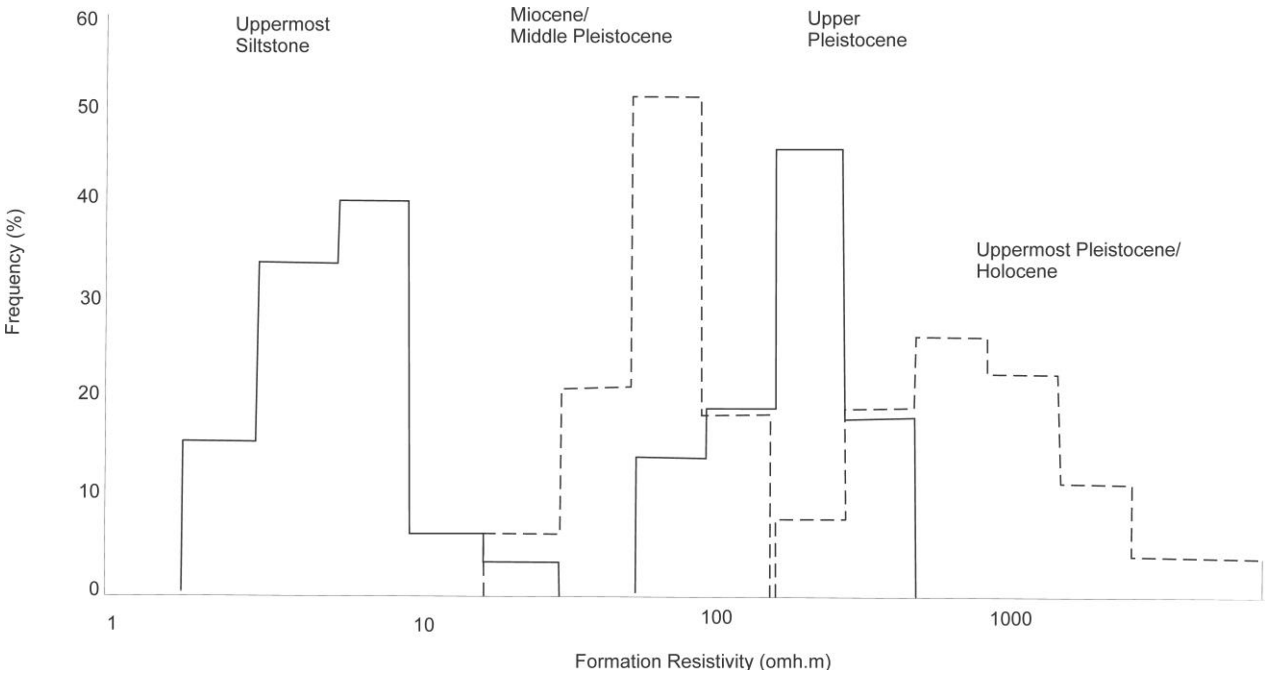


Figure 3.1: Histogram of surface measured formation resistivities based on calibrations soundings (Worthington, 1978).

Table 3.1: Correlation of the biostratigraphic, Lithostratigraphic and geoelectrical subdivision of the Cenozoic and late Mesozoic succession on the Zululand Coastal Plain (Meyer *et al*., 2001).

Biostratigraphic range	**Lithostratigraphic range**	**Geoelectric range**	**Resistivity range (ohm.m)**	**Approximate position of geological Formations**
Holocene- latest Pleistocene	Dune and beach sand	Surficial Unit 1(a) and 1 (b)	250 -7 500	Berea Formation
Late Pleistocene	Fine-grained Aeolian quartz sand	Upper Pleistocene unit 2	90 - 350	Bluff Formation
Middle Pleistocene	very fine- grained quartz sand	Middle Pleistocene Unit 3(a)	24 -75	Port Durnford & Uloa Formations
Middle Palaeocene	Calcarenites, coquina	Miocene unit 3(b)		
Late Cretaceous	Glauconite	Palaeocene Unit 4(a)	8 - 15	St Lucia Formation
	Siltstone	Late Cretaceous Unit 4(b)	3 - 8	Mzinene Formation

Worthington (1978) analysed the aquifer pollution potential in the Mzingazi catchment and subdivided the area into 5 zones, and advised that there will be serious implications on the surface water regime of the Mzingazi catchment if the development of the residential areas is not controlled. These zones are also applicable in the areas around Richards Bay.

Meyer *et al.* (2001) concluded that at a regional scale, the undesirable land use practices are likely to affect the water resource in the area and recommended careful planning of new settlement and agricultural practice. The report further adds that seawater intrusion is not a major threat due to the elevated groundwater levels near the coast and the presence of the dunes acting as barriers. However on a large scale abstraction near the coastline might be something to look out for in case it reverses the flow direction of groundwater, therefore affecting the quality of water resources in the region.

Meyer *et al.* (2001) conducted 68 Transient Electromagnetic Soundings (TEM) in the Zululand coastal area. Some of the TEM were done at the same location as the direct current soundings in order to evaluate the TEM results. TEM method is very effective in identifying conductive layers, whereas the direct current method identifies both conductive and resistive layers as long as they are well defined in terms of thicknesses, and that is why direct current in the Zululand coastal area is always preferred over TEM. Only two cases recorded excellent correlation between what was recorded and the actual borehole results, the rest of the cases the Cretaceous floor was more than 20 m deeper than the interpreted depth to the conductive layer from the TEM results (Figure 3.2). The TEM reported by Meyer *et al*. (2001) defined the first conductive layer very well, but it's not clear as to whether the layer represents the lower Port Durnford or the Cretaceous Formations. The electromagnetic sounding technique is not as extensively used as the direct current technique, mainly because of the expensive equipment and complicated interpretation methods (Fitterman and Stewart, 1986).

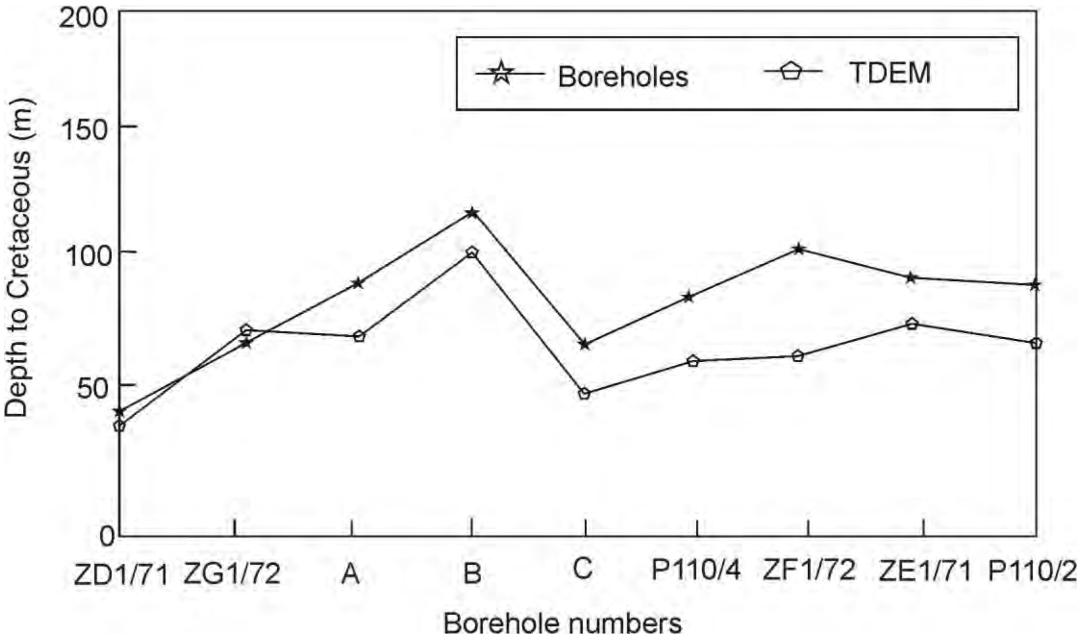


Figure 3.2: Comparison between the results of time domain electromagnetic sounding interpretations (TDEM) and drilling results (modified from Mayer *et al.*, 2001).

3.3 Water balance

The water balance forms basis of analyzing the hydrology of a system, and used as a prediction tool for possible changes in a system. It also quantifies all the input and output parameter within a system by using directly measured and calculated parameters, such as precipitation, recharge, evaporation, evapotranspiration, runoff, base flow, the rate of abstraction and the change in storage.

3.3.1 Recharge estimation

Groundwater recharge can be defined as the downward movement of water that percolates the ground through the unsaturated zone reaching to the water table, hence adding to the groundwater reservoir (Sergio, 1997). Recharge is usually a small percentage of the annual precipitation over the area, but it's highly important in the water balance estimation since it sustain the groundwater storage that has a direct effect on the streams, lakes and wetlands (Sergio, 1997). Groundwater is added into the aquifer in a number of methods such as gravitational flows from surface water sources such as lakes, rivers, rainfall, moist soil, wetlands and estuaries; lateral flows from adjoining aquifers and from dispersion within aquifers (Kelbe and Germishuyse, 2010). Bredenkamp *et al.* (1995) and Beekman and Xu (2003) have reviewed the methods of quantifying recharge to groundwater in the South African context. Van Tonder and Xu (2000) reviewed nine methods of estimating groundwater recharge, where they reported that no single method will produce good estimates of recharge in all cases. They developed recharge estimation methods using an Excel program called RECHARGE, which estimates effective recharge. The methods included in the Excel RECHARGE program include the Chloride Mass Balance method (CMB), Isotope method, Water balance method, Cumulative Rainfall Departure (CRD) method, EARTH model, Carbon-14, Groundwater Model, Qualified guesses and spring flow analysis methods. The review further noted that in the cases where monthly abstraction rates and water levels in boreholes are known in an aquifer, a groundwater flow model, the SVF and CRD methods will usually be superior to other methods.

3.3.1.1 Chloride Mass Balance

This is by far the simplest tracer method for estimating groundwater recharge, and is the most inexpensive method. The method uses chloride (Cl^-) as an environmental tracer, because of it conservative nature and its abundance in precipitation. The method has been applied in quite a number of investigations, to name a few, Eriksson and Khunakasem (1969); Sharma and Hughes (1985); Johnston (1987); Johansson (1987); Dettinger (1989): De Vries and Gieske (1990), Gieske (1992), Bazuhair and Wood (1996), Allison *et al.* (1994), Meinardi (1994) and the most recent and by far the most relevant in relation to the current research study is by Selaolo (1998).

The CMB method has been used to evaluate recharge processes in a wide range of environments, including the semi-arid environment with fractured rock aquifers (Cook *et al.,* 2003), the saturated zones by Eriksson and Khunakasem (1969), in order to estimate recharge on the coastal plain of Israel, and in unsaturated zones as well, by comparing chloride concentrations in groundwater with the chloride deposition at the surface.

The method compares the total chloride deposition at the surface with the concentration in groundwater (Allison *et al.,* 1984). The chloride concentration increases relative to the concentration of rainwater as a result of interception, soil evaporation and root water uptake by vegetation, in this light vegetation cover is vital in assessing the recharge potential at a site, because when vegetation at a specific area is high, the recharge of the groundwater tends to be low (Gee *et al*., 1994). The total chloride deposition and the total precipitation depth determine the chloride concentration of the rainwater at the surface (Allison *et al.,* 1984). For diffusion conditions, the chloride increases in the root zone until a constant value below the constant zone is reached. Whereas under steady state conditions of piston flow, the flux of chloride at the surface is equal to the flux of chloride below the active root zone (Allison *et al.,* 1984). The following are assumption made when applying the method (Allison *et al.,* 1984):

- The chloride ion behaves conservatively, i.e. it is not taken up by or leached from vegetation, unsaturated zone sediments or aquifer Formations.

- Atmospheric input of chloride consisting of wet and dry depositions, is normally considered to be constant with time over longer periods, so long term and continuous monitoring is advisable in order to derive long term averages.
- A piston flow regime is assumed, but can be invalidated by complex transport of moisture vertically and horizontally and this may occur in unsaturated zones as a result of the variability of in rainfall and evapotranspiration or uneven topography.
- Preferential flow paths need to be attended to, as the soil moisture and solutes may be transported through the unsaturated zone by these pathways.

Recently the method has been used in a study done by Meyer *et al.* (2001) on the Zululand coastal plain and was a success. The recharge estimate ranged between 5-18 mm/year. The CMB method is more effective when used in conjunction with other methods, since the chloride used may not be entirely from rain water, it may be from the weathering product of rocks, and therefore this method gives a minimum rate of recharge (Banks *et al.*, 2009).

3.3.2 Runoff Estimation

Runoff is important in determining catchment water balance. Runoff is defined as the amount of precipitation that runoff the surface (Tripathi and Singh 1998). The amount of runoff depends on precipitation, vegetation covering the land-surface, soil types and degree of disturbance, catchment slope and the water bodies in the catchment area. The Soil Conservation Service (SCS) in the early 1950's conducted a study around small watershed in the United States to develop a method of estimating direct runoff from storm rainfall and the effect the land cover had on the volume of direct runoff.

The method was originally developed for small agricultural watersheds using daily rainfall data. The following are the limitations that are encountered in applying the method (USDA, 1986):

- In the development of the equation, the time distribution and storm duration were not taken into consideration.

- The equation tends to over predict runoff volume for discontinuous storm, because it does not account for the recovery of soil storage caused by infiltration during periods of no rain.
- The CN procedure does not work well in areas where large proportion of flow is subsurface, rather than direct runoff.
- Since the SCS curve numbers were developed from annual maximum one-day runoff data, the CN procedure is less accurate when dealing with shorter than one day runoff events.
- The equation predicts that infiltration rate will approach zero for storms with long duration instead of a constant terminal infiltration rate.

The Rational method is another way of estimating runoff from rainfall, first developed by Mulvaney (1951) to solve problems related to land drainage. The method was later applied to sewer design in England and recently Tripathi and Singh (1998) conducted studies on small basins in India and developed the following relationship for estimating the peak discharge:

$$Q = 1/360\ CIA \qquad (1)$$

Where C is the coefficient of runoff and is dependent on the catchment characteristics, I is the intensity of rainfall (mm/h); A is the area of the basin (ha) and Q is the peak rate of runoff in m^3/s. C varies from 0.05 to 0.95 for flat sandy areas to impervious urban surfaces, respectively. Knowledge of the area is very important in the estimation as it helps the user to estimate the acceptable values (Shaw, 1994). Value also varies for different storms of the same catchment, therefore using the average value gives crude runoff estimate which may have a wide margins of error. Weitz and Demlie (2014) used the rationale method on the Sibayi catchment adjacent to the Kosi Bay catchment to estimate runoff rate from the catchment to the lake.

3.3.3 Evapotranspiration

Evapotranspiration represents two terms describing separate processes that occur hand in hand through the natural system. During the process water is lost from the soil by evaporation and from the actual vegetation through transpiration at the same time. Evapotranspiration can be estimated as reference crop evapotranspiration (Allen *et al.,* 1998). Empirical formulas of international standards such as the Bleney-Criddle, radiation, modified Penman-Monteith and pan evaporation methods are used to estimate the crop evapotranspiration. The Bleney-Criddle method is essentially for areas that have air temperature data only, which makes the estimated value less accurate. The method is also recommended for periods of one month or more. The Radiation method is for areas with measured air temperature and sunshine duration, radiation, wind speed and relative humidity data. The method is recommended for ten day or monthly evapotranspiration calculation. Pan evaporation method can be used for periods of ten days or even longer. The FAO Penman-Monteith method also needs climatic data such as air temperature, relative humidity, radiation and wind speed data for daily, weekly, ten-day or monthly calculations (Allen *et al.,* 1998).

In the analysis of the accuracy and performance of the above evapotranspiration estimation methods, studies were undertaken by Committee on Irrigation Water Requirements of the American Society of Civil Engineers (ASCE) in 11 locations with variable climatic conditions and in the European Community by a consortium of European research institutes. The studies showed that different methods performed differently from place to place. The following are observation from the analysis in each of the methods implemented (Allen *et al*., 1998):

- The Penman methods may require local calibration of the wind function to achieve satisfactory results.
- The radiation methods show good results in humid climates where the aerodynamic term is relatively small, but performance in arid conditions are erratic and tend to underestimate evapotranspiration.
- Temperature methods remain empirical and require local calibration in order to achieve satisfactory results. A possible exception is the 1985 Hargreaves' method that has shown reasonable ET_0 results with a global validity.
- Pan Evapotranspiration methods clearly reflect the shortcomings of predicting crop evapotranspiration from open water evaporation. The methods are

susceptible to the microclimatic conditions under which the pans are operating and the consistency of station maintenance. Their performance proves erratic.

- The relatively accurate and consistent performance of the Penman-Monteith approach in both arid and humid climates has been indicated in both the ASCE and European studies.

Allen *et al.* (1998) developed the FAO Penman-Monteith method to estimate reference crop evaporation. This is a combination of the aerodynamic equation and the resistance equation. In practice, the reference evapotranspiration is different from the crop evapotranspiration (ET_c) because the different areas in the field are not necessarily covered by grass. So in order to account for this, the crop coefficient (K_c) was introduced to account for the physiological and physical difference in crops. Therefore, the crop evapotranspiration is the product of ET_o and K_c (Allen *et al.,* 1998).

3.3.4 Open Water Evaporation

Evaporation is one of the most difficult components of the hydrological cycle to quantify, but is very important as it accounts for the large differences that occur between incoming precipitation and water available in the open water bodies. Evaporation can be defined as the transfer of water from open water sources such as the lakes, rivers, streams and reservoirs to the atmosphere, and is influenced by the general climate of the area. There are quite a few techniques to quantify evaporation, directly and indirectly. The direct methods include the use of instruments such as evapotron (Dyer and Maher, 1965). The indirect methods include the water budget method. Tanks and pans are some of the instruments that can be used in quantifying evaporation even though they may prove to be more difficult when it comes to relating measurements from small bodies to the real losses from a large reservoir.

In this research, the Penman (1948) Formula is used to calculate the open water evaporation. This Formula has been used all over the world, especially by practicing engineers. The formula is based on the fundamental physical principles with some empirical concept, and uses meteorological data, combining both the mass transfer method and the energy budget method. The mass transfer method calculates the upward flux of water vapour from the evaporation surface. The energy budget method considers the heat sources and sinks of the water body and air and isolates the energy required for the evaporating process (Shaw, 1994).

3.4 Analysis and modelling of groundwater-surface water interactions

Historically, groundwater and surface water have been discussed in literature as separate entities because of their general different properties. However, in actual fact understanding the processes that develop as a result of surface water-groundwater interactions are becoming more important to protect the integrity of related surface water ecosystems, such as rivers, lakes and wetlands (Kelbe and Germishuyse, 2010). The declaration of the National Water Act (Act 36 of 1998) and the recognition of the connection and the interdependence of groundwater and surface water in the hydrological cycle has required a more holistic approach. As a result of closer working relationships, it has shown that the understanding of surface water - groundwater interaction is poor and many previous hydrological investigations have not addressed this issue adequately and failure to address the issue might perpetuate the poor decision making in the assessment and management of the precious water resources (Kelbe and Germishuyse, 2010).

A simple conceptual models can be very useful in evaluating the groundwater interaction with the surface water bodies, and there are several methods that can be used to achieve it. The conceptual model should consider the main features of the aquifer and the response in the surface water bodies.

Considering the assumption of mass balance approach, any change in surface water (loss or gain) can be related to groundwater. Therefore the change can be identified and measured. The interaction of groundwater and surface water can be determined using a number of methods depending on the type of environment and water body under consideration.

Conceptual and numerical models are useful tools to improve our current understanding of surface water- groundwater interaction. As much as modelling may be a useful tool, failure to calibrate models using measured data merely perpetuates our flawed conceptual thinking, and therefore measurement of flows in rivers, groundwater levels, water chemistry and rainfall must form the basis of further research into this complex issue (Kelbe and Germishuyse, 2010).

Groundwater abstraction could potentially impact effluent streams where groundwater is discharged into the river. However, where the water table is positioned below the base of the river (influent or detached streams), groundwater abstraction is unlikely to have any impact on flow in the river. Similarly, construction of a dam or abstraction of large volumes of surface water directly from a river is unlikely to impact aquifers directly adjacent to effluent streams, but may be of importance in the case of influent streams. Because of this understanding, and given the relatively small area of South Africa drained by perennial rivers, the simplistic assumption that the use of groundwater will result in a corresponding reduction in spring flow and surface water resources (Basson *et al.,* 1997).

Abstracting groundwater from a borehole causes the water table to drop, thereby inducing groundwater flow toward the pumped borehole. This results in a cone of depression forming around the pumped borehole (Fetter, 2001). The depth and extent of the cone of depression is dependent on the rate and duration of abstraction and prevailing geohydrological properties of the aquifer. Should the cone of depression around the pumped borehole reach a surface water body (river, lake, wetland or estuary), then localised hydraulic gradients can change and flow induced from the surface water body into the subsurface. The extent of losses from the surface water body will be dependent on localised hydraulic gradients, hydraulic properties of the subsurface and channel bed and the length of intersection of the cone of depression. The effect of pumping a single borehole will generally remain at a local scale. However, large-scale abstraction from a well field much like the ones in the Kwangwanase and Inkanyezini in Manguzi within the study area or multitude of boreholes could significantly reduce flow in a surface water body on a regional scale. The effect of pumping may only be realised years after pumping started, depending on the rate, volume and duration of groundwater abstracted and the distance between the surface water body and the abstraction points.

3.4.1 Determination of groundwater - surface water interaction using natural environmental tracers

Groundwater movement through the catchments can be traced by naturally occurring dissolved chemical constituents, isotopes and physical properties of water. Useful environmental tracers include common physical parameters such as EC, dissolved chemical constituents or their relative abundance in relation to each other, stable isotopes (^{18}O, ^{2}H), radioactive isotopes (^{3}H, ^{222}Rn), and water temperature (Mazor, 1991). These parameters can be used to identify the source of water, rate of movement and the age of water.Tritium (^{3}H) is a useful indicator of the time water has spent in the subsurface.

Nuclear bomb test during the 1950s and 1960s released high concentrations of ^{3}H into the atmosphere and induced high concentrations of ^{3}H in the atmosphere and eventually in precipitation. Groundwater recharged during the bomb testing period can be identified by increased ^{3}H concentrations in groundwater even today giving a tool of dating groundwater. However, due to radioactive decay, the concentration is reduced, therefore lessening the usefulness of this technique.

Naturally the production of tritium introduces 5 Tritium units (TU) to surface water and precipitation. Anthropogenic activities then increased the amount of tritium to the atmosphere in 1952 in the northern hemisphere through bomb tests (Mazor, 1991). Nevertheless, tritium in groundwater is not significantly affected by chemical processes (Drever, 1997). Tritium concentration tends to vary with seasonal variation, location and mixing of water, so it becomes difficult to accurately estimate when the groundwater was recharged. However, the amount of TU in water can roughly give an estimate. The following is an interpretation of tritium in water, given by Mazor (1991):

Water with zero tritium (<0.5 TU) has a pre-1952 age.

Water with tritium concentration >10 TU has a post 1952 age.

Water with tritium concentration between 0.5 and 10 TU has a mixture of pre- 1952 and post 1952 water.

Elevated concentrations of ^{3}H have been detected in leachate generated by landfills, resulting in ^{3}H becoming a useful tracer for detecting groundwater contamination by waste disposal sites. Chlorofluorocarbons (CFCs) can be used to date groundwater less than 50 years old (Parsons, 1994). These approaches have been used successfully by Richey *et al.* (1998), Saayman *et al.* (2002) and others, but are dependent on the collection and analysis of sufficient samples before, during and after rainfall events. Undertaking simple EC profile along the length of a river during various stages of river flow could be a potentially powerful tool to identify zones where groundwater discharges into a river. This, together with sampling of surface and groundwater, could aid in a better understanding of surface - groundwater interaction (Parsons, 1994).

During the current research, environmental isotopes are used to understand hydrological processes within the study area. The two most useful naturally occurring stable isotope tracers used to trace the interaction between groundwater and surface water are $\delta^{2}H$ and $\delta^{18}O$. They are used to distinguish rainwater flow from pre-event flow. This is because rainwater has different isotopic signatures from the water that is already in the catchment (Kendall and Caldwell, 1998). $\delta^{18}O$ and $\delta^{2}H$ are generally depleted in groundwater compared to surface water because of evaporation in the latter (Coplen *et al.,* 2000).

Craig (1961) measured the isotopic composition of the rivers, lakes and precipitation around the world and established the Global Meteoric Water Line (GMWL). The amount of isotopes the sample water is composed of is expressed in comparison to the amount of isotopes in the standard which is known as the standard mean ocean water (SMOW). Water with less $\delta^{2}H$ and ^{18}O than SMOW has negative $\delta^{2}H$ and $\delta^{18}O$, while water with more deuterium and $\delta^{18}O$ than SMOW has positive $\delta^{2}H$ and $\delta^{18}O$ (Mazor, 1991).

3.5 Previous studies on lake –groundwater interactions

Hydrogeological conceptual modeling can be used for understanding a hydrogeological system. For instance Yihdego and Web (2014) determine the factors causing the freshness of Lake Burrumbeet in southeast Australia, in comparison to the saline lakes scattered across the area using a conceptual hydrogeological model and time variant water budget analysis. They used existing geological information to reconstruct the palaeotopography beneath basalt flows, and hydrogeological data, bore hydrograph and hydrological data together with a time variant lake water balance analysis calibrated from 1998-2008. Revealing that the buried river valley sediments run directly beneath the lake, groundwater leakage into these sediments is enough to transfer enough salts from the lake to maintain a low to moderate lake salinity. The hydrogeological conceptual model integrated with the lake water budget show that the difference in salinity amongst the lakes in the region can be explained by the configuration and hydrogeological setting of the lakes.

Weitz and Demlie (2014, 2015), successfully developed a hydrogeological conceptual model for the Lake Sibayi catchment located adjacent to the current study area using geological, hydrological, physical, hydrochemical and environmental isotope data. The aim was to conceptualise the surface water-groundwater interaction using the conceptual hydrogeological model and later develop the conceptual model into a numerical model. The conceptual model together with the water balance revealed that the groundwater and surface water were highly interconnected, and that groundwater and surface water abstraction will eventually have a negative impact on the environment

CHAPTER 4-METHODOLOGY AND MATERIAL

The methodologies followed and the material used during the course of this research are briefly described in the following sections.

4.1 Desktop studies

Before any research work is undertaken at any level, desktop studies are initiated to clearly map out the plan of action. For the current research desktop study involved delineating the surface water catchment of the Kosi Bay lakes system, thereafter collecting relevant datasets such as, rainfall data from 19 weather station scattered around KwaZulu-Natal and Mpumalanga Provinces; Lake level data measured from stations in each of the lakes (Lakes Mpungwini, Makhawulani and Nhlange); groundwater levels from the KZN Groundwater Resource Information Project (GRIP) database and the National groundwater Archives (NGA), the measured abstraction rate per annum from both surface water sources and groundwater sources, existing geophysical data and borehole data (Pumping test data and chemistry) from consulting firms. All the data collected during the desktop study was used to compliment the original data collected throughout the duration of the research project.

4.2 Fieldwork

Data were collected through a series of field campaigns during April 2013, May 2013 (water sampling) and October-December 2014 (borehole drilling supervision and geophysical data collection). A total of 46 groundwater and surface water samples were collected within and areas surrounding the Kosi Bay catchment during the first and second field campaigns. On the first and second field campaigns (April, May 2013) samples were taken from active (pumping wells), monitoring wells (after purging three bore volumes), streams and lakes within and around the Kosi Bay Lake catchment (Figure 4.1). Depth to water in boreholes was measured using a Solinist TLC dip meter. On site hydrochemical parameters such as temperature; electrical conductivity (EC); total dissolved solids (TDS), dissolved oxygen (DO), redox potential (Eh) and pH were measured insitu using a Hanna HI 9828 multi-parameter water quality instrument. Additional onsite hydrochemical testing for total alkalinity, carbonate and bicarbonate content of groundwater and surface water were undertaken through titration of water samples with 0.02M hydrochloric acid. Anion, cation and trace metal samples were filtered using a 0.45 micrometer filter and collected into polyethylene sampling bottles. The cation and trace metal samples were acidified immediately after sampling to a pH of less than two using ultrapure nitric acid. Samples to be tested for environmental isotopes ($\delta^{18}O$, $\delta^{2}H$ and tritium) were collected using 1 liter polyethylene sampling bottles and were unfiltered and untreated before being collected. The water samples were kept in cooler box below 4 ^{o}C and away from the sun during transportation and in the laboratory.

On the third field campaign (October-December 2014) with the kind permission of Jeffares & Green (Pty) Ltd., geophysical investigation using electrical resistivity method was performed prior to borehole drilling. The Schlumberger array was used because of the nature of the underlying geology and the purpose of investigation. Eight sites were investigated and drilled for production boreholes using a rotary mud flash drilling machine within the study catchment area. The machine is best suited for unconsolidated material. It uses water mixed with bentonite that is carried down into the hole through drill rods, sealing the walls while drilling and preventing the hole from collapsing. The mud created by drilling then travels back to the surface and is collected around the drill pipe for logging and analysis (Figure 4.2).

4.3 Laboratory work

Groundwater flows from high hydraulic head to lower hydraulic head within a hydrogeological system. Along its path it interacts with water and rocks and as a result changes its chemical composition. In nature it is unusual for water to exist in its pure form, it usually contains a mixture of dissolved chemicals, biological organisms and solid particles (Fetter, 2001). The concentrations of the chemicals within the water determine the use of the water. Hydrochemical data often is of value in groundwater investigations as it gives information about the nature of the aquifer system. Hydrochemical data and isotope data can be used to identify zones of interaction and recharge processes and also used regionally to differentiate between deep and shallow aquifers (Banks *et al.,* 2009). Furthermore, isotopes such as tritium can be used in dating and estimating the mean residence time of groundwater. For the purpose of the this study, environmental isotopes ($\delta^{18}O$, $\delta^{2}H$ and tritium) samples were analyzed at the iThemba environmental isotope laboratories in Johannesburg, South Africa, following standard procedures. The measured stable isotopes ($\delta^{18}O$, $\delta^{2}H$) concentration in sampled water were reported with respect to the Standard Mean Ocean Water (SMOW). Major ions were analyzed using Ion Chromatograph (IC), whereas trace elements were analyzed using an inductively coupled plasma mass spectrometry (ICP-MS) at the analytical laboratory of the Department of Geological Sciences, University of KwaZulu-Natal, South Africa.

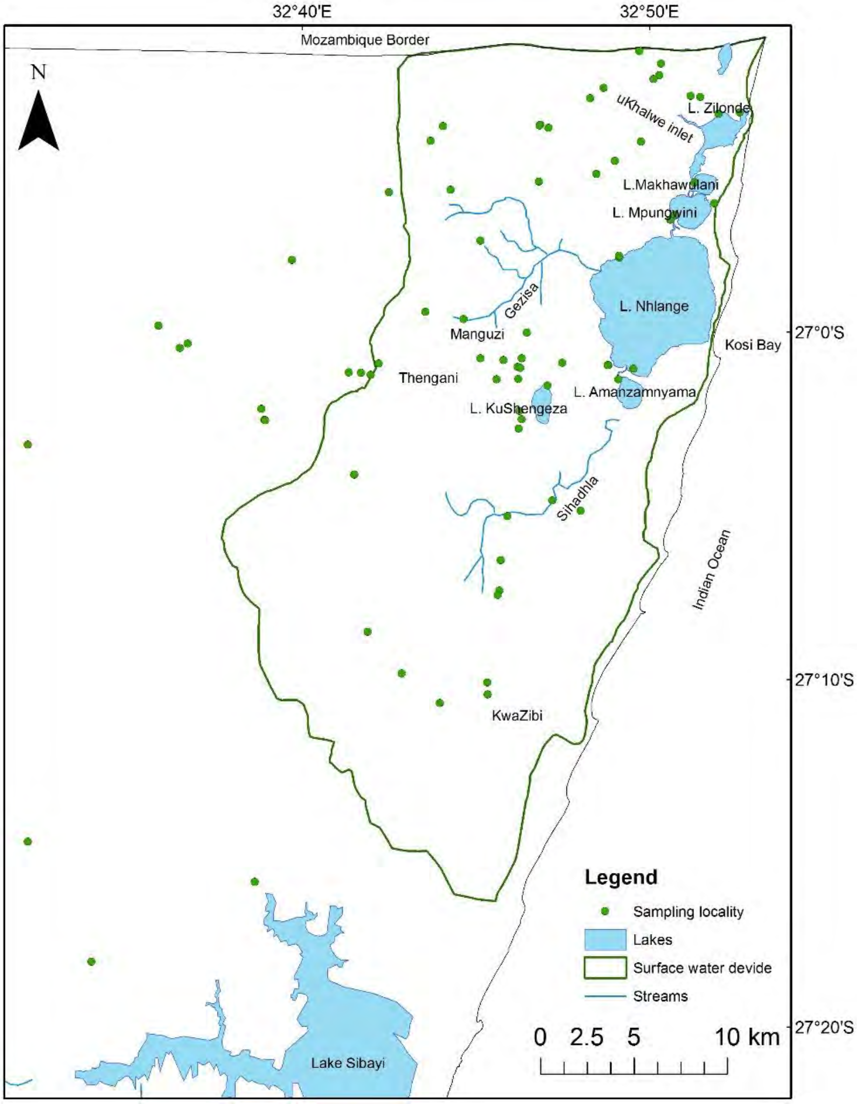


Figure 4.1: Location of groundwater and surface water sampling points within and around the study catchment.

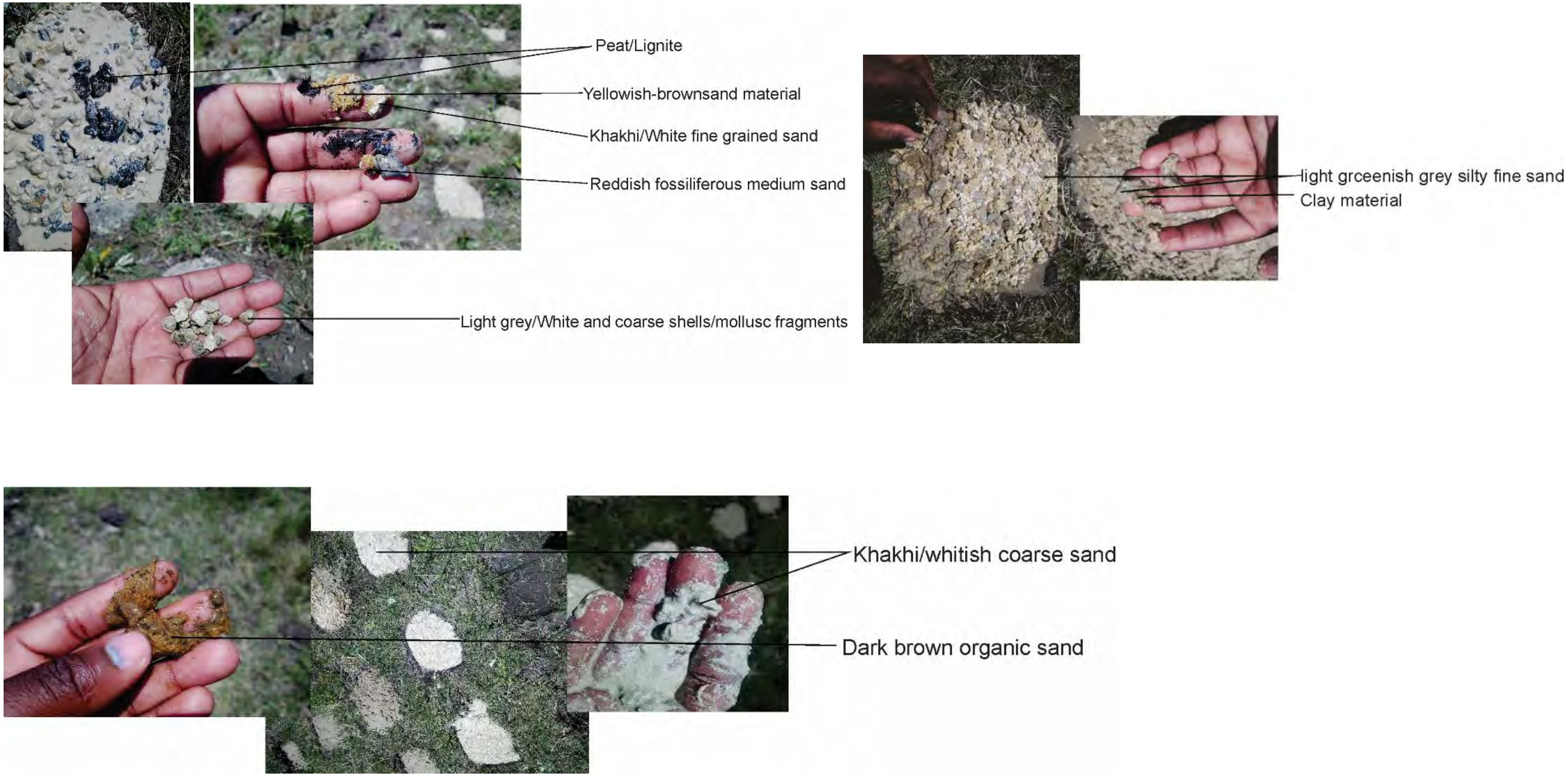


Figure 4.2: Photographs of the borehole samples collected for logging.

4.4 Statistical analysis of hydrochemical data

In general, field and laboratory data can be so large, random and complicated, this could be due to the complex hydrogeological processes that are not visible to the eye and the human activities that has led to uneven distribution of major and minor element on Earth. Thus it is difficult to interpret. That is where multivariate statistical analysis techniques serve an important purpose, as the initial tools to evaluate large hydro-geochemical data sets into manageable classifications with similar characteristics in order to reveal the hidden similarities within the data sets (Suk and Lee, 1999). The technique mathematically reduces the parameter space dimensionally, thus simplifying the representation of data and interpretation.

Factor analysis (FA) is commonly used in hydrochemistry for the sole purpose of interpreting groundwater quality and relating it to changes in hydrogeochemical processes. The analysis can be used to explain the variations within the data. FA explains the variation in data by using common dimension called factors and this is done in such a way that there is little information lost as possible (Hair *et al.* 1992; Suk and Lee, 1999). This analysis is used to identify the underlying variables and provides an empirical classification scheme of grouping into factors. FA has two widely used modes, R-mode describing the similarities amongst variable in data set and the Q- mode that correlates the sample sites. Factor analysis (FA) is applied in the present study to understand the variation in major and minor elements in order to identify the processes responsible for the variations.

IBM SPSS statistical software version No.23 was used in this research to perform descriptive statistics, bivariate correlation and factor analysis (Principal component analysis) on hydrochemical data collected. Descriptive analysis was used on physical and chemical data for both surface and groundwater.

Whilst factor analysis and bivariate correlation were used in the analysis of groundwater chemistry data. In factor analysis the parameters (major ions, EC and pH) were tested for significance using KMO and Bartlett's test of sphericity and extracted using the principal components analysis method based on the Eigenvalue greater than 1. The rotation method used was the varimax with Kaiser Normalization. In Bivariate correlation parameters (EC, pH, TDS, Temperature, Major and isotopes) were correlated using the Pearson's correlation matrix using a two tailed test to test for significance.

4.5 Water balance

Water balance is the basic framework for understanding the hydrological functioning of a system by providing a quantitative estimate of the input, storage, movement through the system and output from the system. Depending on the level of confidence of the water balance estimation, it can be used in the management of both groundwater and surface water resources. The catchment under study is an open system, so in reality it becomes highly difficult to estimate the water balance precisely since the general water balance assumes a closed system where mass is conserved. The following equations 2 and 3 are used to calculate the water balance of the Lakes and the catchment, respectively.

4.5.1 Catchment water balance equation

The water balance for the Kosi Bay Lakes catchment is given by:

$$[P_i - (Et_C + W_s + W_g + G_o)] = \pm \Delta S \qquad (2)$$

Where P_i is the precipitation over the catchment, Et_c is the evapotranspiration from the pine plantation and the forests within the catchment, W_s is the surface water abstraction from the streams and lakes, W_g is the groundwater abstraction, G_o is groundwater outflow from the lakes and ± ΔS is the change in the storage of the lakes.

4.5.2 Water balance analysis for the Kosi Bay Lakes system

The water balance of the Kosi Bay Lakes is given by:

$$\left[\,(P_i + R_{off} + G_{in}\,) - (E_0 + G_o + Ws)\,\right] = \pm \Delta S \qquad (3)$$

Where Pi is the precipitation over the lakes, R_{off} is the runoff from the catchment that flows to the lakes, G_i is the groundwater inflow to the lakes, E_o is evaporation from the lakes, G_o is groundwater outflow from the lakes, W_s is the surface water abstraction from the lakes and ± ΔS is the change in the storage of the lakes.

The methods of estimation of the water balance components is described in the following sections.

4.6 Groundwater recharge

Mean annual groundwater recharge was estimated using the chloride mass balance method developed by Eriksson and Khunakasem (1969). The method uses chloride deposition (both wet and dry) at the surface and compares it with the chloride concentration in groundwater. This is because chloride is conservative in nature and is highly abundant in precipitation. As a result of interception, evaporation and root water uptake by vegetation, the chloride concentration increases. For the current research, the average chloride deposition at the surface measured from 1989-1992 at the Amanzengwenya and Phelindaba meteorological stations by Mayer *et al.* (2001) was used for the recharge calculation. The Thiessen polygon method was used to decide which station's chloride deposition should be used for each of the points where groundwater chloride was measured. Isohyetal map was constructed using a series of meteorological station in KwaZulu-Natal and Mpumalanga to determine the rainfall at each of the points where groundwater chloride was determined. The chloride mass balance equation can be written as:

$$R \times Cl_{gw} = P \times Cl_p \tag{4}$$

Where R is the groundwater recharge in mm/year, P is the mean annual precipitation at a point in mm/year, the Cl_p mean chloride concentrations from precipitation and dry deposition in mg/l, and Cl_{gw} is the mean chloride concentration from groundwater in mg/l.

4.7 Runoff from the catchment

The surface water runoff from the catchment to the lakes was estimated using the Runoff Curve Number (CN) method (USDA, 1986). This method is for estimating Runoff after a rainfall event in a watershed, taking into consideration the hydrologic soil group, cover type, treatment, hydrologic condition, antecedent runoff condition and whether the impervious areas discharges directly to the drainage system or if the flow spreads over pervious area before entering the drainage system. The following is a (SCS) equation from the curve number method described by Woodward *et al.* (2002) for estimation of direct runoff from a rainfall event:

$$R_{off} = \frac{(P - I_a)^2}{(P - I_a) + S} \qquad (5)$$

Where R_{off} is the rate of runoff in mm, P is the average rainfall from Ingwavuma Kosi Bay and Ingwavuma Manguzi rainfall stations in mm/year, S is the potential maximum retention in mm after runoff begins, and I_a is the initial abstraction in mm. I_a is all losses before the runoff begins, this includes water intercepted by vegetation, evaporation, infiltration and water that is retained in the surface depressions such as ponds, rivers and lakes. Because of its viability and the correlation it has with both soil and cover parameters I_a can be expressed using the following equation:

$$I_a = 0.2S \qquad (6)$$

Therefore, from the two equations, Q is given by:

$$R_{off} = \frac{(P - 0.2S)^2}{(P + 0.8S)} \qquad (7)$$

Where, S is related to the soil and cover conditions of the watershed through the CN. CN has a range of 0 to 100, and S is related to CN through the following equation:

$$S = \frac{1000}{CN} - 10 \qquad (8)$$

In this research project the weighted average of CN's for the total impervious area and the pervious area were calculated separately. Thus, runoff from the previous area and the (effective)-impervious area were added together to get the total runoff from the catchment. Effective impermeable area is characteristic of surfaces that are hydraulically connected to the drain system, in this regard the urban area of the study area fall into this category, whilst the rest of the land cover types are pervious. This method introduces the area (A) into the equation following relation:

$$R_{off_{pervious}} = \frac{(P-0.2S)^2}{(P+0.8S)} \left(A_{pervious} / A_{total}\right) \qquad (9)$$

The following is the equation used to calculate runoff from the effective impervious area (urban area):

$$R_{off_{effective\ impervious}} = (P)\left(\frac{A_{effective\ impervious}}{A_{total}}\right) \qquad (10)$$

The total runoff from the catchment is then calculated using the following equation:

$$R_{off} = R_{off_{pervious}} + R_{off_{effective\ impervious}} \qquad (11)$$

The following Table 4.1 lists the land cover/ land use with their respective characteristics as described by Tripathi and Singh (1998) and USDA (1986), the calculation of the runoff per year is included in Appendix A.

Table 4.1: Land use properties

Land use/ Land cover	**Hydraulic conditions/ treatment/ practice**	**Hydraulic soil group**	**CN**	**S mm**	**Area (km^2)**	**P (mm/a)**
Bare soil/pastures	Fair	A	49	2.98	1.35	939
Grassland	Poor	A	55	9.23	282.46	
Woodland/Forest/Bushland	Fair	A	36	10.40	139.93	
Wetland	Wet periods	A	98	0.20	12.66	
Pine plantation	Wet periods	A	98	0.20	18.25	
Cultivated land	Poor	A	81	2.34	60.54	
Urban area/Residential area:	-	A & D	72	2.34	0.17	

4.8 Evaporation from the Lakes

Evaporation rate from the lakes was estimated using data from the Mbazwana Airfield meteorological station, located south of the study area, outside the catchment boundary. The station has been operating since 1997. The calculation was performed using Penman's (1948) equation as described in Shaw (1994), which combines the mass transfer and energy budget methods in order to calculate evaporation from an open water body. This method is based on fundamental physical principles with some empirical concepts. The following is the Penman formula for open water evaporation of which a complete step by step calculation is in Appendix B. The combination and derivation of the equation is found in Shaw (1994).

$$E_o = \frac{\Delta}{\gamma} H + {E_a}\Big/{\frac{\Delta}{\gamma}} + 1 \tag{12}$$

Where Δ is slope of saturation vapour pressure curve at air temperature T in kPa/°C, γ is the psychometric constant in kPa/°C, H is the net amount of heat from sun, expressed as depth of water it could evaporate, E_a is the isothermal evaporation rate in mm/day, and E_o is open water evaporation rate in mm/day.

4.9 Evapotranspiration from the catchment

Evaporation is generally calculated using two major methods i.e., mass transfer and energy budget methods or a combination of both methods. The mass transfer method calculates the upward flux of the water vapour from the evaporating surface while the energy budget isolates the energy needed for evaporation by considering the heat source and sink of the water body and the air (Shaw, 1994).

Penman (1948) developed a formula that combines the two previous methods to calculate evaporation from an open water body based on fundamental physical principles. The method is used in conjunction with meteorological data collected from nearby meteorological stations to the study area.

Evapotranspiration from the catchment was estimated using the FAO Penman-Monteith method (Allen *et al.,* 1998). Monthly Air temperature, humidity and wind speed data used for the calculation was obtained from the Mbazwana Airfield meteorological station and the missing (solar radiation) data were estimated using the FAO irrigation and drainage paper No. 56 (Allen *et al.,* 1998).

$$ETo = \frac{0.408\,(R_n - G) + \gamma\,\frac{900}{T + 273}\,u_2(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34\,u_2)} \tag{13}$$

Where ETo is the reference evapotranspiration [mm day^{-1}], Rn is the net radiation at crop surface [MJ m^{-2} day^{-1}], G is the soil heat flux density [MJ m^{-2} day^{-1}], T is the mean daily air temperature at 2 m height [°C], u_2 is the wind speed at 2 m height [m s^{-1}], e_s is the saturation vapour pressure [kPa], e_a is the actual vapour pressure [kPa], e_s-e_a is the saturation vapour pressure deficit [kPa], Δ is the slope vapour pressure curve [kPa $°C^{-1}$] and γ is the psychrometric constant [kPa $°C^{-1}$]. The complete step by step calculation is in Appendix C.

In practice the reference evapotranspiration is different from the crop evapotranspiration (ET_c) because the different areas in the field are not necessarily covered by grass. So in order to account for this, the crop coefficient (K_c) was introduced to account for the physiological and physical difference in crops. Therefore, the crop evapotranspiration is the product of ET_o and K_c (Allen *et al.,* 1998) the relationship is then expressed as:

$$ETc = K_c \times ET_o \tag{14}$$

Where ETc is in mm day^{-1} and Kc is dimensionless. For the purpose of this research, ETc was calculated under mid-season stage at standard conditions using the single crop coefficient approach. Standard conditions basically means that evapotranspiration occurs from disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions and achieving full production under the given climatic conditions (Allen *et al.,*1998). The calculation is in appendix D.

4.10 Groundwater and surface water abstraction

A large portion of the Kosi Bay Community uses groundwater for everyday purposes and surface water from the Lakes and local streams mostly for irrigation. Table 4.2 presents rate of abstraction collected from the registered water uses database for the UMkhanyakude District Municipality.

Table 4.2 Annual surface water and groundwater abstraction within the Kosi Bay catchment (DWAF, 2015).

Property	**Volume (m3/a)**	**Source**	**Source name**	**Latitude**	**Longitude**
Manguzi town & community	277400.00	Lake	Shengeza lake	-27.03333	32.77778
Manguzi town & community	175200.00	River	Gezisa stream	-26.98889	32.75833
Enkanyezini communal land	498269.00	Borehole	KuNkanini river catchment	-26.90139	32.70342
Manzengwenya plantation	6103674.00	River	Lake Sibayi catchment	-27.20000	32.70000
Reserve no 14	106250.00	Borehole	Malangeni river catchment	-27.15222	32.73058

The current groundwater abstraction is restricted to shallow hand operated boreholes for domestic supply, boreholes for community water supply schemes. The problem is that everyone who abstracts water from the underlying aquifer is not registered with the water use licensing Authority. For the purpose of this study, a 25*l*/person/day is used to estimate the quantity of groundwater that is abstracted from the aquifers. The estimated population residing in the area is about 72275 (Slaughter, 2014). The following Table 4.3 is the breakdown of the groundwater abstraction estimation based on the 25l/person/day minimum requirement.

Table 4.3: Groundwater abstraction estimation.

Water supply schemes around the catchment area	Population	Volume abstracted at 25l/person/day
Inkanyezini	25000	635000
Kwangwanase	38000	950000
KwaZibi	9275	231875

4.11 Groundwater seepage/outflow to the Indian Ocean

Seepage along the coastal dune cordon east of the Kosi Bay lakes was calculated using the Dupuit's equation (Fetter, 2001). Assuming a horizontal flow of water from the aquifer underlying the lakes to the Indian Ocean is given by the equation:

$$q = \frac{\mathrm{K}(h_0^2 - h_1^2)}{2x} \tag{15}$$

Where q is the seepage rate along the coastal dune cordon per unit width of coastline in m^2 /day. K is the mean hydraulic conductivity of the aquifers underlying the lakes, in this case 5 m/d estimated by Mayer and Godfrey (1995). h_o is the hydraulic head elevation of the water in the lake which is 69 m calculated using the base of the aquifer as datum, which in this case is the top of Cretaceous basement siltstone. h_l is the hydraulic head at the coastline calculated the same way as h_o and is 51m. x is the horizontal distance between h_o and h_l which is 1067m. The seepage face is estimated along the coastline as straight line distance from the Kosi Bay mouth to Lake Amanzamnyama using ArcMap which is 16000m. The product of the length of the seepage face and the seepage rate was used to quantify the volume of water that seeps across the dune cordon to the Indian Ocean.

4.12 Geophysical investigation

The resistivity method, particularly the Schlumberger array is one of the vertical electrical sounding investigations suitable for unconsolidated sandy formations such as the area under investigation. It measures the resistance of the soil/ground to conducting electric current. Basically wet soil or ground conduct electricity, hence the resistance becomes less than in dry grounds. The direct current resistivity technique involves the application of applied current into the ground through two current electrodes to measure the potential difference between the potential electrodes. The apparent resistivity is calculated based on these electrode configuration, the applied current and the measured potential difference using equation 16. Where R is the resistivity of the ground, V is the potential difference, I is the applied current, AB is the current electrode spacing and MN is the potential electrode spacing.

The configuration is placed in such a way that there is a fixed reference point, from which the electrodes are expanded outwards (Figure 4.3). In that way a sequence of apparent resistivity values are obtained, mapping deeper as electrodes are expanded. The data recorded is then plotted to produce a sounding curve that represents the variation of resistivity of the underling layers with depth. When the recorded data are inverted and analysed using software such as the IPI2Win, a sounding curve is produced, along with a model showing the depth, thickness and actual resistivity values of each of the horizontal layering.

$$R = \pi \frac{(AB/2)^2 - (MN/2)^2}{MN} \times \frac{V}{I} \qquad (16)$$

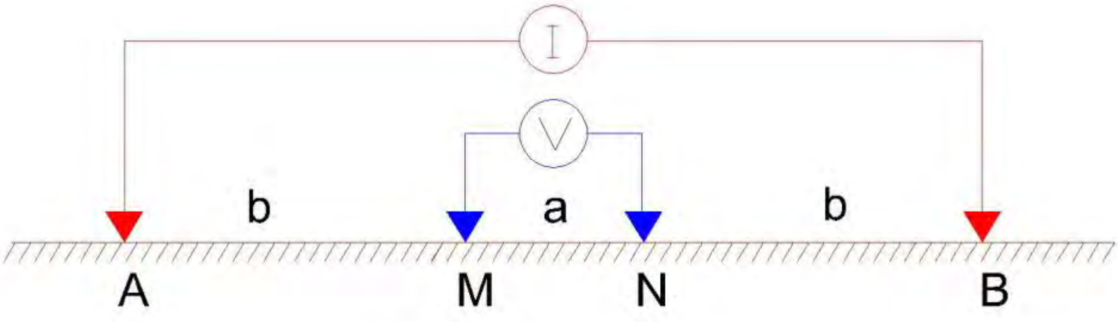


Figure 4.3: A typical Schlumberger array.

The principle behind the method is based on the fact that water saturated soil conducts electricity, while dry grounds are more resistant to electricity. The resistivity meter records the apparent resistivity instead of the actual resistivity. Therefore, the apparent resistivity measured must be inverted to an actual resistivity using appropriate inversion software.

The analysis and interpretation of geo-electrical sounding data is performed using the IPI2Win lite version no. 2.3 software, a computerized software designed for automated and interactive interpretation of geoelectrical sounding data using resistivity curves and pseudo-sections. The program is best used with prior knowledge of the geological properties of an area and is used with prospects of drilling. Amongst the data obtained using this software is the densities, thickness and actual resistivities of the different layer of the subsurface. Twelve (12) each 300m long vertical electrical sounding were undertaken and analyzed to determine the geological succession (Appendix E).

4.13 Delineation of Wetlands and Lakes Capture Zone

Capture zone delineation is used in the study for defining the groundwater contributing area towards the lakes and wetlands in order to calculate the water balance of the lakes and defining the groundwater contributing area towards the groundwater fed wetlands within the study area. The three different methods that can be used in capture zone delineation, particularly of a wetland and a lake system, from the less complicated and cost effective to the most complicated and costly method are (Moreau *et al.*, 2014):

- Desktop review
    - Arbitrary fixed radius
    - Hydrogeological mapping
- Analytical element models
- Numerical model

Numerical models are expensive to use as they need expertise, a dedicated software packages that uses equations as analytical models and obtain solutions using numeral techniques, resulting in their high level of accuracy. Numerical models are mostly used to address complex situations because they are less constrained by the simplifying assumptions required to obtain discrete solutions. Tracers are by far the most useful in detecting preferential flow paths, mixing and travel time of water and are helpful in calibrating models to define the capture zone (Moreau *et al*., 2014).

Another method that can be used to define the wetland capture zone is the analytical element models. These models are implemented on computers and use numerical techniques to approximate complex analytical solutions. They provide two dimensional discrete solution in time or space. They are also less costly in comparison to numerical models and have modest level of accuracy (Moreau *et al*., 2014).

The method one choses depend on a number of factors. In the current research, the hydrogeological mapping method under desktop review is used, mainly because of data limitation. The hydrogeological mapping method delineates the capture zone based on potential recharge area of the wetland, which is inferred from groundwater flow direction, geological data, geophysical and geomorphic properties of the underlying aquifer (Moreau *et al.,* 2014).

4.14 Data analysis tools

The various datasets collected and generated in the course of this research are analysed, interpreted and presented using appropriate software including, ArcMap, Surfer, IPI2 Win, Aquachem, Flow Characteristics (FC) and SPSS.

ArcGIS was used in creating maps, delineating the catchment boundaries and measuring areas and the outline and surface of the conceptual model of the area using a digital elevation model downloaded from the National Aeronautics and Space Administration (NASA, 2014). Thereafter Corel draw was then used for editing for presentation. Surfer 9.0 was used in the creation of groundwater flow direction map using groundwater level and creating spatial distribution maps, which were later edited using coral draw. Aquachem 4.0 was used to define the hydrochemical water type (facies) for the water samples analyzed and was used to construct Piper plots, Wilcox plots and calculating the total hardness of water sample. Flow Characteristics (FC) is a freely available excel program that was used to analyse and calculate aquifer parameters such as sustainable yield and aquifer transmissivity (Van Tonder and Xu, 2000).

4.14.1 Data compilation and analysis

The total alkalinity (TAL), the bicarbonate, the carbonate and the chloride in mg/l are calculated using the following equations, respectively:

$$\mathrm{TAL}\ \left(\frac{\mathrm{mg}}{\mathrm{l}}\ \text{as}\ CaCO_3\right) = \frac{Moles\ of\ acid\ used \times Volume\ of\ HCl\ used \times 50000}{Volume\ of\ sample\ used} \tag{17}$$

$$\mathrm{H}CO_3\ \left(\frac{\mathrm{mg}}{\mathrm{l}}\right) = \frac{\text{Volume of acid used} \times 6.102 \times 10000}{Volume\ of\ sample\ used} \tag{18}$$

$$CO_3\ \left(\frac{\mathrm{mg}}{\mathrm{l}}\right) = \frac{\text{Volume of acid used} \times 3.005}{Volume\ of\ sample\ used} \tag{19}$$

$$Cl^-\ \left(\frac{\mathrm{mg}}{\mathrm{l}}\right) = \frac{\text{Volume of acid used} \times \text{Moles of acid used} \times \text{Molar mass} \times 10000}{Volume\ of\ sample\ used} \tag{20}$$

CHAPTER 5-RESULTS AND DISCUSSION

This chapter presents the results and analysis of the data collected in the course of this research and the discussion of these results. Original data collected during this research are complimented with secondary data. These datasets are collated, interpreted and presented in the forthcoming sections. The interpretation made and the results are compared with other research findings elsewhere and discussed, towards defining and presenting the fundamental components to the hydrogeological conceptualisation of the Kosi Bay Lakes system.

Since the area under investigation is mostly underlain by various combinations of unconsolidated sand, silt and clay deposits, it becomes a challenge to differentiate between the various layers even from borehole logs. The slightest change in color, grain size and texture might be an indication of a different geological Formation. The method of drilling doesn't help either as it mixes the sand with water as it drills. However, efforts were made to collect and interpret geophysical data, borehole logs and pumping tests data, particularly of boreholes drilled by Jeffares & Green (Pty) Ltd, and these were integrated with work done by Worthington (1978), Meyer and Godfrey (1995), to determine the properties of the aquifers that underlie the study area.

5.1 Results of Geophysical investigation and borehole drilling

Geophysical techniques are the most suitable and cost effective way to investigate areas situated in the Zululand Coastal Flat. Electrical resistivity method is used commonly for choosing suitable borehole drilling sites, for the most productive borehole.

During the course of this research 12 electrical resistivity sounding were made within the study area (Figure 5.1). Four of the sounding curves were done for production borehole prospection, and the remaining eight sounding curves were done for sitting of production boreholes as part of Jeffares & Green (Pty) Ltd. These electrical resistivity curves were compared with the electrical resistivity data reported by Worthington (1978) for the area around Richards Bay where the geological successions were grouped into four geoelectric units.

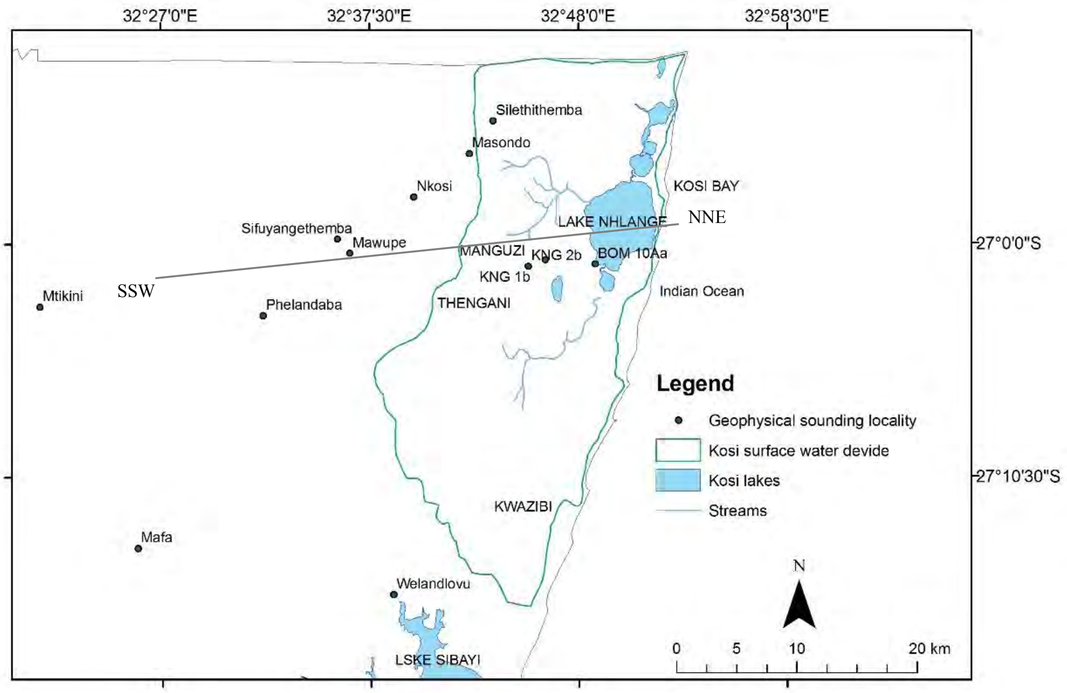


Figure 5.1: Spatial distribution of the location of geophysical investigation sites.

The sounding curves generated indicate a decrease in resistivity with depth (Appendix E). Table 5.1 shows the vertical electrical sounding interpretation of the 12 sites investigated. The information extracted from the sounding curves clearly defines the approximate thicknesses of the geological Formations at each site. Almost all the electrical soundings have electrode spacing of up to 300m. The results show that the Holocene age sediments record resistivity values ranging from 1121 Ω.m (for Mawupe site) to 14715 Ω.m (for Welandlovu site), indicating saturated to dry surface sand. The Pleistocene age Kosi Bay Formation records resistivity of up to 398 Ω.m (for Sifuyangethemba site). The Pleistocene age Port Durnford Formation and the Uloa records resistivity of up to 99.8 Ω.m (for Phelindaba site). The sounding curve that flattens out and records values of up to 19 Ω.m indicates the Cretaceous siltstone. In some of the electrical resistivity sounding curves (Mafa, Mtikini, Welandlovu and Mawupe), the resistance basement is detected and is indicated by the rise of the final segment to a more resistant rock of possibly the Lebombo Group volcanic rocks and this corresponds well with what was observed during drilling of boreholes. The results of the electrical resistivity sounding obtained in this research correspond well with the result reported by Worthington (1978).

Table 5.1: Vertical Electrical Sounding (VES) inversion results found based on the Schlumberger array.

VES location	Resistivity (Ω.m)	Thickness (m)	Geological Formation
Silethithemba	3551	26	KwaMbonambi
	553	25	Kosi Bay with Lignite
	-	13	Port Durnford
	19.4	-	Uloa/Umkhwelane
Masondo	1394-7149	18	KwaMbonambi
	150	35	Port Durnford & Kosi Bay
	67.9-197	-	Kosi Bay
	9.68	-	-
Sifuyangethemba	11882	7	KwaMbonambi
	398	41	Port Durnford & Kosi Bay
Mawupe	1121	13	KwaMbonambi
	76	20	Port Durnford & Kosi Bay
	4.99	2	Uloa/Umkhwelane
	588	-	-
Phelindaba	29.2-114	33	Kosi Bay
Mafa	1127	12	KwaMbonambi
	-	6	Port Durnford & Kosi Bay
Mtikini	1229	6	KwaMbonambi
	8.69	4	Uloa/Umkhwelane
KNG 1b	1862	1	KwaMbonambi
	90-627	20	Kosi Bay with Lignite
KNG 2b	1539-5059	4	KwaMbonambi
	255	28	Port Durnford & Kosi Bay
	0.223	48	-
BOM Aa	5089-10085	4	KwaMbonambi
	585-917	9	Berea
	78.5	51	Port Durnford & Kosi Bay
Welandlovu	14715	11	KwaMbonambi
	135	29	Kosi Bay
	15.6	13	Port Durnford & Uloa
	4980	-	-

Figure 5.2 is a well to well litho-stratigraphic cross-section drawn across the study area, where the direction of the cross-section line is indicated in Figure 5.1. The well to well cross-section describes the underlying geological materials and some of their properties such as colour, texture, grain size and depth at which the changes occurs. None of the boreholes (Appendix F) were drilled deep enough to intersect the hydrogeological basement (the Cretaceous siltstone). It is important to note that the majority of the boreholes logs correspond well with the electrical sounding curves and its interpretation.

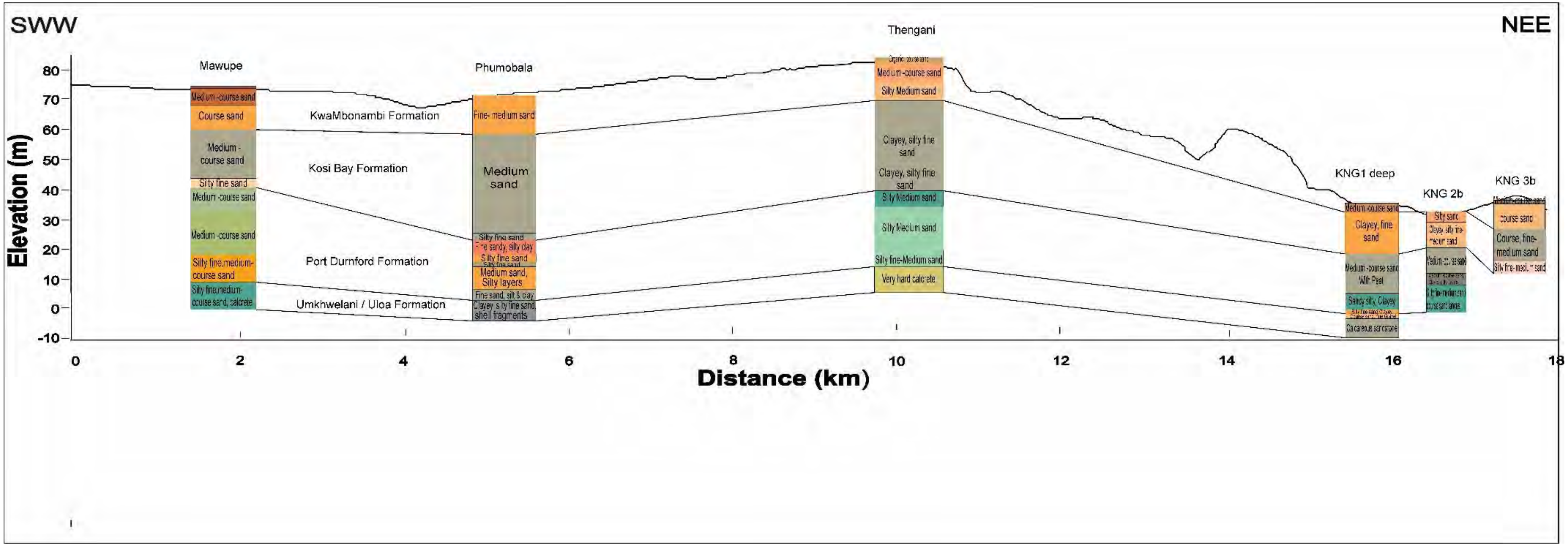


Figure 5.2: Well to well geological cross-section in the Kosi Bay catchment.

5.2 Aquifer classification and their hydraulic properties

The geological Formations underlying study area are broadly grouped into three hydrostratigraphic units, an aquitard and aquiclude of varying thicknesses (Table 5.2 and Figure 5.2), all of which are characterized by primary porosity. The St Lucia Formation is considered as the hydrogeological basement and thus an aquiclude due to its low permeability (Meyer *et al.,* 2001; Weitz and Demlie 2014, 2015). According to Worthington (1978), the Uloa and Umkhwelane Formations (deep aquifers) overlying the siltstone are regarded as the main aquifer in the area with hydraulic conductivity and sustainable yield ranging from 0.5-23.6 m/d and 5-20 l/s, respectively and a storage coefficient between 2 x10^{-4} - 6 x10^{-4}. The thickness of the unconfined aquifer, the aquitard and the leaky confined aquifer are derived from the borehole data collected, which fall within the ranges that has published for the units by Worthington (1978); Meyer and Godfrey (1995); and Meyer *et.al*. (2001).

The Uloa and Umkhwelane Formations are overlain by the Port Durnford Formation, which is a leaky aquifer unit, made up of loosely consolidated sand, silt and clay (Meyer *et al.,* 2001). The porosity and hydraulic conductivity of this unit are 31% (Davies Lynn and Partners, 1992) and 4.3 m/d (Mayer and Godfrey, 1995), respectively. The Kosi Bay Formation, which is made up of silt and silty sand is characterized by relatively low hydraulic characteristics and have a hydraulic conductivity that ranges from 4-5 m/d. A lignite layer is occasionally encountered between the Port Durnford and Kosi Bay Formation (Appendix F). This lignite layer in borehole KNG 1b was encountered at a depths from 16 to 29 m below ground level (bgl), while in Borehole Silethithemba, it was encountered at depth of about 60- 64 m bgl, and is often a thin layer between the Port Durnford and the Kosi Bay Formations.

The extensive Holocene cover sands overlay the Kosi Bay Formation are grouped into the KwaMbonambi and Sibayi Formations. They make up the shallow aquifer and are by far the most exploited aquifer by the rural communities in the area through hand pumps and dug wells. The hydraulic conductivity and sustainable yield of these aquifers range from 0.87-15.6 m/d and 0.5-5 l/s, respectively. Using the Cooper Jacob's method, the average transmissivity for the shallow aquifer was calculated at 305.7 m^2/day, and the deep aquifers have an average of 83 m^2/day (Appendix G).

Table 5.2: Summary of Hydraulic properties of aquifer layers underlying the Kosi Bay area.

Formation	Aquifer type	Thickness (m)	K(m/d)	Porosity (%)	Sustainable yield (l/s)	Transmissivity (m^2/d)	Storage Coefficient
Sibayi & KwaMbonambi	Unconfined aquifer	3-16	0.87-15.6	38	0.5-5	305.7*	-
Kosi Bay	Aquitard	5-33	4-5	36	2-10		-
Port Durnford	Leaky confined aquifer	4-32	4.3	31	2-10		1.9x10^{-3}
Uloa & Umkhwelane	Confined aquifer	3-20	0.5-23.6	42	5-20	83**	2x10^{-4}-6x10^{-4}
St Lucia	Aquiclude	800	Low	-	<1		-

** Deep aquifer
*Shallow aquifer

5.3 Groundwater recharge, local groundwater flow direction and groundwater contributing area

5.3.1 Groundwater recharge rate

Groundwater recharge was calculated using the chloride mass balance method at each borehole based on average chloride deposition measured at Amanzengwenya and Phelindaba stations (data from Meyer *et al.,* 2001) and groundwater chloride concentration measured at each borehole in the course of this research. The results indicate that the recharge ranges between 34 -326 mm/year (Table 5.2) and the mean annual recharge estimated for the catchment is 130 mm, which amounts to about 13% of Mean Annual Precipitation (MAP). This recharge rate is similar to that reported by Weitz and Demlie (2014) for the Lake Sibayi catchment located south of the present study area. Generally, areas closer to the coast are supposed to receive high recharge in comparison to the areas further away, since precipitation decreases inland. However, the recharge distribution for the current study area does not show any distinct pattern (Figure 5.3).

5.2.2 Groundwater flow direction and groundwater contributing area to the lakes

The general local groundwater flow direction for the study catchment is presented in Figure 5.4 and is from west to east, through the lakes to the Indian Ocean. The groundwater level contours shown in Figure 5.5 were established using groundwater level measurements made during the field campaigns (April to May 2013). These original data sets were complemented by groundwater level data from the KZN GRIP project (KZN GRIP, 2013). Based on the groundwater level contours and the associated flow direction, the groundwater contributing area to the Kosi Bay Lakes is delineated and estimated at 331 km^2. The surface water catchment delineation in the coastal plain area is a bit complicated due to the general flat topography and complicated contribution of groundwater discharge. In this light, the total surface water catchment area of the lakes is about 659 km^2.

Table 5.3: Point groundwater recharge estimates using the chloride mass balance method within the study area.

Sample ID	Water point	Chloride deposit(mg/l)	Ground water Chloride(mg/l)	Mean precipitation(mm)	Recharge (mm/yr)	Recharge (% of annual rainfall)
KB 1	borehole	7.10	147.11	950.00	45.88	4.83
KB 3	borehole	7.10	70.90	980.00	98.19	10.02
KB 4	borehole	7.10	20.49	940.00	325.92	34.67
KB 9	borehole	7.10	81.54	940.00	81.90	8.71
KB 10	borehole	3.77	95.72	870.00	34.27	3.94
KB 13	borehole	3.77	28.83	860.00	112.44	13.07
KB 15	borehole	7.10	77.99	910.00	82.89	9.11
KB 21	borehole	7.10	46.09	970.00	149.53	15.41
KB 22	borehole	7.10	51.40	1000.00	138.21	13.82
KB 32	borehole	7.10	36.16	960.00	188.59	19.64
KB 36	borehole	7.10	60.27	950.00	111.99	11.79
KB 44	borehole	7.10	26.84	930.00	246.18	26.47
KB 45	borehole	3.77	42.87	870.00	76.51	8.79
Average				933.08	130.19	13.87

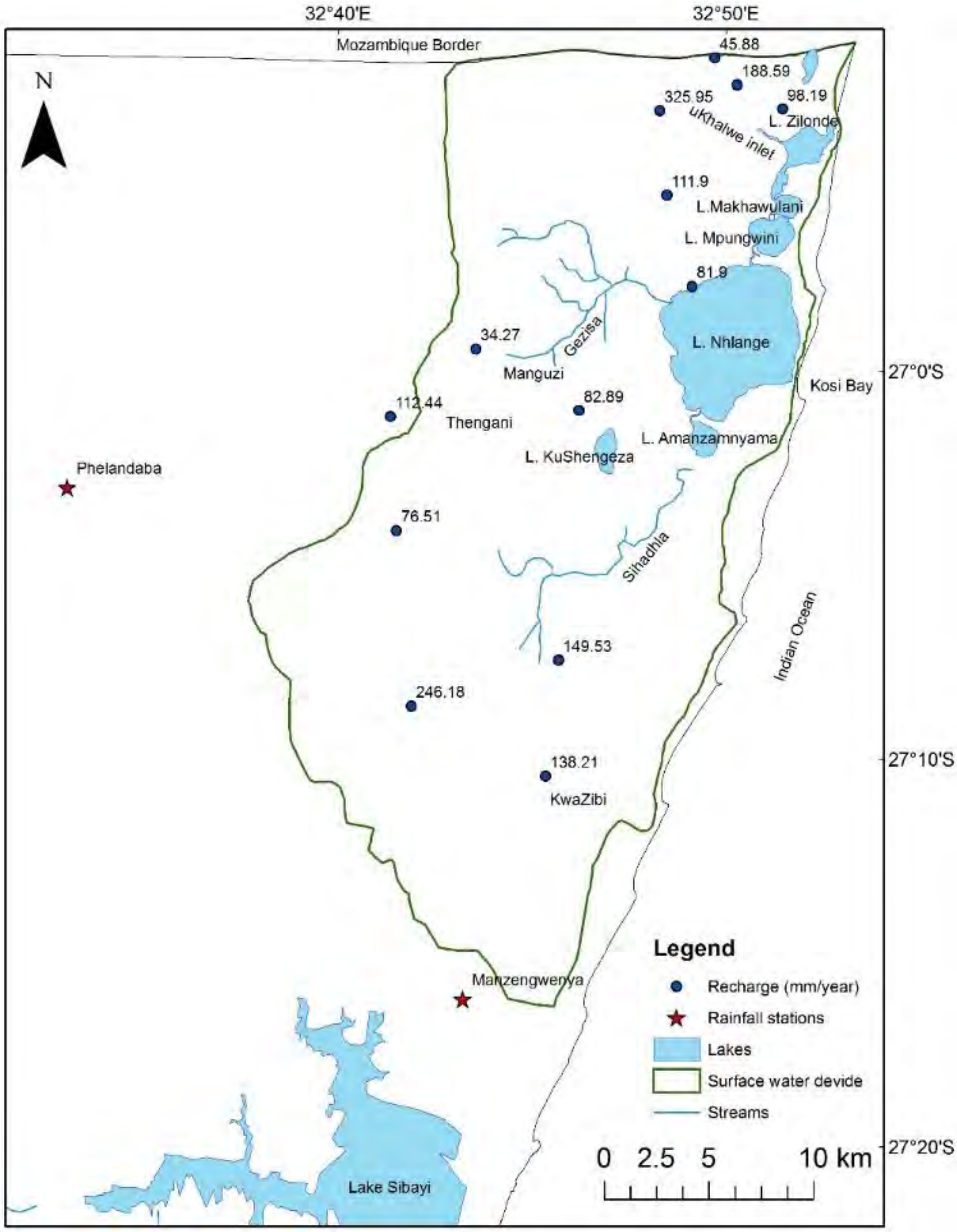


Figure 5.3: Spatial distribution of groundwater recharge within the Kosi Bay catchment using the CMB method.

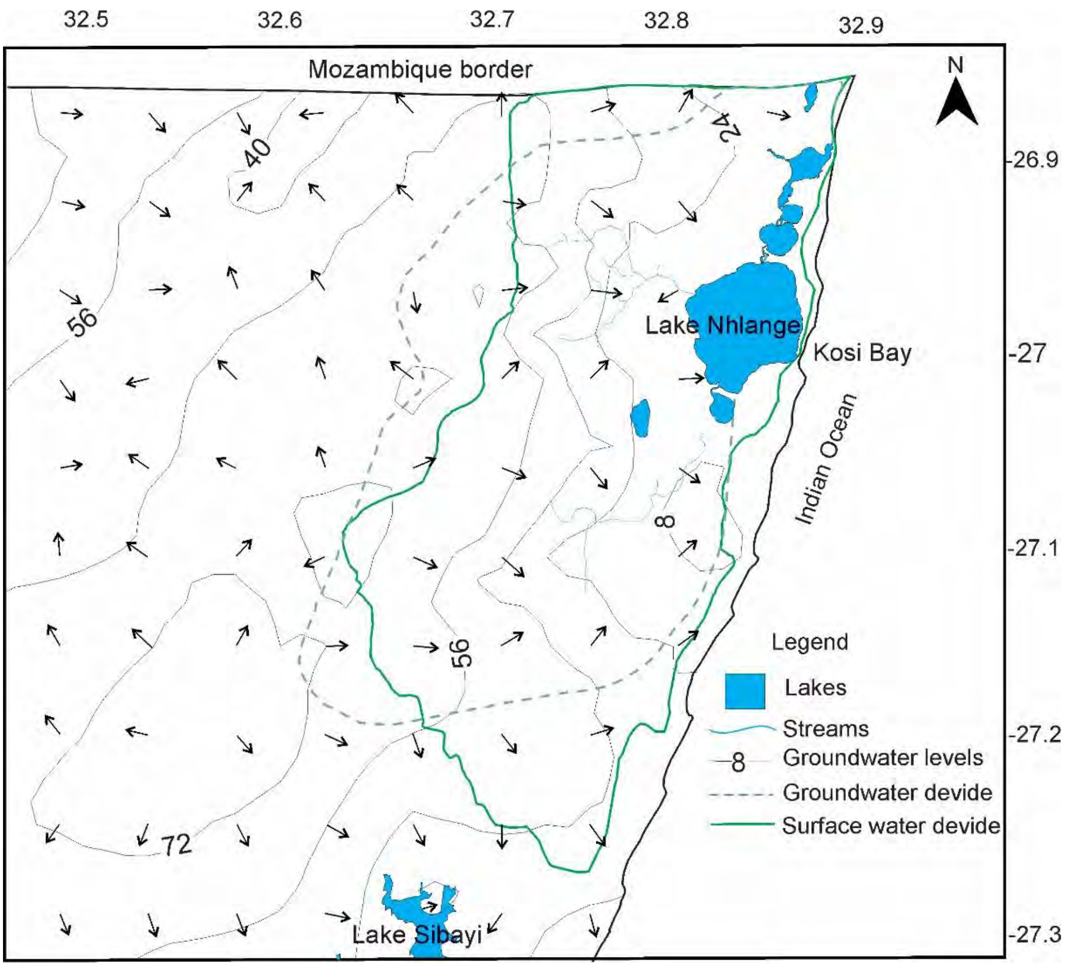


Figure 5.4: Local groundwater flow direction map, with a delineated groundwater boundary (593 km^2) illustrating water that contributes to the overall water balance.

5.4 Wetland Capture zone delineation

In order to preserve and protect natural resources and systems, in this case groundwater feeding part of the ISimangaliso wetland park, a capture zone is delineated. There are several methods that can be used to delineate a capture zone, depending on the requirements of the user, and the limitations of their hydrological data and their resources. For the current research, due to the data limitation a hydrogeological mapping method was used to delineate the capture zone of the wetland in the area of study. Although this method is a desktop review, it does have some level of certainty, but in the low levels. The method uses the surface water catchment, geological maps, and groundwater catchment from water level measurements, well logs, hydrochemistry data, geophysical survey, aquifer test data and tracer tests.

The area generally has a flat topography, with depression in between sand dunes where the main water table lies very close to the surface, hence the distribution of the wetlands. Geologically, the wetlands tend to occur in area where the KwaMbonambi Formation outcrops at the surface, perhaps due to its high porosity and hydraulic conductivity in comparison to the underlying Kosi Bay Formation. Figure 5.5 shows that there is a groundwater divide between the wetland in the east and the one in the west. The capture zone of the eastern wetland has an area of about 644 km^2. Ecologically, since the whole area is a wetland any abstraction, whether from the east or the west has an impact on the water level reduction, which directly affects the wetlands.

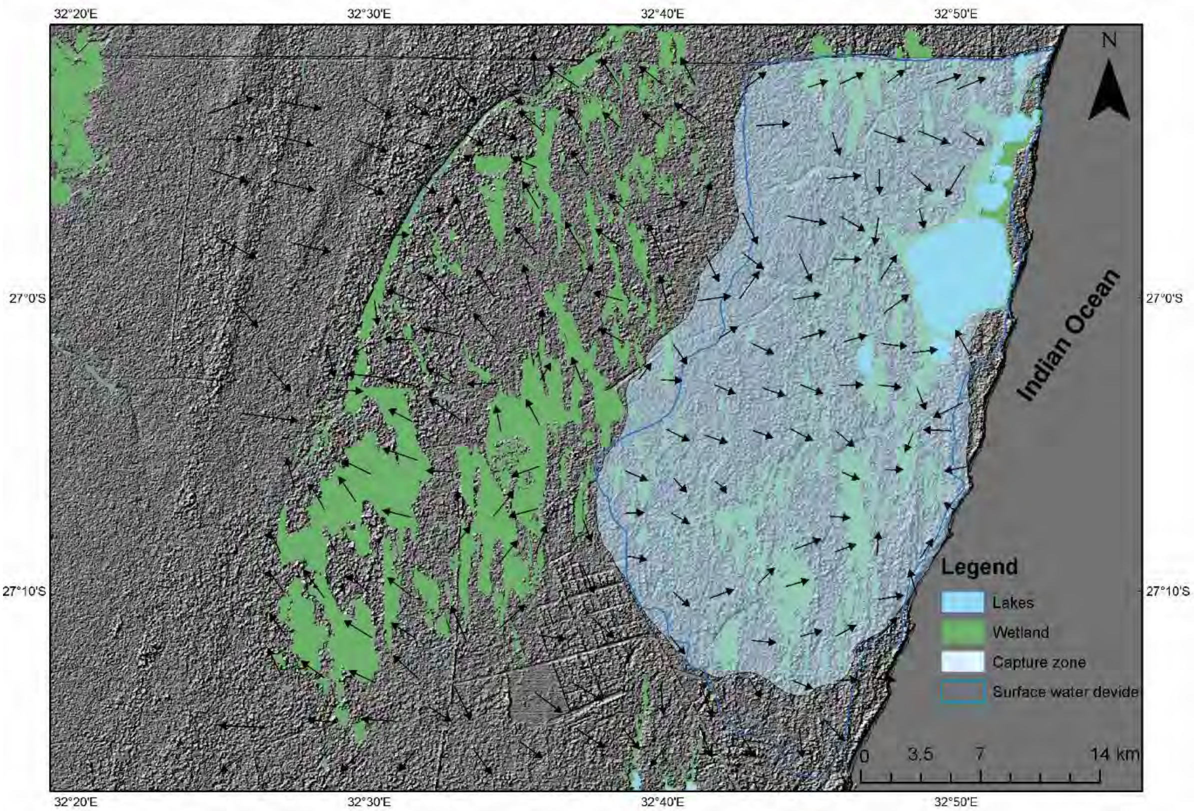


Figure 5.5: Capture zone delineated using the hydrogeological mapping method of wetlands.

5.5 Water balance analysis

5.5.1 Water Balance of the Lakes

The area under study is a dynamic open system. Outflow and inflow through the Kosi mouth is assumed to be negligible for the purpose of this study. Moreover, because of the nature of the lakes (some are interconnected and some are isolated), the attempt to calculate a water balance for each lake was fruitless. Therefore, the Kosi Bay Lakes were simplified and treated as one major lake system for water balance calculation purposes. The total area of the lakes/ water bodies within the Kosi Bay catchment is 48 km^2, the following general water balance equation describing the inflow and outflow of water to and from the lakes system was used:

$$\text{Inflow} - \text{Outflow} = \pm \text{Change in storage} \tag{20}$$

All the inflow and outflow parameters used in the water balance analysis were observed and estimated from 1997-2015 and are tabulated as the mean monthly and mean annual values in Tables 5.4 and 5.5, respectively. The results in Table 5.4 show strong seasonal variation in almost all the water balance parameters. Both the mean monthly and annual water balance of the lakes indicates that the total inflow is greater than the total outflows from the lakes, resulting in positive storage (ΔS). This positive storage leads to a rise in the lake levels, and it is supported by the long-term lake level records in Figure 5.6, that show an increasing trend over time over the main lake (Lake Nhlange). There is a strong direct dependence of the lake levels on the rainfall over the lakes from Figure 5.6, changes in rainfall patterns directly affect the water levels, and i.e. they show a similar trend.

The mean annual volume of precipitation on the surface of the lakes, based on a long -term record from the Ingwavuma Kosi Bay and Ingwavuma Manguzi rainfall stations (SAWS, 2013) is 43948194 m^3/year. The mean annual surface water runoff from the catchment into the lakes is estimated to be 71784917 m^3/year, which is about 14 % of the mean annual precipitation of the catchment area. Groundwater abstraction for plantation/forestry and by the local community is estimated at 1179394 m^3/year. The evapotranspiration from the pine plantation/forestry within the groundwater contributing area is 24948897 m^3/year.

Groundwater inflow into the lakes is estimated to be 32228554 m^3/year. The mean annual open water evaporation for the Kosi Bay lakes is estimated at 62139143 m^3/year, which is higher than the mean annual precipitation falling on the surface of the lakes. Groundwater outflow through the dune cordon towards the sea calculated using the Dupuit's equation (Dupuit, 1863 in Fetter, 2001) is 29564076 m^3/year. The groundwater outflow was estimated based on an average aquifer permeability of 5 m/d and a hydraulic head difference of 18 m. The details of the water balance parameters and calculations are present in Appendix H, I, J, K, L, M and N.

Table 5.4: Mean monthly estimated major Lake water balance components (in 10^6 m^3 for Kosi Bay Lakes).

Parameters	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
P_1	7.05	5.94	6.56	3.37	1.27	2.10	2.74	1.40	2.53	7.86	6.72	4.93
R_{off}	8.86	9.94	7.92	4.84	1.49	1.71	2.61	1.39	2.88	4.02	10.6	6.66
G_{in}	0.34	0.32	0.58	0.10	1.33	1.78	1.75	1.46	1.02	0.93	0.64	0.50
E_o	6.04	5.33	5.59	5.01	4.83	3.52	3.96	4.64	5.29	5.87	5.94	6.06
G_{out}	2.51	2.26	2.51	2.51	2.51	2.51	2.51	2.51	2.51	2.51	2.51	2.51
ΔS	5.91	8.54	6.50	2.01	-3.74	-0.92	0.14	-3.03	-1.29	4.00	9.58	3.49

Table 5.5: Long term mean annual lake water balance of the Kosi Bay Lakes (in 10^6 m^3).

Surface water Catchment area (km^2)	Groundwater contributing area (km^2)	Kosi Bay Lakes area (km^2)	P_i	R_{off}	G_{in}	E_O	G_O	ΔS
659	331	48	52	63	12	62	30	+31

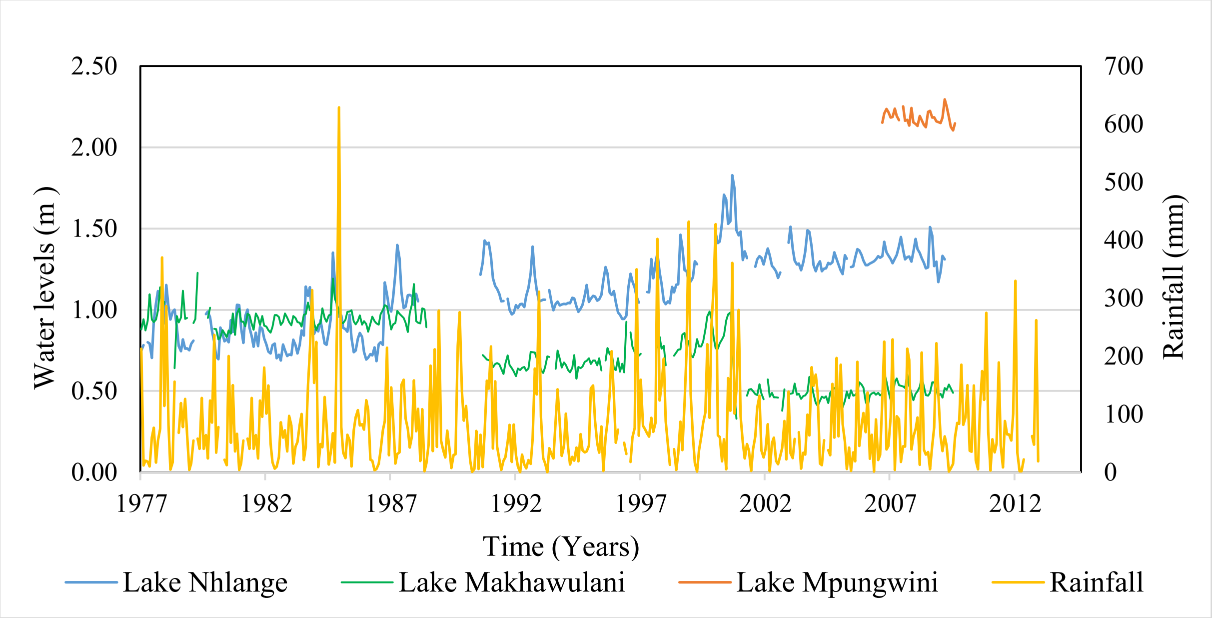


Figure 5.6: Long term lake level changes with monthly precipitation from 1977- 2014 (lake level data from DWA, 2015 and Precipitation data from SAWS, 2014).

5.5.2 Water Balance for the Kosi Bay Lakes Catchment

The catchment water balance estimation has fundamental importance for water resource decision makers as it quantifies the available water resources for a given basin. For the Kosi Bay catchment, an attempt has been made to calculate the water balance based on the available data. The results are presented in Table 5.6 which shows seasonal variation in precipitation, evaporation and evapotranspiration. The precipitation is the biggest contributor to the water balance followed by evapotranspiration and this is expected for an area that is mainly covered by plantation, forests and wetlands. Table 5.7 is the annual catchment water balance estimate, where the mean annual precipitation over the catchment is 718x10^6 m^3. 639x10^6 $m^3$of the precipitation going back to the atmosphere through evapotranspiration, 62x10^6 m^3 is taken up by the lakes occupying the catchment area and is evaporated back to the atmosphere. 30x10^6 m^3 of the precipitation seeps under the sand dunes and make its way to the Indian Ocean. 1.2x10^6 m^3 and 7x10^6 m^3 percent are for groundwater and surface water abstraction, respectively. This trend has been observed in the study area through drying up of once highly productive shallow boreholes by the local inhabitant and Hendrik Du Plessis (personal communication, November, 2014). For further detailed calculations of the water balance parameters, refer to Appendix O, P Q & R.

Table 5.6: Mean monthly estimated catchment's volumetric water balance components (in 10^6 m^3).

Parameters	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
P_l	85.16	84.66	90.19	51.87	15.87	25.03	33.61	17.45	35.09	102.93	93.16	68.45
Wg	0.10	0.96	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Ws	0.55	0.50	0.55	0.53	0.55	0.53	0.55	0.55	0.53	0.55	0.53	0.55
ET	69.83	62.74	64.14	50.12	44.20	29.92	33.23	42.96	52.36	57.57	62.74	69.38
E_o	5.87	5.22	5.55	4.97	4.19	3.54	3.99	4.64	5.29	5.87	5.94	6.06
G_{out}	2.51	2.28	2.51	2.44	2.51	2.44	2.51	2.51	2.44	2.51	2.44	2.51
ΔS	2.72	14.76	17.76	-6.05	-35.98	-35.98	-6..44	-32.54	-24.90	36.46	21.87	-10.01

Table 5.7: Annual catchment water balance of the Kosi Bay Lake (10^6 m^3).

Surface water Catchment area (km^2)	Groundwater contributing area (km^2)	Kosi Bay Lakes area (km^2)	Pi	ET	Wg	Ws	Eo	Go	ΔS
659	331	48	719	639	1.2	7	62	30	-30

5.6 Hydrochemistry

The chemical properties of water are very important in determining its suitability for domestic, industries, agriculture and other uses. When groundwater moves through subsurface geological materials, its chemistry changes as water mixes and react along its path (Mazor, 1991). Water chemistry also gives indications of the rock types through which the water has come in contact with and can give clues about the residence time and flow velocity (Mazor, 1991). The amount of chemicals dissolved in water is attributed to the type of mineral that the water comes in contact with, the temperature, the pH and the environmental conditions. In order to understand the hydrochemistry, water quality and the interaction of groundwater and surface water within the catchment, major ions, trace elements and environmental isotopes data were analyzed.

The results of onsite measured parameters are presented in appendix S. The specific electrical conductivity (EC) which is measured onsite indicates the ability of water to conduct electricity has direct relationship with the ionic concentration of the water being measured. The EC for the Kosi Bay Lakes increases from fresh water to saline in a south to north direction, ranging from 1024 µS/cm (Amanzamnyama) to 24600 µS/cm (Makhawulani). The increase in salinity is perhaps controlled by the position of the lakes along the coastline, high evaporation, termination of the local flow system and connection to the sea through the estuary.

The total hardness of groundwater samples ranged from 5 – 437 mg/l as $CaCO_3$, and can be classified as "soft" to "very hard" depending on the mineral content. Bicarbonate is the dominant major ion in the groundwater. The total hardness of the Lakes ranges from 115 (Amanzamnyama) – 3837 mg/l (Makhawulani) as $CaCO_3$, and classifies as "moderately hard" to "very hard". The total hardness of Gezisa stream, near Thengani is 43 mg/l as $CaCO_3$, classifying the water as "soft (Appendix T & U).

Piper diagrams and Schoeller diagrams are very useful in illustrating the different water types and dominant chemical species in water based on the concentration of the major cations and anions plotted on each of the diagrams (Figures 5.7 and 5.8), revealing the underlying factors influencing groundwater and surface water chemistry. These factors include geology of the area, land use practices, water movement and circulation.

The Surface and groundwater in the catchment are classified into hydrochemical water types (facies) based on the dominant or major cation and anion. The chemical composition in most of the samples is similar, dominated by Na, Ca, Mg, Cl and HCO_3. , Because of the unconsolidated nature and similar hydrogeological characteristics of the sediments underlying area, it becomes a challenge to differentiate between shallow and deep aquifers. Nevertheless, attempts have been made using chemical data (Appendix T and U). The samples can generally be divided into distinct groups based on the type of resource the water is sampled from. In this light, a slight difference can be made between shallow aquifer and deep aquifer systems. The water sample tested in April 2013 were sampled from shallow boreholes, whilst 2005-2014 sample water were mainly sampled from deep production boreholes, hence the plots in Figures 5.7a and 5.8a, show a variation in cations and a similarity in the anions. Therefore, it can be concluded that the shallow aquifer is dominated by Na, Cl and HCO_3 chemical composition (Figure 5.7), whereas, the deep aquifer is dominated by Na, Ca, Mg and Cl (Figure 5.8). The chemical composition of the shallow aquifer perhaps indicate recent recharge from precipitation. Whereas, the deep aquifer, it's an indication of the interaction of water with the limestone or the shell fragments that make up the Uloa and Umkhwelane Formations.

Depending on the occurrence, landscape and the distance away from the coast the deep aquifer can be encountered from a depth of 12 to 74 m below ground level. At Mtikini and BOM 10Ab, respectively, the boreholes drilled further form the coastal areas encounter the deep aquifers at shallow depths in relation to the boreholes drilled closer to the coast.

The lakes are dominated mainly by Na and Cl chemical composition, perhaps highlighting the termination of the flow system and interaction with the Indian Ocean through the Kosi estuary. Streams and the fresh water Lake Amanzamnyama have a similar hydrochemical signature as the shallow aquifers indicating their interrelationship.

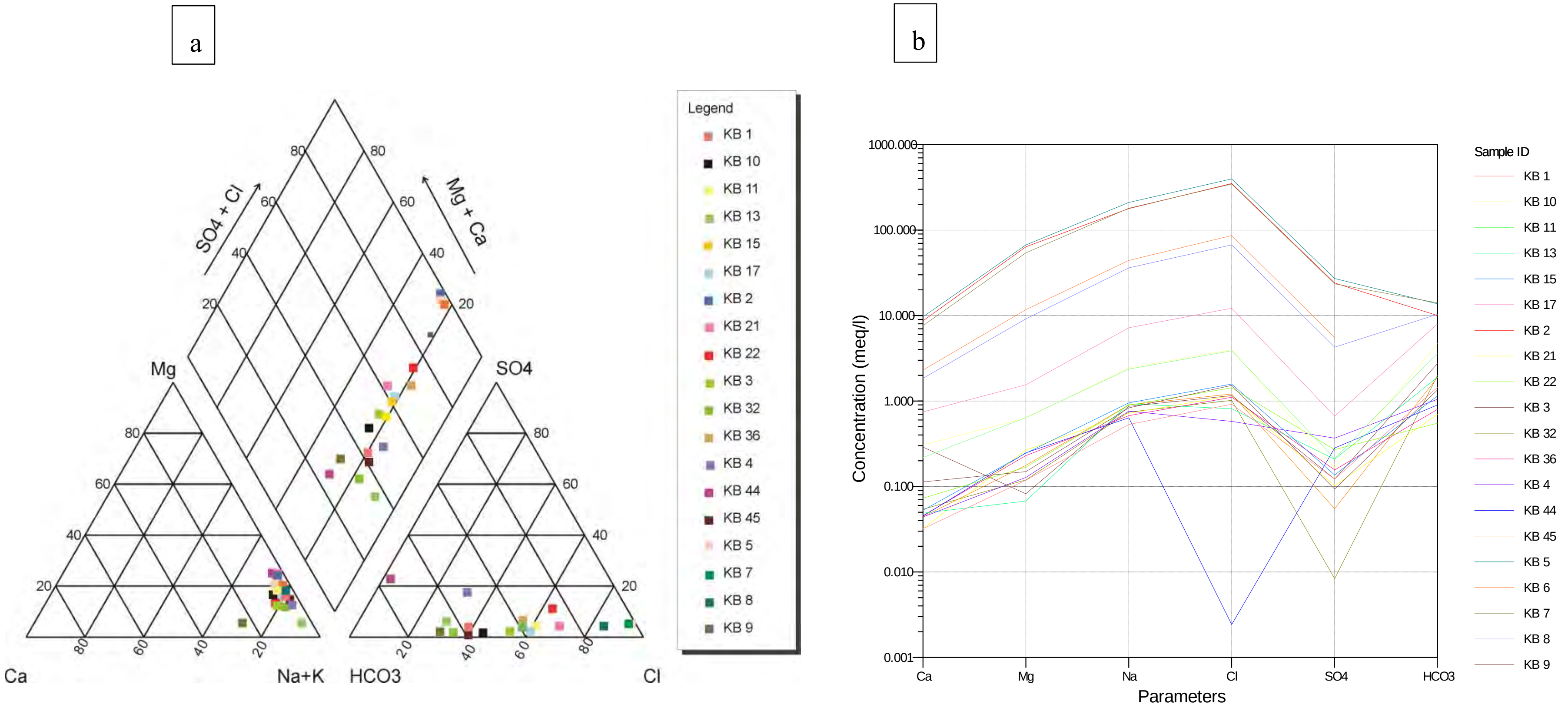


Figure 5.7: (a) Trilinear piper and (b) Schoeller diagram of groundwater and surface samples of April 2013, in and around Kosi Bay Lake Catchment.

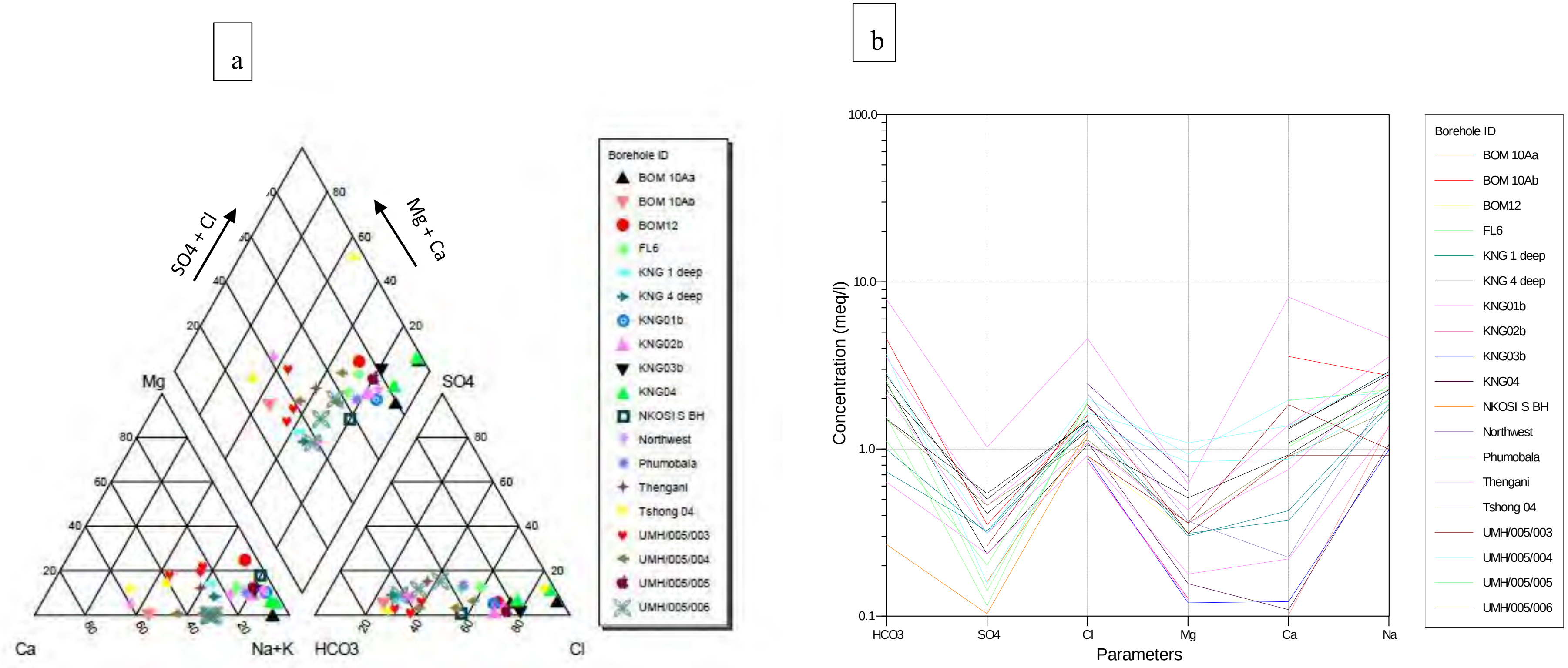


Figure 5.8: (a) Trilinear piper and (b) Schoeller diagram of groundwater sample showing chemical composition, dating from 2005-2014, in and around Kosi Bay Lake Catchment.

5.7 Statistical analysis of hydrochemical data

5.7.1 Correlation matrices

A data set of 67 groundwater chemistry was analysed using the Pearson's correlation matrices in order to find relationship between two or more variables. Only "r" values greater than 0.5 were analysed and the results are presented in Table 5.8. Samples with r greater than 0.7 are considered to be strongly correlated, whilst those with "r" ranging from 0.5 to 0.7 are moderately correlated. Strong correlation exist between the major elements (Na, K, Mg, Cl, HCO_3, NO_3), and EC, indicating that these are the main elements that contribute to the groundwater salinity. SO_4, Na and Ca are moderately correlated, and usually form evaporitic salts such as $CaSO_4$ and $NaSO_4$ under certain conditions. Therefore these results can possibly be an indication that the concentration of the chemicals increase with increased evaporation of groundwater or possibly the interaction of groundwater and the geological formation making up the aquifer.

5.7.2 Factor analysis

Factor analysis of the groundwater within the Kosi Bay Lakes system, using principal component analysis with varimax resulted in the extraction of three principal components which accounts for 89.3% of the variance of groundwater data presented in Table 5.9. The main aim of the analysis was to find the underlying factors or processes responsible for the groundwater chemistry in the study area. Using KMO and Bartlett's test to test the suitability of the data for factor analysis was found suitable, with KMO of 0.554 and Bartlett's test was significant ($p = 0.00$). Three principal components were determined using a Cattell's (1966) scree plot, this method involves plotting the extracted component with the eigenvalue and finding a point or a brake at which the shape of the curve changes direction and becomes flat. All the components above the break before the plot becomes flat are retained as they contribute the most to the explanation of the variance.

Table 5.8: Pearson's correlation matrices for groundwater data. All values in mg/l unless otherwise indicated.

	EC	pH	Temp	TDS	Na^+	K^+	Mg^{2+}	Ca^{2+}	Cl^-	F^-	HCO_3^-	NO_3^-	SO_4^{2-}	$\delta^{18}O$	δ^2H	^3H
EC[a]	1															
pH	-0.270	1														
Temp[b]	-0.610	-0.23	1													
TDS	0.999**	-0.318	-0.088	1												
Na^+	0.983**	0.417**	-0.037	0.239	1											
K^+	0.968**	0.448**	-0.143	0.156	0.632**	1										
Mg^{2+}	0.887**	0.238	0.004	0.221	0.394**	0.151	1									
Ca^{2+}	0.755**	0.328	-0.048	0.226	0.722**	0.368*	0.269	1								
Cl^-	0.978**	0.154	-0.131	0.592**	0.653**	0.421**	0.421**	0.654**	1							
F^-	0.297	0.054	0.041	-0.005	-0.018	-0.236	0.053	-0.157	-0.206	1						
HCO_3^-	0.810**	0.163	-0.087	0.812**	0.839**	0.831**	0.562*	0.825**	0.761**	0.564	1					
NO_3^-	0.709**	0.386	-0.200	0.675**	0.132	0.456	0.493	-0.144	0.35	-0.161	0.582*	1				
SO_4^{2-}	-0.023	0.234	0.273	0.230	0.641**	0.270	0.111	0.733**	0.463	-0.103	-0.251	-0.100	1			
$\delta^{18}O$[c]	-0.335	0.128	-0.415*	-0.330	-0.294	-0.216	-0.360	-0.222	-0.162	-0.373	-0.292	-0.300	-0.305	1		
δ^2H[c]	-0.360	0.146	-0.394*	-0.353	-0.297	-0.265	-0.431	-0.240	-0.199	-0.369	-0.281	-0.309	-0.290	0.959**	1	
^3H[d]	0.939**	0.171	-0.136	0.938**	0.920**	0.922**	0.915**	0.554	0.980**	-0.135	0.768*	0.769	-0.304	-0.531	-0.602	1

Table 5.9: Results of principal component factor analysis with Varimax rotation of groundwater data. All values in mg/l unless otherwise indicated.

	Communality	Component		
		1	2	3
EC[a]	0.979	0.973		
K^+	0.971	0.967		
Na^+	0.995	0.961		
Cl^-	0.931	0.940		
HCO_3^-	0.868	0.888		
Ca^{2+}	0.718	0.791		
Mg^{2+}	0.852	0.791	0.421	
NO_3^-	0.858	0.647	0.612	
pH	0.908		0.919	
SO_4^{2-}	0.892			0.934
Explained variance		6.640	1.229	1.062
Cumulative % of variance		66.39	78.68	89.30

[a] in µS/cm

The resultant components are positively correlated. In Figure 5.9, principal component 1 is weighted with K, Na, Cl, Mg, Ca, HCO_3, NO_3 and EC. This indicates a known positive relationship between EC and the major ions and the possibility of intermixing between deep and shallow aquifer systems, since the presence of HCO_3 indicates active recharge and Ca, Mg is characteristic of Uloa Formation located at deeper boreholes of the study area.

Principal component 2 is weighted with Mg NO_3 and pH. NO_3 and pH could be indication of possible pollution from fertiliser or other wastes. Principal component 3 is weighted with SO_4 only and traditionally a component must at least load two or more variable for meaningful interpretation (Gorsuch, 1983; Henson and Robert 2006). Nevertheless, SO_4 often indicates possible redox reactions and land use practices.

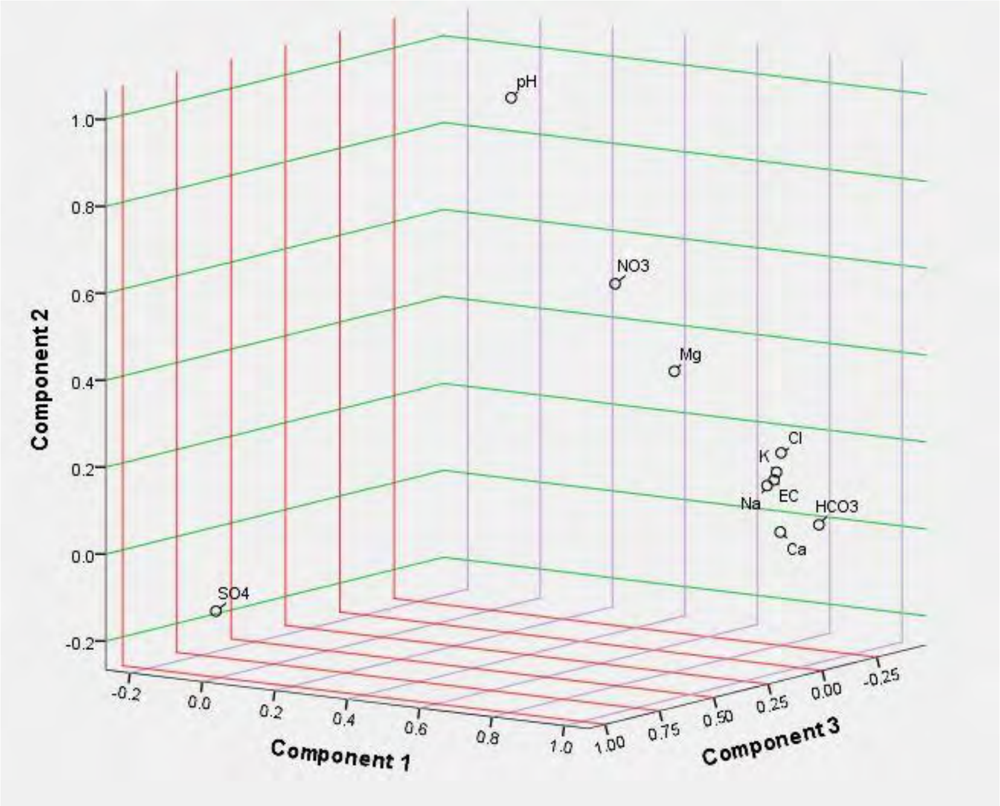


Figure 5.9: Results of principal component analysis in rotated space of the groundwater chemistry data.

5.8 Environmental isotopes (δ^2H, $\delta^{18}O$ and ^3H)

In order to trace the origin and movement of water in the catchment under investigation, environmental isotopes of water such as Deuterium (δD), $\delta^{18}O$ and tritium (^3H) were analysed, and the results are presented in Figures 5.10, 5.11, 5.12 and Appendix V. Work done by Vogel and Van Urk (1975) near St Lucia suggested that the isotopic composition of the groundwater might decrease from the coast inland as a result of rainout effects and this can be useful in tracing the movement of groundwater and its recharge areas. Meyer et al. (2001) and Weitz and Demlie (2014, 2015) successfully applied environmental isotope in the study of the Lake Sibayi (a freshwater lake situated a few kilometres south of the study area), in order to trace the movement of Lake's water under the dune cordon to the Indian Ocean. Similar method is applied in the current study (i.e. use of f $\delta^{18}O$, δ^2H and ^3H) to evaluate the interaction and movement of surface and groundwater of the Kosi Bay Lakes system.

The results from the stable isotope plot (Figure 5.10) along with the local and global meteoric water lines show a clear distinction between groundwater, streams and the Lakes. The groundwater in the area plot on the local meteoric water line but characterised by the lighter isotopes (relatively depleted isotopic signal) indicating that it is recharged from local rainfall and experienced little or no evaporation before infiltration. This is in line with the flat topography, and permeable nature of the cover sands. The lake samples plot on the local meteoric water line but are characterised by heavy isotopes (enriched isotopic signal) indicating strong evaporation (Gat and Gonfiantini, 1981). The stream samples have a similar isotopic signal as the groundwater. Despite the limited number of stream isotope data, the results support the fact that groundwater and streams are highly interconnected and that the streams are fed by groundwater flow.

Figures 5.10 and 5.11 indicate that, Lake Amanzamnyama has isotopic characteristics between groundwater and streams, and other lakes, indicating that it is mainly fed by groundwater and streams and less influenced by the other lakes. This is further explained by the low salinity and dilute chemistry of this Lake compared to the rest of the Lakes. Lake KuShengeza (an isolated Lake located west of the main lakes) experienced high evaporation as indicated by its heavy isotopic signal (Figure 5.11). The rest of the Lakes and the estuary are characterised by isotopic signals typical of open water body subjected to evaporation.

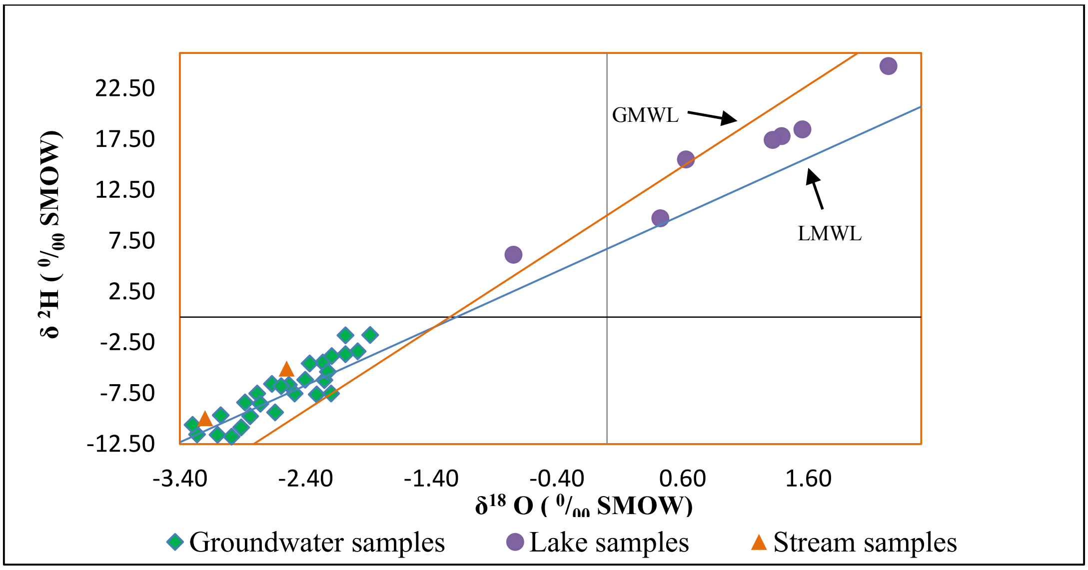


Figure 5.10: Plot of $\delta^{18}O$ and $\delta^{2}H$ of water samples collected within the Kosi Bay Lakes catchment along with the Local (LMWL) and Global meteoric water lines (GMWL).

The separate isotopic plot of groundwater samples (Figure 5.12), indicate their recharge area, altitude and depth to groundwater. One of the samples (Sample KB 10) taken from a borehole that taps the deep aquifer (Uloa Formation) has relatively the most depleted isotopic signature indicating a further inland recharge altitude or recharge from a separate precipitation climate regime.

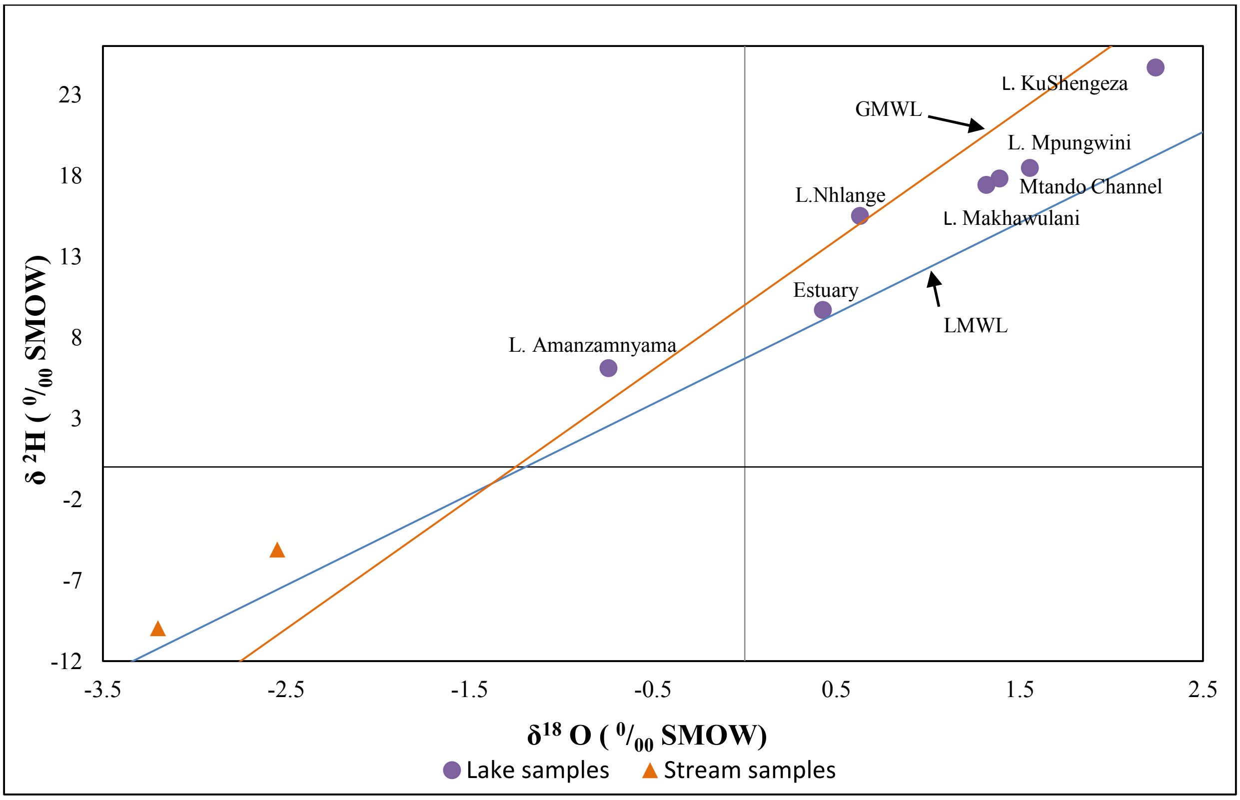


Figure 5.11: 18-Oxygen versus Deuterium cross plot for the surface water samples along with the LMWL and GMWL.

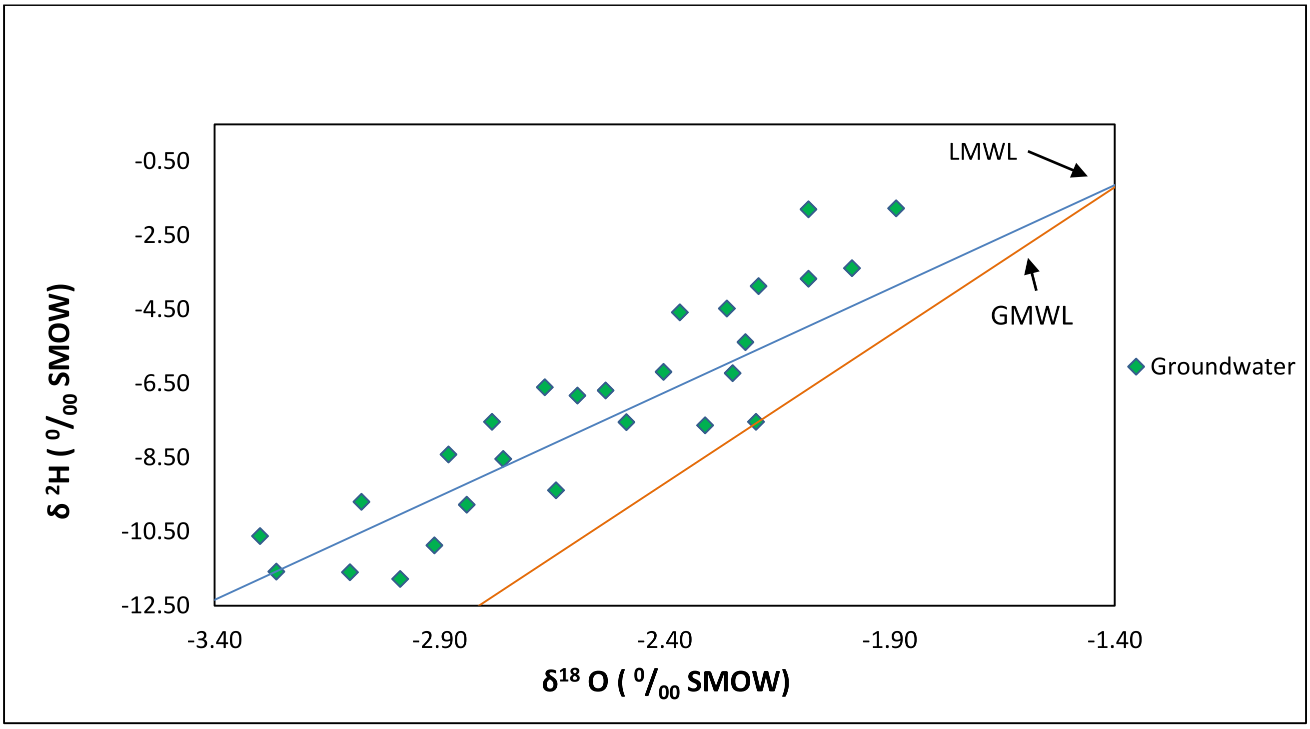


Figure 5.12: 18-Oxygen versus Deuterium cross plot for the Kosi Bay catchment groundwater samples along with the Local and Global meteoric water lines.

Results of the groundwater tritium analysis range from 0.5 to 4 TU (Appendix R). Based on the classification of tritium signal by Clark & Fritz (1997), the majority of the groundwater samples show a mixture between sub-modern and recent recharge signature. This is with the exception of two samples KB10 and KB3. Sample KB10 has a high tritium signature (4 TU) and was sampled from a well that taps the Uloa Formation indicating perhaps recharge from a different precipitation regime than todays. Sample KB3 has a very low tritium signature (0.5 TU) indicating that it was recharged pre-bomb times.

5.9 Water resource quality in the Kosi Bay Lakes catchment

Generally natural water moves from the mountains and ends up in the sea. Along its path it doesn't only experience physical processes but it is also subjected to biological and chemical exchanges with the water, rocks and other biomass. In nature it's unusual for water to exist in its pure nature. It usually contains a mixture of dissolved chemicals, biological organisms and solid particles. Processes such as precipitation, infiltration, overland flow, subsurface flow, groundwater flow, and stream flow aid in the dissolution of rocks and other material, chemical precipitation and movement of atmospheric, water and land chemicals and transforms the quality of water resources (Sergio, 1997). The quality of water from Gezisa stream is generally good, this is due to the slow movement of water through vegetated land with soft sandy soil. Nevertheless, it needs simple treatment before intake.

In most environmental processes involving the hydrological cycle, water act as a solvent, dissolving solids at different degrees. Groundwater and surface water quality analyzed during the study are evaluated in terms of the South African Water Quality guidelines for domestic, agricultural and industrial purposes (SAWQ, 1996); and the World Health Organization guidelines (WHO, 2011). These guidelines put a maximum allowable concentration of a water quality parameter. The guidelines indicate that if the limit is exceeded it will result in adverse health effects. Table 5.10 compares the range of water quality data collected with the SAWQ (1996) and WHO (2011) guidelines.

The primary data is data collected during April to May 2013 field campaign, while the secondary data is obtained Jeffares & Green (Pty) Ltd (2014). The results show that the primary data adheres to both guidelines, therefore concluding that the groundwater is safe for drinking, domestic, agricultural and industrial purposes except for microbiological parameters which were not analyzed. Results from the secondary data show that the majority of the sampled water fall within the limits of both standards as well, with the exception of two samples taken in July 2008, BOM 10Aa and Northwest. BOM 10Aa sample has calcium concentration that exceeds the SAWQ 1996 guidelines for domestic use. The Northwest sample (Appendix W & X) has chloride, sodium and fluoride concentrations that are above the safe target for domestic and agricultural use. The water quality of the Lakes except Lake Amanzamnyama is very poor owing to the high salinity and therefore not fit for many uses unless treated.

Table 5.10: South African Water Quality guidelines for domestic, industrial and agricultural use (SAWQ, 1996) and World Health Organization guidelines for drinking water (WHO, 2011).

	SAWQ Guidelines (1996)			WHO Guidelines (2011)	Primary data	Secondary data
	Safe target water quality (mg/l)			mg/l		
Chemical	Domestic	Agriculture	Industry		Measured parameters	Measured parameter
Alkalinity			0-1200			1.6-257
Aluminum	0-0.15	0-5		0.9	0.001-0.7	
Arsenic	0-0.01	0-0.1		0.01	0.003-0.005	
Barium				0.04	0.0176-0.3575	
Cadmium	0-5	0-10		0.003	0.0004	
Calcium	0-32				0.64-6.12	0.7-71.7
Chloride	0-100	0-100	0-500		20.48-141.53	29.9-162.5
Chromium	0-0.05	0-0.1		0.05	0.0007-0.0017	
Cobalt		0-0.05			0.002-0.0095	
Copper	0-1	0-0.2		2	0.001-0.010	
Fluoride	0-1	0-2		1.5	0.013-0.089	0.07-9.08
Iron	0-0.1	0-5	0-10		0.0319-4.782	0.023-20
Lead	0-0.01	0-0.2		0.01	0.0009-0.0023	
Magnesium	0-30				0.82-7.68	0.11-13.2
Manganese	0-0.05	0-10	0-10		0.004-0.229	0.01-10
Mercury	0-0.001			0.006	0.002	
Molybdenum		0-0.01				
Nickel		0-0.20		0.07	0.002-0.003	
Nitrate+Nitrate	0-6	0-5		53	0.036-8.55	0.12-0.91
pH	6.0 -9.0				4.5-8.8	5.39-8.11
Potassium	0-50				0.053-8.558	1.27-8.69
Silica		0-150			1.518-9.95	
Selenium				0.04		
Sodium	0-100	70			12.21-56.173	19-106
Sulphate	0-200		0-500		0.401-17.659	0.55-49.2
TDS	0-450	40	0-1600		44-205	13.2-81.2
Zinc	0-3	0-1			0.02-0.66	

5.10 Hydrogeological conceptualization of the Kosi Bay Lakes catchment

Based on the analysis of geological, hydrological, geophysical, hydrochemical and environmental isotope data, a conceptual hydrogeological model for the study area is proposed (Figure 5.13). The conceptual model attempts to summarize the hydrogeological information generated and collected during the course of this research and presents the hydrology of the area systematically. The model is based on the SSW – NNE cross sectional line that cuts across the main Lake Nhlange of the Kosi Bay Lakes system (Figure 2.6). Six borehole logs with static water levels and thickness of the layers were used to define the three aquifer units (KwaMbonambi, Port Durnford and Uloa-Umkhwelane Formations) and an aquitard unit (Kosi Bay Formation) underlying the study area. From the borehole data, the thickness of the KwaMbonambi Formation range from 3 to 16m, whereas the thickness of Kosi Bay Formation ranges from 6 to 33m, the Port Durnford Formation ranges from 4 to 32m. The entire succession is saturated from the top of the hydrogeological basement (siltstone) up to the current water table. The water table is relatively shallow and mimicking the gentle topography of the area.

It is evident from the chemical and isotopic data that there is a direct hydraulic link between groundwater, local streams and the Lakes. The hydrochemical evolution is from a more sodium-chloride-bicarbonate rich (fresh/young) water, with depleted isotopic signals to more sodium- chloride (saline/old) water towards the east, with an enriched isotopic signal. This is in line with the general groundwater flow direction within the Kosi Bay catchment which is from west to east. Bicarbonate is mainly sourced from the shallow aquifers that are directly recharge by the local precipitation, while the magnesium and calcium is known to be the products of the weathering of the karstic deeper aquifers made up of the Uloa and Umkhwelane Formations. Sodium and chloride are present in both shallow and deep aquifers, indicating direct contact with coastal water bodies. There is intermixing between the deep and the shallow aquifer systems. The lakes are the sinks of the local flow system, where groundwater and surface water flow are intercepted. Mean annual volume of precipitation for the catchment is about 718x10^6 m^3/year, of which 517x$10^6$$m^3$/year fall directly onto the lakes, and 12x10^6 m^3/year recharges the groundwater. Groundwater abstraction rate is estimated at 1.2 x10^6 m^3/year and surface water abstraction from the Gezisa stream and Lake KuShengeza is about 7x10^6 m^3/year. The surface water runoff to the lakes is estimated to be 63x10^6 m^3/year, whereas evaporation from the lakes is estimated at 62x10^6 m^3/year. Seepage from the Kosi Bay Lakes to the Indian Ocean under the dune cordon is estimated at a rate of 30x10^6 m^3/year, the lake change in storage is 31x10^6 m^3/year. The overall annual water balance of the lakes is positive indicating that inflows are higher than the outflows.

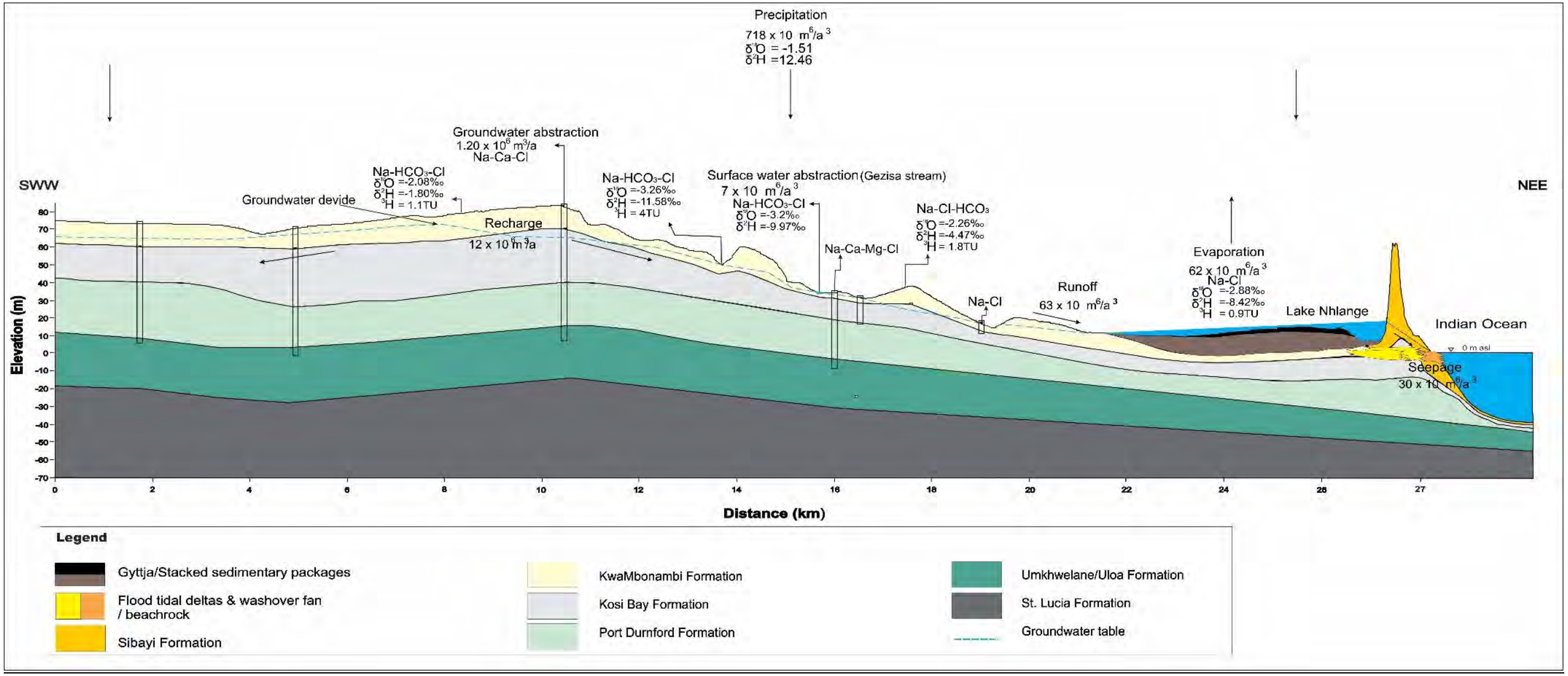


Figure 5.13: Hydrogeological conceptual model of the Kosi Bay catchment.

CHAPTER 6- CONCLUSIONS AND RECOMMENDATIONS

The Kosi Bay Lakes catchment, located along the northeastern coastal area of South Africa is investigated to understand the hydrogeology and interactions between groundwater-surface water and wetlands. Towards the end, geological, hydrological, physical, hydrochemical and environmental isotope data were collected and analyzed. The Kosi Bay catchment is characterized by unconsolidated sediments of varying thicknesses and hydrogeological properties. The geological, groundwater level, dissolved ion concentrations and isotopic signatures data assisted to identify recharge and discharge areas, to delineate the groundwater divide of the Kosi Bay lakes catchment, to define the capture zone of the wetlands, to understand groundwater-surface water interactions and conceptualise the hydrogeology of the study area. Geological, hydrological, physical, hydrochemical and environmental isotope data were integrated to conceptualize the hydrogeology of the Kosi Bay Lakes system and understand the surface water-groundwater interactions.

The general groundwater flow direction is from west to east towards the lakes and eventually to the Indian Ocean. The hydrochemistry and environmental isotope signature of groundwater and streams are similar indicating groundwater surface water interconnection. These groundwater and stream samples plot close to the LMWL indicating their meteoric origin. The lakes are characterized by high salinity, Na-Cl hydrochemical water type and an enriched stable isotopic signal (positive δD and $\delta^{18}O$ signals) indicating strong evaporation and terminations of the local surface and groundwater flow system. The lakes are further characterised by a salinity and isotopic series that increases from south to north. The sample from Lake Amanzamnyama show an intermediate isotopic signature between the groundwater and the rest of the lakes, indicating recharge from streams and groundwater and no influenced by sea water. Tritium data indicates that the groundwater in the study area receives recharge from modern precipitation. The range of tritium values observed in the study area is between 0.5 and 4 TU.

Major ion hydrochemical data revealed five groundwater hydrochemical facies. The shallow and deep groundwater systems have distinct hydrochemical characteristics. The shallow water is dominated Na-HCO_3-Cl facies indicating active recharge and flushed system. While, the deep groundwater is dominated by Na-Ca-Cl facies, indicating the dissolution of the calcium rich

Umkhwelane Formation. The three underlying factor identified in the factor analysis of hydrochemical data are interpreted in terms of intermixing between deep and shallow aquifer systems, possible pollution from fertilizers, and redox reactions.

Groundwater flow and geological and hydrogeological settings have allowed the wetland capture zone to be delineated. Long term lake level record and the water balance calculation show an increasing lake level trend. Increase in groundwater demand by the local community and the increasing plantations which pumps a vast amount of groundwater through evapotranspiration is creating pressure on the groundwater system which eventually will affect the lakes and wetlands. Conceptual model developed reveals that the Kosi Bay Lakes are connected hydraulically to the groundwater system. This interconnection of groundwater and surface water means that a change in one system has direct influence on the other.

The overall quality of the groundwater in the study area is generally good, and can be used for both domestic and irrigation purposes. The lakes range from fresh (Amanzamnyama) to brackish (Nhlange) to saline (Makhawulani).

The following are recommendations emanated from the present study:

1. Seasonal sampling of physical and chemical parameter of groundwater and surface water samples to observe the influence of climate change on both surface water and groundwater;
2. Additional sampling of rainfall for chloride analysis to improve the groundwater recharge through the Chloride Mass Balance Method;
3. Additional environmental isotope analysis to improve the temporal coverage of data;
4. Continuous groundwater and lake level measurements are needed to better understand the water balance of the lakes system and to improve the conceptual model;
5. The amount of water used by the pine plantation and other forestry needs to be estimated in order to understand the water balance of the catchment;

6. Further numerical groundwater flow modeling of the system is needed to understand the various stresses on the catchment.

REFERENCES

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop Evapotranspiration: Guidelines for computing crop water requirements. Irrigation and Drainage Paper No.56. Rome: Food and Agriculture Organization of the United Nations. 326pp.

Allison GB, Gee GW, Tyler SW (1994) Vadose zone techniques for estimating groundwater recharge in arid and semi-regional. Soil Sci. Soc. Am.J., 58: p6-14.

Allison GB, Hughes MW, Leaney FWJ (1984) Effect of climate and vegetation on oxygen-18 and deuterium profiles in soil. Isotope Hydrology. Proc. Symp. Vienna, IAEA, p105-123.

Anderson MP, Woessner WW (1992) Applied groundwater modelling – Simulation of flow and advective transport. Academic Press Inc., San Dieago. 381pp.

Australian Groundwater Consultants (Pty) Ltd (1975). Richards Bay Groundwater Investigations- Richards Bay Heavy Minerals project.

Banks E.W, Simmons CT, Love AJ, Werner AD, Bestland EA, Wood M, Wilson T (2009) Fractures bedrock and Saprolite hydrogeologic control on groundwater/surface water interaction: a conceptual model (Australia). Hydrogeol. J, 17(8): p1969- 1989.

Basson, MS, Van Niekerk PH, Van Rooyen JA (1997) Overview of the water resources availability and utilization in South Africa. Department of Water Affairs and Forestry, Pretoria.

Bazuhair SA, Wood WW (1996) Chloride mass balance method for estimating groundwater recharge in arid areas: Examples from western Saudi Arabia. J. Hydrol., 186: p153-159.

Beekman HE, Xu Y (2003) Review of groundwater recharge estimation in arid and semi-arid Southern Africa. In: Xu Y and Beekman, HE (eds.) Groundwater Recharge Estimation in South Africa. UNESCO IHP Series No. 64: p3−18.

Begg G (1978) The estuaries of Natal. Report, Natal town and Regional Planning, 41(2): p23-41.

Bredenkamp DB, Botha LJ, Van Tonder GJ, Van Rensberg HJ (1995) Manual on quantitative estimation of groundwater recharge and aquifer storativity. WRC Project No TT 73/95, Pretoria.

Bruton, M.N. and Cooper, K.H. (1980): Studies on the Ecology of Maputaland – Rhodes University and the Natal Branch of The Wildlife Society of Southern Africa, Durban; Cape and Transvaal, p1-7.

Clark ID, Fritz P (1997) Environmental Isotopes in Hydrogeology. New York. Lewis Publishers.

Coetsee VdA (1991) Bepaling van gesteente hidrouliese en geoelektriese eieskappe. CSIR internal Report No. EMA-I 9113.

Cook PG, Favreau G, Dighton JC, Tickell S (2003) Determining natural groundwater influx to a tropical river using radon, chlorofluorocarbons and ionic environmental tracers. J. of Hydrol. 277: p74-88.

Cooper JAG, Kilburn RN, Kyle R (1989) A late Pleaistocene molluscan assemblage from Lake Nhlange. Zululand and its paleaoenvironmental implications. South Afr. J. of Geol. 92: p73-83.

Coplen T, Herczeg A, Barnes C (2000) Isotope engineering-using stable isotopes of the water molecule to solve practical problems, in Cook PG, Herczeg AL, eds, Environmental Tracers in Subsurface Hydrology: Boston, Kluwer Academic Publishers, p79-110.

Craig H (1961) Isotopic variations in meteoric waters. Science 133: p1702–1703.

Davies Lynn and Partners (1992) Landform geomorphology and geology. In : Environmental impact assessment, Eastern shores of Lake St Lucia, Kingsa/ Tojan Lease Area, Vol 1, Part 1, specialist reports. Coastal and environmental services, Grahamstown, SR2: p21-62.

Dettinger MD (1989) Reconnaissance estimates of natural recharge to desert basin in Nevada, U.S.A. by using chloride-balance calculations. J. Hydrol., 106: p55-78.

De Vries JJ, Grieske A (1990) A simple chloride balance routing method to regionalize groundwater recharge: a case study in semi-arid Botswana. IAHS Publ., No. 191: p81-89.

Drever JI (1997) The geochemistry of natural waters: surface and groundwater environments. Prentice-hall, New Jersey.

DWAF (1998) 1:500 000 Hydrogeological Map Series of the Republic of South Africa.

DWAF (2015) UMkhanyakude District municipality registered water uses database.

Dyer, A.J. and Maher, E.J. (1965). The Evapotron: an Instrument for the Measurement of Eddy Fluxes in the Lower Atmosphere. Div. of Meteorological Physics Tech. Paper 15, CSIRO, Australia.

Eriksson E, Khunakasem V (1969) Chloride concentration in groundwater, recharge rate and rate of deposition of chloride in the Israel coastal plain. J. of Hydrol.,7: p178–197.

Esri (2016), ArcGIS [online], http://www. resources.arcgis.com/en/Tutorials/, Accessed January 2016.

Fetter CW (2001) Applied Hydrogeology, 4th ed. Prentice Hall, Inc. Upper saddle River, New Jersey, 598pp.

Fitterman DV, Stewart MT (1986) Transient Electromagnetic Sounding for Groundwater. Geology Faculty Publications. Paper /11. http://scholarcommons.usfedu/gly_facpub. Accessed in November 2015.

Gat JR, Gonfiantini (1981) Stable isotope hydrology. Technical Report No. 210, IAEA, Vienna, 337pp.

Gee GW, Wierenga PJ, Andraski BJ, Young MH, Fayer MJ, Rockhold ML (1994) Variations in water balance and recharge potential at three western desert sites. Soil Sci. Soc. Am J. (58): p63-71.

Gorsuch RL (1983) Factor analysis. Hillsdale, NJ: Erlbaum.

Grieske A (1992) Dynamics of groundwater recharge; a case study in arid regions: review and critique of estimation methods. Hydrological Processes, Vol. 2: p255-266.

GRIP (2013) Groundwater Resource Information Project [online], http://www.dwa.gov.za/Groundwater/GroundwaterOffices/KZN/GRIP_KwaZulu-Natal.pdf. Accessed March 2013.

Grobler R, Moning E, Sliva J, Bredenkamp G , Grundling, P (2004) Subsistence farming and conservation constraints in coastal peat swamp forests of the Kosi Bay Lake system, Maputaland, South Africa. Géocarrefour [On-line], Vol. 79, No. 4: p316-324.

Grundling P, Baartman L, Mazus H, Blackmore A (2013) Peat resources of KwaZulu-Natal wetlands: Southern Maputaland and the North and South Coast, Council for Geoscience Report No. 2000-0132, Pretoria, South Africa.

Hair JT, Anderson RE, Tatham RL, Black WC (1992) Multivariate data analysis with readings (3rd Ed), Macmillan.

Henson RK, Roberts JK (2006) Exploratory factor analysis reporting practices in published research. In B. Thompson (Ed.), Advances in social science methodology, Vol. 6. Stamford, CT: JAI Press.

Holliday J (2012) Enkanyezini & Kwangwanase Rural Water Supply Projects at Manguzi, near Kosi Bay: SAICE'S [Online]. Accessed May 2015.

Hunter IT (1988). Climate and weather of Natal in Coastal Ocean Studies of Natal. South Africa. In Coastal ocean studies of Natal, South Africa (E.H Schumann, ed.). Lecture notes on coastal and estuarine studies 26: p81-100.

James NC, Beckley LE, Mann BQ, Kyle R (2001) The recreational fishery in the Kosi estuarine lake, South Africa.

Jeffares & Green Ltd (Pty) (2008). Consultants Report titled: eManguze Implementation Results – Summary Report.

Jeffares & Green Ltd (Pty) (2012) UMkhanyakude District Municipality Groundwater Monitoring Network. Implementation Report. Jeffares and Green (Pty) Ltd., Project Number 2911.

Johansson PO (1987) Distribution of environmental chloride in relation to subsurface hydrology. J. Hydrol., 94: p67-88.

Johnston CD (1987) Method for estimating of direct natural groundwater recharge directly from precipitation.

Kelbe BE, Germishuyse T, Snyman N, Fourie I (2001) Geohydrological Studies of Primary Aquifers in Zululand, Water Research Commission, University of Zululand, RSA.

Kelbe BE, Germishuyse, T (2010) groundwater / surface water relationships with specific reference to Maputaland. WRC Report No. 1168/1/10, Pretoria, WRC.

Kendall C, Caldwell EA (1998) Fundamentals of Isotope Geochemistry, in: Isotope Tracers in Catchment Hydrology, edited by: Kendall C and McDonnell JJ. Elsevier Science, Amsterdam.

King LC (1972) The Natal Monocline: explaining the origin and scenery of Natal. (1st Ed.) University of Natal Press, Pietermaritzburg, Natal, South Africa, p113

Maud RR (1968) Quaternary geomorphology and soil formation in coastal Natal. Ann.Geomorphol, 7: p155 - 199.

Mazor E (1991) Applied chemical and isotopic groundwater hydrology. Milton Kenen. Open University Press, 274pp.

Meinardi CR (1994) Groundwater recharge and travel times in the sandy regions of the Netherlands. Ph.D. thesis, Vrije Universiteit, Amsterdam.

Meyer R, De Beer JH (1981) A geophysical study if the Cape Flats aquifer-Trans. Geol. Soc S. Afr., 84: p107-114.

Meyer R, De Beer JH, Blume J (1982). A geophysical-geohydrological study of an area around Lake Sibayi, northern Zululand. CSIR Report No. Kon/Gf/81/1.

Meyer R, Godfrey L (1995) KwaZulu-Natal Geohydrological Mapping Project: Mapping Unit 7. CSIR Report No. EMAP-C-95024. Pretoria. CSIR.

Meyer R, Huyssen RMJ, Coetsee VdA, Aucamp JJ (1987) A geoelectrical survey of an area between lake Sibayi and Lake Kosi, Northern Zululand. CSIR Report No. C-FIS 129.

Meyer R, Talma AS, Duvenhage AWA, Eglington BM, Taljaard J, Botha JP, Verwey J, van der Voort I (2001) Geohydrological Investigation and Evaluation of the Zululand Coastal Aquifer. WRC Report No. 221/1/1.Pretoria. WRC.

Moreau M, Nokes C, Cameron S, Hadfield J, Gusyev M, Tschritter C, Daughney C (2014) Capture zone guidelines for New Zealand. GNS Science. Report 2013/56, 52pp.

Mulvaney, T. J. (1851). On the use of self-registering rain and flood gages, in making observations of the relation of rainfall and flood discharges in a given catchment. Proceedings of the Institute of Civil Engineers of Ireland, 4: p18-31

NASA (2014*)* National Aeronautics and Space Administration [online], http://www.nasa.gov/. Accessed March 2014.

Ndlovu M, Demlie MB (2015) Hydrogeological study of the Kosi Bay Lakes system, North Eastern South Africa. Unpublished 14th Biennial Groundwater Division conference paper.

NGA (2013) National Groundwater Archive. Digital Information as Supplied by the Department of Water Affairs.

Parsons R (1994) Surface Water – Groundwater Interaction in a Southern African Context: A geohydrological perspective. WRC Report No. TT 218/03

Penman HL (1948) Natural evaporation from open water, bare soil and grass. Proceedings of the Royal Society, A193: p120-145.

Porat N, Botha GA (2008) The chronology of dune development on the Maputaland coastal plain, southeast Africa. Quat. Sci. Rev. 27: p1024–1046.

Rawlins BK, Kelbe BE (1998) Groundwater modelling of the impact of commercial forestry on an ecologically sensitive coastal lake, in H Wheater and C Kirby (eds.), Hydrology in a changing environment, Chichester, England, John Wiley and Sons Ltd.

Richey DG, McDonnell JJ, Erbe MW, Hurd TM (1998) Hydrograph separations based on chemical and isotopic concentrations: a critical appraisal of published studies from New Zealand, North America and Europe, J. Hydrology (NZ) Vol 37 No 2: p95–111.

Robins NS, Davies J, Farr JL, Calow RC (2006) The changing role of hydrogeology in semi-arid southern and eastern Africa. Hydrogeol. J., 14: p1483-1492.

Saayman IC, Scott D, Prinsloo E, Moses, G (2002) The determination of recharge and the contribution of groundwater to base flow (Phase 1) Draft Final Report No. 1234. WRC project, Pretoria.

SAWQ (1996) South African Water Quality Guidelines. Department of Water Affairs, Domestic water use (2nd Ed).

SAWS (2013, 2014) South African Weather Service. Durban Weather Office-Meteorological Data.

Selaolo ET (1988) Tracer studies and groundwater recharge assessment in the Eastern fringe of the Botswana Kalahari. Published Ph.D. thesis, Free University of Amsterdam. GRES project publication.

Sergio SE (1997) Hydrology for Engineers, Geologists and Environmental Professionals. An integrated treatment of surface, subsurface, and contaminated hydrology. HydroScience Inc., 438pp.

Sharma ML, Hughes WM (1985) Groundwater recharge estimation using chloride deuterium and oxygen-18 profiles in the deep coastal sands of Western Australia. J. Hydrol., 81: p93-109.

Shaw EM (1994) Hydrology in Practice, London, Chapman & Hall, 628pp.

Slaughter R (2014) Water, Sanitation, Electricity, Roads and Maintenance backlog eradication, Water Summit 2/14.

South African National Biodiversity Institute [online], Conservation area shapefile, http://bgis.sanbi.org/webpages/downloads. Accessed May 2014.

South African National Biodiversity Institute [online], KwaZulu-Natal land cover, http://bgis.sanbi.org/kznlandcover/landcover2008.asp, Accessed May 2014.

Stats SA (2012) Census 2011 Municipal report, KwaZulu-Natal. Report No. 03-01-53, 195pp.

Suk H, Lee KK (1999) Characterisation of a groundwater hydrochemical system through multivariate analysis: Clustering into ground water zones. Groundwater Vol 37 (3): p358–366.

Tripathi RP, Singh HP (1998) Soil erosion and conservation. New Age International (P) LTD Publishers, pp316.

United Nations Educational, Scientific & Cultural Organization (2015). n.d. ISimangaliso Wetland Park. [Online]. Available at: http://whc.unesco.org/en/list/914, Accessed 10 July 2015.

United States Department of Agriculture (USDA) (1986) Urban hydrology for small watersheds. Technical Report No. 55.

Van Tonder G, Xu Y (2000). Recharge – Programme to estimate recharge and the groundwater reserve. http://www.unesco.org/water. Accessed May 2015.

Van Zilj JSV (1971) Results of an electrical sounding profile, Eastern shores area, St Lucia. CSIR Report. Pretoria.

Vogel JC, Van Urk H (1975) Isotopic investigation of Lake St Lucia. Internal NPRL, CSIR Report. Pretoria.

Watkeys MK, Mason TR, Goodman PS (1993) The role of geology in development of Maputaland, South Africa. J. Afr. Earth Sci. 16: p205-221.

Weitz J, Demlie M. (2014) Conceptual modelling of groundwater-surface water interactions in the Lake Sibayi Catchment, Eastern South Africa. J. of Afric. Earth Science 99: p613-624.

Weitz J, Demlie M. (2015) Hydrogeological system analyses of the Lake Sibayi catchment, North-Eastern South Africa, South African Journal of Geology, 2015, Vol.118.1: p91-106.

WHO (2011) World Health Organization. Guidelines for drinking water quality, (4th Ed).

Woodward DE, Hawkins RH, Hjelmfelt AT, Van Mullem JA, Quan QD (2002) Curve number method – Origins, applications and limitations. U.S. Department of Agriculture, Natural Resources Conservation Service, Hydraulics and Hydrology Technical Reference.

Worthington PF (1978) Groundwater conditions in the Zululand Coastal Plain around Richards Bay: An intergrated case history of detailed hydrogeological evaluation. Report No. RFIS 182. Council for scientific and industial research. Pretoria, 209pp.

Wright CI (2002) Aspects of the Cenozoic Evolution of the Northern KwaZulu-Natal Coastal Plain, South Africa. Bulletin No.132. Council for Geoscience.

Wright CI, Miller WR, Cooper JAG (2000) The late Cenozoic evolution of coastal water bodies in Northern KwaZulu-Natal, South Africa, International journal of marine geology, geochemistry and geophysics 167: p207–229.

Yihdego Y, Web JA (2014) Use of a conceptual hydrogeological model and a time variant water budget analysis to determine controls on salinity in Lake Burrumbeet in southern Australia. J. Environ Earth Sci. 73: p1587- 1600.

APPENDICES

Appendix A: Reference Runoff calculation (USDA, 1986).

Landuse/Land cover	hydraulic conditions/ treatment/ practice	Hydraulic soil group	CN	S=(1000/CN)-10	Area (km2)	P(mm/a)	$Q=(P-0.2S)^2/(P+0.8S)$	$Q_{pervious} = Q*(A_i/A_T)$	$Q_{effective\ impervious}$	Qtotal (mm/year)	%
Baresoil/pastures	Fair	A	77	2.99	1.35	924.29	920.72	2.41		152.68	16.52
Grassland	Poor	A	52	9.23	282.46	924.29	913.31	500.56			
Woodland/Forest/Bushland	Fair	A	49	10.41	139.93	924.29	911.92	247.59			
Wetland	Wet periods	-	98	0.20	12.66	924.29	924.05	22.71			
Pine plantation	Wet periods	-	98	0.20	18.25	924.29	924.05	32.73			
Cultivation land	Poor	A	81	2.35	60.54	924.29	921.48	108.25			
Urban area/Residential area:	-	A & D	81	2.35	0.17	924.29	921.48		0.31		
Total					515.37						

Appendix B: Reference evaporation calculation (Shaw, 1994).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
T_{mean} (^{0}C)	25.78	26.14	25.44	23.10	20.69	18.84	18.33	19.91	21.06	22.21	23.81	25.16	
T_{mean} (K)	298.94	299.30	298.60	296.26	293.85	292.00	291.49	293.07	294.22	295.37	296.97	298.32	
e_a (kPa)	3.42	3.51	3.37	2.95	2.59	2.32	2.25	2.47	2.62	2.77	3.05	3.31	
e_a (mmHg)	25.69	26.30	25.31	22.10	19.45	17.43	16.87	18.53	19.69	20.80	22.85	24.79	
e_d (kPa)	2.52	2.54	2.41	2.05	1.66	1.45	1.41	1.58	1.76	2.00	2.23	2.41	
e_d (mmHg)	18.88	19.09	18.07	15.41	12.44	10.90	10.59	11.86	13.20	15.01	16.76	18.10	
$e_a - e_a$ (kPa)	0.91	0.96	0.97	0.89	0.93	0.87	0.84	0.89	0.87	0.77	0.81	0.89	
U_2 (m/s)	1.91	1.91	1.91	1.91	1.91	1.14	1.31	1.61	2.00	2.20	2.26	2.13	
U_2 (miles/d)	102.40	102.40	102.40	102.40	102.40	61.13	70.50	86.59	107.17	117.96	121.48	114.45	
N(hrs/d)	13.41	12.84	12.14	11.37	10.73	10.41	10.57	11.14	11.89	12.64	13.28	13.58	
n(hrs/d)	6.63	6.96	7.17	7.19	7.61	6.71	7.26	7.63	6.65	5.66	5.68	6.14	
n/N	0.49	0.54	0.59	0.63	0.71	0.64	0.69	0.69	0.56	0.45	0.43	0.45	
Ra(mm/d)	17.52	16.34	14.22	11.53	9.32	8.25	8.73	10.60	13.21	15.54	17.11	17.71	
Ri(1-r) (mm/d)	7.52	7.42	6.82	5.78	5.05	4.19	4.63	5.61	6.12	6.29	6.75	7.21	
σTa^4 (mm/d)	15.57	15.65	15.50	15.02	14.54	14.17	14.08	14.38	14.61	14.84	15.17	15.44	
Ro (mm/d)	1.43	1.53	1.74	2.08	2.60	2.53	2.70	2.58	2.05	1.58	1.41	1.39	
H (mm/d)	6.09	5.89	5.08	3.71	2.44	1.65	1.93	3.03	4.07	4.71	5.34	5.83	
Ea (mm/d)	3.67	3.67	3.67	3.67	3.67	2.67	2.90	3.29	3.78	4.04	4.13	3.96	
Δ (mb/°C)	0.20	1.56	1.49	1.29	1.07	0.95	0.93	1.03	1.13	1.26	1.22	1.49	
P(kPa)	100.33	100.33	100.33	100.33	100.33	100.33	100.33	100.33	100.33	100.33	100.33	100.33	
Υ (mb/°C)	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	
Δ/Υ	0.30	2.33	2.22	1.94	1.61	1.43	1.39	1.54	1.69	1.89	1.82	2.23	
Eo (mm/d)	4.22	6.69	6.04	4.86	3.76	2.55	2.81	3.83	4.93	5.73	6.11	6.75	
Eo (mm/month)	130.80	187.27	187.14	145.86	116.71	76.39	87.08	118.69	147.89	177.58	183.30	209.31	1768.02

Appendix C: Reference evapotranspiration calculation (Allen *et al.*, 1998).

Monthly	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
DoY	15.00	46.00	74.00	105.00	135.00	166.00	196.00	227.00	258.00	288.00	319.00	349.00
lat	-27.47	-27.47	-27.47	-27.47	-27.47	-27.47	-27.47	-27.47	-27.47	-27.47	-27.47	-27.47
elev (m)	82.00	82.00	82.00	82.00	82.00	82.00	82.00	82.00	82.00	82.00	82.00	82.00
Tmax (°C)	30.53	31.08	30.53	28.48	27.29	25.63	24.97	26.28	26.98	26.96	28.47	29.84
Tmin (°C)	21.23	21.33	20.46	17.82	14.78	12.67	12.31	13.92	15.59	17.40	19.26	20.47
ea (kPa)	2.52	2.54	2.41	2.04	1.68	1.47	1.43	1.59	1.77	1.99	2.23	2.41
U_2 (m/s)	1.91	1.91	1.91	1.91	1.91	1.14	1.31	1.61	2.00	2.20	2.26	2.13
n (hrs)	6.63	6.96	7.17	7.19	7.61	6.71	7.26	7.63	6.65	5.66	5.68	6.14
Tmonth,i (°C)	25.88	26.21	25.49	23.15	21.04	19.15	18.64	20.11	21.28	22.19	23.87	25.19
Tmount,i-1(°C)	25.19	25.88	26.21	25.49	23.15	21.04	19.15	18.64	20.11	21.28	22.19	23.87
Tmean (°C)	25.88	26.21	25.49	23.15	21.04	19.15	18.64	20.10	21.29	22.18	23.86	25.15
Delta (kPa °C^{-1})	0.20	0.20	0.19	0.17	0.15	0.14	0.13	0.15	0.16	0.16	0.18	0.19
P(kPa)	100.33	100.33	100.33	100.33	100.33	100.33	100.33	100.33	100.33	100.33	100.33	100.33
γ (kPa/°C)	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
$(1+.34U_2)$	1.65	1.65	1.65	1.65	1.65	1.39	1.45	1.55	1.68	1.75	1.77	1.72
$\Delta/(\Delta+\gamma)((1+.34U_2)$	0.64	0.65	0.64	0.61	0.58	0.60	0.58	0.58	0.58	0.58	0.60	0.62
$\gamma/(\Delta+\gamma)((1+.34U_2)$	0.22	0.21	0.22	0.24	0.25	0.29	0.29	0.27	0.25	0.24	0.23	0.22
$900/(Tm+273)U_2$	5.74	5.74	5.75	5.80	5.84	3.51	4.05	4.95	6.10	6.70	6.86	6.44
e(Tmax) (kPa)	4.37	4.51	4.37	3.89	3.63	3.29	3.16	3.42	3.56	3.56	3.88	4.20
e(Tmin) (kPa)	2.52	2.54	2.41	2.04	1.68	1.47	1.43	1.59	1.77	1.99	2.23	2.41
es(kPa)	3.45	3.53	3.39	2.96	2.65	2.38	2.30	2.50	2.67	2.77	3.06	3.31
es-ea (kPa)	0.93	0.99	0.98	0.92	0.97	0.91	0.87	0.91	0.89	0.78	0.83	0.90
dr	1.03	1.02	1.01	0.99	0.98	0.97	0.97	0.98	0.99	1.01	1.02	1.03
Δ	-0.37	-0.23	-0.05	0.17	0.33	0.41	0.37	0.24	0.04	-0.17	-0.33	-0.41

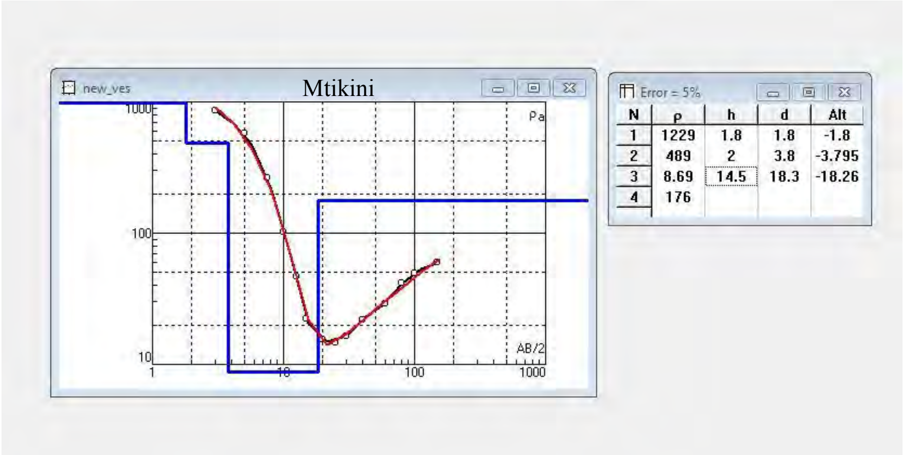
Monthly	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
lat	-0.48	-0.48	-0.48	-0.48	-0.48	-0.48	-0.48	-0.48	-0.48	-0.48	-0.48	-0.48
Ω s	1.77	1.69	1.60	1.48	1.39	1.34	1.36	1.44	1.55	1.66	1.75	1.80
Ra	42.90	39.83	34.95	28.30	22.74	19.97	21.02	25.59	32.04	37.89	41.92	43.52
N (hrs)	13.55	12.93	12.19	11.33	10.64	10.27	10.43	11.03	11.85	12.68	13.39	13.73
n/N	0.49	0.54	0.59	0.63	0.72	0.65	0.70	0.69	0.56	0.45	0.42	0.45
Rs (MJ m^{-2} day^{-1})	21.22	20.68	19.01	16.05	13.82	11.51	12.58	15.25	16.99	17.92	19.37	20.62
Rso (MJ m^{-2} day^{-1})	32.25	29.94	26.27	21.27	17.09	15.01	15.80	19.24	24.08	28.48	31.50	32.71
Rs/Rso	0.66	0.69	0.72	0.75	0.81	0.77	0.80	0.79	0.71	0.63	0.61	0.63
Rns (MJ m^{-2} day^{-1})	16.34	15.92	14.64	12.36	10.64	8.86	9.69	11.74	13.09	13.80	14.91	15.87
σTmax^4	41.70	42.01	41.70	40.59	39.96	39.08	38.73	39.42	39.79	39.78	40.58	41.33
σTmin^4	36.82	36.87	36.44	35.15	33.70	32.72	32.56	33.30	34.09	34.95	35.85	36.45
Avg (σT^4's)	39.26	39.44	39.07	37.87	36.83	35.90	35.65	36.36	36.94	37.36	38.22	38.89
$0.34-0.14\sqrt{(ea)}$	0.12	0.12	0.12	0.14	0.16	0.17	0.17	0.16	0.15	0.14	0.13	0.12
1.35Rs/Rso-0.35	0.54	0.58	0.63	0.67	0.74	0.69	0.72	0.72	0.60	0.50	0.48	0.50
Rnl (MJ m^{-2} day^{-1})	2.49	2.69	3.01	3.54	4.33	4.19	4.46	4.28	3.42	2.66	2.40	2.39
Rn (MJ m^{-2} day^{-1})	13.85	13.23	11.63	8.81	6.31	4.67	5.23	7.46	9.67	11.14	12.51	13.48
G (MJ m^{-2} day^{-1})	0.10	0.05	-0.10	-0.33	-0.30	-0.26	-0.07	0.21	0.16	0.13	0.24	0.18
Rn-G (MJ m^{-2} day^{-1})	13.76	13.19	11.73	9.14	6.61	4.93	5.30	7.26	9.50	11.01	12.28	13.30
0.408(Rn-G) (mm/day)	5.61	5.38	4.79	3.73	2.70	2.01	2.16	2.96	3.88	4.49	5.01	5.43
Eto (mm/day)	4.76	4.69	4.29	3.54	3.01	2.13	2.27	2.94	3.62	3.87	4.29	4.64
Eto (mm/month)	147.52	131.42	133.14	106.19	93.31	63.88	70.44	91.29	108.46	120.05	128.61	143.96
Eto (mm/year)	1338.28											

Appendix D: Crop evapotranspiration calculation (Allen *et al*., 1998).

			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
wind speed (m/s)			1.91	1.91	1.91	1.91	1.91	1.14	1.31	1.61	2.00	2.20	2.26	2.13
Land cover types	**Standard Kc**	**Max height (m)**	**Calculated Kc Values**											
Forest & woodland	1	10	0.79	0.79	0.79	0.79	0.79	0.76	0.77	0.78	0.80	0.80	0.81	0.80
Plantation	1	10	0.79	0.79	0.79	0.79	0.79	0.76	0.77	0.78	0.80	0.80	0.81	0.80
Wetland	1.2	2	1.07	1.07	1.07	1.07	1.07	1.04	1.05	1.06	1.07	1.08	1.09	1.08
grassland	0.75	0.3	0.68	0.68	0.68	0.68	0.68	0.64	0.65	0.66	0.68	0.69	0.69	0.68
Water bodies	1.25	0	1.25	1.25	1.25	1.25	1.25	1.22	1.22	1.23	1.25	1.26	1.26	1.26
Bushland	1	0.85	0.90	0.90	0.90	0.90	0.90	0.87	0.88	0.89	0.90	0.91	0.91	0.91
Cultivated land	1	2.5	0.86	0.86	0.86	0.86	0.86	0.83	0.84	0.85	0.87	0.87	0.88	0.87

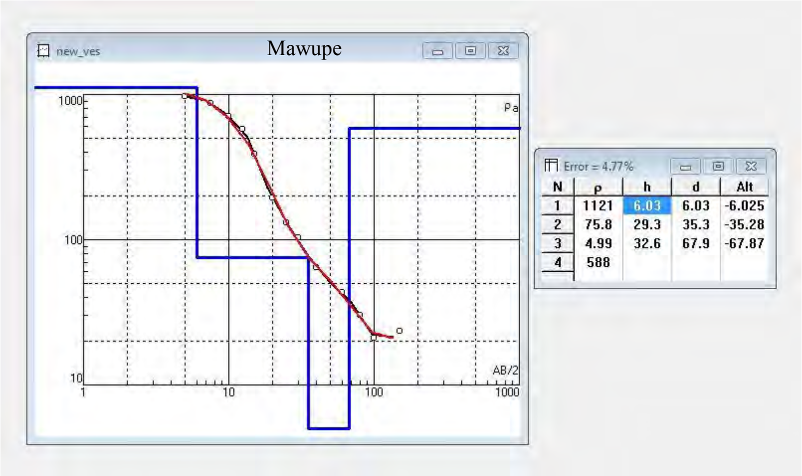
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
	Eto (Reference)												
	147.52	131.42	133.14	106.19	93.31	63.88	70.44	91.29	108.46	120.05	128.61	143.96	1338.28
Land cover types	**Calculated Etc**												
Forest & woodland	117.00	104.23	105.59	84.22	74.00	48.70	54.18	71.33	86.40	96.60	103.83	115.47	1061.55
Plantation	117.00	104.23	105.59	84.22	74.00	48.70	54.18	71.33	86.40	96.60	103.83	115.47	1061.55
Wetland	157.98	140.74	142.58	113.72	99.93	66.45	73.75	96.69	116.54	129.96	139.56	155.46	1433.35
grassland	99.62	88.75	89.91	71.72	63.01	41.18	45.88	60.58	73.63	82.46	88.68	98.51	903.95
Water bodies	183.85	163.79	165.93	132.35	116.29	77.66	86.10	112.70	135.56	151.01	162.12	180.71	1668.06
Bushland	132.66	118.19	119.73	95.50	83.91	55.49	61.66	81.02	97.92	109.35	117.49	130.76	1203.68
Cultivated land	127.19	113.32	114.80	91.56	80.45	53.12	59.05	77.64	93.90	104.90	112.72	125.42	1154.08
Average	125.24	111.58	113.03	90.16	79.22	52.28	58.11	76.43	92.47	103.31	111.02	123.51	1136.361

Appendix E: Geophysical sounding Curves.



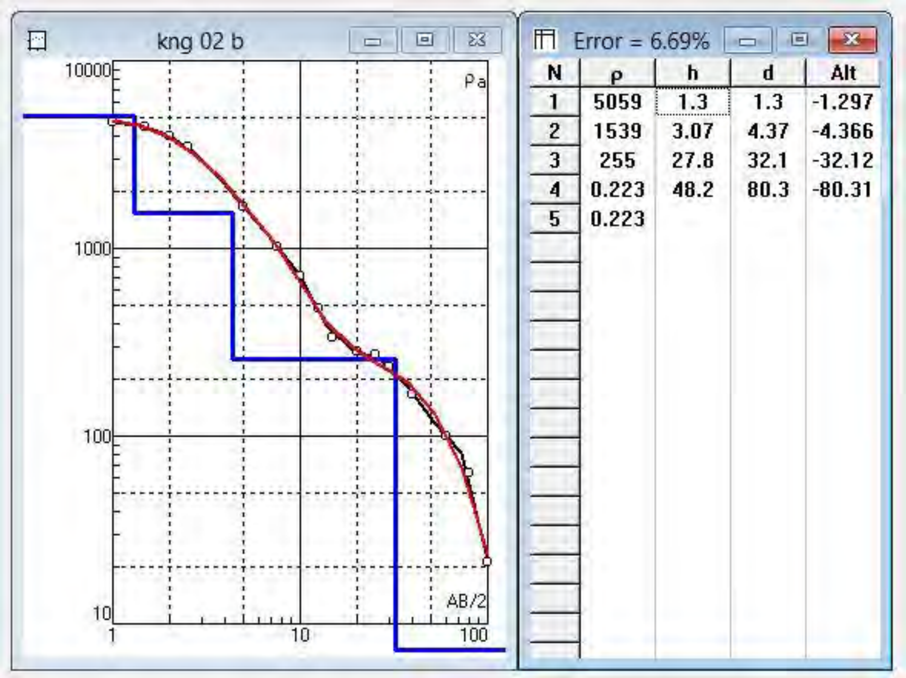
Error = 5%

N	ρ	h	d	Alt
1	1229	1.8	1.8	-1.8
2	489	2	3.8	-3.795
3	8.69	14.5	18.3	-18.26
4	176			



Error = 4.77%

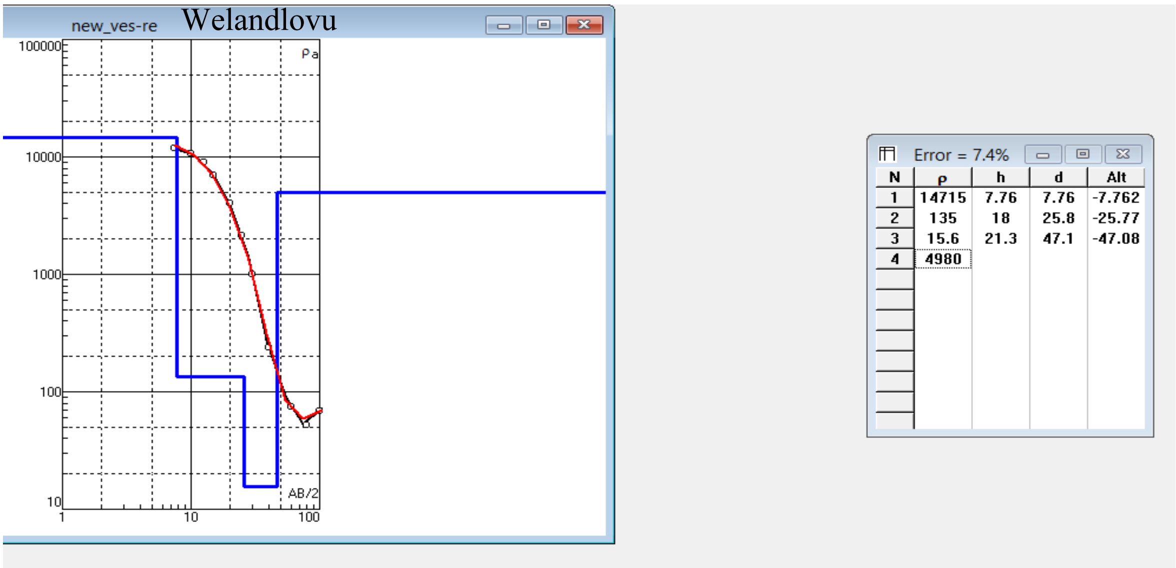
N	ρ	h	d	Alt
1	1121	6.03	6.03	-6.025
2	75.8	29.3	35.3	-35.28
3	4.99	32.6	67.9	-67.87
4	588			



Error = 6.69%

N	ρ	h	d	Alt
1	5059	1.3	1.3	-1.297
2	1539	3.07	4.37	-4.366
3	255	27.8	32.1	-32.12
4	0.223	48.2	80.3	-80.31
5	0.223			

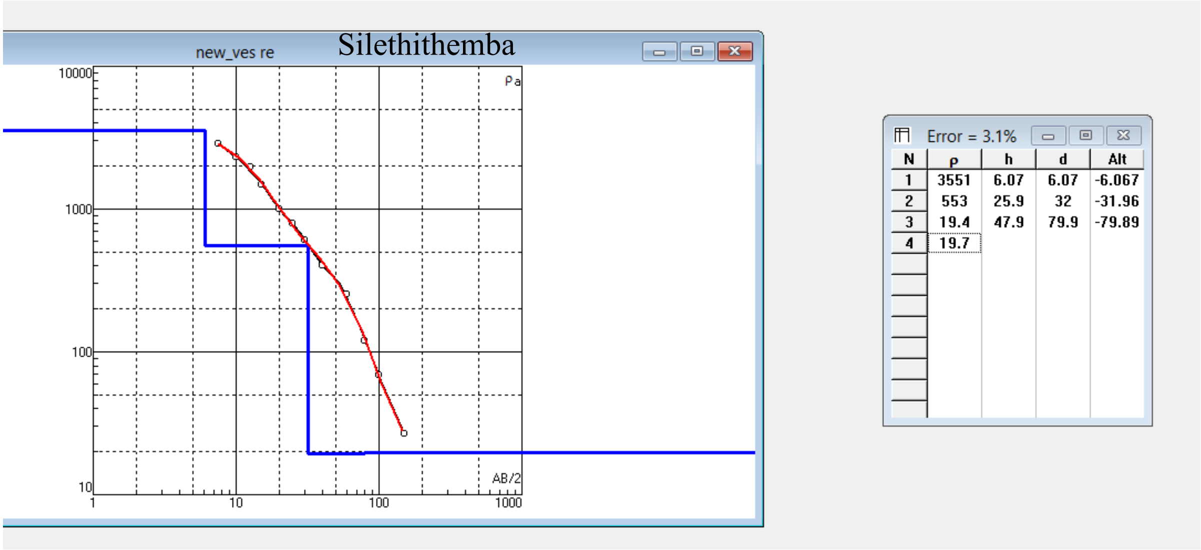
Welandlovu



Error = 7.4%

N	ρ	h	d	Alt
1	14715	7.76	7.76	-7.762
2	135	18	25.8	-25.77
3	15.6	21.3	47.1	-47.08
4	4980			

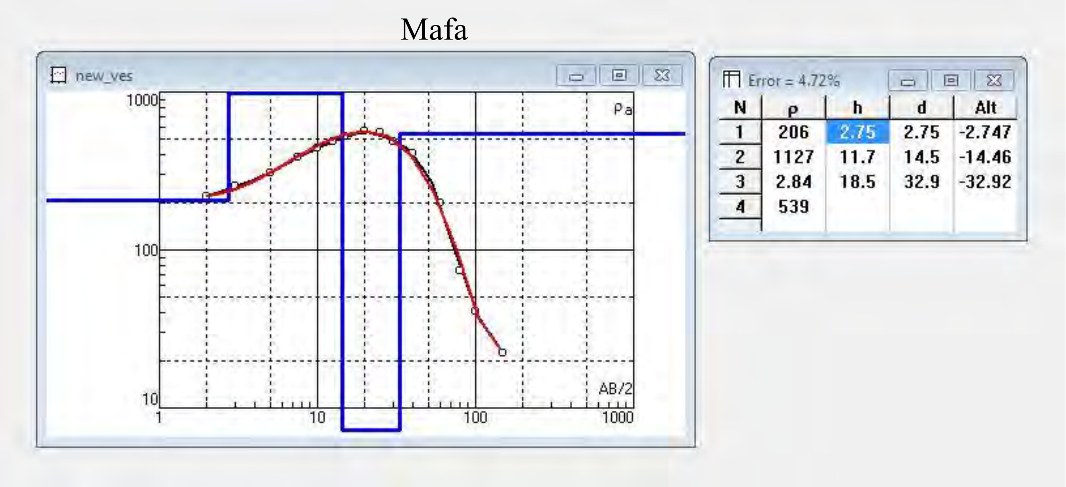
Silethithemba



Error = 3.1%

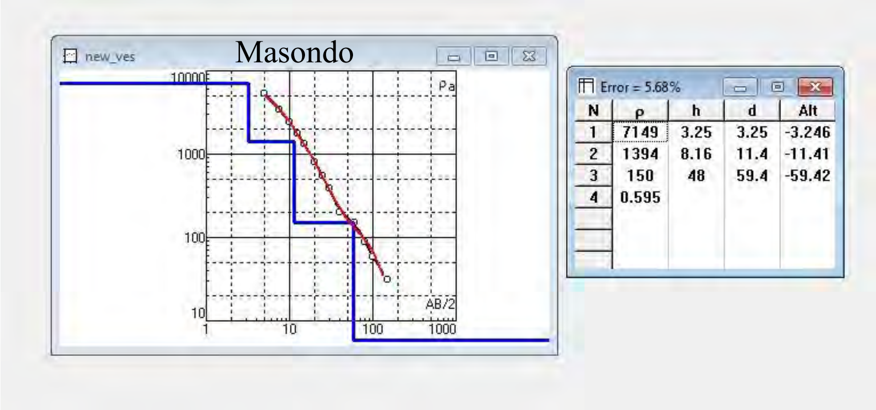
N	ρ	h	d	Alt
1	3551	6.07	6.07	-6.067
2	553	25.9	32	-31.96
3	19.4	47.9	79.9	-79.89
4	19.7			

Mafa

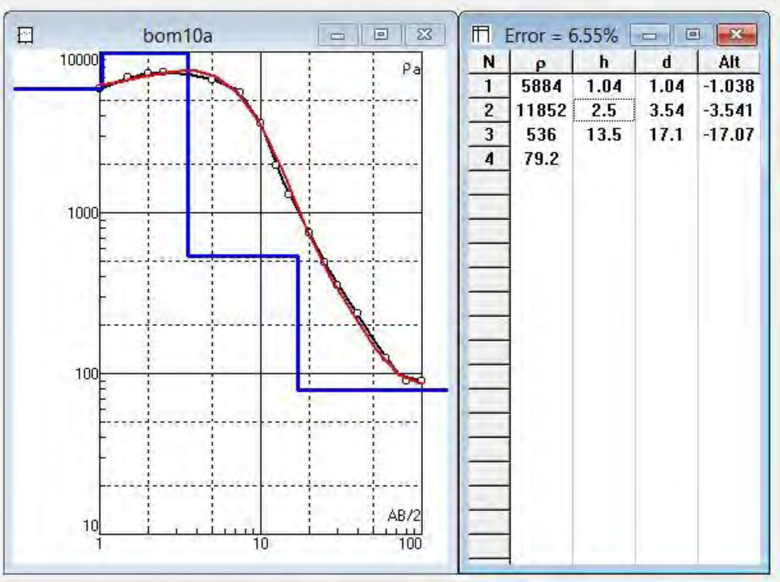


Error = 4.72%

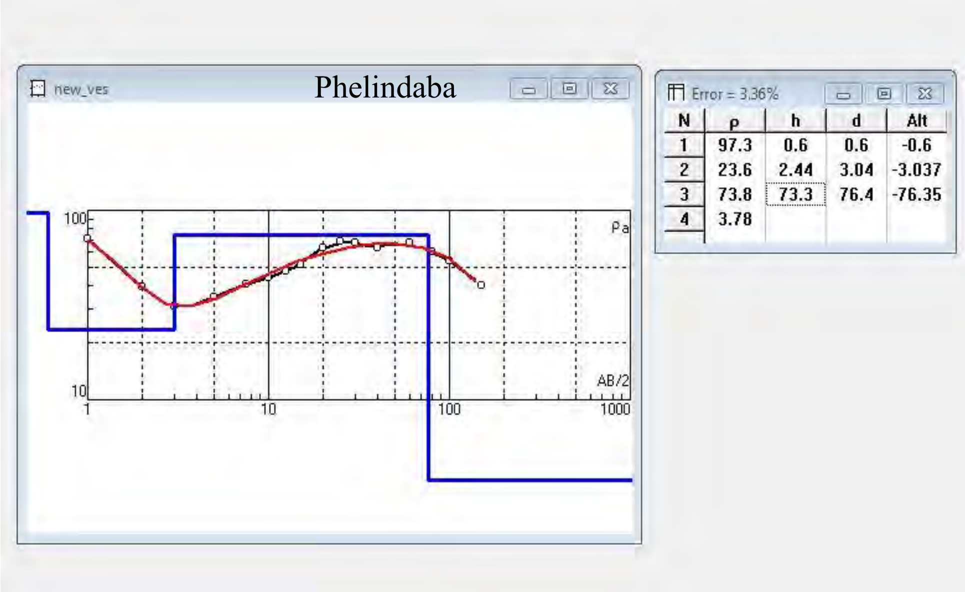
N	ρ	h	d	Alt
1	206	2.75	2.75	-2.747
2	1127	11.7	14.5	-14.46
3	2.84	18.5	32.9	-32.92
4	539			



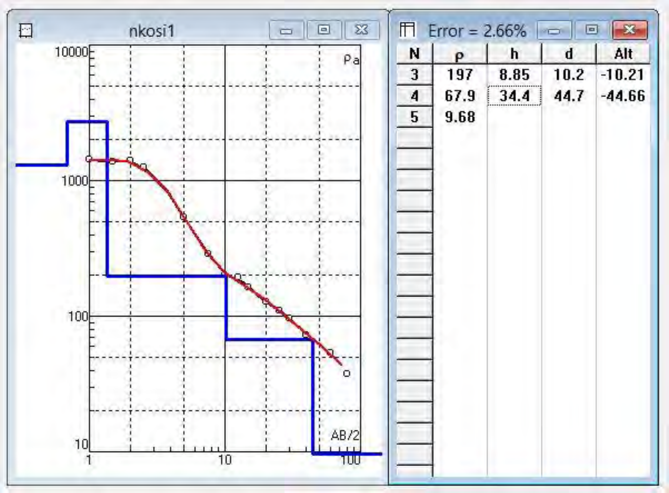
N	ρ	h	d	Alt
1	7149	3.25	3.25	-3.246
2	1394	8.16	11.4	-11.41
3	150	48	59.4	-59.42
4	0.595			



N	ρ	h	d	Alt
1	5884	1.04	1.04	-1.038
2	11852	2.5	3.54	-3.541
3	536	13.5	17.1	-17.07
4	79.2			

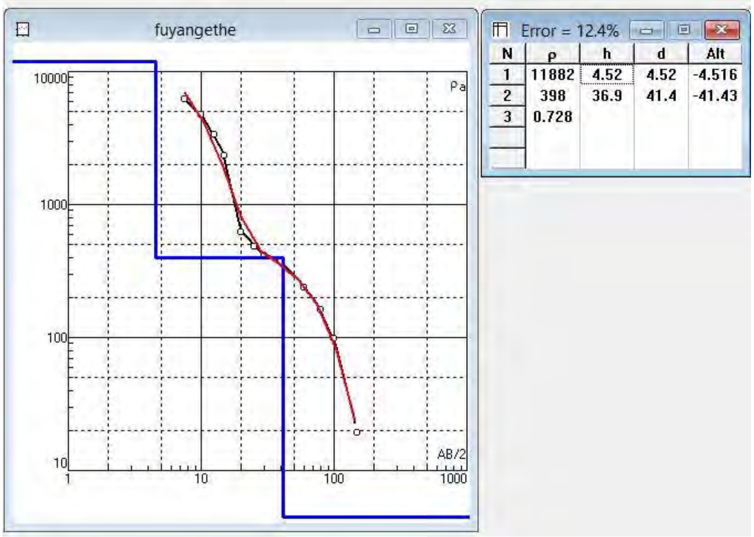


N	ρ	h	d	Alt
1	97.3	0.6	0.6	-0.6
2	23.6	2.44	3.04	-3.037
3	73.8	73.3	76.4	-76.35
4	3.78			



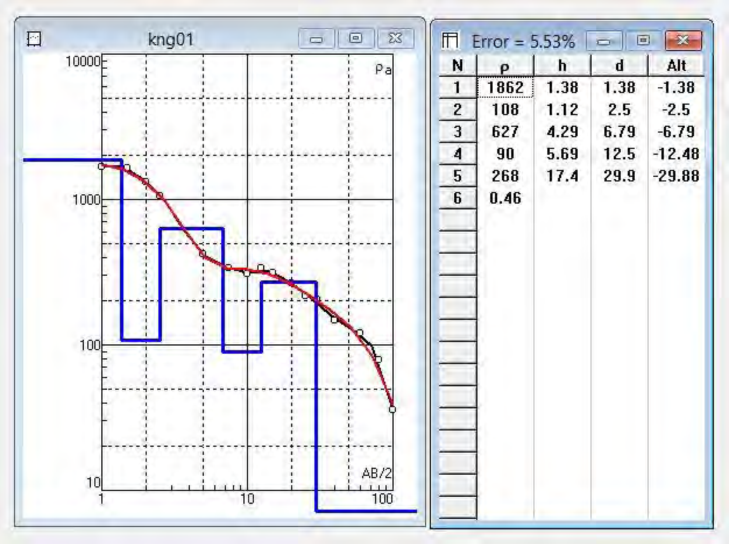
Error = 2.66%

N	ρ	h	d	Alt
3	197	8.85	10.2	-10.21
4	67.9	34.4	44.7	-44.66
5	9.68			



Error = 12.4%

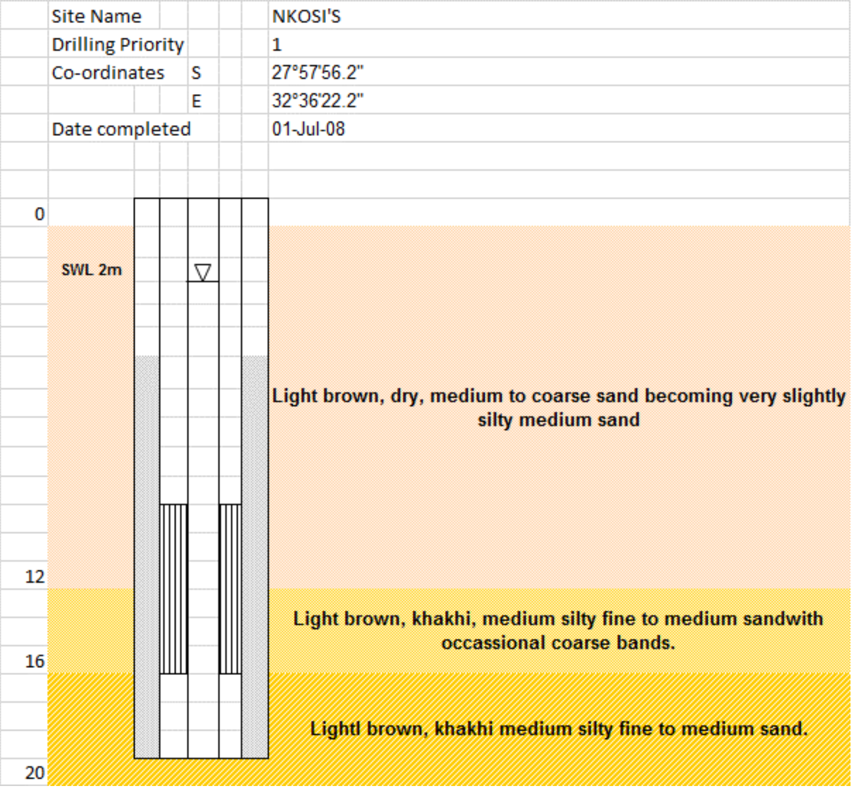
N	ρ	h	d	Alt
1	11882	4.52	4.52	-4.516
2	398	36.9	41.4	-41.43
3	0.728			



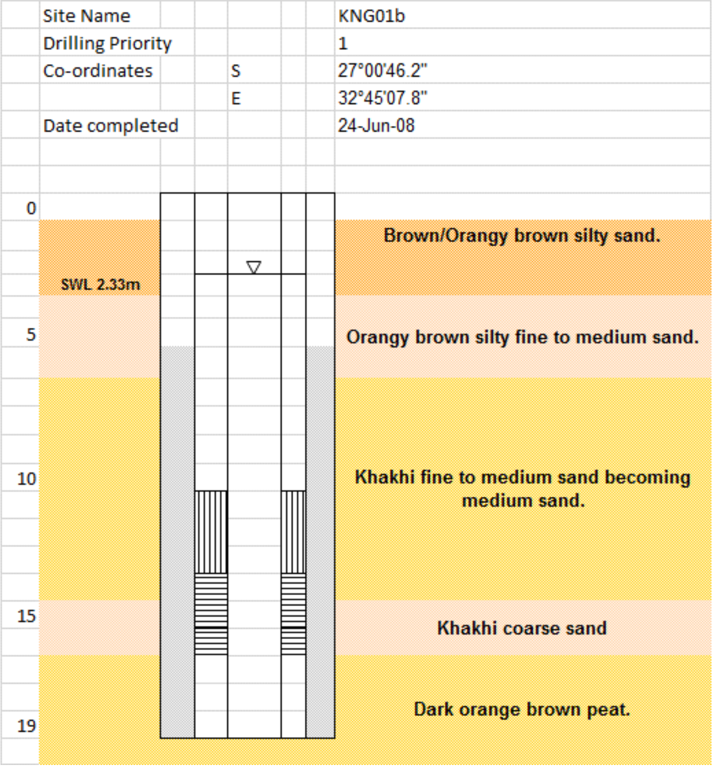
Error = 5.53%

N	ρ	h	d	Alt
1	1862	1.38	1.38	-1.38
2	108	1.12	2.5	-2.5
3	627	4.29	6.79	-6.79
4	90	5.69	12.5	-12.48
5	268	17.4	29.9	-29.88
6	0.46			

Appendix F: Borehole logs.

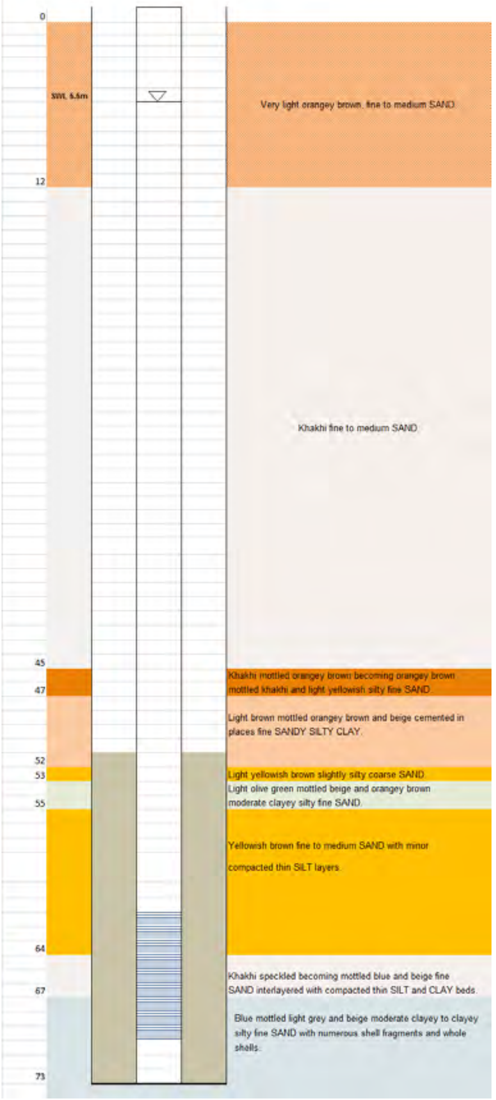


Site Name		NKOSI'S
Drilling Priority		1
Co-ordinates	S	27°57'56.2"
	E	32°36'22.2"
Date completed		01-Jul-08



Site Name		KNG01b
Drilling Priority		1
Co-ordinates	S	27°00'46.2"
	E	32°45'07.8"
Date completed		24-Jun-08

Site Name		Phumobala
DWAF BH No.		KZN140023
Drilling Priority		A
Co-ordinates	S	27.03697°
	E	32.64706°
Date completed		12-Feb-14



Very light orangey brown, fine to medium SAND.

Khakhi fine to medium SAND.

Khakhi mottled orangey brown becoming orangey brown mottled khakhi and light yellowish silty fine SAND.

Light brown mottled orangey brown and beige cemented in places fine SANDY SILTY CLAY.

Light yellowish brown slightly silty coarse SAND.

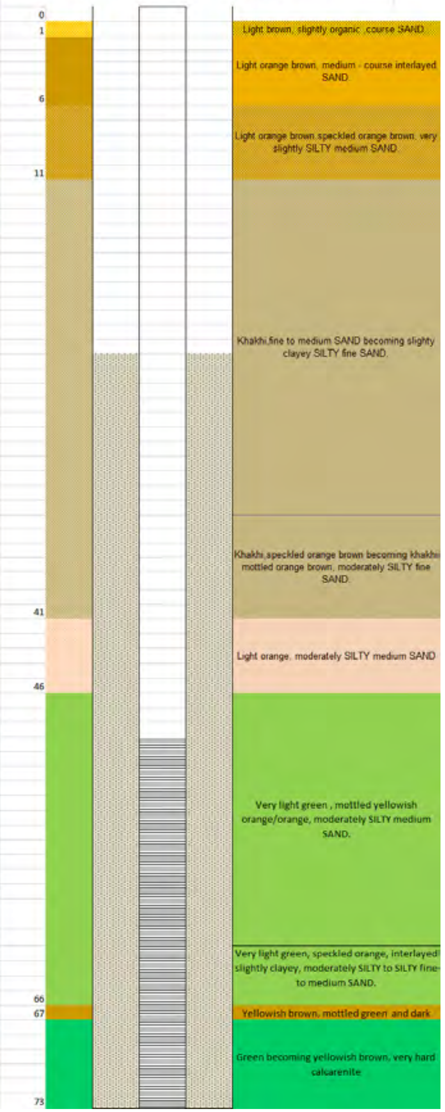
Light olive green mottled beige and orangey brown moderate clayey silty fine SAND.

Yellowish brown fine to medium SAND with minor compacted thin SILT layers.

Khakhi speckled becoming mottled blue and beige fine SAND interlayered with compacted thin SILT and CLAY beds.

Blue mottled light grey and beige moderate clayey to clayey silty fine SAND with numerous shell fragments and whole shells.

Site Name		Thengani
DWAF BH No.		KZN 140119
Drilling Priority		A
Co-ordinates	S	27.020633°
	E	032.699050°
Date completed		03-Jun-14



Light brown, slightly organic, course SAND.

Light orange brown, medium - course interlayed SAND.

Light orange brown speckled orange brown, very slightly SILTY medium SAND.

Khakhi,fine to medium SAND becoming slighty clayey SILTY fine SAND.

Khakhi,speckled orange brown becoming khakhi mottled orange brown, moderately SILTY fine SAND.

Light orange, moderately SILTY medium SAND

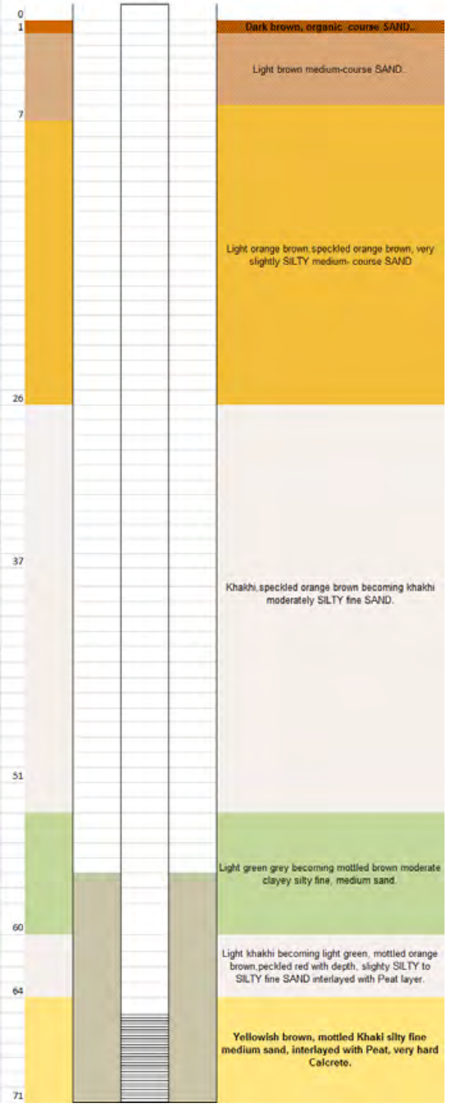
Very light green , mottled yellowish orange/orange, moderately SILTY medium SAND.

Very light green, speckled orange, interlayed slightly clayey, moderately SILTY to SILTY fine-to medium SAND.

Yellowish brown, mottled green and dark

Green becoming yellowish brown, very hard calcarenite

Site Name		Silethithemba
Drilling Priority		A
Co-ordinates	S	26.90841°
	E	32.72823°
Date completed		03-Dec-14



Dark brown, organic course SAND..

Light brown medium-course SAND.

Light orange brown.speckled orange brown, very slightly SILTY medium- course SAND

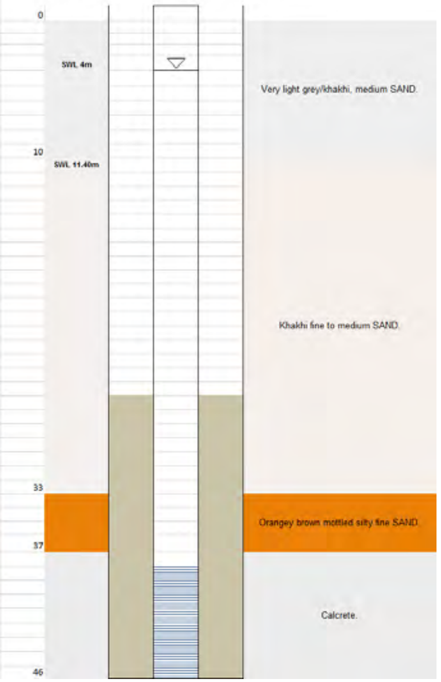
Khakhi,speckled orange brown becoming khakhi moderately SILTY fine SAND.

Light green grey becoming mottled brown moderate clayey silty fine, medium sand.

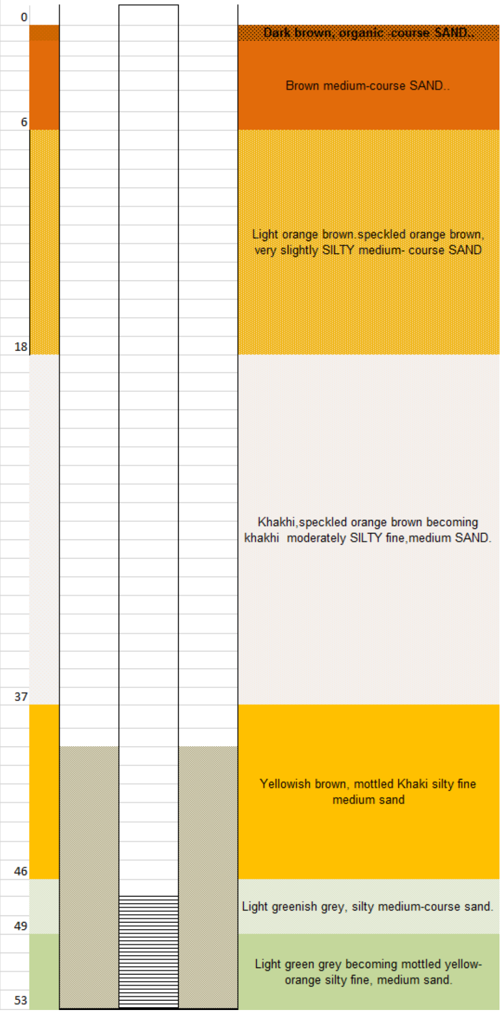
Light khakhi becoming light green, mottled orange brown,peckled red with depth, slighty SILTY to SILTY fine SAND interlayed with Peat layer.

Yellowish brown, mottled Khaki silty fine medium sand, interlayed with Peat, very hard Calcrete.

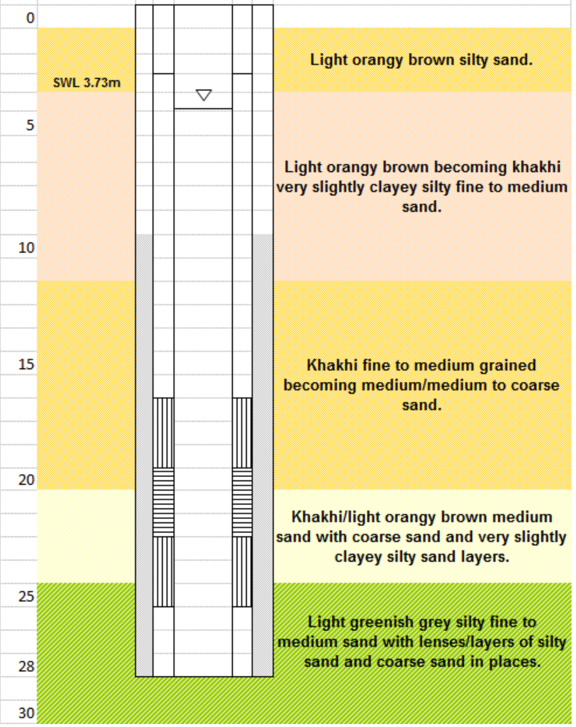
Site Name			Phelandaba
DWAF BH No.			KZN140022
Drilling Priority			A
Co-ordinates	S		27.054175°
	E		32.535051°
Date completed			04-Dec-14
Logged by			Mark Schapers

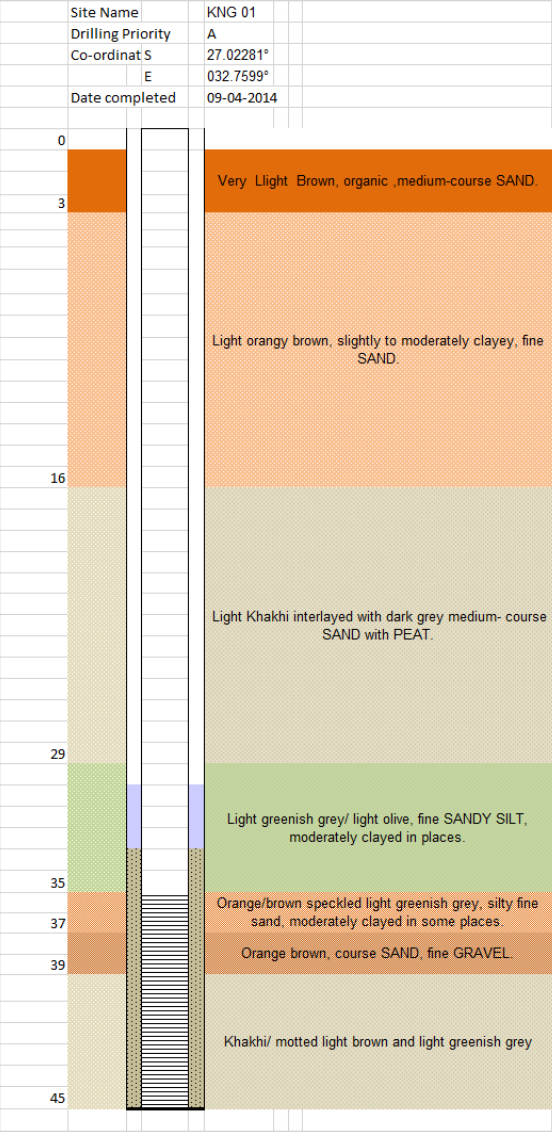


Site Name			Masondo
Drilling Priority			A
Co-ordinates	S		26.93306°
	E		32.70832°
Date completed			02-Dec-14



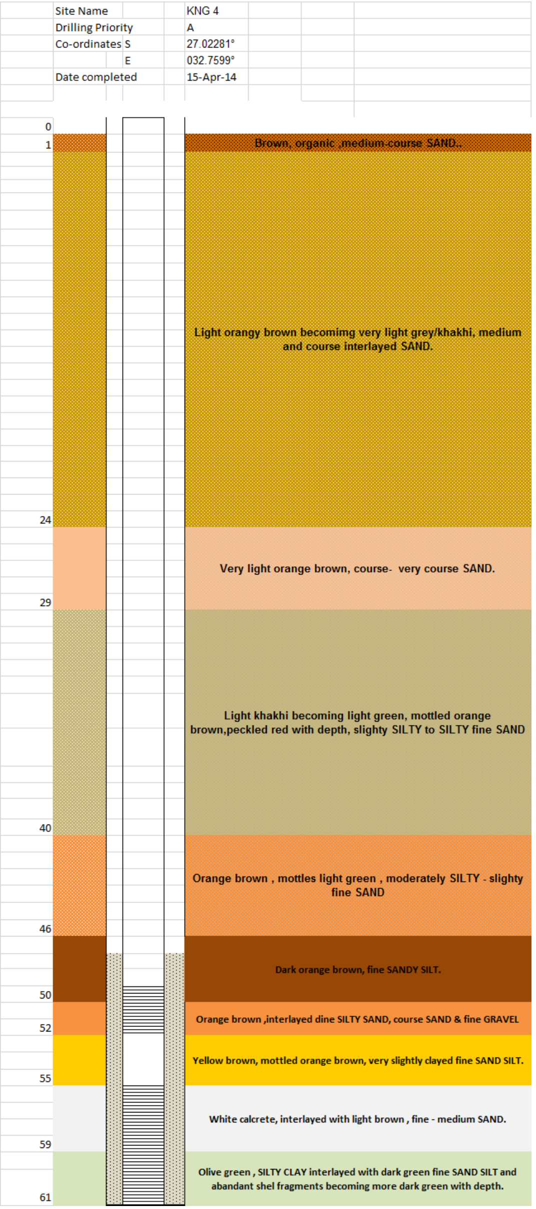
Site Name			KNG02b
Drilling Priority			1
Co-ordinates		S	27°01'03.7"
		E	32°45'27.2"
Date completed			25-Jun-08





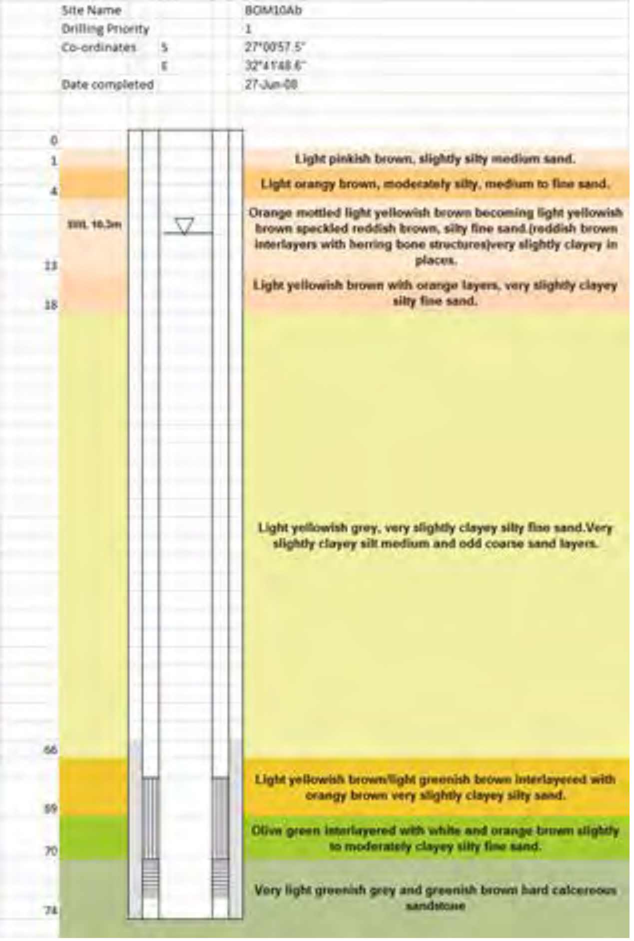
Site Name		KNG 01
Drilling Priority		A
Co-ordinat	S	27.02281°
	E	032.7599°
Date completed		09-04-2014

0	
3	Very Light Brown, organic ,medium-course SAND.
16	Light orangy brown, slightly to moderately clayey, fine SAND.
29	Light Khakhi interlayed with dark grey medium- course SAND with PEAT.
35	Light greenish grey/ light olive, fine SANDY SILT, moderately clayed in places.
37	Orange/brown speckled light greenish grey, silty fine sand, moderately clayed in some places.
39	Orange brown, course SAND, fine GRAVEL.
45	Khakhi/ motted light brown and light greenish grey



Site Name		KNG 4
Drilling Priority		A
Co-ordinates	S	27.02281°
	E	032.7599°
Date completed		15-Apr-14

0	
1	Brown, organic ,medium-course SAND..
24	Light orangy brown becomimg very light grey/khakhi, medium and course interlayed SAND.
29	Very light orange brown, course- very course SAND.
40	Light khakhi becoming light green, mottled orange brown,peckled red with depth, slighty SILTY to SILTY fine SAND
46	Orange brown , mottles light green , moderately SILTY - slighty fine SAND
50	Dark orange brown, fine SANDY SILT.
52	Orange brown ,interlayed dine SILTY SAND, course SAND & fine GRAVEL
55	Yellow brown, mottled orange brown, very slightly clayed fine SAND SILT.
59	White calcrete, interlayed with light brown , fine - medium SAND.
61	Olive green , SILTY CLAY interlayed with dark green fine SAND SILT and abandant shel fragments becoming more dark green with depth.



Site Name		BOM10Ab
Drilling Priority		1
Co-ordinates	S	27°00'57.5"
	E	32°41'48.6"
Date completed		27-Jun-08

Light pinkish brown, slightly silty medium sand.

Light orangy brown, moderately silty, medium to fine sand.

Orange mottled light yellowish brown becoming light yellowish brown speckled reddish brown, silty fine sand.(reddish brown interlayers with herring bone structures)very slightly clayey in places.

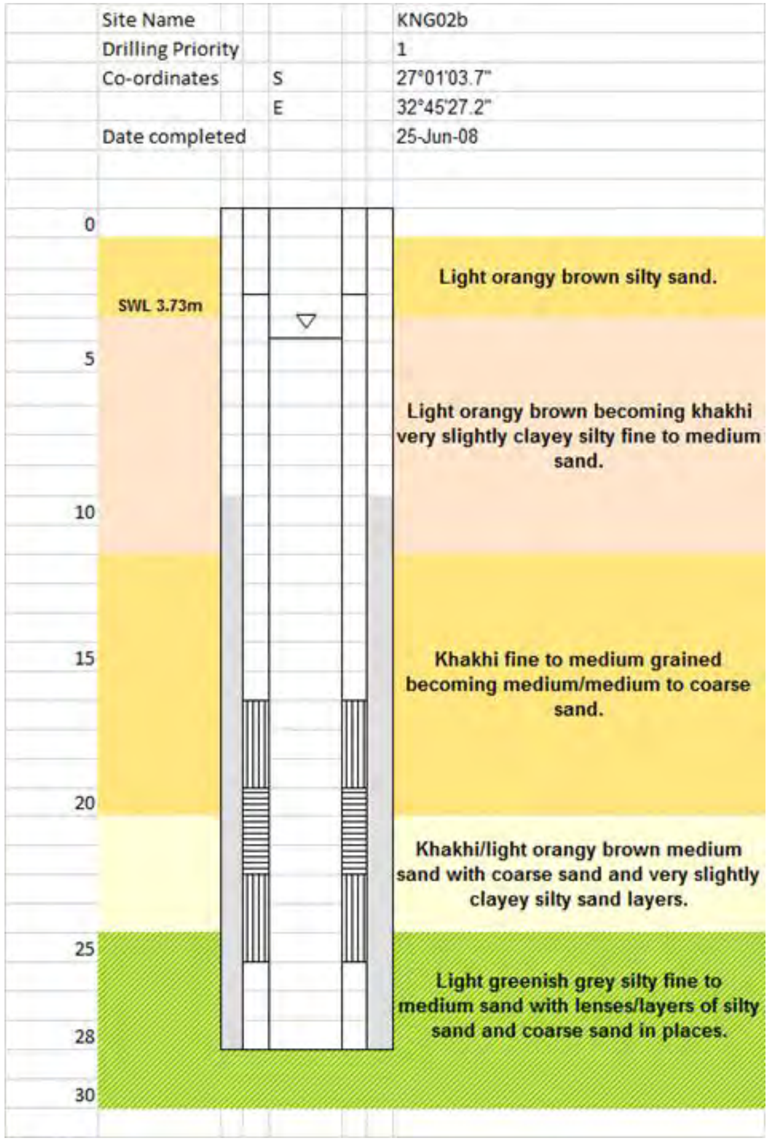
Light yellowish brown with orange layers, very slightly clayey silty fine sand.

Light yellowish grey, very slightly clayey silty fine sand.Very slightly clayey silt medium and odd coarse sand layers.

Light yellowish brown/light greenish brown interlayered with orangy brown very slightly clayey silty sand.

Olive green interlayered with white and orange brown slightly to moderately clayey silty fine sand.

Very light greenish grey and greenish brown hard calcereous sandstone



Site Name		KNG02b
Drilling Priority		1
Co-ordinates	S	27°01'03.7"
	E	32°45'27.2"
Date completed		25-Jun-08

Light orangy brown silty sand.

Light orangy brown becoming khakhi very slightly clayey silty fine to medium sand.

Khakhi fine to medium grained becoming medium/medium to coarse sand.

Khakhi/light orangy brown medium sand with coarse sand and very slightly clayey silty sand layers.

Light greenish grey silty fine to medium sand with lenses/layers of silty sand and coarse sand in places.

Appendix G: Transmissivity using Cooper Jacob and Flow Characteristics (FC), (data from Jeffares & Green database, 2014).

Borehole Number	Date Tested	Aquifer	Assessed Safe Abstraction		Daily Delivery	LATE Transmissivity (T)	LATE Transmissivity (T)
						FC	**Cooper Jacob**
			Pump Rate (l/s)	**Pump cycle (hrs/day)**	**(m^3/day)**	**m^2/day**	**m^2/day**
BOM10Ab	03 July 2008	Deep	0.40	24.00	34.60	1.20	3.20
BOM 10A	20 February 2007	Deep	4.00	24.00	345.60	22.70	35.20
	24 November 2008	Deep	4.50	24.00	388.80	23.30	123.30
UMH/05/003	06 December 2006	Deep	2.35	24.00	203.00	42.90	37.40
UMH/05/004	05 December 2006	Deep	9.25	24.00	799.20	27.60	84.90
UMH/05/006	02 December 2006	Deep	7.50	24.00	648.00	321.50	214.0
Average						**73.20**	**83.00**

Borehole Number	Date Tested	Aquifer	Assessed Safe Abstraction		Daily Delivery	LATE Transmissivity (T)	LATE Transmissivity (T)
						FC	**Cooper Jacob**
			Pump Rate (l/s)	**Pump cycle (hrs/day)**	**(m^3/day)**	**m^2/day**	**m^2/day**
KNG01a	07 July 2008	Shallow	7.33	24.00	633.30	244.00	380.60
KNG02a	01 July 2008	Shallow	10.13	24.00	875.20	175.70	492.80
KNG03a	10 July 2008	Shallow	7.45	24.00	643.70	170.20	332.00
KNG04	08 December 2006	Shallow	6.46	24.00	558.10	154.90	74.90
	14 July 2008	Shallow	5.25	24.00	453.60	157.40	248.10
Average						180.40	305.70

Appendix H: Runoff estimation for the study catchment using Curve Number Method (USDA, 1986) in m^3/month.

	January	February	March	April	May	June	July	August	September	October	November	December
1997	34738519.73	5561386.41	15307704.85	7255173.45	6689615.78	5953739.99	5400608.35	8672001.35	6205554.31	7740523.98	40085259.07	11706694.95
1998	14421624.02	19035392.04	8033982.48	3880741.18	688516.84	0.00	3246853.46	89667.58	2405089.26	7993496.11	3089224.81	11422165.05
1999	20186303.42	43115732.04	12875830.55	5440791.89	963409.11	13764.06	3010561.58	5400608.35	7760757.33	9584460.50	21583177.02	8682133.70
2000	24936719.60	31923523.29	42687169.63	5601598.81	5320263.99	1232430.49	4909013.83	129120.55	15613116.50	9878686.33	35881714.45	9412027.94
2001	13607619.51	27588648.51	8945625.81	4309026.72	1658821.92	4079740.43	3030217.49	26391.92	3227128.87	5450838.93	10457248.04	12550426.96
2002	3010018.42	1847937.68	3207410.13	7558460.07	13658.70	4269119.51	5189771.43	1259788.95	781272.48	2115504.74	3464190.03	8084594.50
2003	1527116.01	13262318.11	2502171.90	1734242.83	4989185.87	0.00	6165249.22	209939.37	2658003.19	2337286.47	9239630.33	5611652.99
2004	17516876.41	14279718.09	16213841.71	12845321.58	867253.80	663591.18	4758793.55	0.00	3069549.19	2202096.12	14625730.59	5189771.43
2005	19146906.96	5430745.30	17996207.92	7518010.52	4478769.74	162123.11	3513672.90	22220.34	2697050.13	1223327.42	18454645.75	3781387.41
2006	7345580.36	9503311.51	6145098.74	13099577.48	1602470.20	5702159.80	13347.13	8368101.91	1416113.17	2269619.52	11838816.64	22041874.07
2007	2688018.42	3192180.27	7393794.23	19017024.08	68514.14	7565801.75	7153068.29	961315.39	3175331.26	3091141.62	17615700.85	15955302.96
2008	267129.52	458315.91	569418.84	738518.26	57018.34	1704485.20	264668.86	197529.84	230539.72	10076.47	327647.28	593409.26
2009	1842826.68	1084924.16	456611.09	245491.42	462578.67	323431.29	1132.69	19966.08	71396.48	442978.42	656889.94	644872.30
2010	1526361.76	631142.08	744537.87	1222193.82	248821.07	238839.63	1217012.11	116256.51	11408.47	871072.03	1430412.94	998648.92
2011	2296223.90	526626.65	3629.22	417447.65	228881.81	354677.52	1560078.48	323431.29	30449.74	688666.32	487321.29	489882.59
2012	401254.03	797879.36	2774942.50	224740.17	1365.49	1592.77	131226.02	0.00	2531694.93	0.00	463431.34	338618.65
2013	1428636.41	104588.68	312480.09	623420.91	15744.58	112351.23	0.00	636290.37	81011.39	713586.54	624278.74	1469307.93
2014	594219.07		3614800.17	135196.19	42623.23	15744.58	0.00	32930.74	5113.90	15794470.11	564280.40	310796.67
2015	1042595.07	714446.07	714446.07	132019.10	3629.22	120176.68	153600.68	7609.53				
Average	8869713.12	9947712.01	7921037.04	4842052.43	1494796.97	1711251.01	2616782.95	1393324.74	2887254.46	4022657.31	10604977.75	6626864.91

Appendix I: Groundwater abstraction from the ground water contributing area.

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Days/month	31	28	31	30	31	30	31	31	30	31	30	31
[1]Wg (m^3)	51342.70	46374.06	51342.70	49686.49	51342.70	49686.49	51342.70	51342.70	49686.49	51342.70	49686.49	51342.70
[2]Wg (m^3)	48825	44100	48825	47250	48825	47250	48825	48825	47250	48825	47250	48825
Total Wg (m^3)	100167.71	90474.06	100167.71	96936.49	100167.71	96936.49	100167.71	100167.71	96936.49	100167.71	96936.49	100167.71

1 Groundwater abstraction from the registered uses in UMkhanyakude district (DWAF, 2015)
2 Estimated groundwater abstraction based on the 25 L/person/day water requirement within the study area.

Appendix J: Evapotranspiration from the groundwater contributing area using FAO Penman-Monteith Method (from 1997-2015) in m^3/month.

	January	February	March	April	May	June	July	August	September	October	November	December
1997								1419932.75	1817711.51	2450678.88	2379940.92	2907089.85
1998	2981427.22	2729551.70	3025114.86	2554499.21	2291576.94	1310948.58	1534898.27	1905011.99	2351104.30	2334165.78	2867241.46	2850806.25
1999	2936635.83	2597848.89	2597380.70	2087718.21	1823924.18	1352866.77	1484437.96	1846296.10	2297213.60	2572259.58	2686075.02	2654602.54
2000	2549586.38	2250337.62	2345065.70	1872347.16	1732455.11	1147663.46	1231797.23	1778488.60	2213353.62	1970163.39	2356848.80	2907901.64
2001	2931065.66	2314447.35	2527274.02	1887097.15	1803457.24	1054465.14	1273363.61	1617581.45	2110192.94	2134329.59	2313517.33	2962108.30
2002	3306465.82	2714162.18	3086836.63	2342190.51	2357233.67	1147611.32	1256101.35	1498862.46	2016756.33	2641123.73	2889463.22	2803210.17
2003	3056731.65	2748911.88	2994547.52	2186185.33	1867958.07	1032401.25	1324252.39	1993573.32	2018389.33	2375512.83	2640153.59	3153363.98
2004	3007587.58	2681285.74	2567991.15	2154137.65	1881308.02	1181835.57	1301838.39	1654628.42	2289223.53	2661279.57	2813082.17	3048306.52
2005	2781555.55	2554907.13	2454034.88	1947600.28	1836342.92	1257469.98	1315649.43	1852621.54	2348015.88	2535635.75	2583021.91	2895651.22
2006	2844533.85	2638772.87	2649945.00	2177011.30	1922839.53	1090617.91	1520999.87	1843930.99	2144679.17	2409826.88	2581859.35	2884953.59
2007	2864749.25	2563125.23	2668023.29	2081657.14	1824068.36	1190615.69	1350869.48	1612849.48	1750341.74	2041546.54	2209696.97	2452381.50
2008	2382869.62	2156772.39	2030807.63	1533772.09	1209331.93	972065.08	1023545.17	1494689.48	1862385.26	2038064.67	2126243.17	2467068.63
2009	2538991.31	2204924.89	2177582.23	1675557.74	1311928.30	1045081.60	1147511.90	1399244.26	1778061.74	1940913.84	2084702.52	2479335.04
2010	2432452.12	2128971.86	2090707.65	1572072.35	1334493.47	1146967.77	1103826.88	1436008.84	1772204.34	2021397.82	2373656.93	2527216.90
2011	2606864.24	2362571.16	2480275.42	1919760.98	1613185.39	1131482.43	1153102.97	1501937.67	1794639.63	2090127.93	2272460.98	2498418.77
2012	2675031.37	2412989.73	2313688.06	1809078.42	1511176.98	1168456.93	1283505.14	1640751.23	1835552.95	2019304.89	2219514.03	2448469.17
2013	2582416.74	2365581.77	2366622.77	1857400.72	1551511.50	1253060.64	1208365.46	1729421.69	2030910.68	2244135.39	2359184.83	2456261.19
2014	2433274.51	2342505.56	2303043.07	1802893.06	1573471.01	1297951.30	1443536.63	1689679.56	2140747.62	2182298.34	2265569.60	2558044.46
2015	2162041.50	2327604.13	2396831.86	1760849.43	1620910.24	1246662.17	1400152.29	1696455.22				
Average	2726348.90	2449737.34	2504209.58	1956768.26	1725954.05	1168234.64	1297653.02	1677335.13	2044339.57	2247769.80	2449546.58	2708711.76

Appendix K: Groundwater inflow into the Kosi Bay Lakes in m^3/month.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1997								3013985.486	2916760.148	3013985.486	2916760.148	3013985.486
1998	32558.265			362260.934	722408.543	1605811.571	1479087.218	1108973.498	565655.847	679819.702	49518.689	163179.239
1999	77349.657	124460.584	416604.782	829041.940	1190061.307	1563893.378	1529547.525	1167689.388	619546.543	441725.901	230685.124	359382.946
2000	464399.107	471971.851	668919.789	1044412.988	1281530.374	1769096.684	1782188.255	1235496.886	703406.524	1043822.096	559911.344	106083.847
2001	82919.831	407862.119	486711.469	1029663.002	1210528.243	1862295.012	1740621.877	1396404.033	806567.203	879655.900	603242.818	51877.181
2002	0.000	8147.292	0.000	574569.633	656751.814	1769148.828	1757884.136	1515123.027	900003.818	372861.757	27296.924	210775.321
2003	0.000	0.000	19437.961	730574.816	1146027.414	1884358.900	1689733.099	1020412.168	898370.818	638472.659	276606.561	0.000
2004	6397.911	41023.731	445994.337	762622.502	1132677.466	1734924.579	1712147.093	1359357.064	627536.619	352705.913	103677.978	0.000
2005	232429.934	167402.341	559950.602	969159.864	1177642.562	1659290.169	1698336.060	1161363.945	568744.263	478349.739	333738.233	118334.268
2006	169451.631	83536.606	364040.484	739748.847	1091145.958	1826142.235	1492985.617	1170054.496	772080.978	604158.610	334900.801	129031.892
2007	149236.232	159184.245	345962.193	835103.010	1189917.123	1726144.453	1663116.008	1401136.004	1166418.408	972438.949	707063.181	561603.989
2008	631115.868	565537.077	983177.858	1382988.059	1804653.560	1944695.070	1990440.314	1519296.010	1054374.891	975920.814	790516.973	546916.855
2009	474994.175	517384.579	836403.260	1241202.410	1702057.185	1871678.548	1866473.583	1614741.227	1138698.412	1073071.647	832057.624	534650.450
2010	581533.362	593337.607	923277.833	1344687.801	1679492.014	1769792.373	1910158.603	1577976.646	1144555.806	992587.663	543103.219	486768.585
2011	407121.246	359738.314	533710.068	996999.170	1400800.096	1785277.720	1860882.517	1512047.816	1122120.522	923857.559	644299.167	515566.717
2012	338954.114	309319.746	700297.427	1107681.726	1502808.506	1748303.221	1730480.343	1373234.252	1081207.199	994680.596	697246.116	565516.314
2013	431568.744	356727.705	647362.720	1059359.433	1462473.990	1663699.508	1805620.023	1284563.793	885849.464	769850.095	557575.319	557724.299
2014	580710.979	379803.910	710942.414	1113867.088	1440514.480	1618808.843	1570448.858	1324305.921	776012.524	831687.142	651190.552	455941.027
2015	851943.987	394705.343	617153.624	1155910.721	1393075.241	1670097.980	1613833.200	1317530.262				
Average	306260.280	290596.650	544702.754	959991.886	1288031.438	1748525.504	1716332.463	1424931.154	985994.999	891091.790	603299.487	465407.690

Appendix L: Evaporation estimation from the Lakes using Penman's 1948 method (Penman, 1948) in m^3/month.

	January	February	March	April	May	June	July	August	September	October	November	December
1997	9048360.73	7260560.61	6366660.54	5648687.62	3435334.01	3195217.24	3387786.14	5068057.33	5304139.51	7011615.12	6477526.17	7636818.01
1998	7748677.61	7094163.28	7549441.96	6934478.91	6756376.49	3759662.18	5012398.31	5226166.03	6721125.05	6562011.23	7476761.95	7151817.10
1999	6635191.00	5980489.32	6266635.80	5555817.90	5412434.99	4056081.33	4659305.63	4936486.52	6641408.18	7066975.31	6972204.75	6182070.39
2000	6134214.80	5711129.89	5986390.53	5263384.31	5248840.22	3562280.95	3498901.33	4422518.15	6374261.28	6116924.28	6792943.12	7266040.75
2001	6672442.79	5669659.86	6152882.77	5576798.28	5480766.23	3137732.76	4215976.45	4677172.57	5998896.61	6413532.14	6277466.32	7416488.37
2002	8166115.65	7130548.29	7950224.75	7012240.60	7102605.47	3744812.34	3930926.85	4729478.47	5233060.36	7871138.57	7805965.54	7360316.00
2003	7029528.49	6362171.18	6818127.39	5975530.53	5796912.91	3631634.35	4438610.03	6361811.98	6103047.04	7121806.61	7249099.51	8101626.89
2004	7060769.42	6428352.64	6636412.74	6110513.52	5928731.49	3645381.60	4212325.94	4711692.94	6390965.61	7492101.52	7059074.99	7169417.25
2005	6548942.82	5795386.66	6113599.49	5540670.95	5356102.61	3865852.66	4064148.42	5535887.60	6162380.73	7009525.16	7542665.27	7351725.94
2006	6955711.99	6151146.95	6495374.54	6000677.86	5816687.38	3217677.43	4411831.45	5535653.89	5931400.54	6667813.34	6802524.83	6771366.49
2007	6225735.02	5565973.46	5878977.94	5279930.94	5099638.86	3551484.80	3718857.54	4314180.77	3939937.96	4445158.34	4618012.36	4599297.67
2008	4402491.92	4029424.43	4052386.93	3448115.60	3276152.61	3206297.14	3118748.63	4215275.47	4647446.77	4771111.58	4805114.25	5020131.63
2009	5048541.46	3693308.73	4039633.16	3806020.07	3871492.86	3562013.80	3909682.57	3920731.22	4169525.27	4460262.24	4112570.11	4192242.25
2010	3709806.00	3280899.77	3529288.65	3295761.89	3297981.53	3535728.36	3435113.19	3620779.58	3931835.17	4050262.79	4433380.81	4399810.20
2011	5632646.94	4982699.66	5380042.16	4660393.45	4459973.06	3296948.01	3863996.83	4368332.32	3996620.98	4623592.92	4733699.29	4933217.45
2012	5235388.51	4828909.32	4847600.52	4156356.33	4002509.57	3420681.68	3841978.60	4106706.28	4736583.36	4652585.76	4795114.55	4860331.64
2013	5209819.26	4605439.76	4786199.97	4166933.95	3962655.93	3510138.76	3487521.32	4574132.55	4724963.67	5162982.54	5145343.73	4905279.79
2014	3689188.39	3244875.27	3557206.53	3412750.83	3751920.32	3627144.68	3980137.32	3859025.71	4294387.18	4182452.60	3945535.83	3875181.31
2015	3659050.40	3514909.84	3962299.91	3441444.61	3847120.16	3469117.93	4065376.77	4106291.61				
Average	6042769.64	5333160.47	5598388.75	5015079.38	4837065.09	3526099.37	3960717.02	4646862.16	5294554.74	5871214.00	5946944.63	6066287.73

Appendix M: Estimation of groundwater seepage from the Lakes using Dupuit's equation (Dupuit, 1863) in m^3/month..

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1997	2510921.53	2267929.13	2510921.53	2429924.06	2510921.53	2429924.06	2510921.53	2510921.53	2429924.06	2510921.53	2429924.06	2510921.53
1998	2510921.53	2267929.13	2510921.53	2429924.06	2510921.53	2429924.06	2510921.53	2510921.53	2429924.06	2510921.53	2429924.06	2510921.53
1999	2510921.53	2267929.13	2510921.53	2429924.06	2510921.53	2429924.06	2510921.53	2510921.53	2429924.06	2510921.53	2429924.06	2510921.53
2000	2510921.53	2348926.60	2510921.53	2429924.06	2510921.53	2429924.06	2510921.53	2510921.53	2429924.06	2510921.53	2429924.06	2510921.53
2001	2510921.53	2267929.13	2510921.53	2429924.06	2510921.53	2429924.06	2510921.53	2510921.53	2429924.06	2510921.53	2429924.06	2510921.53
2002	2510921.53	2267929.13	2510921.53	2429924.06	2510921.53	2429924.06	2510921.53	2510921.53	2429924.06	2510921.53	2429924.06	2510921.53
2003	2510921.53	2267929.13	2510921.53	2429924.06	2510921.53	2429924.06	2510921.53	2510921.53	2429924.06	2510921.53	2429924.06	2510921.53
2004	2510921.53	2348926.60	2510921.53	2429924.06	2510921.53	2429924.06	2510921.53	2510921.53	2429924.06	2510921.53	2429924.06	2510921.53
2005	2510921.53	2267929.13	2510921.53	2429924.06	2510921.53	2429924.06	2510921.53	2510921.53	2429924.06	2510921.53	2429924.06	2510921.53
2006	2510921.53	2267929.13	2510921.53	2429924.06	2510921.53	2429924.06	2510921.53	2510921.53	2429924.06	2510921.53	2429924.06	2510921.53
2007	2510921.53	2267929.13	2510921.53	2429924.06	2510921.53	2429924.06	2510921.53	2510921.53	2429924.06	2510921.53	2429924.06	2510921.53
2008	2510921.53	2348926.60	2510921.53	2429924.06	2510921.53	2429924.06	2510921.53	2510921.53	2429924.06	2510921.53	2429924.06	2510921.53
2009	2510921.53	2267929.13	2510921.53	2429924.06	2510921.53	2429924.06	2510921.53	2510921.53	2429924.06	2510921.53	2429924.06	2510921.53
2010	2510921.53	2267929.13	2510921.53	2429924.06	2510921.53	2429924.06	2510921.53	2510921.53	2429924.06	2510921.53	2429924.06	2510921.53
2011	2510921.53	2267929.13	2510921.53	2429924.06	2510921.53	2429924.06	2510921.53	2510921.53	2429924.06	2510921.53	2429924.06	2510921.53
2012	2510921.53	2348926.60	2510921.53	2510921.53	2510921.53	2510921.53	2510921.53	2510921.53	2510921.53	2510921.53	2510921.53	2510921.53
2013	2510921.53	2267929.13	2510921.53	2510921.53	2510921.53	2510921.53	2510921.53	2510921.53	2510921.53	2510921.53	2510921.53	2510921.53
2014	2510921.53	2267929.13	2510921.53	2510921.53	2510921.53	2510921.53	2510921.53	2510921.53	2510921.53	2510921.53	2510921.53	2510921.53
2015	2510921.53	2267929.13	2510921.53	2510921.53	2510921.53	2510921.53	2510921.53	2510921.53	2510921.53	2510921.53	2510921.53	2510921.53
Average	2510921.53	2284981.23	2510921.53	2446976.16	2510921.53	2446976.16	2510921.53	2510921.53	2446976.16	2510921.53	2446976.16	2510921.53

Appendix N: Lake Water Storage (± ΔS) Estimation using the mass balance method, values in m^3 in m^3/month.

	January	February	March	April	May	June	July	August	September	October	November	December
1997								8618827.02	4738536.64	5306351.40	53264032.96	10506441.43
1998	11374051.94	18966648.47	2120007.68	-2897025.81	-7229001.09	-4565621.06	-876705.40	-6319986.67	-4669147.09	3770071.33	-4923950.48	7699412.13
1999	21011779.11	55570679.82	10995179.09	1273013.77	-4966801.35	-4815091.68	-799999.19	2092157.56	3391494.67	5388039.48	22956012.67	4865098.56
2000	28865951.94	39698342.34	55242077.29	2017701.93	1775262.18	-2046314.59	3419662.50	-5288764.13	15270311.51	7372301.38	44429250.11	4600068.04
2001	11329820.81	33401040.61	5408731.28	-216401.71	-3957889.00	2716649.41	-116430.18	-5608864.51	-2461765.54	401082.98	7700397.00	9003042.13
2002	-5879218.64	-6286943.46	-5370840.28	2678292.33	-8829475.94	2296143.70	3377224.52	-3505495.29	-5279839.03	-6501015.20	-4696928.68	2660173.65
2003	-6957771.17	11250882.08	-5224569.16	-4739515.17	603700.43	-4136245.90	4238082.49	-7295756.83	-3319015.71	-5154930.49	4613935.34	-1972095.75
2004	16600067.59	12675829.00	15552373.19	11532178.11	-5688939.68	-3041487.85	2414654.64	-5820938.68	-3266521.39	-6012749.53	12537168.95	-1661468.75
2005	19728722.77	516268.73	18803596.74	4484983.52	323215.58	-4167141.72	709552.03	-6716300.79	-3649909.86	-6877795.94	17900354.20	-3761933.51
2006	1937340.34	6065388.31	825965.31	11992265.71	-4498072.88	4993246.92	-5317044.05	5860756.40	-5133671.46	-4836201.74	8935216.19	23648227.85
2007	-3993206.44	-2295150.73	3880695.14	23071689.21	-6119618.90	7935106.17	6984109.37	-3569225.19	152495.67	-758074.04	21433969.15	18654275.20
2008	-4118482.18	-2387325.52	-1421321.51	768184.95	-3283980.27	7858284.63	-1492139.47	-3512087.43	-4106346.11	-6025487.28	-3879208.59	-2668202.74
2009	5365814.55	2074483.53	-2295782.04	-2977554.02	-1222736.73	-1582936.49	-4453621.64	-4431301.15	-4654201.84	-2569452.01	-980533.14	-1515829.47
2010	4754372.04	-396709.60	186972.44	4033349.77	-2088509.41	-2223362.44	4346126.49	-3420417.77	-4922347.18	560796.07	3448269.20	536715.02
2011	7658742.05	-3016708.30	-7168662.05	-2934197.74	-3663247.03	-1197098.17	6098683.80	-2828518.10	-4824109.43	-1271684.85	-2900437.36	-3291494.65
2012	-4353404.79	-1220568.43	11845080.77	-3682029.37	-4881352.19	-4045657.85	-3383802.61	-5202074.83	10756299.71	-6126507.96	-3146927.15	-4166275.38
2013	2469377.82	-5470419.49	-4183834.28	-1107498.39	-4667752.90	-3253098.43	-4150504.09	-1203936.23	-5472059.50	-1802272.87	-2582079.66	3164219.38
2014	-1297900.78	-5094777.11	18598121.36	-3544809.11	-4238132.71	-4177271.92	-4878291.25	-4542460.97	-5816811.11	97130357.86	-1681490.00	-3475430.30
2015	1929090.55	-284833.55	-748672.40	-3553655.50	-4776374.87	-3150305.80	-3568339.23	-5050053.54				
AVG	5912508.20	8542562.59	6502506.59	2011054.03	-3744983.71	-922344.61	141734.37	-3039181.11	-1292589.28	3999601.59	9579280.59	3490274.60

Appendix O: Evapotranspiration from the entire catchment area, using FAO Penman-Monteith Method (from 1997-2015) in m^3/month.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1997								36370354.45	46559114.96	62772028.98	60960137.18	74462602.96
1998	76366690.67	69915116.08	77485711.82	65431297.42	58696769.87	33578818.81	39315097.29	48795241.47	60221511.90	59787646.38	73441920.69	73020946.89
1999	75219397.71	66541661.98	66529669.85	53475103.95	46718247.09	34652517.21	38022599.97	47291284.51	58841148.11	65886214.03	68801498.49	67995357.90
2000	65305459.40	57640460.16	60066838.24	47958560.03	44375345.69	29396411.26	31551425.25	45554453.85	56693146.93	50464038.52	60368652.39	74483396.19
2001	75076722.52	59282575.73	64733947.45	48336368.21	46194004.13	27009216.35	32616112.21	41432955.84	54050774.97	54669014.26	59258754.00	75871853.26
2002	84692274.40	69520926.78	79066661.83	59993192.93	60378510.45	29395075.62	32173954.33	38392071.05	51657476.55	67650109.79	74011112.07	71801814.26
2003	78295548.74	70411010.44	76702755.93	55997254.53	47846137.32	26444068.86	33919584.45	51063663.67	51699304.45	60846715.27	67625260.42	80770702.70
2004	77036765.61	68678825.12	65776881.72	55176380.64	48188084.74	30271700.29	33345469.29	42381882.05	58636489.20	68166384.36	72054677.15	78079746.30
2005	71247149.98	65441745.86	62857990.14	49886103.98	47036342.53	32209010.56	33699227.00	47453305.28	60142404.76	64948125.97	66161881.84	74169612.22
2006	72860284.97	67589894.42	67876059.10	55762269.61	49251878.56	27935238.59	38959101.77	47230704.31	54934109.94	61725640.08	66132103.66	73895601.77
2007	73378085.03	65652245.31	68339118.94	53319854.86	46721940.22	30496595.66	34601358.30	41311750.49	44833496.26	52292456.36	56599484.82	62815640.05
2008	61035153.14	55243867.45	52017388.47	39286251.16	30975995.79	24898609.82	26217228.10	38285183.71	47703394.47	52203271.38	54461887.79	63191838.35
2009	65034075.86	56477252.22	55776893.37	42917968.46	33603913.60	26768865.16	29392529.16	35840436.66	45543520.09	49714836.47	53397859.80	63506031.74
2010	62305166.32	54531780.83	53551676.00	40267279.28	34181901.02	29378591.79	28273574.99	36782129.74	45393487.98	51776364.41	60799178.02	64732484.48
2011	66772582.48	60515225.55	63530118.81	49173024.14	41320354.49	28981947.96	29535739.51	38470839.94	45968148.47	53536826.82	58207130.97	63994845.13
2012	68518624.85	61806653.74	59263127.08	46337985.79	38707496.91	29929017.91	32875878.88	42026429.84	47016108.00	51722755.72	56850940.48	62715429.22
2013	66146380.87	60592339.70	60619004.02	47575719.72	39740630.82	32096069.16	30951240.69	44297647.28	52020028.15	57481595.38	60428487.65	62915014.96
2014	62326230.96	60001262.58	58990464.90	46179553.07	40303104.74	33245904.88	36974947.56	43279686.89	54833406.76	55897692.68	58030614.09	65522105.83
2015	55378831.04	59619575.22	61392783.99	45102641.61	41518219.99	31932177.80	35863694.99	43453239.58				
Average	69833079.14	62747912.18	64143171.76	50120933.86	44208826.55	29923324.32	33238264.65	42963494.79	52363997.47	57574687.52	62743026.14	69381318.90

Appendix P: Groundwater abstraction from the whole catchment in m^3/month.

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Days per month	31	28	31	30	31	30	31	31	30	31	30	31
[1]Wg(m^3)	51342.71	46374.06	51342.71	49686.49	51342.71	49686.49	51342.71	51342.71	49686.49	51342.71	49686.49	51342.71
[2]Wg(m^3)	56013.13	50592.50	56013.13	54206.25	56013.13	54206.25	56013.13	56013.13	54206.25	56013.13	54206.25	56013.13
Total	107355.83	96966.56	107355.83	103892.74	107355.83	103892.74	107355.83	107355.83	103892.74	107355.83	103892.74	107355.83

1 Groundwater abstraction from the registered uses in UMkhanyakude district (DWAF, 2015)
2 Estimated groundwater abstraction based on the 25 L/person/day water requirement within the study area.

Appendix Q: Surface water abstraction from the catchment in m3.

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Days per month	31	28	31	30	31	30	31	31	30	31	30	31
Ws (m^3)	556834.23	502947.04	556834.23	538871.84	556834.23	538871.84	556834.23	556834.23	538871.83	556834.23	538871.83	556834.23

1 Groundwater abstraction from the registered uses in UMkhanyakude district (DWAF, 2015)
2 Estimated groundwater abstraction based on the 25 L/person/day water requirement within the study area.

Appendix R: Catchment’s groundwater Storage (±ΔS) Estimation using the mass balance method, values in m^3/month.

	January	February	March	April	May	June	July	August	September	October	November	December
1997								17837968.14	-8580357.77	-16570064.18	194605348.01	-3118941.04
1998	11954920.13	49220977.91	-30415965.38	-44860864.97	-60193057.96	-40411169.63	-21142607.20	-54428719.10	-49322725.59	-11994069.20	-58685771.29	-3542975.59
1999	52071933.92	209800953.01	13814016.98	-20706738.65	-44204959.44	-40517515.34	-20521782.96	-14251648.39	-12001373.10	-7694466.70	67265579.95	-14783805.66
2000	92639414.21	146095269.75	212691859.63	-14382232.98	-12732097.51	-23510380.85	-860138.17	-49857083.59	40815603.14	10032025.61	167730615.84	-18167848.53
2001	9605957.32	117071068.72	-9779807.59	-23035683.30	-38740647.72	-785165.91	-14540166.03	-47146805.78	-36355288.39	-22776923.76	5474362.87	1213181.00
2002	-70698267.42	-62145970.75	-63538763.94	-14842250.34	-69110893.29	-2526004.76	487341.46	-33021126.89	-50264253.71	-59423925.73	-56541094.41	-23656607.63
2003	-73206198.76	12691689.25	-64680204.86	-48323109.13	-18261471.77	-32505627.27	4733683.98	-55718797.18	-37826275.56	-50248143.42	-11667883.99	-49404951.12
2004	-60047116.29	22615708.63	37766315.48	27101241.26	-44961906.29	-26322346.47	-1845185.30	-47757765.06	-40496419.38	-57013975.95	20806883.28	-46702853.62
2005	51362717.13	-31044946.13	52740520.30	-1636139.51	-18525035.21	-33027227.80	-10288265.48	-52203582.95	-44277950.07	-60166741.20	50994488.30	-52266928.23
2006	-29678008.55	-9259084.11	-32075545.24	25842763.88	-43086677.53	8345795.34	-45755244.82	4027530.20	-50099199.13	-51798565.02	6499482.86	64696520.14
2007	-56946131.64	-44299261.51	-15183608.48	89238525.56	-52360690.68	26406830.90	18869072.56	-37004942.86	-22191122.86	-30916726.29	75945014.18	56992350.68
2008	-42911756.66	-21627732.09	-10083486.99	16336644.60	-29123860.00	104708204.39	-7007788.33	-25510170.78	-32622129.88	-56986294.56	-31893890.68	-20380481.58
2009	73172071.08	25597096.31	-22529038.12	-25809077.17	273381.94	-3287267.60	-35686523.33	-38455079.48	-43164334.00	-17942010.31	-4699918.56	-15912785.59
2010	53120316.09	-6774323.33	2348923.75	52477870.18	-16403794.15	-12526608.79	63834400.22	-30068520.92	-49037111.80	13290561.20	46690252.53	9738093.72
2011	105381058.97	-22499367.94	-70108272.57	-19474906.23	-26285839.15	-2796984.62	88305652.06	-15897983.86	-47370058.09	-3014031.34	-23178518.90	-29070474.17
2012	-40750024.96	-2893603.27	150118260.81	-31307928.23	-44698918.07	-35185385.70	-25131369.08	-49308247.72	143979822.53	-59550453.08	-23809941.14	-39448372.45
2013	40332388.27	-55544622.20	-39320715.59	-1583239.78	-42924398.34	-25579894.03	-37613873.61	2254708.57	-49420577.93	-5587089.52	-15348517.49	46965593.65
2014	-18118030.95	-66113980.58	215604316.96	-37654890.01	-40310636.66	-36072735.67	-44130196.47	-44382824.21	-59974980.05	1144691743.12	-16363836.03	-43444598.74
2015	23750241.20	-5200880.74	-7674861.27	-36331400.49	-46006617.51	-24177110.01	-25940549.14	-47410008.56				
Average	6724193.50	14204943.94	17760774.66	-6052856.41	-35981006.63	-11098366.32	-6346307.76	-32542268.44	-24900485.09	36462824.98	21879036.41	-10016438.04

Appendix S: On site measured groundwater and surface water physical parameter within the study area.

Sample Id	Water point	Date measured	Altitude	Depth to water	Depth to water	*EC	**EC	TDS	Temp	pH	DO	Eh	ORP	TAL
Units			m.a.m.s.l	m.bgl	m a.m.s.l	µS/cm	µS/cm	mg/l	°C		mg/l	mVolt	mVolt	mg/l
KB 1	borehole	2013-04-04	9.00	3.84	5.16	88.00	86.00	44.00	24.11	5.70	0.81	7.70	60.00	29.50
KB 2	river mouth	2013-04-04	0.00		0.00	19190.00	17740.00	9602.00	21.00	7.00	1.51	1.70	26.50	100.00
KB 3	borehole	2013-04-04	59.00		59.00	142.00	137.00	71.00	22.90	6.35	2.46	29.50	61.00	13.50
KB 4	borehole	2013-04-04	42.00	7.24	34.75	103.00	102.00	52.00	24.50	5.83	2.15	39.00	67.00	10.50
KB 5	Lake 1	2013-04-04	5.00		5.00	25300.00	24600.00	12620.00	23.75	8.41	3.40	-48.00	6.50	137.00
KB 6	Lake interface	2013-04-04	-2.00		-2.00	6059.00	5618.00	3109.00	21.17	9.37	4.20	-72.50	8.50	
KB 7	lake 2	2013-05-04	0.00		0.00	22090.00	21670.00	11040.00	24.24	7.69	2.85	-18.00	15.60	141.00
KB 8	lake 3	2013-05-04	3.00		3.00	4854.00	4829.00	2426.00	24.69	8.60	3.77	-71.50	38.10	104.00
KB 9	borehole	2013-05-04	12.00		12.00	144.00	144.00	72.00	25.00	6.60	1.00	27.00	22.00	27.50
KB 10	borehole	2013-05-04	57.00		57.00	373.00	374.00	186.00	24.50	6.76	2.00	19.50	53.00	47.00
KB 11	stream	2013-05-04	31.00		31.00	343.00	341.00	171.00	24.60	7.28	2.90	-15.70		36.50
KB 12	borehole	2013-05-04	91.00	9.50	81.5.00	125.00	125.00	63.00	24.60	6.60	2.50	-26.00	13.30	34.10
KB 13	borehole	2013-05-04	83.00	18.37	64.63	112.00	112.00	56.00	25.00	5.70	1.10	78.00	90.00	19.00
KB 14	borehole	2013-05-04	79.00	9.19	69.81	144.00	143.00	72.00	24.60	5.60	1.20	86.00	107.00	
KB 15	borehole	2013-06-04	35.00		35.00	149.00	149.00	74.00	25.00	5.80	2.00	45.00	-15.00	11.50
KB 16	lake	2013-06-04	26.00		26.00	509.00	531.00	254.00	27.34	9.13	4.22	-98.30	-0.30	
KB 17	lake 4	2013-06-04	4.00		4.00	1014.00	1024.00	507.00	25.50	7.70	2.61	-30.80	62.00	80.00
KB 18	borehole	2013-06-04	38.00		38.00	107.00	107.00	54.00	24.00	6.00	2.50	43.00	-58.00	
KB 19	stream	2013-06-04	12.00		12.00	262.00	243.00	131.00	21.20	7.42	3.34	-12.90	23.60	51.00
KB 20	dugwell	2013-06-04	9.50	9.00	0.50	411.00	399.00	205.00	23.50	4.50	0.80	153.00	351.00	

Sample Id	Water point	Date measured	Altitude	Depth to water	Depth to water	*EC	**EC	TDS	Temp	pH	DO	Eh	ORP	TAL
KB 21	borehole	2013-06-04	31.00		31.00	116.00	115.00	58.00	24.40	8.80	2.00	71.00	111.00	7.00
KB 22	borehole	2013-06-04	48.00	3.73	44.27	146.00	146.00	73.00	25.20	5.16	2.30	110.00	195.00	5.50
KB 23	borehole	2013-06-04	54.00	5.64	48.36	170.00	165.00	83.00	24.40	5.95	3.11	66.90	165.60	
KB 24	ocean inlet	2013-04-04	0.00		0.00	49510.00	49010.00	24880.00	24.49	8.43	2.51	-61.70	-27.20	
rainfall	rainfall	2013-05-05	48.00		48.00	88.00	77.00	47.00	17.00	5.30				
river	stream	2013-06-04	17.00		17.00	242.00	227.00	120.00	21.60	7.57	3.20	-21.00	53.00	
KB 25	borehole	24/5/2013	33.00	9.70	23.30	294.00	294.00	147.00	24.88	5.29	4.00	87.00	104.00	
KB 26	borehole	24/5/2013	40.00		40.00	170.00	160.00	85.00	21.73	6.15				
KB 27	borehole	24/5/2013	40.00	7.51	32.49	108.00	108.00	54.00	24.94	5.50	1.57	70.70	29.40	
KB 28	borehole	24/5/2013	45.00	7.83	37.17									
KB 29	borehole	24/5/2013	52.00	8.35	43.65	154.00	153.00	77.00	24.47	5.4	1.4	77.80	122.00	
KB 30	borehole	24/5/2013	49.00	6.215	42.78	115.00	115.00	58.00	25.12	5.64	1.71	59.00	88.00	
KB 31	borehole	24/5/2013	38.00	5.66	32.34	143.00	142.00	71.00	24.85	5.42	2.11	78.50	107.60	
KB 32	borehole	24/5/2013	32.00	9.48	22.52	112.00	111.00	56.00	24.83	5.62	1.41	63.70	81.70	20.00
KB 33	borehole	24/5/2013	29.00	9.12	19.88	103.00	103.00	52.00	25.00	5.70	2.50	56.00	79.00	
KB 34	borehole	24/5/2013		9.51	-9.51	156.00	156.00	78.00	24.88	4.87	2.20	109.5	152.00	
KB 35	borehole	24/5/2013	31.00	8.07	22.93	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
KB 36	borehole	24/5/2013	35.00	8.91	26.09	120.00	122.00	60.00	25.48	5.12	2.57	93.00	124.00	8.00
KB 37	borehole	24/5/2013	47.00		47.00	283.00	281.00	141.00	24.60	5.92	1.09	39.00	-13.30	
KB 38	borehole	24/5/2013	46.00	7.21	38.79	162.00	162.00	81.00	25.18	5.30	2.90	77.00	68.00	
KB 39	borehole	24/5/2013	51.00	12.97	38.03	162.00	162.00	81.00	24.28	5.81	2.50	48.00	85.00	
KB 40	borehole	24/5/2013	30.00	4.90	25.10	236.00	238.00	118.00	25.54	5.25	3.16	85.50	139.00	
KB 41	borehole	24/5/2013	34.00	5.55	28.45	151.00	150.00	75.00	25.30	5.72	5.50	51.20	110.00	
KB 42	borehole	24/5/2013	49.00		49.00	202.00	201.00	101.00	24.75	5.02	1.41	100.60	151.30	
KB 43	borehole	24/5/2013	55.00	2.78	52.22	398.00	400.00	199.00	25.00	4.86	2.26	95.00	146.00	
KB 44	borehole	24/5/2013	61.00	3.88	57.12	114.00	114.00	57.00	24.98	5.85	2.79	23.00	71.50	9.00
KB 45	borehole	24/5/2013	76.00	8.73	67.27	134.00	132.00	67.00	24.43	5.95	1.41	93.00	-80.00	19.00

Appendix T: Sodium adsorption ratio and hardness for the primary data collected in April/May 2013.

Sample Id	Water point	Sampling date	Na	K	Mg	Ca	Cl	HCO_3^-	NO_3^-	SO_4^{2-}	Water type	SAR	Total Hardness
Unit			(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)			
KB 1	borehole	2013-04-04	12.21	0.63	1.44	0.64	32.53	88.64	0.03	5.85	Na-Cl-HCO_3	1.90	7.540
KB 2	river mouth	2013-04-04	4095.56	147.05	774.40	173.80	12448.91	610.20		1154.51	Na-Cl	29.61	3623.09
KB 3	borehole	2013-04-04	19.14	1.86	1.81	2.26	54.08	82.37	0.28	4.47	Na-Cl-HCO_3	2.30	13.13
KB 4	borehole	2013-04-04	17.49	0.363	1.55	0.88	20.48	64.07	2.86	17.65	Na-HCO_3-Cl-SO_4	2.60	8.59
KB 5	Lake 1	2013-04-04	4843.34	173.41	814.00	194.15	14084.13	835.97		1302.53	Na-Cl	34.36	3836.99
KB 6	lake interface	2013-04-04	1015.18	39.03	142.56	46.06	3061.54		0.44	265.31	Na-Cl	16.67	702.12
KB 7	lake 2	2013-05-04	4149.53	149.94	658.35	152.96	12272.28	860.38		1128.04	Na-Cl	32.47	3093.13
KB 8	lake 3	2013-04-05	830.91	32.45	111.10	36.96	2378.50	631.56	1.43	204.63	Na-Cl	15.42	549.82
KB 9	borehole	2013-04-05	19.92	1.57	0.99	5.79	41.07	167.81	0.36	5.86	Na-HCO_3-Cl	2.01	15.59
KB 10	borehole	2013-04-05	56.17	8.55	7.68	6.12	141.53	286.79	8.55	7.93	Na-HCO_3-Cl	3.57	46.97
KB 11	stream	2013-04-05	54.36	4.61	7.78	4.37	137.28	222.72	1.02	10.20	Na-Cl-HCO3	3.61	43.01
KB 13	borehole	2013-04-05	21.35	0.05	0.82	0.97	28.83	115.94	0.47	10.01	Na-HCO_3-Cl	3.85	5.82
KB 15	borehole	2013-04-06	21.91	0.74	2.98	1.05	56.01	70.173	0.36	6.54	Na-Cl-HCO3	2.47	14.91
KB 17	lake 4	2013-04-06	165.28	7.03	18.83	14.93	432.57	488.16	0.93	31.91	Na-Cl-HCO3	6.71	114.86
KB 21	borehole	2013-04-06	16.50	0.40	3.23	0.64	41.07	42.71	4.08	4.88	Na-Cl-HCO3	1.86	14.93
KB 22	borehole	2013-04-06	20.57	0.85	2.04	1.46	50.58	33.56	0.44	12.97	Na-Cl-HCO3	2.58	12.08
KB 32	borehole	2013-05-24	17.05	0.92	1.45	1.08	36.16	122.04	0.04	0.401	Na-HCO_3-Cl	2.52	8.69
KB 36	borehole	2013-05-24	15.51	0.89	2.79	0.91	39.28	48.81	0.40	7.521	Na-Cl-HCO3	1.82	13.79
KB 44	borehole	2013-05-24	14.63	0.87	3.01	0.90	26.83	54.91	0.60	13.57	Na-HCO_3-Cl	1.66	14.67
KB 45	borehole	2013-05-24	20.764	0.28	2.14	0.88	42.86	115.94	0.37	2.641	Na-HCO_3-Cl	2.72	11.04

Appendix U: Reaction error, sodium adsorption ratio and hardness for the secondary data collected dating back from 2005 - 2014.

Sample Id	Sample Date	Na	Mg	Ca	Cl	SO4	F	K	HCO3	NO3	Total Hardness as CaCO3	Water types	SAR	Reaction error (%)
BOM 10Aa	Dec-08	31.80	0.01	2.04	42.70	4.38	0.10	5.79	1.64	0.05	5.12	Na-Cl	5.58	0.44
BOM 10Aa	Feb-07	29.00	0.03	2.00	49.00	4.70	0.17	6.00	20.22	-	5.14	Na-Cl-HCO$_3$	6.11	0.95
BOM 10Ab	Jul-08	63.20	0.28	71.70	56.40	16.90	0.16	6.00	277.76	0.05	180.22	Ca-Na-HCO$_3$-Cl	2.05	-6.7
BOM12	Dec-06	19.00	3.90	1.40	32.00	3.30	0.14	3.80	20.48	-	19.56	Na-Mg-Cl-HCO$_3$	1.87	2.90
FL6	Dec-08	42.60	3.67	8.57	49.00	15.10	0.10	4.39	60.59	<0.05	34.38	Na-Cl-HCO$_3$	2.97	0.23
FL6	Mar-05	40.00	3.80	7.50	52.30	15.50	0.13	4.10	44.48	-	36.52	Na-Cl-HCO$_3$	3.07	0.61
KNG 1 deep	Jun-14	49.50	6.20	18.50	37.70	11.26	0.14	7.33	150.77	-	71.73	Na-Ca-HCO$_3$-Cl	2.54	0.56
KNG 4 deep	Jun-14	82.00	5.26	27.80	49.90	21.99	1.31	3.01	215.42	-	91.09	Na-Ca-HCO$_3$-Cl	3.74	-0.02
KNG01b	Jul-08	22.90	1.55	1.05	29.90	2.82	0.10	2.98	21.00	0.05	9.01	Na-Cl-HCO$_3$	3.32	1.84
KNG02b	Jul-08	22.80	1.46	2.45	31.50	0.55	0.10	1.52	22.40	0.05	12.13	Na-Cl-HCO$_3$	2.85	2.83
KNG03b	Jul-08	24.60	1.90	2.19	38.90	1.24	0.10	1.84	15.48	0.05	13.29	Na-Cl	2.94	3.74
KNG04	Jul-08	29.80	1.21	1.31	41.90	4.96	0.10	3.84	16.37	0.05	8.25	Na-Cl	4.57	0.97
KNG04	Dec-06	28.00	1.00	0.70	44.00	7.70	0.13	4.00	1.78	-	5.87	Na-Cl	5.03	1.97
NKOSI	Dec-08	55.60	6.78	1.76	63.30	0.59	0.10	3.04	81.66	0.05	32.32	Na-Cl-HCO$_3$	4.26	2.07
NKOSI	Jul-08	56.10	8.32	1.00	87.00	0.16	0.10	3.13	48.30	0.05	36.76	Na-Mg-HCO$_3$-Cl	4.03	1.00
Northwest	Dec-08	21.90	1.51	1.22	29.90	1.70	0.10	1.27	17.44	0.05	436.71	Ca-Na-HCO$_3$-Cl	2.21	0.66
Northwest	Jul-08	63.90	4.37	15.1	38.70	15.00	9.08	3.69	128.42	0.05	9.27	Na-Cl-HCO3	3.13	3.52
Northwest	Mar-05	106.00	7.50	162.50	163.00	49.20	0.13	4.90	479.4	0.15	55.71	Na-HCO3-Cl	3.73	0.10
Phumobala	Jun-14	31.1	2.17	4.41	32.6	11.34	0.07	1.49	38.56	-	19.95	Na-Cl-HCO$_3$	3.03	4.58
Thengani	Jun-14	39.2	4.37	18.1	40.3	22.11	0.05	5.05	91.43	-	63.20	Na-Ca-HCO$_3$-Cl	2.15	0.66
Tshong 04	Dec-08	22.90	4.40	36.90	32.20	2.40	0.10	2.50	140.34	0.05	110.27	Na-Ca-HCO$_3$-Cl	0.95	0.10
Tshong 04	Mar-05	21.00	3.80	18.30	65.70	12.60	0.25	3.50	5.39	0.91	61.35	Na-Ca-Cl	1.17	-1.19
UMH/005/003	Dec-08	44.90	10.20	17.40	49.80	2.24	0.10	5.80	143.50	0.05	85.46	Na-Ca-Mg-HCO$_3$-Cl	2.11	1.06
UMH/005/003	Dec-06	50.00	11.30	39.40	71.00	15.00	0.13	3.90	173.82	0.10	123.29	Na-Ca-HCO$_3$-Cl	2.59	0.04
UMH/005/003	May-05	66.00	13.20	27.60	58.40	7.50	0.10	6.82	225.72	-	144.93	Na-Ca-HCO$_3$-Cl	1.81	0.14
Tshong 04	Dec-08	22.90	4.40	36.90	32.20	2.40	0.10	2.50	140.34	0.05	110.27	Na-Ca-HCO$_3$-Cl	0.95	0.10

Sample Id	Sample Date	Na	Mg	Ca	Cl	SO4	F	K	HCO3	NO3 + NO2 as N	Total Hardness as CaCO3	Water types	SAR	Reaction error (%)
UMH/005/004	Dec-08	55.20	0.25	20.60	68.80	5.53	0.10	6.38	94.64	0.05	52.48	Na-Ca-Cl-HCO_3	3.32	0.44
UMH/005/004	Dec-06	52.00	0.09	39.00	61.00	6.80	0.13	8.40	156.20	0.10	54.15	Na-Ca -HCO_3-Cl	2.66	0.06
UMH/005/004	Jun-05	45.00	0.11	21.50	66.40	9.70	0.19	6.10	67.75	-	97.77	Na-Ca-Cl-HCO_3	2.29	0.31
UMH/005/005	Jun-05	53.00	4.50	4.50	75.90	2.70	1.53	2.20	41.42	0.00	29.77	Na-Cl-HCO_3	4.23	5.16
UMH/005/006	Dec-08	66.90	0.09	26.40	45.60	19.70	0.10	8.69	168.07	0.12	67.55	Na-Ca-HCO_3-Cl	3.39	0.43
UMH/005/006	Dec-06	52.00	0.07	21.80	52.00	26.00	0.25	7.00	92.24	0.10	54.73	Na-Ca-HCO_3-Cl	3.06	0.01
UMH/005/006	Jun-05	64.00	0.09	26.90	52.60	24.00	0.13	4.50	137.79	-	66.30	Na-Ca-HCO_3-Cl	3.58	0.02

Appendix V: Environmental isotope results collected from groundwater and surface water of the study area along with some field parameters.

SAMPLE ID	DATE	ALTITUDE	DEPTH TO GROUNDWATER	EC	TDS	TEMP	pH	$\delta^{18}O$	$\delta^{2}H$	^{3}H
		(m.amsl)	(m.bgl)	(µS/cm)	(mg/l)	ºC		$(^{0}/_{00})$	$(^{0}/_{00})$	TU
KB 1	2013-04-04	9.00	3.84	86.00	44.00	24.11	5.70	-1.98	-3.38	1.30
KB 2	2013-04-04	0.00	-	17740.00	9602.00	21.00	7.00	0.43	9.71	
KB 3	2013-04-04	59.00	-	137.00	71.00	22.90	6.35	-2.67	-6.60	0.50
KB 4	2013-04-04	42.00	-	102.00	52.00	24.50	5.83	-2.99	-11.77	1.30
KB 5	2013-04-04	5.00	-	24600.00	12620.00	23.75	8.41	1.39	17.81	
KB 6	2013-04-04	-2.00	-	5618.00	3109.00	21.17	9.37	1.32	17.43	
KB 7	2013-05-04	0.00	-	21670.00	11040.00	24.24	7.69	1.56	18.47	
KB 8	2013-05-04	3.00	-	4829.00	2426.00	24.69	8.60	0.63	15.51	
KB 9	2013-05-04	12.00	-	144.00	72.00	25.00	6.60	-2.88	-8.42	0.90
KB 10	2013-05-04	57.00	-	374.00	186.00	24.50	6.76	-3.26	-11.58	4.00
KB 11	2013-05-04	31.00	-	341.00	171.00	24.60	7.28	-3.20	-9.97	
KB 12	2013-05-04	91.00	9.50	125.00	63.00	24.60	6.60	-3.07	-9.69	
KB 13	2013-05-04	83.00	18.37	112.00	56.00	25.00	5.70	-2.08	-1.80	1.10
KB 14	2013-05-04	79.00	9.19	143.00	72.00	24.60	5.60	-2.78	-7.53	
KB 15	2013-06-04	35.00	-	149.00	74.00	25.00	5.80	-2.26	-4.47	1.80
KB 16	2013-06-04	26.00	-	531.00	254.00	27.34	9.13	2.24	24.68	
KB 17	2013-06-04	4.00	-	1024.00	507.00	25.50	7.70	-0.74	6.11	
KB 19	2013-06-04	12.00	-	243.00	131.00	21.20	7.42	-2.55	-5.09	
KB 20	2013-06-04	9.50	9.00	399.00	205.00	23.50	4.00	-3.30	-10.62	
KB 21	2013-06-04	31.00	-	115.00	58.00	24.40	8.80	-2.08	-3.67	1.40
KB 22	2013-06-04	48.00	3.73	146.00	73.00	25.20	5.16	-2.19	-3.87	
KB 23	2013-06-04	54.00	5.64	165.00	83.00	24.40	5.95	-2.64	-9.39	
KB 25	2013-24-05	33.00	9.70	294.00	147.00	24.88	5.29	-2.25	-6.22	

SAMPLE ID	DATE	ALTITUDE	DEPTH TO GROUNDWATER	EC	TDS	TEMP	pH	$\delta^{18}O$	$\delta^{2}H$	^{3}H
		(m.amsl)	(m.bgl)	(µS/cm)	(mg/l)	ºC		$(^{0}/_{00})$	$(^{0}/_{00})$	TU
KB 27	2013-24-05			108.00	54.00	24.94	5.5	-2.20	-7.53	
KB 29	2013-24-05			153.00	77.00	24.47	5.4	-2.31	-7.63	
KB 32	2013-24-05			111.00	56.00	24.83	5.62	-1.89	-1.77	
KB 36	2013-24-05			122.00	60.00	25.48	5.12	-2.84	-9.77	
KB 37	2013-24-05			281.00	141.00	24.60	5.92	-3.10	-11.59	
KB 38	2013-24-05			162.00	81.00	25.18	5.3	-2.53	-6.69	
KB 39	2013-24-05			162.00	81.00	24.28	5.81	-2.37	-4.58	
KB 40	2013-24-05			238.00	118.00	25.54	5.25	-2.59	-6.83	
KB 41	2013-24-05			150.00	75.00	25.30	5.72	-2.22	-5.38	
KB 42	2013-24-05			201.00	101.00	24.75	5.02	-2.40	-6.18	
KB 43	2013-24-05			400.00	199.00	25.00	4.86	-2.48	-7.54	
KB 44	2013-24-05			114.00	57.00	24.98	5.85	-2.91	-10.87	
KB 45	2013-24-05			132.00	67.00	24.43	5.95	-2.76	-8.53	

Appendix W: Hydrochemical data of groundwater and surface water in the study area in mg/l.

Sample Id	Sampling date	**EC	TDS	pH	Na	K	Mg	Ca	Cl	HCO_3^-	NO_3^-	SO_4^{2-}	Si	F	Fe	Br
UNITS		µS/cm	mg/l		mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
KB 1	2013-04-04	86.00	44.00	5.7.00	12.21	0.63	1.44	0.64	32.531	88.64	0.03	5.85	1.77	0.03	0.10	0.10
KB 2	2013-04-04	17704.00	9602.00	7.00	4095.56	147.05	774.40	173.80	12448.91	610.20		1154.51	6.00	0.81	1.81	25.63
KB 3	2013-04-04	137.00	71.00	6.35	19.14	1.86	1.81	2.26	54.08	82.37	0.28	4.47	4.31	0.01	0.02	0.16
KB 4	2013-04-04	102.00	52.00	5.83	17.49	0.36	1.55	0.88	20.48	64.07	2.86	17.65	2.73	0.03	0.09	0.35
KB 5	2013-04-04	24600.0	12620.00	8.41	4843.34	173.41	814.00	194.15	14084.13	835.97		1302.53	7.5	0.63	2.05	29.13
KB 6	2013-04-04	5618.00	3109.00	9.37	1015.18	39.03	142.56	46.06	3061.54		0.44	265.31	5.17	0.21	0.34	6.22
KB 7	2013-05-04	21670.00	11040.00	7.69	4149.53	149.94	658.35	152.96	12272.28	860.38		1128.04	6.75	0.83	1.44	25.36
KB 8	2013-04-05	4829.00	2426.00	8.60	830.91	32.45	111.10	36.96	2378.50	631.56	1.43	204.63	4.60	0.18	0.20	4.75
KB 9	2013-04-05	144.00	72.00	6.60	19.92	1.57	0.99	5.79	41.07	167.81	0.36	5.86	5.11	0.08	0.15	0.19
KB 10	2013-04-05	374.00	186.00	6.76	56.17	8.55	7.68	6.12	141.53	286.79	8.55	7.93	9.95		0.03	0.33
KB 11	2013-04-05	341.00	171.00	7.28	54.36	4.61	7.78	4.37	137.28	222.72	1.02	10.20	6.93	0.06	0.16	0.27
KB 13	2013-04-05	112.00	56.00	5.70	21.35	0.05	0.82	0.97	28.834	115.94	0.47	10.01	3.59	0.02	0.73	0.12
KB 15	2013-04-06	149.00	74.00	5.80	21.91	0.74	2.98	1.05	56.017	70.17	0.36	6.54	2.81	0.01	1.72	0.15
KB 17	2013-04-06	1024.00	507.00	7.70	165.28	7.03	18.83	14.93	432.57	488.16	0.93	31.91	3.56	0.07	0.24	0.89
KB 21	2013-04-06	115.00	58.00	8.80	16.50	0.40	3.23	0.64	41.07	42.714	4.08	4.88	2.93	0.02	0.17	0.11
KB 22	2013-04-06	146.00	73.00	5.16	20.57	0.85	2.04	1.46	50.58	33.56	0.44	12.97	1.51	0.03	0.09	
KB 32	2013-05-24	111.00	56.00	5.62	17.05	0.92	1.45	1.08	36.16	122.04	0.04	0.40	2.73	0.01	0.33	0.23
KB 36	2013-05-24	122.00	60.00	5.12	15.51	0.89	2.79	0.91	39.28	48.81	0.40	7.52	2.99	0.03	0.04	0.13
KB 44	2013-05-24	114.00	57.00	5.85	14.63	0.87	3.01	0.90	26.83	54.91	0.6	13.57	2.51		0.09	0.08
KB 45	2013-05-24	132.00	67.00	5.95	20.76	0.28	2.14	0.88	42.86	115.94	0.37	2.64	3.15	0.01	0.17	0.06
UMH/005/004	2008-12	46.10	272.00	6.71	55.20	6.38	0.25	20.60	68.80		<0.05	5.53		<0.10	0.77	
UMH/005/006	2008-12	45.10	288.00	7.00	66.90	8.69	0.09	26.40	45.60		<0.05	19.7		<0.10	1.02	
BOM 10Aa	2008-12	21.60	126.00	6.11	31.80	5.79	0.01	2.04	42.70	1.64	0.12	4.38		<0.10	0.46	

Sample Id	Sampling date	**EC	TDS	pH	Na	K	Mg	Ca	Cl	HCO_3^-	NO_3^-	SO_4^{2-}	Si	F	Fe	Br
UNITS		µS/cm	mg/l		mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
BOM 10Ab	2008-07	72.00	43.80	7.16	63.20	6.00	0.28	71.7	56.40	277.76		16.90		0.16	0.10	
UMH/005/003	2008-12	36.70	213.00	6.82	44.90	5.80	10.20	17.4	49.80	143.50	<0.05	2.24		<0.10	2.22	
KNG01b	2008-07	15.19	111.00	5.65	22.90	2.98	1.55	1.05	29.90	21.00	<0.05	2.82		0.10	1.30	
KNG02b	2008-07	15.03	90.30	5.39	22.80	1.52	1.46	2.45	31.50	22.40	<0.05	0.55		<0.10	1.76	
KNG03b	2008-07	18.20	112.00	5.47	24.60	1.84	1.90	2.19	38.90	15.48	<0.05	1.24		<0.10	2.83	
KNG04	2008-07	18.80	116.00	5.76	29.80	3.84	1.21	1.31	41.90	16.37	<0.05	4.96		<0.10	0.69	
BOM12	2006-12	17.20	98.00	6.35	19.00	3.80	3.90	1.40	32.00	20.48		3.30		0.14	2.20	
UMH/005/005	2006-12	36.20	206.30	6.05	53.00	2.20	4.50	4.50	75.90	41.42		2.70		1.53	8.97	
NKOSI'S BH	2006-12	32.30	198.00	6.42	55.60	3.04	6.78	1.76	63.30	81.66	<0.05	0.59		<0.10	3.59	
KNG 1 deep	2006-12	38.40		7.13	49.50	7.33	6.20	18.5	37.67	150.77	<0.08	11.26		0.14	1.35	
KNG 4 deep	2014-06			7.79	82.00	3.01	5.26	27.8	49.86	215.42	<0.08	21.99		1.31	<0.02	
Phumobala	2014-06			5.56	31.10	1.49	2.17	4.41	32.57	38.56	<0.08	11.34		0.07	4.78	
Thengani	2014-06			6.42	39.20	5.05	4.37	18.1	40.31	91.43	<0.08	22.11		<0.05	1.06	
Tshong 04	2008-12		187.00	8.01	22.90	2.50	4.40	36.9	32.2	140.34	<0.05	2.40		<0.10	0.15	
FL6	2008-12		192.00	6.19	42.60	4.39	3.67	8.57	49.000	60.59	<0.05	15.10		<0.10	0.21	
Northwest	2008-12		86.30	6.43	21.90	1.27	1.51	1.22	29.90	17.44	<0.05	1.70		<0.10	0.29	

Appendix X: Trace metal data of groundwater and surface water in the study area (ppm).

Time	Li	Al	Cr	Mn	Co	Ni	Cu	Zn	As	Rb	Sr	Cd	Cs	Ba	Hg	Pb	U
KB 1	0.0005	0.1038	0.0010	0.0078	0.0020	0.0022	0.0010	0.0254	0.0057	0.0020	0.0118	0.0004	0.0001	0.0719	0.0020	0.0009	0.0004
KB 2	0.2261	0.1614	0.0312	0.0235	0.0800	0.0800	0.1931	1.0560	0.2653	0.0761	4.6200	0.0160	0.0040	0.2178	0.0800	0.0400	0.0194
KB 3	0.0005	0.0020	0.0007	0.0081	0.0020	0.0020	0.0011	0.0338	0.0039	0.0053	0.0269	0.0004	0.0001	0.1166	0.0020	0.0010	0.0005
KB 4	0.0005	0.0224	0.0015	0.0081	0.0020	0.0020	0.0063	0.1133	0.0033	0.0009	0.0114	0.0004	0.0001	0.1606	0.0020	0.0010	0.0004
KB 5	0.2469	0.1000	0.0420	0.0051	0.1000	0.1000	0.1958	0.1083	0.3085	0.0819	4.9170	0.0200	0.0050	0.0863	0.1000	0.0500	0.0240
KB 6	0.0402	0.0240	0.0089	0.0086	0.0240	0.0240	0.0323	0.0431	0.0628	0.0238	0.8751	0.0050	0.0012	0.1277	0.0240	0.0120	0.0054
KB 7	0.1648	0.0900	0.0333	0.0073	0.0900	0.0900	0.1514	0.0782	0.2440	0.0658	3.8461	0.0180	0.0045	0.0945	0.0900	0.0450	0.0213
KB 8	0.0217	0.0200	0.0070	0.0049	0.0200	0.0200	0.0266	0.0427	0.0468	0.0198	0.7161	0.0040	0.0010	0.1188	0.0200	0.0100	0.0045
KB 9	0.0005	0.0353	0.0008	0.0132	0.0020	0.0030	0.0034	0.6655	0.0038	0.0017	0.0374	0.0004	0.0001	0.2068	0.0020	0.0010	0.0004
KB 10	0.0026	0.0020	0.0007	0.2299	0.0095	0.0038	0.0031	0.0266	0.0038	0.0145	0.1028	0.0004	0.0001	0.3575	0.0020	0.0010	0.0004
KB 11	0.0016	0.0083	0.0007	0.0286	0.0020	0.0035	0.0026	0.0820	0.0043	0.0098	0.0764	0.0004	0.0000	0.2431	0.0020	0.0010	0.0005
KB 13	0.0005	0.0227	0.0007	0.0063	0.0020	0.0020	0.0011	0.0294	0.0036	0.0015	0.0129	0.0004	0.0001	0.0665	0.0020	0.0010	0.0004
KB 15	0.0005	0.0668	0.0010	0.0368	0.0020	0.0038	0.0015	0.0275	0.0040	0.0022	0.0231	0.0004	0.0001	0.0583	0.0020	0.0010	0.0005
KB 17	0.0068	0.1097	0.0021	0.0016	0.0040	0.0040	0.0108	0.4510	0.0108	0.0092	0.1718	0.0008	0.0002	0.5478	0.0040	0.0037	0.0009
KB 21	0.0005	0.0014	0.0008	0.0118	0.0020	0.0020	0.0042	0.2134	0.0033	0.0035	0.0183	0.0004	0.0001	0.0823	0.0020	0.0011	0.0004
KB 22	0.0005	0.7271	0.0011	0.0339	0.0020	0.0020	0.0011	0.0381	0.0038	0.0019	0.0317	0.0004	0.0001	0.0936	0.0020	0.0010	0.0005
KB 32	0.0005	0.0339	0.0017	0.0188	0.0020	0.0020	0.0105	0.0325	0.0038	0.0020	0.0135	0.0004	0.0001	0.0765	0.0020	0.0023	0.0004
KB 36	0.0005	0.0363	0.0010	0.0114	0.0020	0.0020	0.0017	0.0294	0.0033	0.0024	0.0183	0.0004	0.0001	0.0497	0.0020	0.0014	0.0004
KB 44	0.0005	0.0279	0.0012	0.0313	0.0020	0.0020	0.0010	0.0416	0.0035	0.0026	0.0203	0.0004	0.0001	0.0176	0.0020	0.0010	0.0004
KB 45	0.0005	0.0020	0.0007	0.0040	0.0020	0.0020	0.0010	0.0207	0.0034	0.0016	0.0201	0.0004	0.0001	0.0792	0.0020	0.0010	0.0004