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Department:
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RESERVE DETERMINATION STUDIES FOR SELECTED SURFACE WATER, GROUNDWATER, ESTUARIES AND WETLANDS IN THE USUTU/MHLATUZE WATER MANAGEMENT AREA

WP 10544

A RAPID GROUNDWATER RESERVE DETERMINATION FOR THE LAKE SIBAYI AND KOSI BAY ESTUARINE LAKES

FINAL

JULY 2016

Report No. RDM/WMA6/CON/COMP/2113

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DEPARTMENT OF WATER AND SANITATION

CHIEF DIRECTORATE: WATER ECOSYSTEMS

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Client: Department of Water & Sanitation

Approved for the DWS:

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Chief Director: Water Ecosystems

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List of Abbreviations

BHN	Basic Human Need
CMB	Chloride Mass balance
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
EC	Specific Electrical Conductivity
EWR	Ecological Water Requirements
GIS	Geographic Information System
GRDM	Groundwater Resources Directed Measures
GRIP	Groundwater Resources Information Project
RU	Groundwater Resource Units
MAP	Mean Annual Precipitation
MAR	Mean Annual Recharge
NGA	National Groundwater Archive
NWA	National Water Act
RDM	Resource Directed Measures
SI	Stress Index
RQOs	Resource Quality Objectives
TDS	Total Dissolved Solids
ToR	Terms of Reference
WARMS	Water Authorization and Registration Management System
WMA	Water Management Area
WMS	Water Management System
WRC	Water Research Commission

1 INTRODUCTION

1.1 Background

This hydrogeological and Groundwater Reserve determination study of the Lakes Sibayi and Kosi Bay catchments is undertaken as part of the Project "Reserve Determination Studies for Selected Surface Water, Groundwater, Estuaries and Wetlands in the Usutu/Mhlatuze Water Management Area (WMA)" that has been undertaken by Tlou Consulting (PTY) LTD. This report focuses on hydrogeological investigations including water balance of the Lakes; Groundwater Reserve determination, and water resources management and monitoring requirements for the Lake Sibayi and Kosi Bay catchments. The report provides a detailed literature review, hydrogeological conceptualization, water balance of the lakes, groundwater reserve determination and monitoring requirements for the Lake Sibayi and Kosi Bay catchments.

1.2 Scope of work and Terms of Reference (ToR)

The overall scope of the groundwater study includes hydrogeological characterisation including water balance of the lakes and the groundwater system in the two catchments, groundwater reserve determination, modelling of lake-groundwater interaction in the Lake Sibayi catchment including analysis of potential risks of seawater intrusion, setting resource quality objectives (RQOs) and management and monitoring requirements for both catchments.

The terms of reference (ToR) which formed the basis of this study as provided by Tlou Consulting (Pty) Ltd, is broken down into the following main deliverables:

- Literature review and conceptual model of the Lakes Sibayi and Kosi Bay system
- Groundwater report for the Lakes Sibayi and Kosi Bay systems
- Ecoclassification and Groundwater reserve determination for the Lakes Sibayi and Kosi Bay system
- Water balance analysis for the Lake Sibayi and Kosi Bay systems
- Modelling of groundwater, lake levels and assessment of the risk of saltwater intrusion for the Lake Sibayi system
- Setting RQOs and associated monitoring requirements for the Lake Sibayi and Kosi Bay systems

This documents compiles all reports pertaining to literature review, conceptual hydrogeological model of aquifer functioning, water balance for the lakes, numerical groundwater flow modelling for the Lake Sibayi catchment, Ecoclassification and groundwater reserve determination for Lakes Sibayi and Kosi Bay catchments and RQOs, management and monitoring requirements for both Systems.

1.3 Project Objectives

The main objective of the geohydrological study is to accomplish the list of deliverables outlined in section 1.2 so as to come up with a detailed groundwater reserve for the Lakes Sibayi and Kosi Bay systems and set associated RQOs and monitoring requirements.

2 GROUNDWATER RESERVE DETERMINATION

2.1 General Methodology

The general methodology followed in this groundwater reserve determination study is that of Dennis et al. (2012), WRC (2008), Parsons and Wentzel (2007), Parsons and Wentzel (2004), Xu et al. (2002) and Colvin et al. (2003). The reserve as defined in the National Water Act (NWA) (Act 36 of 1998) constitutes the quantity and quality of the groundwater required to:

- Satisfy the basic human needs (BHN) set at 25 L/d per person. This BHN must be met first for all persons who are or will be dependent on the groundwater resource.
- Protect aquatic ecosystems to ensure ecologically sustainable development and use of the relevant water source (i.e. ecological requirement or EWR).

Therefore, through the provision of the Reserve, the National Water Act recognises the need to develop and use the country’s water resources, however not to the detriment of future users. Thus, Resource directed measures (RDM) strives to ensure that the water resources are afforded a level of protection that will assure a sustainable development for the future. In this regards, Groundwater Resources Directed Measures (GRDM) comprises the following three main interrelated components:

- Classification
- Reserve
- Resource quality Objectives

The detailed sequential steps to be followed when assessing these three GRDM components are described in detail elsewhere (for instance, Dennis et al., 2012; Dennis and Dennis, 2009; Parsons and Wentzel, 2007). A brief description of each step is outlined below (Dennis et al., 2012; WRC, 2008):

Description of the study area: Description of the study area in terms of physical and geohydrological characteristics in sufficient detail appropriate to the level of GRDM assessment required. This step of the GRDM process is where data and information are collected by the project geohydrologist with input from other specialists. As these data and information are crucial to the rest of the GRDM assessment process; standard approaches, methods and tools typically used in geohydrological assessments are used. The collected data and information are analysed in order to develop a conceptual understanding of the geohydrology of the study area. The key outcome of this phase is a geohydrological report of the area, including maps and tables, documenting study area characteristics such as climate, drainage, geology, geohydrology, groundwater use, surface water – groundwater interactions and groundwater-dependent ecosystems, etc.

Delineation of Resource Units: Groundwater resource units are delineated based on the description of the study area. Groundwater resource units are areas of similar physical or ecological properties that are grouped to simplify the groundwater reserve determination process. The resource units are delineated based on quaternary catchment boundaries, aquifer types (primary aquifers, secondary aquifers, and dolomitic aquifers) and other physical, management and/or functional criteria. The outcome of this step is a map showing the extent of the groundwater resource units and GRDM assessment data sheet, in which the name of each unit and its aerial extent are recorded. Each of these resource units is to be classified, a Reserve assessment undertaken, and RQOs and monitoring requirements set.

Resource Classification: The present status category and water resource category of each groundwater resource unit are defined using the prescribed categorisation system, the output of which will feed into processes for setting desired management classes for significant water resources. Based on the conceptual understanding of the geohydrological conditions in the area, the difference between reference conditions and present conditions is assessed. Based on a set of guideline tables, the present status category and water resource category of each groundwater resource unit is determined. The outcome of the resource classification is the categorisation of each groundwater resource units (natural, good, fair, poor) GRDM assessment data sheet in which the category of each unit is recorded.

Quantification of the Reserve: The purpose of this step is to quantify the volume of groundwater that can be abstracted from a groundwater unit without impacting the ability of the groundwater system to contribute to the Reserve (basic human needs, ecological requirements). The reserve is quantified by determining the recharge to the resource unit, the groundwater contribution to baseflow and groundwater-dependent systems using appropriate methods and quantification of the basic human needs of the unit to be met from the groundwater.

Setting Resource Quality Objectives (RQOs) and Recommending a groundwater monitoring programme: RQOs are set for each resource unit to guide management and monitoring activities. RQOs are set based on the conceptual understanding of the area. It is done by key measurable indicators (drivers) such as water levels, total dissolved solids (TDS), faecal coliforms, etc. and the level at which they should be maintained (natural, slightly modified, etc.). During this final step, monitoring protocols are defined to generate the data to assess whether the RQOs are being met. A monitoring programme is developed based on conceptual flow model and the proposed RQOs. The monitoring program includes list of sites to be monitored and sampled, parameters to be measured, means and frequencies of measuring records, reporting mechanism and information dissemination. The outcome of this stage of the GRDM processes is a list of RQOs to guide management and monitoring activities.

2.2 Levels of Reserve Determination

Four levels of GRDM assessment are recognized, namely; desktop, rapid, intermediate and comprehensive, with each higher level providing an increased level of confidence. However, increased levels of commitment and resources are required to attain higher levels of confidence.

***Desktop assessment:* -** This level of assessment can be completed by means of already available data and information in a short time. It is the first step in any GRDM assessment as a multilevel GRDM assessment is generally adopted.

Rapid level assessments: - are undertaken for low usage areas where usage is expected to have limited impact. Rapid assessment takes few weeks which includes short field work to assess the present state and is aimed at individual licence applications.

Intermediate level assessment: - requires field investigations by experienced geohydrologists and takes a good number of months to complete (usually < 6 moths). The assessment yields results of medium confidence and used to assess individual licences for moderate impacts in relatively stressed catchments.

Comprehensive level assessment: - This level aim to produce high confidence results and are based on site specific data collected by a team of specialists. It is used for all compulsory licensing exercises, as well as for individual license applications that could have a large impact in any catchment, or a relatively small impact in ecologically important and sensitive catchments. It takes normally up to two years to complete. However, because of time-series geohydrological data limitations, GRDM assessments are rarely undertaken at this level.

2.3 Delineation of Integrated Resource Units (RUs)

The objective of the delineation of resource units is to group areas of similar geohydrological properties into clusters. It indicates the required level of detail of assessment for each unit. Water resource units are delineated based on a multi-tiered approach. Quaternary catchments are normally used as the primary delineation units of water resource units in RDM studies (Dennis et al., 2012; WRC, 2008; Parsons and Wentzel, 2007). Secondary delineation takes into account surface water features, when it is necessary to delineate zones of similar ecology within the study area. Groundwater resource units specifically relate to geohydrological characteristics, but may also coincide with other significant water resource units or ecoregions. Three criteria are recognised as the basis of groundwater resource unit delineation. These are physical, management and functional criteria (Dennis et al., 2012; WRC, 2008; Parsons and Wentzel, 2007).

Physical criteria consider geohydrological, hydrological and ecological characteristics of an area. These physical groundwater resource unit delineation characteristics could be geology, climate, topography, recharge, groundwater level and flow direction, springs, groundwater quality, groundwater use and stress, groundwater-dependent ecosystem, etc. Management criteria consider resource management issues such as property, water user association, catchment management, water management and other political boundaries. Functional criteria considers the role the groundwater resource plays in sustaining the environment, that is, its unique role in the hydrological and ecological functioning of the water resource.

2.4 Classificaton

Classification of the groundwater resource unit delineated is a very important and integral part of the GRDM process. The main objective of the classification process is to ensure that the resource can be utilised sustainably in the long term if the proposed class is adhered to. During this process, classes and categories of resources must be distinguished. However, identification of resource classes is normally undertaken through a public participation process, whereas, the categories of the resource unit are based solely on technical input by the assigned expert.

Classification of the resource unit into present status categories (PSC) can be done on the base of different criteria, including:

- Observed environmental impact indicators
- Groundwater stresses
- Groundwater quality and contamination

The final identification/determination of the classes/categories should include both water quantity and quality aspects. Table 1 outlines guidelines for setting the present class of a groundwater resource unit.

TABLE 1. GUIDELINES FOR SETTING THE PRESENT CLASS OF A GROUNDWATER RESOURCE UNIT BASED ON OBSERVED ENVIRONMENTAL IMPACT INDICATORS (DENNIS ET AL., 2012)

Present Class	Generic description	Affected environment
Minimally used (I)	The water resource is minimally altered from its pre-development condition	No sign of significant impacts observed
Moderately used (II)	Localised low level impacts, but no negative effects apparent	Temporal, but not long-term significant impact to: ▪ spring flow ▪ river flow ▪ vegetation land subsidence ▪ sinkhole formation ▪ groundwater quality
Heavily used (III)	The water resource is significantly altered from its pre-development condition	Moderate to heavy impacts to: ▪ spring flow ▪ river flow ▪ vegetation ▪ land subsidence ▪ sinkhole formation ▪ groundwater quality

The resource classification process not only categories the water resource but it also indicates the relationship between the available water and water used. This relationship is determined by the groundwater stress index (SI) and is defined by the current groundwater use (gw_{use}) to groundwater (gw_{rech}) recharge as follow:

$$\mathbf{SI\ (\%) = (gw_{use} / gw_{Re}) \times 100}$$

The stress index indicates the level of groundwater use compared to natural recharge to the aquifer. In calculating the stress index, the variability of annual recharge is taken into account, which implies that no more than 65% of average annual recharge can be allocated on a catchment scale. A guide to determine the level of stress of a groundwater unit is shown in Table 2.

TABLE 2. GUIDE FOR DETERMINING THE LEVEL OF STRESS OF A GROUNDWATER RESOURCE UNIT (DENNIS ET AL., 2012)

Present class	Description	Compliance (spatial/temporal)
I	Minimally used	≤ 20%
II	Moderately used	20-65%
III	Heavily used	65%

The NWA states that the system for classifying water resources may consider water quality requirements of water users. Dennis et al. (2012) states that domestic use (human consumption) is considered as the highest beneficial use, with the supposedly most stringent quality requirements and it is assumed that any water resource, which is deemed fit for human consumption, also meets the requirements of aquatic ecosystems. Dennis et al. (2012) further recommends to use the South African Water Quality Guidelines (DWAF, 1996), or the national drinking water standard (SANS 241: 2006) for assessing the present status category of a water resource (Table 3).

TABLE 3. PRESENT STATUS CATEGORY BASED ON DWA WATER QUALITY GUIDELINES FOR DOMESTIC USE (AFTER DENNIS ET AL., 2012)

Present class	Description	Compliance (Spatial/Temporal)
I	DWA Class 0 or 1 or natural background	95%
II	DWA Class 2 (95% compliance) or natural background (75% compliance)	75%
III	DWA Class 3 or 4 or natural background (<75% compliance)	<75%

2.5 Reserve

The Reserve is part of the national water resource within each water management area that is under the direct control of the Minister (Dennis et al., 2012; Parsons and Wentzel, 2007). It is water that is 'set aside' to:

- provide for basic human needs (BHNs), and
- Protect water ecosystems (sustain healthy ecosystems, EWRs).

The Reserve is the only right to water in the National Water Act. It, therefore, has priority over all other water uses. In other words, the amount of water required for the Reserve must be met before water resources can be allocated to other water users.

The groundwater component of the reserve is the part of the groundwater resource that sustains basic human needs and in some instances contributes to environmental water requirements (EWR). To be able to quantify the groundwater component of the reserve, the volume of groundwater needed for BHNs and contributing to EWR needs to be quantified. The EWRs of the resource in question must consider the following:

- Groundwater contribution to baseflow in rivers
- Groundwater contribution to wetlands
- Groundwater contribution to springs and other groundwater–dependent ecosystems

The groundwater component of the reserve is defined by the following relationship:

$$Reserve(\%) = \frac{EWRgw + BHNgw}{Re} \times 100$$

Where, **Re** stands for recharge, **BHN$_{gw}$** is basic human needs derived from groundwater and **EWR$_{gw}$** is groundwater contribution to environmental water requirement (EWR).

Groundwater should only be allocated to users and potential users once the volume of groundwater that contributes to sustaining the Reserve has been quantified and RQOs have been met. Note that RQOs can be based on both the reserve and classification.

2.6 Sources of Information for GRDM Study

While undertaking the study reported in this document, apart from detailed field investigation, information and additional data were sourced from the following sources:

- Various literatures and maps
- National Groundwater Archive (NGA)
- Groundwater Information Project (GRIP) for KwaZulu-Natal (KZN)
- WARMS data base
- Local and Regional Municipalities
- Regional and local experts
- Consultant reports
- Published scientific articles
- Hydrometeorological information from DWS and Weather SA

3 DESCRIPTION OF THE STUDY AREA

3.1 Introduction

The study area considered in this report covers the surface and groundwater catchments of the Lake Sibayi and Kosi Bay Lakes system as shown in Figure 1. The study area lies along the northern part of the Zululand coastal plain of South Africa. Lake Sibayi is the largest inland freshwater lake in South Africa. The Kosi Bay Lakes system is an interconnected coastal lakes-wetland – estuary system composed of four main interconnected, roughly circular lakes. These lakes from north to south are called Makhawulani (Lake-1), Mpungwini (Lake-2), Nhlange (Lake-3) and Amanzimnyama (Lake-4). A broad channel (tidal flat) leading to an estuary opens to the Indian Ocean. Two smaller isolated Lakes located west and north of the main interconnected Lakes form part of the system.

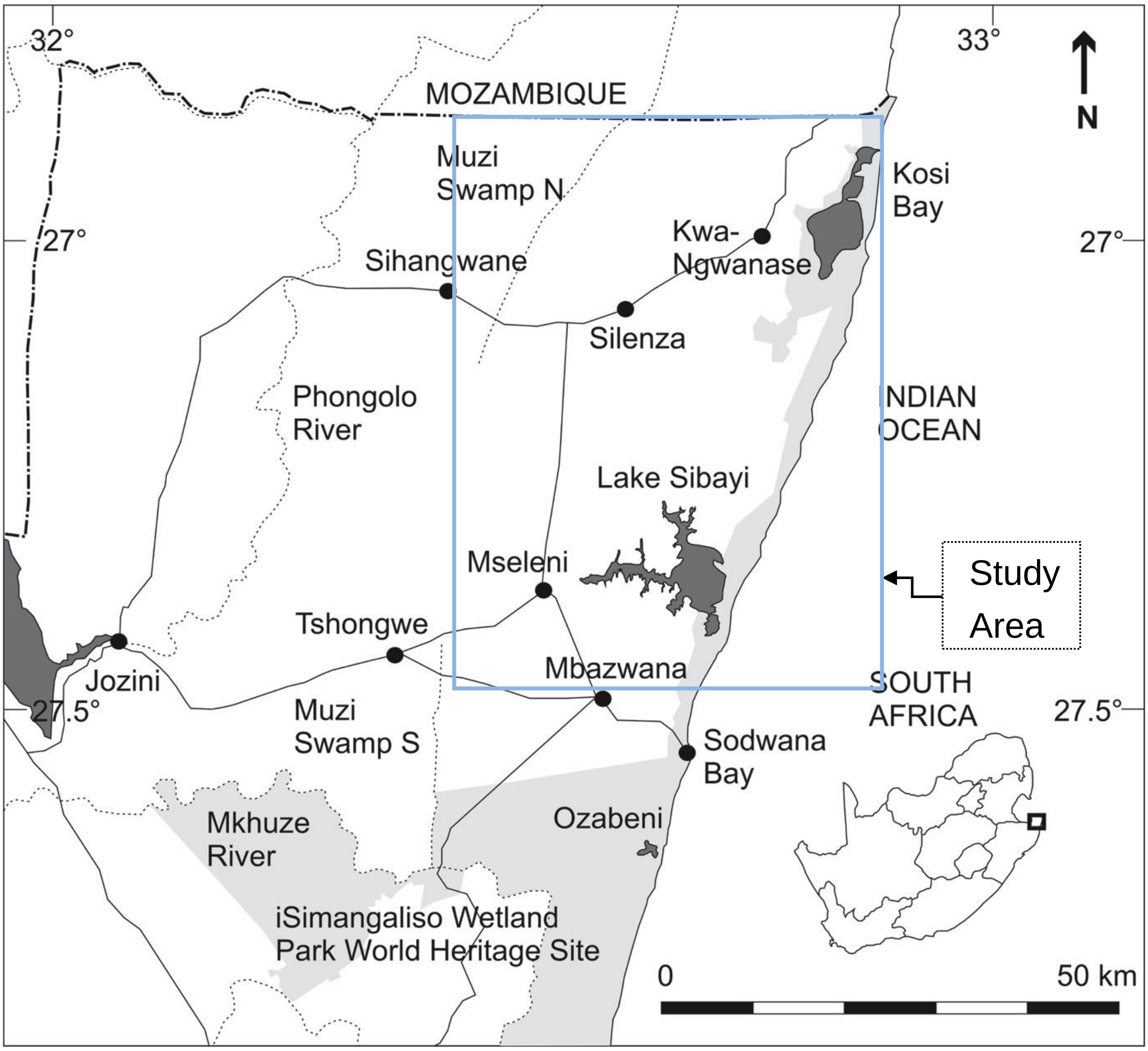

FIGURE 1. LOCATION MAP OF THE STUDY AREA IN NORTH-EASTERN SOUTH AFRICA

3.2 Climate and Water Resources

The climate variations in the study area are closely related to elevation and proximity to the coast. The study area, particularly along the coast experiences humid sub-tropical climatic conditions, with warm to hot summers and mild winters. A strong seasonal precipitation pattern is observed in the region with most of the rainfall occurring during the summer months, mainly from January to March (Table 4, Figure 2). The rainfall distribution map (Figure 3) of the area constructed based on data from the South African Weather Service (SAWS, 2013), indicates a strong precipitation gradient to the west or an increase in precipitation in an easterly direction over the study area. Precipitation is found to increase from approximately 700 mm/a along the western margin of the study area to approximately 1 000 mm/a along the coastal areas of Lake Sibayi. These observations compare well with those reported by Pitman and Hutchison (1975) which ranged from 700 mm/a in the southwest of the catchment to 1 200 mm/a in the east. Perhaps, a gradual decrease in rainfall across the area might have occurred through in the last 4 decades.

TABLE 4. MEAN MONTHLY CLIMATE VARIABLES FROM THE MBAZWANA AIRFIELD METEOROLOGICAL STATION

Climate Variables	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall	136.0	132.3	113.8	68.5	28.3	38.3	34.9	28.4	45.5	86.9	109.5	107.0
Temperature (°C)	26.0	26.2	25.5	23.2	21.0	19.2	18.6	20.1	21.3	22.2	23.9	25.2
Wind speed (m/s)	2.6	2.6	2.6	2.6	2.6	1.5	1.8	2.2	2.7	2.9	3.0	2.9
Sunshine duration (hours)	6.6	7.0	7.2	7.2	7.6	6.7	7.3	7.6	6.7	5.7	5.7	6.1
Humidity (%)	82.8	84.6	87.3	89.6	89.3	91.1	91.2	87.3	83.0	81.7	80.5	80.4
Pan evaporation	189.9	165.7	153	115.9	90.1	70.1	77.2	101.4	122.7	140.7	152.4	178.7

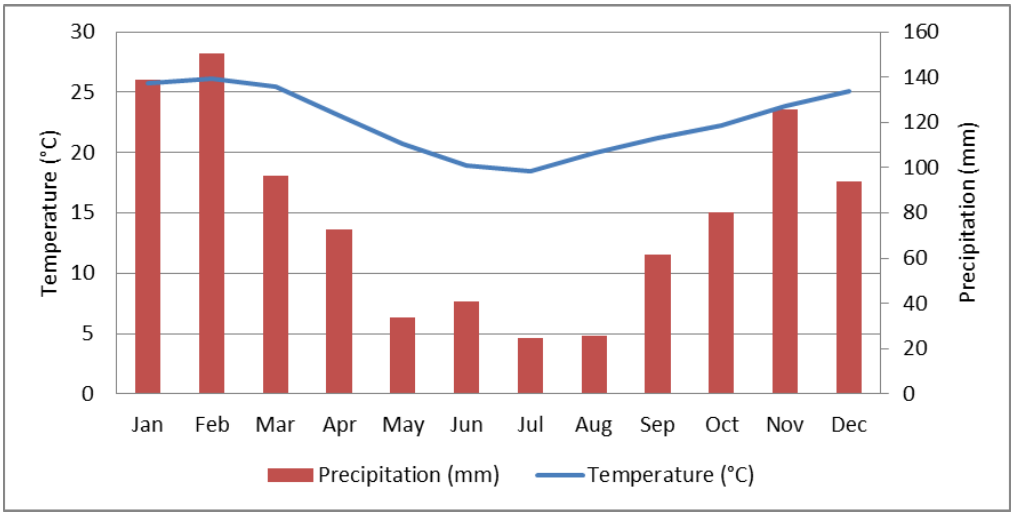

FIGURE 2. AVERAGE RAINFALL FROM THE HLABISA MBAZWANA AND TEMPERATURE FROM MBAZWANA AIRFIELD STATION (DATA FROM SAWS, 2015).

The mean annual temperature varies between 19 and 27°C (Figure 2) and evaporation rates for the Lakes are high, peaking during the summer months. Pan evaporation data recorded for the area ranged between 1400 mm/a and 1500 mm/a.

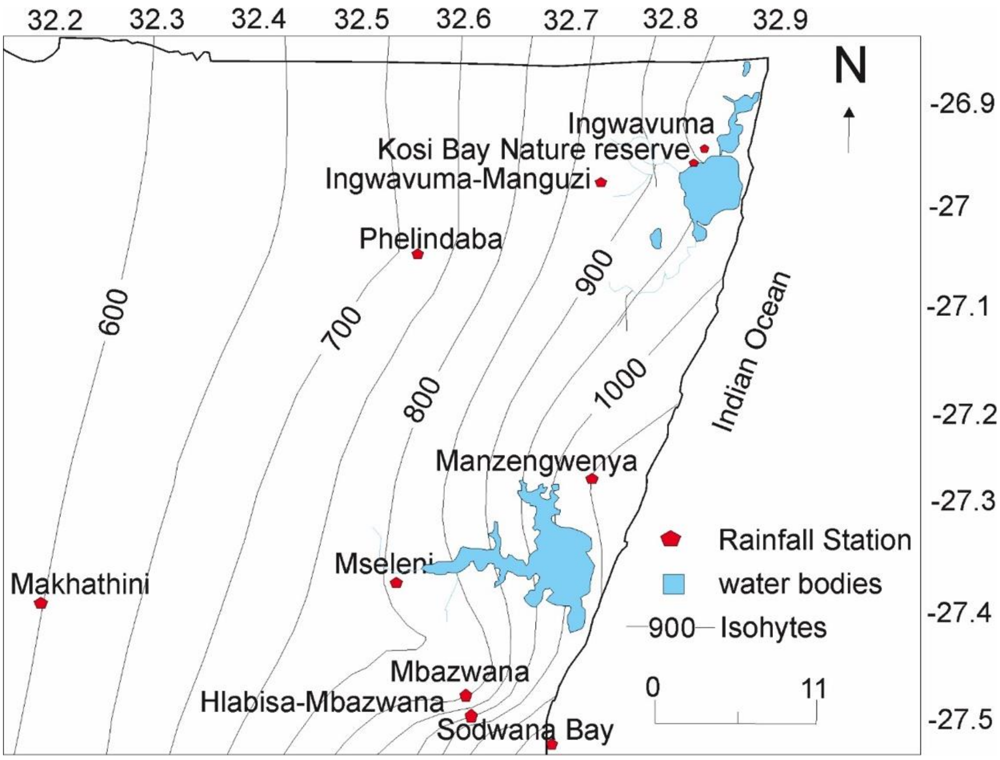

FIGURE 3. MEAN ANNUAL RAINFALL (MM) DISTRIBUTION OVER THE LAKES SIBAYI-KOSI BAY SYSTEM (RAINFALL DATA FROM SAWS, 2015)

3.3 Topography, Drainage, Land use – land cover and Soils

A number of large and ecologically important freshwater lakes occur within the Zululand coastal plain, including Sibayi, Mzingazi, Nhlabane and Cubhu. Apart from these freshwater lakes, there are also two lake systems with direct connection to the sea through an estuary mouth. They are Lakes Kosi Bay and St Lucia.

The lakes under study, the Lakes Sibayi – Kosi Bay system is located within the Usutu to Mhlathuze Water Management Area (WMA), specifically within the quaternary catchment W70A. It is bounded in the west by the Pongola River drainage system and in the east by the Indian Ocean. Due to the flat nature of the topography (Figure 4), the numerous pans, swamps and marshes and highly porous Holocene cover sands, the study area has an ill-defined drainages system. The main water bodies are Lake Sibayi and the Kosi Bay lakes.

The only significant surface water drainage feature for the Lake Sibayi catchment is the Mseleni River feeding the western arm of the lake. Several non-perennial streams are found to feed various other parts of the lake. The KuMzingwane and Velindlovu streams feed into the northern arm of the lake, while the Umtibalu and Iswati streams and the Umsilalane stream feed the southern and northern portion of the western arm, respectively (Figure 5). The Kosi Bay Lakes system has four interconnected lakes, namely, Makhawulani, Mpungwini, Nhlange, Amanzamnyama from north to south, respectively and a tidal flat connected to the sea through an estuary mouth. Two perennial rivers, namely; the Gezisa and Sihadhla drain into Lake Amanzimnyama and Nhlange, respectively. The semi-perrnial Ukhawe streams drains into the tidal flat from the northwest.

The sandy substrate of the catchment coupled with a relatively flat topography and shallow water table have resulted in a close relationship between surface waters (i.e. lakes, streams, and wetlands and the groundwater. This relationship is evident as the lake forms a surface expression of the groundwater (Meyer et al., 2001; Weitz and Demlie, 2014). Figure 4 and Figure 5 show the digital elevation model and the drainage map of the region, respectively, where the study area is located.

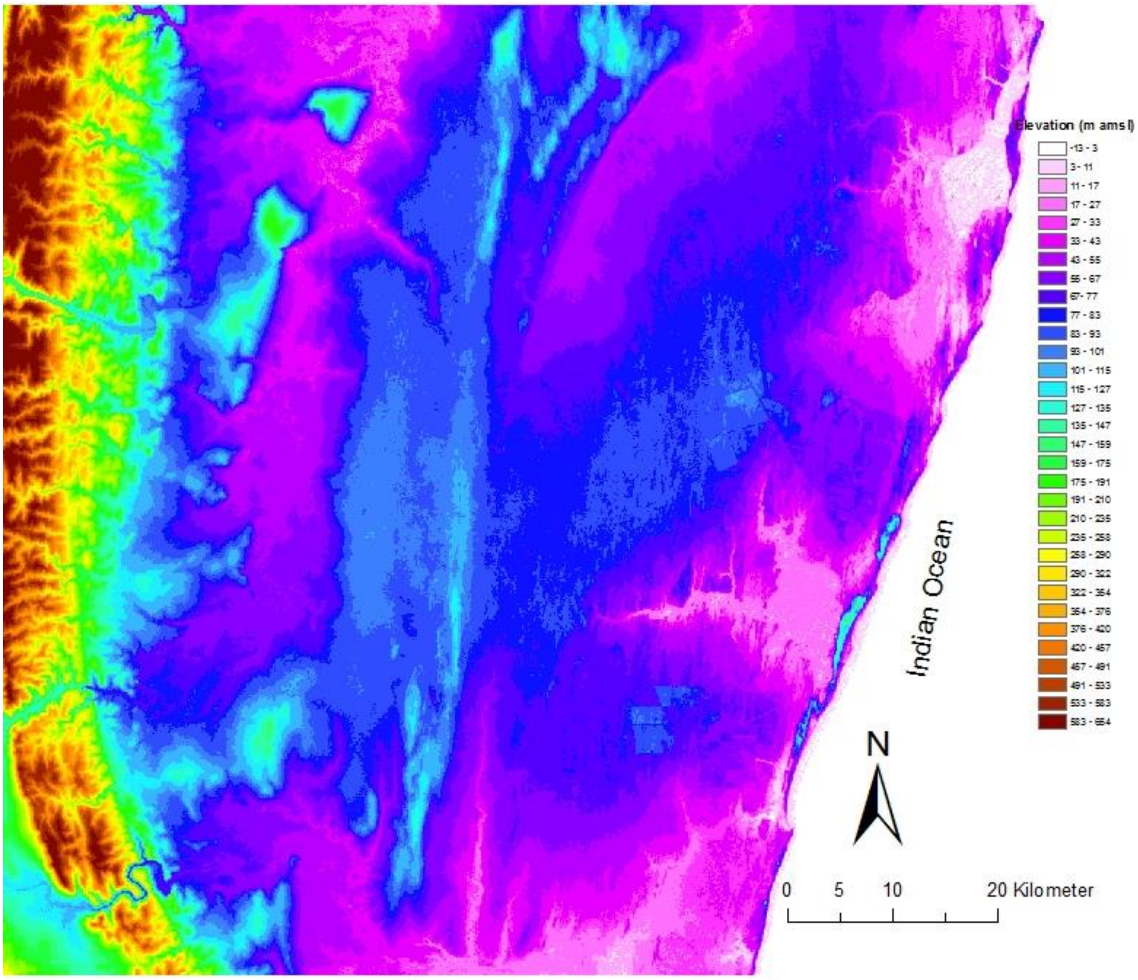

FIGURE 4. DIGITAL ELEVATION MODEL OF THE STUDY AREA SHOWING THE LEBOMBO RANGE IN THE WEST AND THE LAKES SIBAYI – KOSI BAY SYSTEM IN THE EAST (DATA FROM NASA, 2014).

The main population centres within the study area are the towns of Mbazwana, Mseleni and Manguzi. The rest of the area are characterised by scattered rural population. The Lake Sibayi and the Kosi Bay system are the main water bodies that occupy part of the catchment. The Sibayi and Kosi Bay lakes are part of the iSimangaliso Wetland Park (Figure 5) which has a UNESCO listed Wetland world Heritage status and is classified as one of the RAMSAR convention wetlands of international Importance (RAMSAR Site #528) (Obura et al., 2012), especially as Waterfowl Habitat. Apart from the iSimangaliso Wetland Park, the Sileza, Manguzi and Tembe Nature Reserve sites are present within and around these catchments. The area is characterised by a chain of barrier lakes, lagoons and swamps, situated behind high vegetated dunes. The natural vegetation of the area consists of a mosaic of coastal thicket, Licuati sand forest, woodlands, woody edaphic grassland and patches of hygrophilous grassland, reed swamps and swamp forests (Matthews et al., 2001).

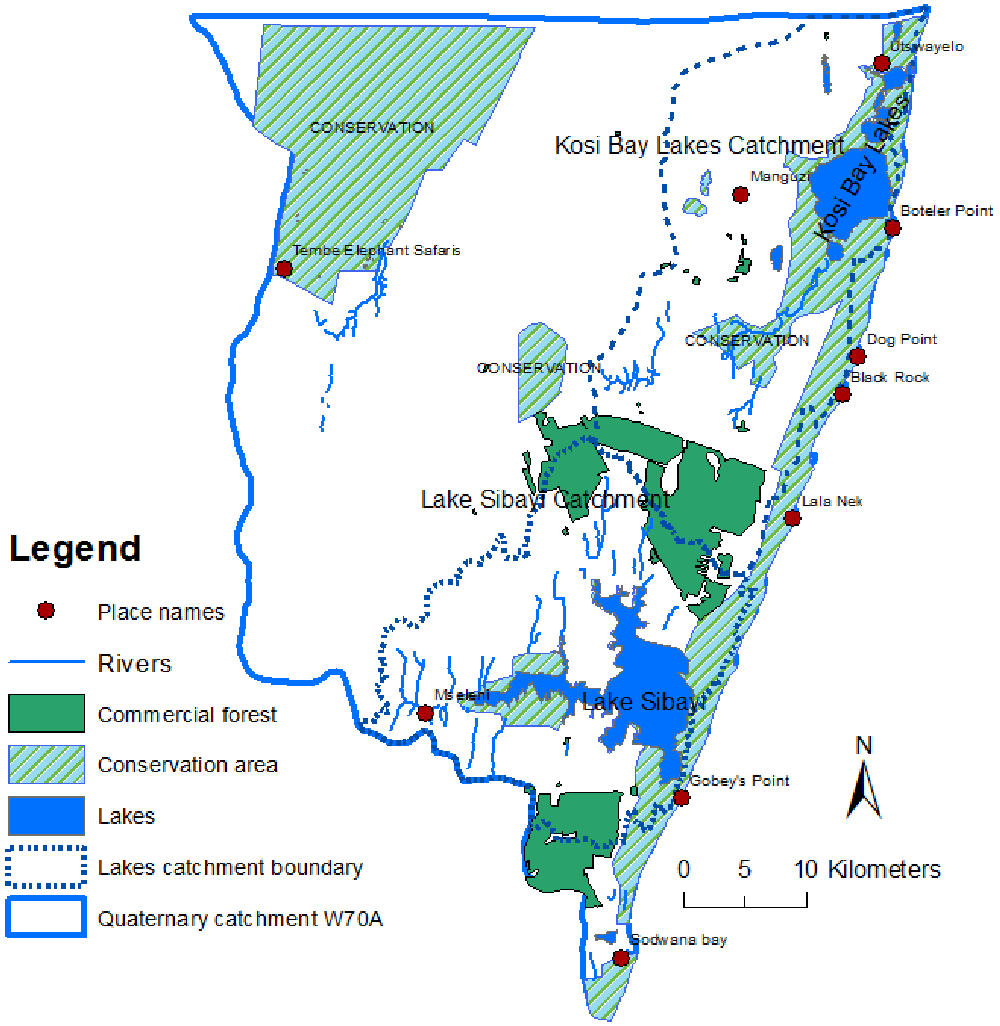

FIGURE 5. LAND USE AND DRAINAGE MAP OF THE LAKE SIBAYI AND KOSI BAY CATCHMENTS WITHIN THE QUATERNARY CATCHMENT W70A.

Commercial plantations cover a substantial part of the Lake Sibayi (58 km^2) and southern Kosi Bay (67 km^2) catchments (the main plantations are shown on Figure 5). The most prominent of these are the Mbazwana and Manzengwenya plantations situated on the southern and northern side of the Lake Sibayi, respectively. The area is characterized by soil cover that is associated with the Maputaland Group dune sands including the dune cordon. Thus, the broad soil patterns can be described as deep, grey, structure-less and mainly non-calcareous soils. These reddish and greyish sandy soils are excessively drained.

3.4 Geological Setting

Geological study of the Zululand coastal plain dates back to the first reconnaissance geological survey of eastern Zululand by Anderson (1901). The area is covered by parts of two 1: 250,000 geological maps series 2632 Kosi Bay and 271/232 St. Lucia published by the Council for geoscience (1985a, b). Because of the heavy mineral mining activities, good body information on the geology of the Zululand coastal plain has been published through the years. These studies are mainly concentrated in the southern part of the coastal plain, south of Lake St. Lucia (Meyer et al., 2001). Some of the studies on the geology of the northern half of the coastal plain, north of Lake St. Lucia are reported in Maud, 1961; Van Wyk, 1963; Orme, 1973, Hoday and Orme, 1974, Maud and Orr, 1975; Fockema, 1986; Walmarans and Du Preez, 1986; Partridge and Maud, 1987; 2000; Kruger and Meyer, 1988; Davies et al., 1992; Maud and Botha, 2000. The geological evolution of the coastal plain, particularly the evolution of Lakes St.Lucia, Sibayi and Kosi bay has been described by Hoday (1975,1979), Miller (2001), Neumann et al., 2008; Orme (1973, 1974, 1975, 1990), Porat and Botha, 2008; Taylor 2006; Wright (1995, 2002); Wright et al., 2000. The evolution of the continental Shelf and associated coral reefs has been described by Ramsay (1996), Ramsay and Cooper (2002), Green and Uken (2005).

According to these studies, the Zululand Basin sedimentation has formed the Makatini, Mzinene and St.Lucia Formations which collectively called the Zululand Group sediments during the Cretaceous Period. These sediments were deposited when the continental margin was submerged as a shallow continental shelf (Kennedy and Klinger, 1975; Dingle et al., 1983; Botha and Singh, 2012). The late Miocene to Pliocene regression event in the Zululand coastal deposited the Uloa Formation, which is mainly boulder beach and shallow marine shelly limestone and sandstone (Maud and Botha, 200; Partridge and Maud, 2000; Botha and Sing, 2012). These Palaeo-Shoreline deposits are overlain by cross-stratified Umkwelane Formation aeolianite (Botha and Porat, 2007; Botha and Singh, 2012). The Umkwelane Formation aeolianites are in turn overlain by the fossiliferous estuarine Port Durnford Formation deposits which are linked to lower than present sea level.

The Port Durnford Formation is overlain by the Kosi Bay Formation which are characterised by weathered dune sand and lignite deposits. Over much of the coastal plain, the Kosi Bay Formation is buried by the surficial dunes of the KwaMbonambi Formation (Porat and Botha, 2008; Botha and Singh, 20120. The high coastal barrier parabolic dunes form the Sibayi Formation and overlie the KwaMbonambi Formation along the coastline.

The following is a simplified description of the main stratigraphic units of hydrogeological importance in the northern half of the Zululand coastal plain, where the catchments of Lake Sibayi and Kosi Bay are located. Figure 6 illustrates a simplified geology and stratigraphy of the northern Zululand coastal plain.

Zululand Group sediments: The Zululand Group underlies the coastal plain area and its outcrops are in the eastern Lebombo foothills and Phongola River valleys (Botha and Singh, 2012). The succession comprises the Makatini, Mzinene and St. Lucia Formations (Kennedy and Klinger, 1975; Meyer and Godfrey, 2003; Shone, 2006). The Makatini Formation unconformably overlies the Lebombo Group volcanics. It comprises small–pebble conglomerate, sandstones, siltstones and limestones. The Mzinene Formation consists of siltstones and cross-bedded sandstones containing fossils and shell fragments. The St. Lucia Formation is similar in composition to the underlying Mzinene Formation. Due to its very low permeability, the Zululand Group rocks are considered as the impermeable or hydrogeological basement units to the overlying Maputaland Group sediments.

Maputaland Group sediments: The lowermost unit of the Maputaland Group sediments is the late Miocene to Pliocene Uloa/Umkwelane Formation. These weathered and calcareous sediments form a karst weathered decalcified profile at depth beneath much of the coastal plain (Botha and Singh, 2012). Thicknesses of up to 35 m were encountered in the north and north-west of the Lake Sibayi catchment (Kruger and Meyer, 1988). The Kosi Formation is mainly silty sands and silts and of Late Pleistocene in age. In places, it is occurs in the form of ferricrete and ferruginized sands. The elevation of the upper surface of the Kosi Bay Formation was found to increase from 50 m above mean sea level (amsl) in the southeast of Lake Sibayi (Fockema, 1986; Kruger and Meyer, 1988; Davies, Lynn and Partners, 1992) to 60 m amsl towards the north-west of the lake (Meyer, 1994). Most of the catchment areas of Lake Kosi Bay, west of the lakes system is covered by this unit. The Kosi Bay Formation is overlain by sediments associated with the superficial dune sands of the Late Pleistocene KwaMbonambi Formation (Botha and Porat, 2007; Porat and Botha, 2008). Most of the inland sand ridges are formed from parabolic dunes of the KwaMbonambi Formation. The KwaMbonambi Formation is overlain by the Holocene Sibayi Formation which is made up of composite Aeolian deposits. It constitutes the high coastal barrier dune cordon that stretches along the shoreline from St Lucia estuary to the Mozambique border (Botha and Porat, 2007).

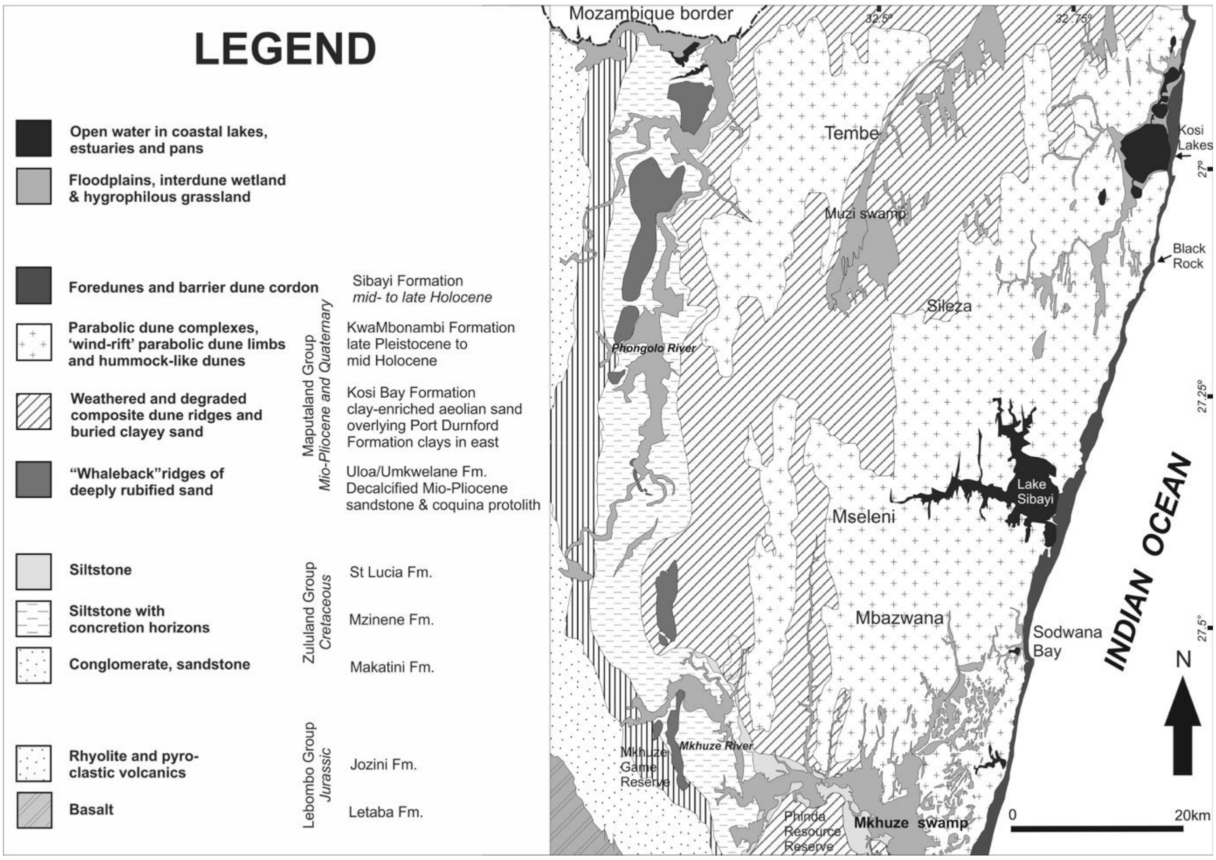

FIGURE 6. SIMPLIFIED GEOLOGICAL MAP OF THE NORTHERN ZULULAND COASTAL PLAIN (MODIFIED FROM PORAT AND BOTH, 2008)

3.5 Hydrogeological setting and aquifer description

Large part of the understanding of the hydrogeology of the coastal plain comes from a study by Australian Groundwater Consultants (1975), Pitman and Hutchinson (1975), Worthington (1978), Meyer and Kruger (1987), Rawlins and Kelbe (1991), Davis Lyn and Partners (1992), Meyer (1994), DWAF (1995), DWAF (2008), Kelbe and Germishuyse (2010), Kelbe et al. (2001), Meyer et al. (2001), Dennis and Dennis (2009), Kelbe and Germishuyse, 2010, Botha and Singh (2012), Meyer and Godfrey (2013), Kelbe et al. (2013), Weitz and Demlie (2014). The Zululand coastal plain which is underlain by unconsolidated to semi-consolidated sands hosts the most extensive and the largest primary aquifer in South Africa.

Due to very low permeability, groundwater quality and quantity, the Zululand Group Cretaceous-age succession that underlie the Miocene to Holocene sediments of the Maputaland Group are considered as the impermeable or hydrogeological basement units within the coastal plain. The majority of the sedimentary succession above the Cretaceous floor rocks can all be treated as potential aquifer units. The Quaternary sediments that cover the coastal plain are highly permeable and promote rapid recharge to the aquifer and have strong interactions with wetland and other surface water bodies, including lakes in the region. Borehole and hand dug wells data have indicated that the arenaceous succession is generally fully saturated from the interface with the Cretaceous formations up to a generally shallow groundwater level.

Generally, the coastal plain can be characterised by two major aquifers and an aquitard, while the regional Cretaceous basement acts as an aquiclude (Table 5). The two most productive aquifer systems are the shallow Pleistocene KwaMbonambi Formation and the deep Mio-Pliocene Port Durnford and Uloa/ Umkwelane Formations. Due to the low transmissivity and high adhesive forces of the overlying Kosi Bay Formation, it acts as an aquitard, creating a leaky confined aquifer underlying it. Moreover, the large storage capacity afforded by the Kosi Bay Formation help it ti be a storage reservoir for the underlying Port Durnford and Uloa Formations.

Studies by Australian Groundwater Consultants (1975), Worthington (1978), Meyer and Kruger (1988), Meyer and Godfrey (1995), Meyer et al, (2001) and Weitz and Demlie (2014) identified the Mio-Pliocene decalcified, locally karstified and weathered Uloa/ Umkwelane Formation as the main aquifer in the region. For example, northwest of Lake Sibayi, large scale irrigation of pecan nut plantations from the Uloa and overlying Port Durnford Formations has been successfully operated for many years (Meyer and Godfrey, 2003). Pumping tests conducted on boreholes tapping the Uloa aquifer gave sustainable yields of between 40 m3/d and 1 500 m^3/d, and average permeability, transmissivity and storativity of 4.5 m/d, 116 m^2/d and 0.019, respectively (Meyer and Godfrey, 1995). The presence of numerous dissolution channels has increased the porosity and permeability of this unit significantly. Furthermore, Worthington (1978) reported borehole yields of up to 25 L/s in areas where the aquifer layer is more than 20 m thick.

The Uloa Formation is overlain by a thick succession of relatively low-yielding silty sands and silts of the Late Pleistocene Kosi Bay Formation (Porat and Botha, 2008). However, the Kosi Bay Formation could also potentially be a good aquifer, effectively connecting the overlying unconfined unit to the lower aquifer. The hydraulic conductivity of this unit ranges from 4 m/d to 5 m/d (Meyer and Godfrey, 1995). The uppermost KwaMbonambi Formation extends to variable depths and is frequently exploited by the local community through shallow wells and hand-dug wells (Meyer and Godfrey, 1995; Botha and Porat, 2007; Porat and Botha, 2008; Weitz and Demlie, 2014). Pumping tests undertaken by Jeffares and Green (2012) indicated sustainable yields of between 190 m^3/d and 1 700 m^3/d and average transmissivity of 1 490 m^2/d. While Meyer and Godfrey (1995) reported permeability ranges from 0.87 m/d to 15.6 m/d for the same aquifer. Table 5 presents three broad productive hydrogeological units in the region based on variations in their hydraulic properties and proportions of sand, silt and clay composition

TABLE 5. HYDRAULIC CHARACTERISTICS OF THE DIFFERENT AQUIFER UNITS PRESENT WITHIN THE ZULULAND COASTAL PLAIN (DATA FROM MEYER AND GODFREY, 1995; JEFFARES AND GREEN, 2012, AND OTHER VARIOUS SOURCES)

Aquifer name	Thickness (m)	K (m/d)	T (m2/d)	Borehole yields (L/s)
Sibayi/KwaMbonambi Formations	20-30*	0.87-15.6 (mean: ~5)	1490	0.5-5
Kosi Bay/Port Durnford Formations	15-20*	4-5 (mean: 4.3)	-	2-10
Uloa/Umkwelane Formation	5-20	0.5-25 (mean: 4.5)	116	5-25
St Lucia Formation	900	-	-	<1

* The relationship between the KwaMbonambi and Kosi Bay Formations is very complex and therefore the thicknesses of the units in the study area are based on rough approximations.

3.5.1 Groundwater levels and groundwater flow directions

Groundwater level measured within the two lakes catchment and regional water level data (Figure 7) obtained from the Groundwater Resources Information project (GRIP, 2013) were used to construct a groundwater level contour map for the area (Figure 8). The results indicate that there appears to be a close relationship between water levels and surface topography and that a regional north-south striking groundwater divide exists west of the Lake Sibayi-Kosi Bay catchments. From this regional groundwater divide, groundwater flows towards the coast. Around the lakes, this regional flow pattern is somewhat distorted with flow lines directed towards the lakes and wetlands. Near the western catchment boundaries of the lakes, the groundwater elevation is around 70-80 m amsl (way above the stage of Lake Sibayi and Kosi Bay) from where it drops towards the coast to the altitude of the surface of the lakes. Over the section between the western groundwater divide and the lake, the ground water gradient is approximately 1:250 to 1:300 with a flow direction perpendicular to the coastline. Groundwater levels and flow patterns are affected by the presence of the various wetlands and lakes. Closer to the lakes, water level contours broadly follow the edge of the lakes, while flow directed towards the lakes shorelines. Meyer et al. (2001) reported that along the 2-3 km wide coastal dune cordon, between Lake Sibayi and the Indian Ocean, the groundwater level gradient steepens to about 1:100 as manifested by freshwater discharge along the coastline. Similar situations are expected in the section between Lakes of Kosi Bay and the Indian Ocean.

Based on the groundwater level map (Figure 8) and groundwater flow directions, the groundwater contributing area to Lake Sibayi and Kosi Bay has been delineated. It was observed that the surface water dive and groundwater divide don’t coincide for both lakes. For example, the groundwater contributing area to Lake Sibayi is about 569 km^2 which is much higher than the 457 km^2 surface water catchment of the lake. In case of the Kosi Bay lakes, the surface water catchment area is much higher than the groundwater contributing area to the lakes.

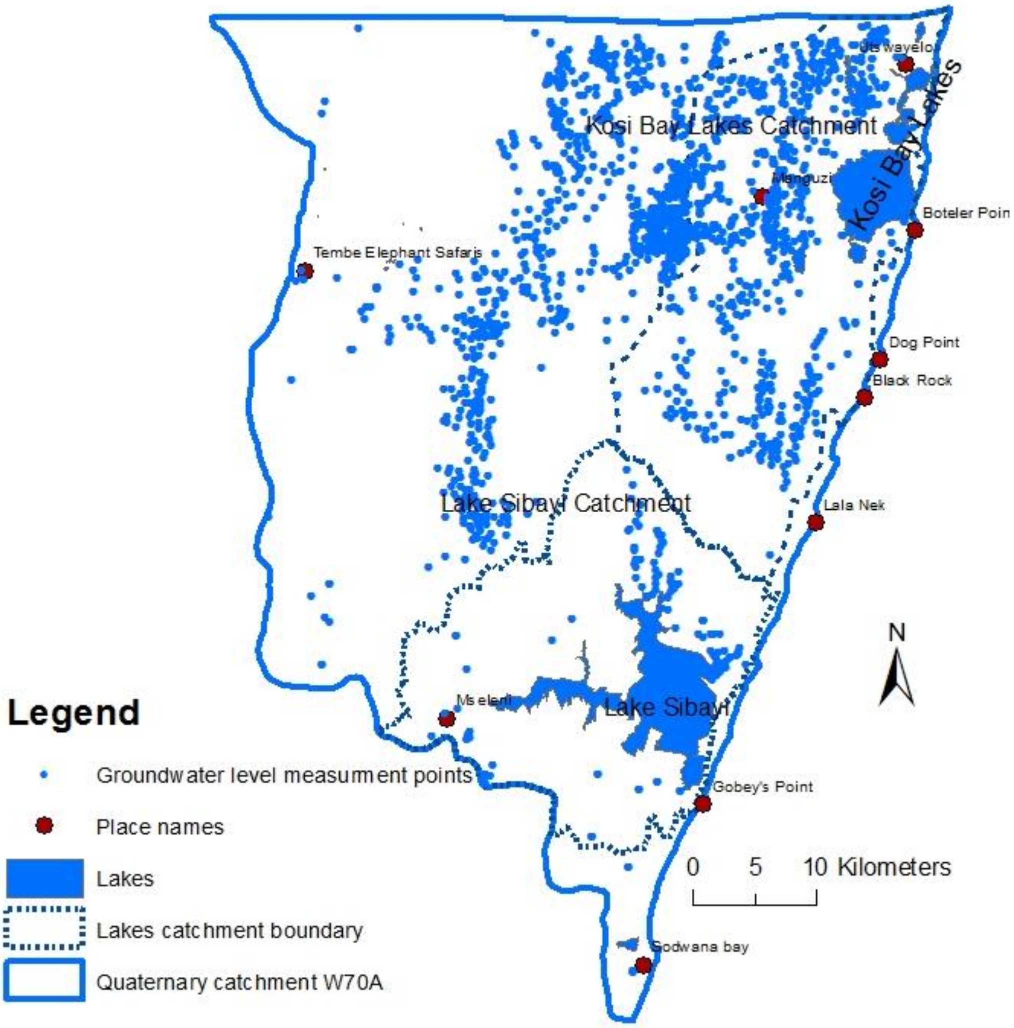

FIGURE 7. MAP SHOWING THE DISTRIBUTION OF ALL WELLS CONSIDERED IN CONSTRUCTING THE GROUNDWATER LEVEL CONTOUR MAP OF FIGURE 8 (FIELD DATA COMPLEMENTED BY DATA FROM THE KZN-GRIP PROJECT).

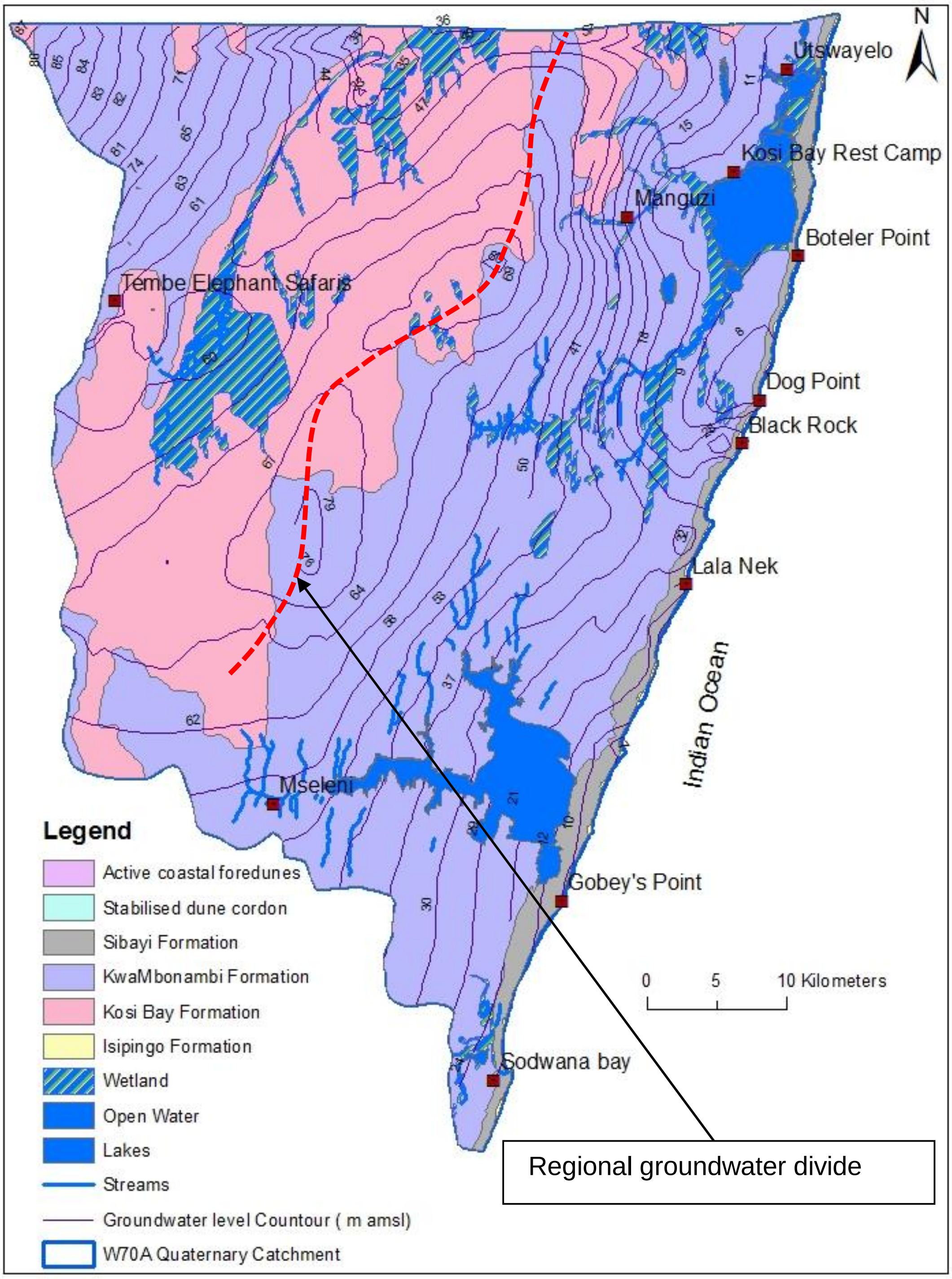

FIGURE 8. GROUNDWATER LEVEL CONTOUR MAP FOR QUATERNARY CATCHMENT W70A.

3.5.2 Groundwater recharge

Environmental isotope measurements in this part of the coastal plain, where the Lakes Sibayi and Kosi Bay catchments are situated, show that the aquifers are recharged from rainfall. Most of this replenishment is stored within the aquifer and discharges into the lakes, wetlands and to the sea.

Various attempts have been made to estimate groundwater recharge for different areas of the Zululand Coastal Plain. Worthington (1978) reported net recharge based on a water balance approach in the vicinity of Richards to be approximately 24% of the mean annual precipitation (MAP); Meyer and Kruger (1987) reported an approximate recharge rate of 21% of MAP for an area just north of Lake Sibayi; Bredenkamp et al. (1995) estimated recharge values ranging between 7% and 37% of MAP using the chloride mass balance (CMB) method and Meyer et al. (2001) used the CMB method for estimating groundwater recharge for the coastal plain. Meyer et al. (2001) used a three-year period rainfall chloride deposition data and came up with a recharge estimate ranging from 18% near the coast to about 5% (MAP) at a distance of 50 km inland.

A number of recharge estimation method (CMB, ACRU, based geology, qualified guess and from published maps) were applied in this study to estimate groundwater recharge for the coastal region under investigation. The CMB method, based on the average rainfall chloride data reported by Meyer et al. (2001) for the area and based on recent groundwater chloride analysis across the study catchments, gave a reasonable recharge estimate for the Lake Sibayi and Kosi Bay catchment and adjoining areas. The simplest form of the CMB method is given by:

$$R = \frac{P\ x\ Cl_p}{Cl_{gw}}$$

Where,

R is mean recharge rate (mm)

P is precipitation (mm/a)

Clp is the average atmospheric chloride deposition (mg/L)

Clgw is the measured groundwater chloride concentration (mg/L)

The CMB recharge estimate was found to be 12% of MAP or 112 mm/a. The estimation was made based on a 23 year average annual rainfall value of 937 mm measured at Hlabisa Mbazwana, Manguzi and Kosi Bay stations. This recharge estimate is found to be reasonable and can be considered as a conservative value, given the high permeability of the cover sand and relatively flat topography of the catchment. The combined total annual recharge for the two catchments (1165 km^2 in area) is estimated at $130x10^6$ m^3/a.

3.5.3 Groundwater use and discharge

Groundwater use within and around the Lake Sibayi and Kosi Bay catchments is limited to rural towns water supply, small scale irrigation and water use by commercial forestry (Figure 9). The WARMS registered groundwater uses for the area is 1645204 m^3/a all of these registered groundwater abstraction points are located within the Kosi Bay Catchment, mainly around the town of Manguzi. However, a brief hydrocensus undertaken in 2013 indicates many unregistered wells that abstract groundwater mainly using shallow and intermediate depth wells. These wells are present scattered throughout the region. Moreover, the total registered water use by forestry up until April, 2010 is about 12.2 $x10^6$ m^3/a.

However, a minimum of 157 km^2 area of the catchment of the lakes is covered by commercial plantations which might use more than the registered groundwater use. The balance of the annual groundwater recharge that is left after groundwater abstraction is expected to flow into streams, wetlands, lakes and to the sea.

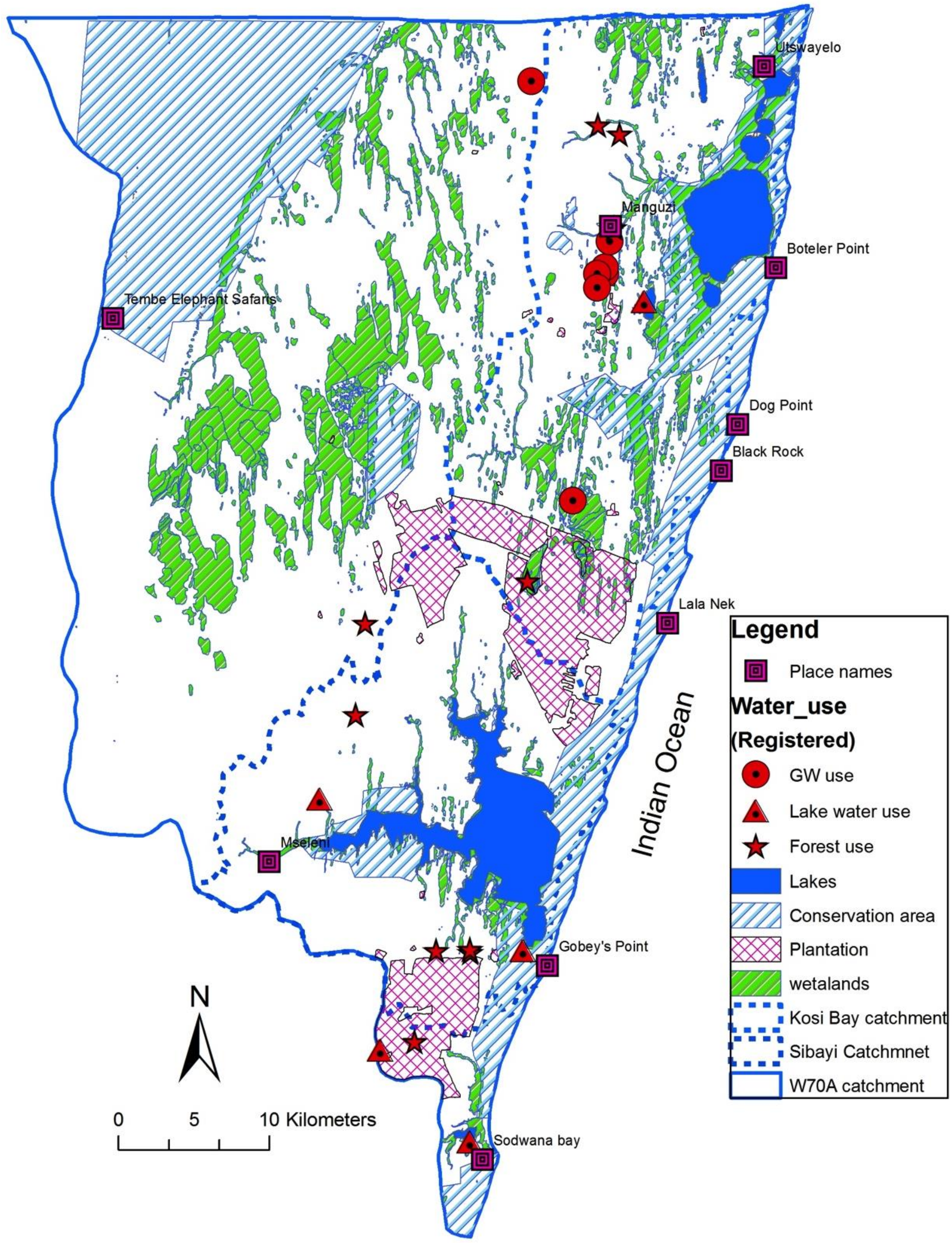

FIGURE 9. MAP SHOWING THE DISTRIBUTION OF REGISTERED WATER USE IN THE STUDY AREA

3.5.4 groundwater – surface water interactions

The interaction of groundwater and the lakes and wetlands within the northern part of the Zululand coastal plain is complex, as the groundwater system is intricately linked to the wetland and the lakes. Under no groundwater abstraction scenario from the catchment, the annual net groundwater recharge to the catchment is expected to discharge as natural outflows to the lakes and wetlands. Groundwater contours and associated flow directions and gradients (Figure 8) indicate that flow is generally towards the lake and the coast. The local groundwater flow vectors indicate that groundwater flow within the northern Zululand coastal plain is towards the lakes, numerous wetlands and pans.

Therefore, shallow water level situations over most of the study area resulted in the formation of numerous groundwater fed pans and wetlands of different size throughout the area. These lakes and pans are often the result of surface manifestation of the groundwater surface. Lake Sibayi is the largest groundwater fed freshwater lakes in the coastal plain. The surface elevation of most of the wetlands and the lakes is merely a reflection of the local groundwater level. Groundwater level decline as a result of groundwater abstraction and/or extremely low recharge events may result in the temporarily drying up of these pans, when and where ever these pans are shallow. These situations are more frequent these days within the northern half of the coastal plain. When the hydrological years receive above average rainfall and the groundwater balance forces the water level to recover as a result of increased aquifer recharge, these wetland, pans and small lakes get wet again, after the groundwater levels have again equilibrated. Recent isotopic studies within the Lake Sibayi catchment (Weitz and Demlie, 2014) and Kosi Bay system (Demlie and Ndlovu, in preparation) further indicated that not only lakes, pans and wetlands are groundwater fed, but most perennial rivers are sustained by groundwater discharge. Examples are the Mseleni, Sihandhla and Gasiza Rivers where groundwater and river stable isotopic signals are almost the same indicating that their flow is supported from groundwater discharge.

Lake Sibayi receives groundwater inflow from the western, south western and northern sides where groundwater levels are above Lake stage, while it losses water through groundwater to the coast in the eastern side of the lake where lake stage is higher than groundwater level. The Kosi Bay lakes system receives groundwater inflow from the western side of the catchment and discharge in the east to the Indian Ocean.

3.6 Water Quality

3.6.1 Groundwater quality

Groundwater quality analyses from samples collected recently from boreholes within and around the Lake Sibayi and Kosi Bay catchments are presented in Figure 10. These samples were taken from the shallow (KwaMbonambi /Sibayi) and the deeper (Uloa) aquifer systems. The groundwater specific electrical conductivity (EC) distribution for the entire W70A quaternary catchment is also shown in Figure 11. The groundwater of the Lake Sibayi and Kosi Bay catchments are characterized by relatively low EC and low concentration of major ions. The groundwater quality data were compared to DWAF’s (1996) water quality class. The comparison indicated that the water conforms in almost all instances (more than

95% of the chemical parameters) to the "ideal water quality" category of DWAF. Few boreholes indicated relatively high chloride (Cl) (class I) and total iron (Fe) (class III) concentrations. High concentrations of Fe are common in the groundwaters of the Northern Zululand coastal plain as recently reported by Demlie et al. (2014) and the sources are natural geologic. Elevated concentrations of chloride in coastal groundwaters are also a common occurrence because of marine derived salts and however, the source could be diverse. No indication of groundwater pollution and polluted hotspot areas are identified within the study areas.

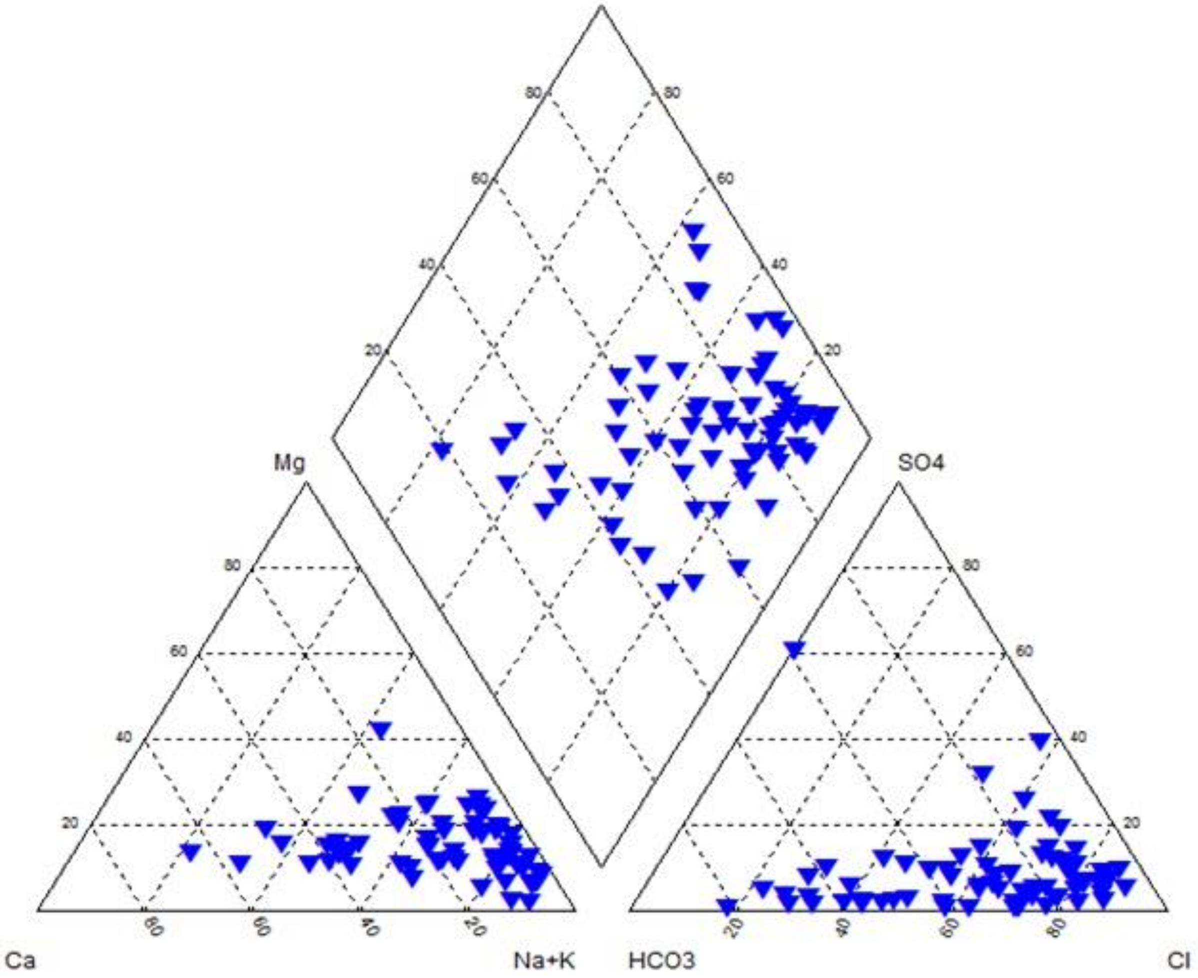

FIGURE 10. PIPER PLOT OF GROUNDWATER MAJOR ION CHEMISTRY DATA FOR THE STUDY AREA

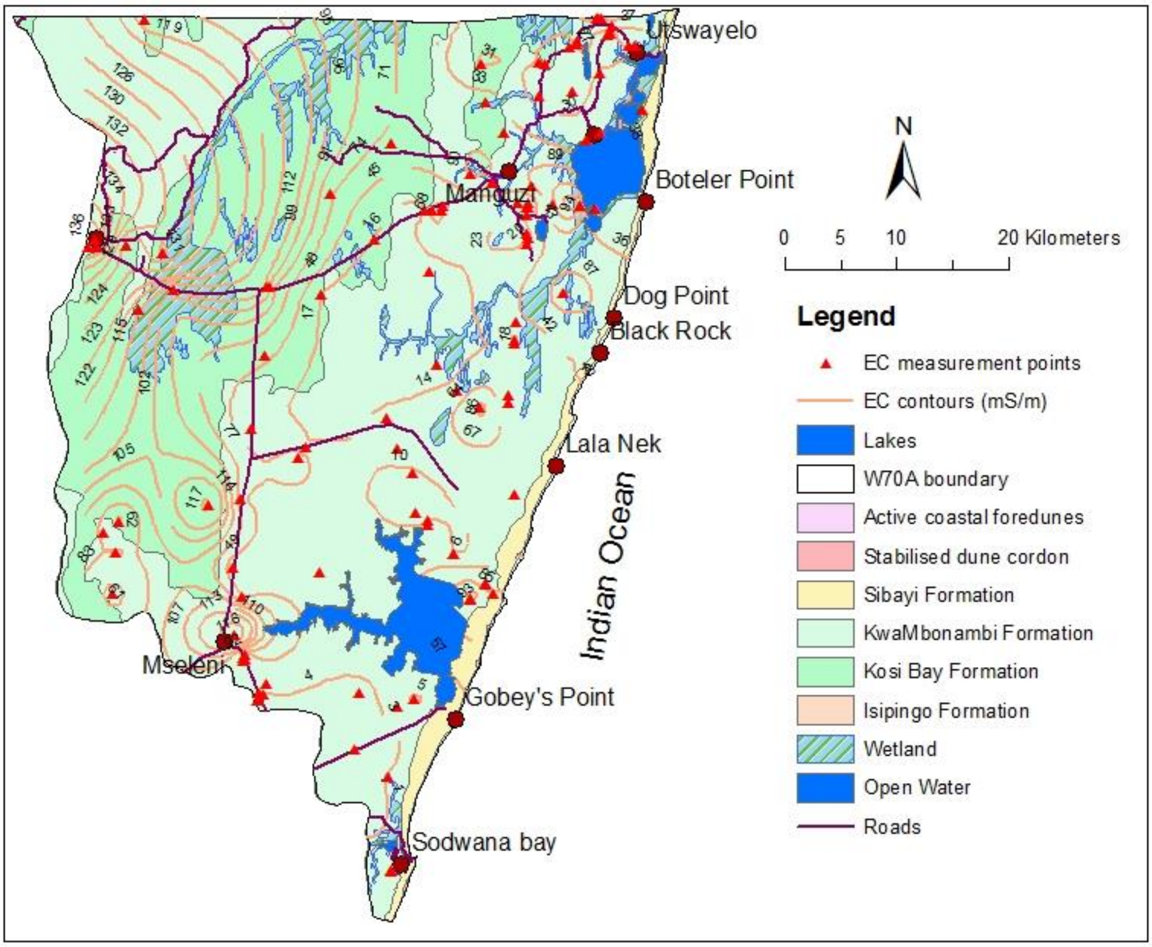

FIGURE 11. GROUNDWATER EC DISTRIBUTION MAP FOR THE W70A QUATERNARY CATCHMENT IN GENERAL AND THE STUDY ARE IN PARTICULAR.

3.6.2 Surface water quality (Lakes and Rivers

Water quality data for Lake Sibayi and Kosi Bay catchments is presented as a piper plot in Figure 12. The figure shows two groups of waters, namely a highly saline Kosi Bay lakes and estuary samples and rives and Lake Sibayi samples. Except Lake Amanzimnyama, three of the Kosi bay lakes are saline. Whereas, all streams and Lake Sibayi have fresh water chemistry with all chemical parameters except chloride are within DWAF's “Ideal” water quality class. The Kosi Bay lakes have a salinity series that ranges from 102.4 mS/m for Lake Amanzimnyama, 485.4 mS/m for Lake Nhlange, 2209 mS/m for Lake Mpungwini, to 2530 mS/m for Lake Makhawulani, from south to north, respectively. The estuary had an EC of 4951 mS/m during the time of measurement (April-June, 2013).

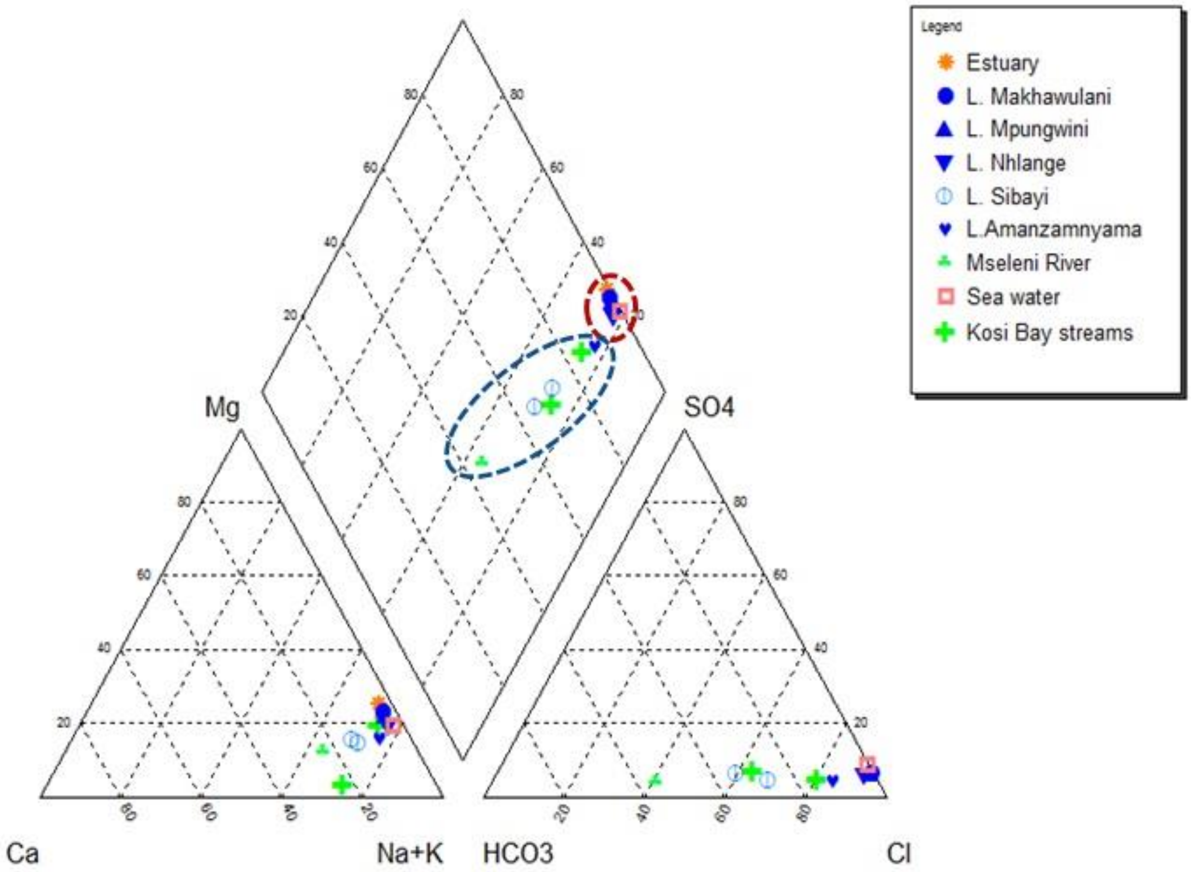

FIGURE 12. PIPER PLOT OF THE SURFACE WATER CHEMISTRY DATA FOR THE LAKES SIBAYI AND KOSI BAY CATCHMENTS (NOTE THE GROUPING OF FRESH AND SALINE WATERS).

4 DELINEATION OF RESOURCE UNITS, CATEGORIZATION AND DETERMINATION OF GROUNDWATER COMPONENT OF THE REERVE

4.1 Delineation of Groundwater Resource Units (RUs)

Resource units are usually delineated based on quaternary catchments (Dennis et al., 2012; Parsons and Wentzel, 2007)). However, geological, hydrogeological, hydrological, ecological, and other management and functional criteria plays a role in the delineation of these resource units of analysis (RUs). The purpose of the delineation is to undertake RU specific classification, reserve assessment and to set RQOs.

Although both the Lake Sibayi and Kosi Bay catchments are located within a similar hydrogeological environment, they divided into two separate groundwater RUs; namely, the Lake Sibayi catchment and Lake Kosi Bay catchments RUs, based on the surface water catchment area of the two lakes for ease of classification and reserve assessment. However, it is worth noting that the climate and subsurface hydrological conditions of these catchments are similar. The most important difference between the two catchments/RUs is in the lakes water quality, function and their ecological setting.

4.2 Lake Sibayi Catchment Resource Unit

4.2.1 Resource Unit Categorization and Groundwater Reserve for the Lake Sibayi catchment

The Lake Sibayi system hosts the largest freshwater lake in South Africa having a lake surface area of about 55.5 km^2. The lake is a source of water for the local communities residing around the catchment and sustains an important ecosystem, rich in biodiversity (Both fauna and flora).

4.2.2 Location and catchment characteristics

The Lake Sibayi catchment lies within the northern Zululand coastal plain and covers the surface water and groundwater catchments of Lake Sibayi (Figure 12). The most prominent hydrologic feature within the catchment is Lake Sibayi, the largest natural freshwater lake in South Africa. The estimated total surface water catchment area of Lake Sibayi is 513 Km^2, out of which 56 km^2 was covered by the lake in 2014, a reduction of about 20 km^2 from the 1993 lake surface area, which was 76 km^2 (Miller, 2001). The groundwater contributing area or capture zone of the lake delineated manually using all available groundwater level data is 612 km^2 which is larger than the total surface water catchment of the lake (Figure 13).

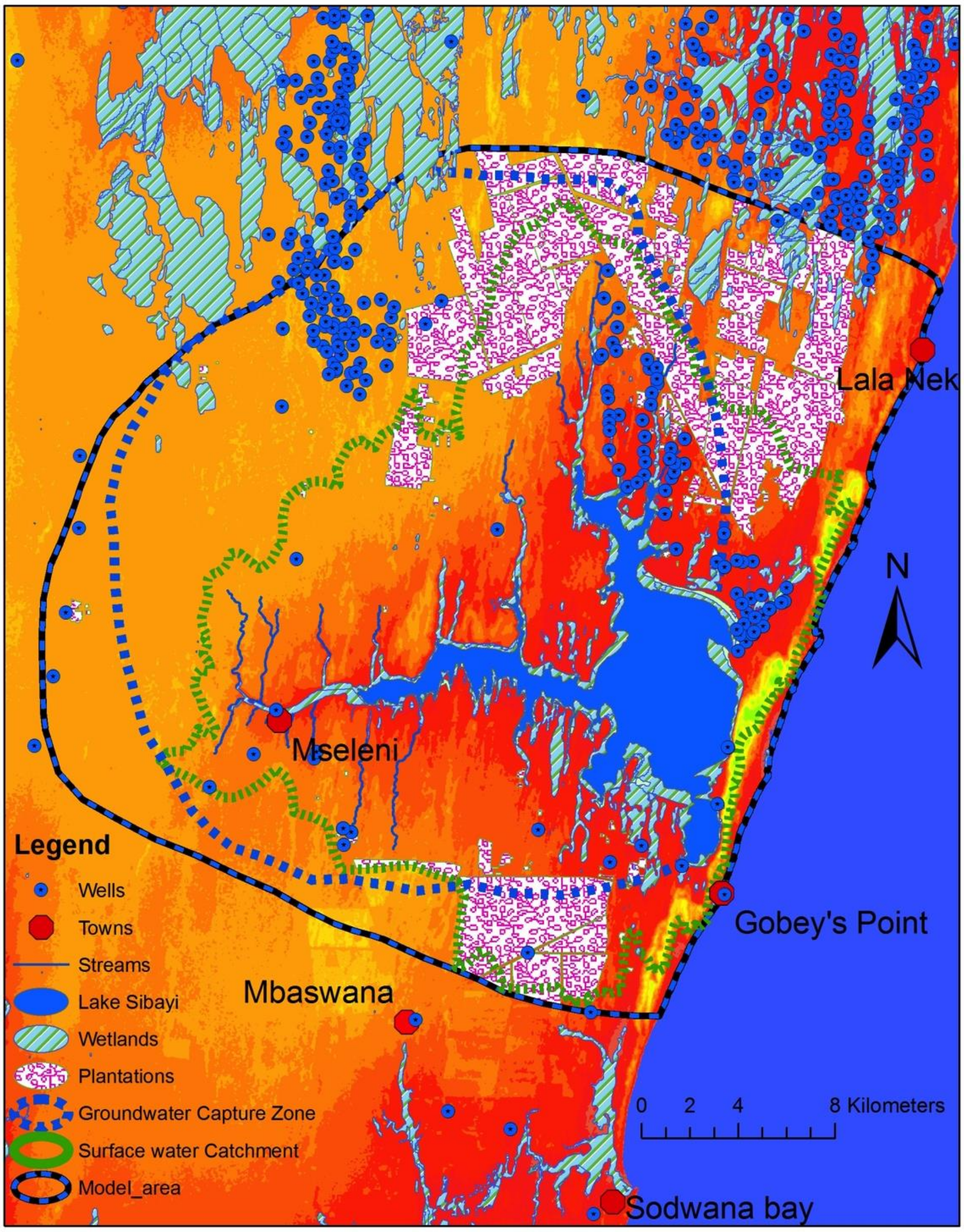

FIGURE 13. MAP SHOWING LAKE SIBAYI, ITS SURFACE WATER CATCHMENT AND GROUNDWATER CATCHMENT, PLANTATIONS AND THE MODEL DOMAIN.

The lake and its catchment are located within the W70A quaternary catchment and within Usutu-Mhlathuze Water Management Area (WMA 6). Furthermore, the lake, excluding its catchment, falls within the iSimangaliso Wetland Park conservation area which has World Heritage Site status (Botha and Singh, 2012). The Lake and its catchment fall within the uMkhanyakude District Municipality. The main rural towns around the lake are Mbazwana and Mseleni with a population of 27492 and 15717, respectively (census, 2011).

Due to the sandy substrate surrounding the lake, the amount of surface runoff is limited and consequently the water levels within the lake are maintained largely by groundwater inflow

(Weitz and Demlie, 2014; Meyer et al., 2001; Pitman and Hutchinson, 1975). The only significant surface drainage feature for the Lake Sibayi catchment is the Mseleni River feeding the western arm of the lake. Several non-perennial streams are found to feed various other parts of the lake. The KuMzingwane and Velindlovu streams drain into the northern arm of the lake, while the Umtibalu and Iswati streams and the Umsilalane stream drain into the southern and northern portion of the western arm, respectively (Figure 12). The sandy substrate of the catchment coupled with a relatively flat topography and shallow water table result in a close relationship between surface waters of the lake and the groundwater.

The most recent bathymetric data of the lake was reported by Miller (2001) and indicates maximum depth of the lake to be 41 m (Figure 14).

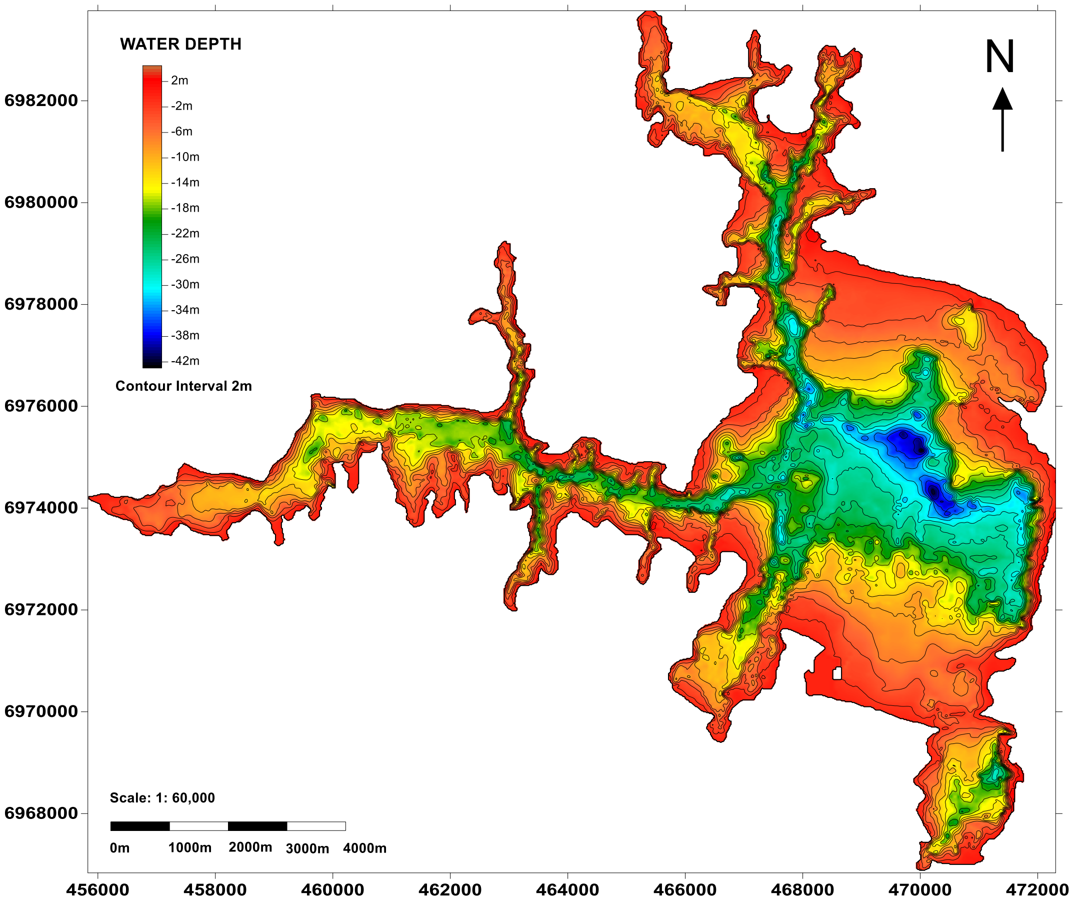

FIGURE 14. BATHYMETRIC MAP OF LAKE SIBAYI (DATA FROM MILLER, 2001)

The area surrounding Lake Sibayi is covered by extensive commercial plantations; the most prominent of these are the Mbazwana and Manzengwenya plantations situated on the southern and northern side of the lake, respectively. These plantations occupy an area of approximately 58 km^2 within the lake's catchment. These plantations consist mainly of Eucalyptus grandis, Eucalyptus camaldulensis (50%) and Pinus elliottii (30%), while the remaining 20% of the plantation is clear-felled (DWA, 2014).

4.2.3 Groundwater levels and flow directions

Groundwater level measured within the lake's catchment along with regional water level data obtained from the Groundwater Resources Information project (KZN-GRIP, 2013) were used to construct a groundwater level contour map for the area (Figure 14). The result indicates that there appears to be a close relationship between water levels and surface topography. Near the western catchment boundary of the lake, the groundwater elevation is around 70-80 m above mean seal level (amsl) (way above the stage of Lake Sibayi) from where it drops towards the coast to the altitude of the surface of Lake Sibayi.

Based on the groundwater level map (Figure 14), groundwater flow direction and the groundwater catchment of the lake are estimated. It was observed that surface water divide and groundwater divide don't coincide. The estimated groundwater contributing area to the lake (groundwater capture zone of the lake) (Figure 15) is approximately 569 km^2, much higher that the surface water catchment area of the lake (457 km^2).

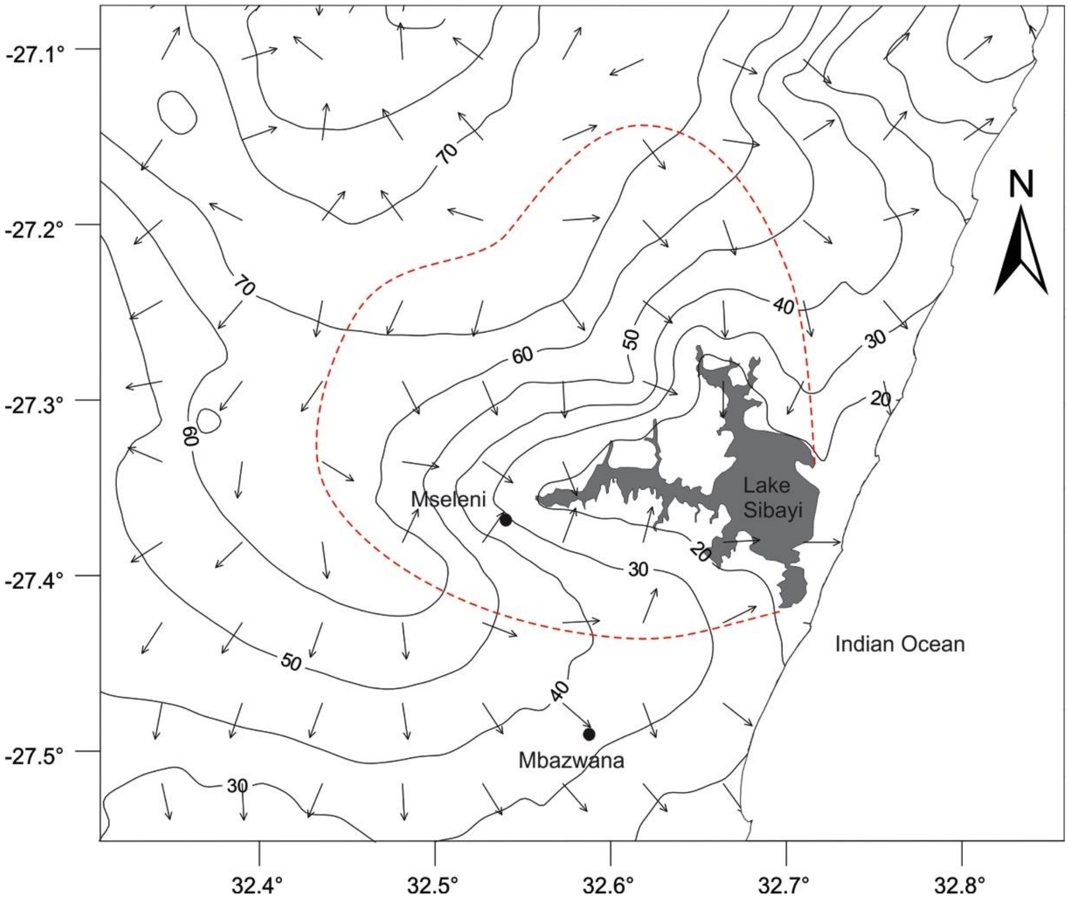

FIGURE 15. GROUNDWATER LEVEL, GROUNDWATER FLOW DIRECTION AND GROUNDWATER CONTRIBUTING AREA TO THE LAKE

4.2.4 Groundwater recharge

The average groundwater recharge volume estimated based on the 12% or 112 mm/a recharge rate for the Lake Sibayi groundwater and surface water catchments are 63x10^6 m^3/a and 51x10^6 m^3/a, respectively.

4.2.5 Groundwater use

Groundwater use within and around the Lake Sibayi catchment is limited to rural and towns water supply (mainly using shallow wells), small scale irrigation and forestry. There is no WARMS registered groundwater use in the catchment except for the forestry sector. However, a brief hydrocensus undertaken in 2013 indicates a minimum of 118 groundwater abstraction points mainly in the form of shallow and intermediate wells scattered within the lake Sibayi groundwater contributing area. The domestic groundwater uses are estimated to be $1.5x10^6$ m^3/a. The small scale irrigation uses an estimated $1.5x10^6$ m^3/a. The total registered water use by forestry as of 0//07/2010 is about 6.9 $x10^6$ m^3/a.

However, a total of about 37 km^2 of the groundwater contributing area to the lake and 58 km^2 of the surface water catchment of the lake is covered by commercial plantation. Using the Penmann - Montieth (Allen et al., 1998) method of evapotranspiration computation, a 14 year average evapotranspiration rate of 1300 mm/a (from hydrological year 1999 to 2013) was determined. Thus, based on this evapotranspiration estimate, the total groundwater discharge through commercial plantation from the groundwater contributing area is estimated at 21 $x10^6$ m^3/a. Meyer et al. (2001) simulated the impact of afforestation on the groundwater conditions around Lake Sibayi. Because of uncertainties in the water consumption by plantations under the prevailing climatic and groundwater conditions, different scenarios were simulated. Varying evapotranspiration rates (0, 200, 1000, 1500 and 2000 mm/a per unit area) with an annual groundwater recharge of 150 mm were used in the simulations. The lake level was kept constant at 20 m amsl. Along a section line through Lake Sibayi and perpendicular to the coast, the groundwater gradient remained towards Lake Sibayi even under the worst evapotranspiration condition of 2000 mm/a. However, the impact on ground water levels extends for about 4 km north and south of the Lake. At these distances groundwater levels can be up to 15 m lower at maximum evapotranspiration rates.

4.2.5 Groundwater discharge and Groundwater – Surface water interactions

Groundwater in the area is discharged in the form of abstraction for domestic and agricultural use, natural evapotranspiration, forestry, natural outflow to the lake and ocean. Under no groundwater abstraction scenario from the catchment, the annual net groundwater recharge to the catchment is expected to discharge as natural outflows to the lake and wetlands. Groundwater flow directions and gradients (Figure 15) indicate that flow is towards the lake.

Therefore, shallow water level situations over most of the coastal plain results in the formation of numerous shallow lakes, pans and wetlands of different size throughout the area. Lake Sibayi is the largest groundwater fed firewater lakes in the coastal plain. These lakes and pans are often the result of surface manifestation of the groundwater surface. The surface elevation of these lakes is merely a reflection of the local groundwater level. Recent isotopic studies within the Lake Sibayi catchment (Weitz and Demlie, 2014) indicated that not only lakes, pans and wetlands are groundwater fed, but most perennial rivers sustain their flow from groundwater discharge. One such example is the Mseleni River where groundwater and river stable isotopic signals are almost the same indicating that its flow is supported from groundwater discharge. In the case of Lake Sibayi, it receives groundwater inflow from the western, south western and northern sides where groundwater levels are above Lake stage and it losses water through groundwater to the coast in the eastern side of the lake where lake stage is higher than groundwater level.

4.2.6 Water Balance of Lake Sibayi

Base on the preceding geological, hydrogeological and hydrological information and discussions, the overall conceptual water balance of Lake Sibayi is given by the following equation:

$$P_l + G_{in} + S_{roff} - E_o - G_{out} - ABS = \pm\Delta S$$

Where:

P_l is precipitation on the surface of the lake

G_{in} is groundwater inflow to the lake

S_{roff} is surface runoff from the catchment to the lake

E_o is evaporation from the surface of the lake

G_{out} is subsurface lake water outflow/seepage to the sea

ABS is abstraction from the lake

$\pm\Delta S$ is change in the storage of the lake reflected as lake level changes

Precipitation on the Lake (P_l):

Based the long-term mean annual precipitation of 937 mm/a measured at the Hlabisa Mbazwana meteorological station, the mean annual precipitation volume over the lake is about 52.5 x10^6 $m^{3/}$a.

Surface runoff to the Lake (S_{roff}):

Since the river and streams that flow into Lake Sibayi are not gauged and also since not all surface water flow into the lake are channelized, an area-weighted runoff coefficient of 0.01 (1%) was estimated for the catchment excluding the lake. Based on this runoff coefficient, the total volume of surface runoff that flows into the lake is estimated at 4.3 x 10^6 m^3/a.

GROUNDWATER INFLOW TO THE LAKE (G_{IN}):

The south-western, the western and northern section of the lake receive groundwater inflow from the catchment (Figure 15). It is assumed that the net groundwater recharge within the groundwater contributing area enters the lake. This net groundwater discharge to Lake Sibayi is estimated from average recharge to the groundwater catchment of the lake minus groundwater abstraction for irrigation, domestic supply and evapotranspiration losses from commercial plantations. The total estimated net annual groundwater inflow to the lake was estimated to be 39 x10^6 m^3/a.

Evaporation from the lake (E_o):

Water loss from the lake through evaporation was calculated using the Penman equation from available meteorological data within and around the catchment. The fourteen year average annual evaporation loss from the lake is 1500 mm/a or an estimated volume of 84 x 10^6 m^3/a.

Lake water abstraction (ABS):

A total of 2776835 m^3/a registered water is being abstracted form the lake since 01/03/2004 for domestic supply. Lake water abstraction has increased from 1825000 m^3/a in 1975 to the present rate of 2776835 m^3/a. It is very important to note that this volume reflects only the WARMS registered one and in really it may be more than that.

Lake water seepage to the sea (G_{out}):

The groundwater level map indicates that groundwater level east of the lake is below lake stage. More over recent isotopic investigation (Meyer et al., 2001; Weitz and Demlie, 2014) indicated that the lake is discharging relatively large volumes of water to the sea. This seepage out of the lake is one of the factors that kept the lake water to have low salinity (fresh). Seepage from Lake Sibayi through the dune cordon (Groundwater outflow to the sea) is calculated using the following equation (Dupuit, 1863):

$$\boldsymbol{Q = (Kxa(\,h_0{}^2 - h_1{}^2))/2L}$$

where:

Q is the amount of ground water outflow to the sea
K is the hydraulic conductivity of the aquifer
a is the length of the seepage face
L is the length of the flow path
h_o - h_1 is the head difference between the lake stage and the sea surface above the impermeable cretaceous unit.

The Lake seepage through the groundwater out is calculated based on a mean hydraulic conductivity of 6 m/d (Table 5), a seepage face thickness of 45 meters (the depth of the Cretaceous basement below sea level), an average flow length of 2.5 km from the lake to the coast and a seepage face length of 12 km along the coast. The mean annual out flow to the sea is 11.9 X 10^6 m^3/a

The mean annual water balance components are summarized in Table 6. The water balance calculation gives a negative change in storage which is an indication of non-equilibrium condition in the system and indicates lake level decline.

TABLE 6. MEAN ANNUAL WATER BALANCE COMPONENTS FOR LAKE SIBAYI (IN 10^6 M^3).

Precipitation on the lake surface	Surface runoff to Lake	Net groundwater inflow	Lake Evaporation	Seepage From the Lake	Abstraction from the Lake	±ΔS
52.5	4.3	39	84	11.9	2.8	-2.9

Lake level record from 1980 to 2013 indicates that the water level of the lake has been declining since the early 2000s (Figure 16). The declining trend appears to be in response to rainfall changes and changes in the rate of water abstraction from the catchment. The mean water level for December 2013 was 15.89 m amsl, much lower than that measured in December 1980 which was 18.89 m amsl (Figure 16).

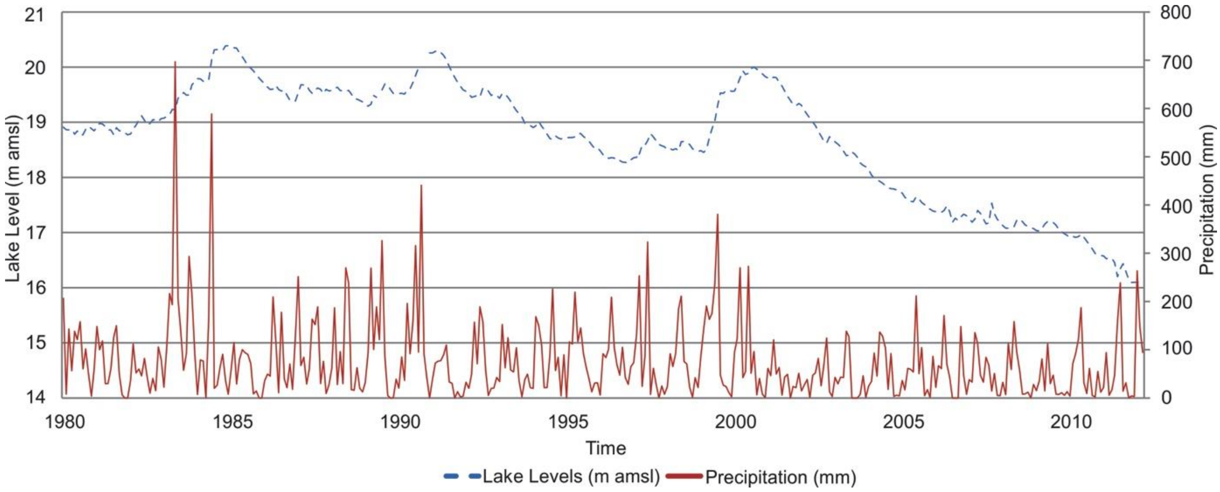

FIGURE 16. LONG-TERM LAKE LEVEL FLUCTUATIONS WITH MONTHLY PRECIPITATION FROM 1980 TO 2012 (DWA, 2013 AND SAWS, 2013).

4.2.7 Water Quality

Groundwater quality:

Groundwater quality analyses from samples collected recently from boreholes within and around the Lake Sibayi catchment is reported in Tables 7 along with DWAF's water quality class for comparison. These samples were taken from the shallow (KwaMbonambi /Sibayi) and the deeper (Uloa) aquifer systems. It is clear from the water quality data that the water conforms in almost all instances to the "ideal water quality" category of DWAF except for Fe in few wells. High concentrations of Fe are common in the groundwaters of the Northern Zululand coastal plain as recently reported by Demlie et al. (2014) and the sources are geologic.

Lake Sibayi water quality:

Water quality data for Lake Sibayi at different times is presented in Table 8. All the parameters except chloride is within DWAF's "Ideal" water quality class. There is slight variation in the concentration of the chemical parameters when the 1990s samples are compared with recent samples. Although there is a gradual reduction in lake level and eventually lake volume, because of variation in the analytical techniques used and also accuracy of the analytical techniques used, it is difficult to attribute the slight water quality change with any anthropogenic or natural stresses

.

TABLE 7. GROUNDWATER QUALITY DATA FROM BOREHOLES WITHIN THE LAKE SIBAYI CATCHMENT

Determinant	Unit	Boreholes with sampling dates								
		07/04/2013	09/04/2013	30/09/2012	08/04/2013	08/04/2013	01/10/2012	08/04/2013	08/04/2013	07/04/2013
		SIB06	SIB09	SIB10	SIB19	SIB20	SIB22	SIB25	SIB26	SIB34
K as K	mg/l	0.798	3.5	2.98	6.31	6.68	2.43	1.56	0.68	2.15
Na as Na	mg/l	20.24	31.2	25.6	53	60	19.1	19.1	20.9	30.29
Ca as Ca	mg/l	0.38	0.6	0.6	10.74	17.5	1.9	1.4	1.04	1.51
Mg as Mg	mg/l	1.02	1.66	1.5	5.78	7.5	3.9	3.35	1.36	4.35
SO4 as SO4	mg/l	5.94	6.15	5.5	118.7	3.61	7.29	14.9	3.25	1.15
Cl as Cl	mg/l	41.9	78.76	46.03	126.1	105.37	47.8	39.87	48.85	72.81
TAL as CaCO3	mg/l	6.1	7.32	6.1	13.41	129.26	3.66	9.76	9.75	86.58
NO3 as N	mg/l	0.26	0.08	0.34	0.77	0.3	0.4	0.4	0.4	0.03
Fe as Fe	mg/l	0	0	0.01	12.5	0.07	0.01	1.18	0.45	11.66
Mn as Mn	mg/l	0.003		0.004		0.06	0.03	0.03	0.02	
EC	mS/m	11.8	18.9	17.4	43.3	52.6	17.4	13.3	12.9	25.4
PH		5.7	5.8	5.4	6.18	7	5.75	5.7	5.8	6.8

….Table 7 continued

Determinant	Unit	Boreholes with sampling dates			DWA (1996) Water Quality Class				
		07/04/2013	08/04/2013	09/04/2013	0	I	II	III	IV
		SIB38	SIB39	SIB40	Ideal	Good	Marginal	Poor	Unacceptable

Determinant	Unit	Boreholes with sampling dates			DWA (1996) Water Quality Class				
		07/04/2013	08/04/2013	09/04/2013	0	I	II	III	IV
K as K	mg/l	1.08	0.27	4.8	<25	25-50	50-100	100-500	>500
Na as Na	mg/l	16.94	25.74	27.4	<100	100-200	200-400	400-1000	>1000
Ca as Ca	mg/l	0.82	1.12	21.34	0-80	80-150	150-300	>300	ns
Mg as Mg	mg/l	1.22	1.69	3.63	0-70	70-100	100-200	200-400	>400
SO4 as SO4	mg/l	6.98	6.6	6.5	<200	200-400	400-600	600-1000	>1000
Cl as Cl	mg/l	36.68	59.66	46.24	<100	100-200	200-600	600-1200	>1200
TAL as CaCO3	mg/l	9.76	10.37	160.35					
NO3 as N	mg/l	0.05	0.03	0.04	<6	5 −10	10 − 20	20-40	>40
Fe as Fe	mg/l	0.02	0.48	6.4	<0.5	0.5-1.0	1.0-5.0	5 to 10	>10
Mn as Mn	mg/l				<0.1	0.1-0.4	0.4-1.0	1.0-5	>5
EC	mS/m	10.8	15.7	32.2	0-70	70-150	150-370	370-520	>520
PH		6.5	5.9	7.18	6.0-9.0	5.0-9.0	4.0-10.0	3.5-10.5	<3.5 or >10.5

TABLE 8. WATER QUALITY DATA FOR LAKE SIBAYI MEASURED AT VARIOUS PERIODS

Determinant	Unit	Sampling Dates								
		*1/7/1988	*2/2/1989	*1/6/1989	*3/8/1989	*21/12/1989	*15/02/1990	30/09/2012	1/10/2012	8/4/2013
Potassium as K	mg/l	7	7	9	7	7	7	4.69	8.5	7.5

Determinant	Unit	Sampling Dates								
		*1/7/1988	*2/2/1989	*1/6/1989	*3/8/1989	*21/12/1989	*15/02/1990	30/09/2012	1/10/2012	8/4/2013
Sodium as Na	mg/l	81	81	83	81	81	78	97.4	85	95
Calcium as Ca	mg/l	23	23	23	23	24	23	32	16.5	16.7
Magnesium as Mg	mg/l	9	9	9	9	9	9	10.1	10.6	10.67
Sulphate as SO4	mg/l	10	9	9	9	8	9	5.5	20.4	19.71
Chloride as Cl	mg/l	110	111	113	112	113	111	146.03	137	140
Alkalinity as CaCO3	mg/l	124	124	124	124	124	124	6.1	112	123
Nitrate as N	mg/l	0	0	0	0	0	0	0.34	0.6	0.04
Conductivity (EC)	mS/m	60	60	60		61	60	72.1	64.8	68.8
Silica as Si	mg/l							11.05	8.89	8.08
Iron as Fe	mg/l							0.13	0.08	0.04
Manganese as Mn	mg/l							0	0.08	0
PH								7.8	8.96	8.92

(*) Data from Mayer and Godfrey (2003)

Groundwater recharge: Ground water recharge for the Lake Sibayi catchment presented in preceding sections. The groundwater contributing area to the Lake's catchment differs from the Lake's surface water catchment area. Table 9 gives the volume of annual recharge to the Lake Sibayi surface water and groundwater catchments.

TABLE 9. GROUNDWATER RECHARGE FOR THE CATCHMENT

Mean annual recharge (MAR)	Surface water Catchment area excluding the lake	Groundwater contributing area excluding the lake	Recharge volume within the surface water catchment	Recharge volume within the groundwater contributing area of the catchment
112 mm	457 km^2	569 km^2	51.2 Mm^3/a	63.7 Mm^3/a

Basic human needs (BNHs): The basic human need from groundwater is calculated based on the 2011 census population data for Mbazwana and Mseleni, which are the main population centres within and in the vicinity of the catchment. The basic human needs based on various population growth scenarios are given in Table 10. Based on the high growth scenario and taking 25 l/day/person water use, the total annual basic human needs is 607000 m^3/a.

TABLE 10. POPULATION DATA FOR THE MAIN POPULATION CENTRES IN THE CATCHMENT

Towns	2011 Census	2040 low growth scenario	2040 medium growth scenario	2040 high growth scenario
Mseleni	15717	17202	19630	22387
Mbazwana	27492	29414	36050	44116
Total	43209	46616	55680	66503
BHN (Mm3/a)	0.079	0.425	0.508	0.607

Groundwater contribution to baseflow (EWR): No stream flow data is available for the small number of streams that drain into Lake Sibayi. Recent high level groundwater reserve assessment undertaken by Dennis et al. (2009) for the quaternary catchment W70A used the Pitman model among a suit of methods. Baseflows estimated for the catchment using various methods are given in Table 11. Net groundwater flow into the lake estimated using the water balance of the Lake Sibayi catchment is 39 x10^6 m^3/a.

TABLE 11. GROUNDWATER CONTRIBUTION TO BASEFLOW

Groundwater contribution to baseflow							
GRDM Mm^3/a	Hughes Mm^3/a	Shultz Mm^3/a	*Pitman Mm^3/a	vTonder Mm^3/a	Min Mm^3/a	Max Mm^3/a	Herold Mm^3/a
92.46	11.73	6.34	10.19	9.16	6.34	35.71	10.19

*better estimate of baseflow.

Groundwater use: Groundwater use in the lake Sibayi catchment is presented in Table 12 below.

TABLE 12. GROUNDWATER USE VOLUME IN THE CATCHMENT

Groundwater use

WARMS (only for Forest) (Mm^3/a)	Estimated Forest use based on forest area (Mm^3/a)	Hydrocensus (domestic use) (Mm^3/a)	Irrigation (Mm^3/a)	Total (Mm^3/a)
6.9	**21**	1.5	1.5	24

Groundwater quality: The groundwater quality within the lake Sibayi catchment has been described in section 4.2.7. The groundwater quality is presented in Table 7. The overall quality of groundwater from boreholes within the catchment is within the DWAF's "Ideal" water quality class except for total iron.

4.2.8 Resource category

The present status category (PSC) is determined based on at least the following three factors (Dennis et al., 2012):

a) Based on observed environmental impact indicators

b) Based on the level of stress of the groundwater units Index and

c) Based on DWA water quality guideline for domestic use.

Groundwater level monitored data within and around the catchment shows declining trend (Figure 16). Additionally, the level of Lake Sibayi, which is groundwater driven, is showing a gradual decline trend as well. It is not yet clear whether abstraction from the lake or from groundwater by forestry and from the scattered domestic wells or both of them is contributing to these water level reductions. However, since the lake and the groundwater around it is a connected system, all water abstraction is believed to be working in tandem to impact both groundwater and lake level. Therefore, based on observed environmental impact indicators, the groundwater of the lake Sibayi Catchment is moderately used (II based on Dennis et al., 2012) or Moderate levels of widespread impacts, i.e. limited but noticeable effect on the environment (**C** to **D** based on parsons and Wenzel, 2007).

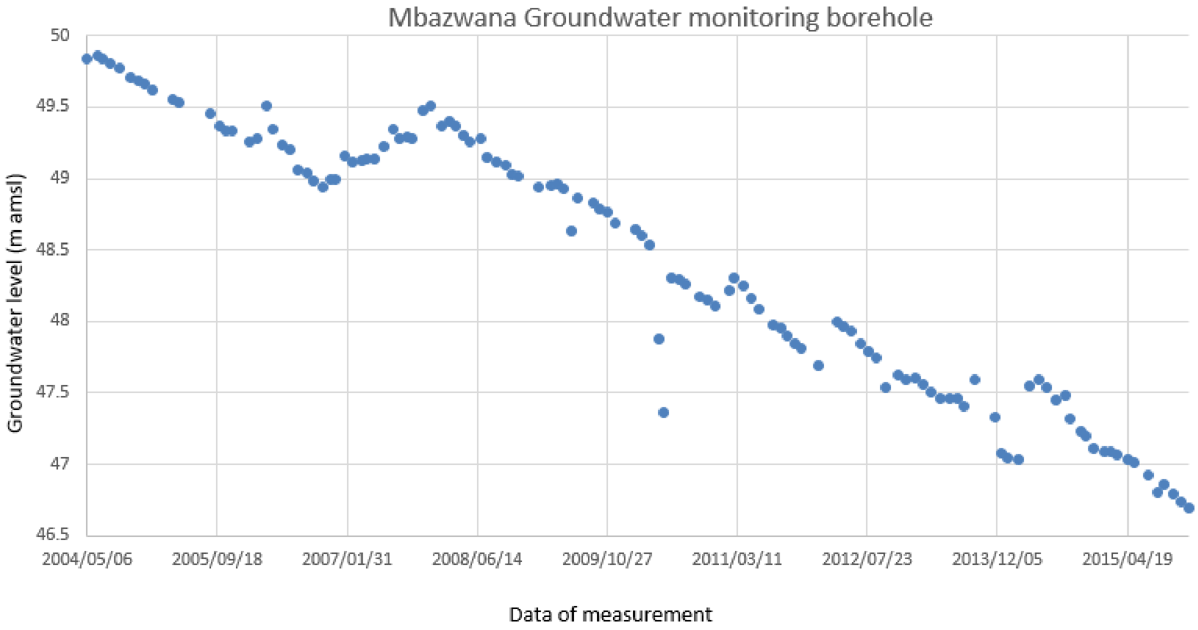

FIGURE 17. GROUNDWATER LEVEL REDUCTION IN TWO MONITORING BOREHOLES AROUND THE LAKE SIBAYI CATCHMENT

Groundwater stress index: Stress index is a quantitative way of defining stress and can be calculated using the abstraction to recharge relationship described in section 2. The SI indicates the present status category (PSC) of the resource. The SI for the Sibayi catchment is 39.9%. Based on this SI, the PSC for groundwater of the catchment is **II** (moderately used) or C (moderately stressed).

The water quality category for all the boreholes in the catchment based on DWA's water quality guideline is given in Table 13.

TABLE 13. PRESENT STATUS CATEGORY BASED ON DWA WATER QUALITY GUIDELINE FOR DOMESTIC USE

Present class	Description	Compliance (spatial/temporal)
I or B	DWA class 0 or 1 or natural background	95%

Overall, the surface and groundwater quality is largely not affected except for slight changes through time for Lake Sibayi. An equivalent present status category of **B** (localized, low levels of contamination, but no negative impacts apparent. The final present status category for the lake Sibayi resource unit is II or C (moderated modified). The water resource category is **Good to Fair**.

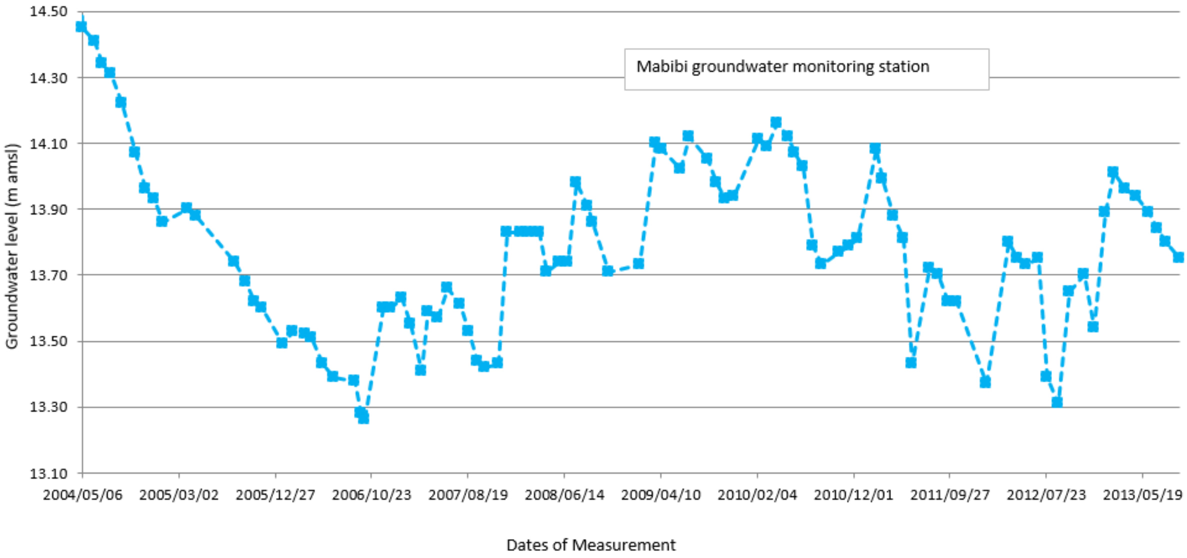

TABLE 14. GROUNDWATER RESOURCE CATEGORY FOR THE LAKE SIBAYI RESOURCE UNIT

Groundwater resources categorization							
GRU	**Area (Km2)**	**Recharge (Mm3/a)**	**Groundwater use (Mm3/a)**	**Stress Index, SI (%)**	**Present Category (SI)**	**Present category (Impact)**	**Present Category (quality)**
Lake Sibayi	**569**	**63.7**	**24**	**39.9**	**II (C)**	**II (C to D)**	**I (B)**

4.2.9 Groundwater Reserve for the Lake Sibayi Catchment

The groundwater component of the reserve is the part of the groundwater resource that sustains basic human needs and contributes to environmental water requirements (EWR). To be able to quantify the groundwater component of the reserve, the volume of groundwater needed for Basic Human needs (BHN) and contributing to EWR needs to be quantified. The EWRs of the resource in question must consider the following:

- Groundwater contribution to baseflow in rivers
- Groundwater contribution to wetlands
- Groundwater contribution to springs and other groundwater –dependent ecosystems

Groundwater should only be allocated to users and potential users once the volume of groundwater that contributes to sustaining the reserve has been quantified and resource quality objectives (RQOs) have been met. The RQOs can be set based on both the reserve and the resource class. The groundwater reserve for the lake Sibayi catchment is summarized in Table 15.

TABLE 15. GROUNDWATER RESERVE FOR THE LAKE SIBAYI CATCHMENT.

	Reserve				**Allocation**	
Baseflow (Mm^3/a)	**BHN (Mm3/a)**	**Reserve**	**Recharge (Mm^3/a)**	**Reserve (% of recharge)**	**Current use (Mm^3/a)**	**Allocable (Mm^3/a)**
39	**0.6**	**39.6**	**63.7**	**62**	**24**	**None**

***Note that only a maximum of 65% of recharge may be allocated due to its spatial and temporal variability**

4.2.10 Numerical Groundwater Flow Modelling of the Lake Sibayi Catchment

Background

There numerous lakes and wetlands in the Zululand coastal plain which are known to be connected to the groundwater system. Groundwater fluxes, though difficult to measure, are important to the water balance and chemistry of these lakes and wetlands. Therefore, stresses on the groundwater system and the consequent changes to these fluxes affect the level of lakes and wetlands and in turn affect groundwater levels in a dynamic feedback process. The most important problems in the Zululand coastal plain is to understand and quantify this feedback process including the effect of land use changes (particularly commercial forests) and climate change (known or perceived) on the lake-groundwater hydrologic system.

Traditionally, separate models have been used to analyse surface water and groundwater systems. Numerical groundwater flow models generally assume that surface water levels are known inputs, and therefore do not recognize the true nature of the connection between surface water and groundwater systems. However, in the Zululand coastal plain, lakes, wetlands and streams are connected to the unconfined aquifer system. Recent developments in groundwater flow modelling and the recognition of the interaction of surface water and groundwater has led to the need to develop a fully integrated model that analyses groundwater and groundwater linked surface water systems simultaneously (Michael et al., 2000; Council, 1997; Cheng and Anderson, 1993). Early attempts of analysing lake-aquifer interactions were simulated using cross-sectional models with fixed lake stages as specified head or head dependent flux boundaries (Winter, 1976; Anderson and Munter, 1981; Hunt *et al*., 1998). More sophisticated packages for the industry standard modular finite difference groundwater flow modelling, MODFLOW (McDonald and Harbaugh, 1988) have been developed in recent years. These lake-aquifer interaction modelling packages (modules) called Lake Packages include LAK1 developed by Cheng and Anderson (1993); LAK2 developed by Council (1998). Recently, Merrit and Konikow (2000) developed a new version of the Lake Package (LAK3). These packages allow for the calculation of lake stages in response to changes in precipitation, evaporation, surface water and groundwater fluxes, and calculate lake water budgets (Hunt *et al*., 2003). The Lake Packages have powerful post-simulation reporting features and allow for explicit inclusion of surface water flow to and from lakes (Hunt *et al*., 2003).

Another approach to simulate lake-aquifer interaction without using specific modular package for the lake is by simply representing parts of the model grid as having the hydraulic characteristics of a lake by specifying a high hydraulic conductivity for the lake-volume grid cells, here after referred to as the “High-K” techniques (Merritt and Konikow, 2000). This method has been successfully applied in simulating the interaction of various lakes and aquifers (Hunt and Krohelski, 1996; Lee, 1996; Swain et al., 1996; Merritt, 1997; Anderson et al., 2002; Yihdego and Becht, 2013).

For the simulation of lake-aquifer interaction in the Lake Sibayi catchment, initially the LAK3 package was used by integrating the bathymetry of the lake with the digital elevation model (DEM) of the model domain. One of the main objectives of applying the LAK3 module package was to determine the groundwater fluxes into and from the lake. However, the model was found to be unstable and often times crushed. The lengthy efforts of applying all possible troubleshooting procedures were unsuccessful. As a result, the High-K approach was used as an alternative to the LAK3 package, even though it doesn’t generate explicit water balance of the lake. This is because of the fact that the lake is modelled as part of the aquifer, that means the lake and aquifers are seamlessly interconnected. But, the High-K approach is able to simulate lake stage in a similar fashion as it simulates groundwater levels within the model domain.

Thus, a groundwater flow model has been developed within and around the lake Sibayi catchment using the High-K technique as part of the Project “Reserve Determination of Selected Water Resources in the Usutu-Mhlatuze Water Management Area (WMA)” that is being undertaken by Tlou Consulting (PTY) LTD. This report present the Lake-aquifer interaction modelling results for the Lake Sibayi catchment and its immediate vicinity.

Objectives of the modelling

The main aim of modelling of lake - ground water interaction in the lake Sibayi catchment to assist in setting resource quality objectives (RQOs) and recommend monitoring requirements. The main objective of the numerical groundwater flow modelling undertaken for the Lake Sibayi catchment is

a) To calibrate a steady state and transient groundwater flow model for the lake Sibayi catchment to understand lake-aquifer interactions.

b) To determine the effects on lake level of various stresses on the catchment including potential climate change.

c) to understand any potential sea water intrusion as a result of reduced lake levels based on which management and monitoring requirement will be recommended

Modelling procedures and methods

The interaction between Lake Sibayi and the surrounding groundwater can only be accurately evaluated using the 3-D numerical flow model. In order to develop a well calibrated numerical model, a proper characterisation of the subsurface geology and representation of the sources and sinks within the Lake Sibayi catchment are essential. The modelling described in this report was developed to simulate groundwater and Lake levels based on a number of input parameters related to soil-vegetation-atmosphere transfer processes, rainfall-runoff relationships, and groundwater-surface water interactions. The processes followed during model design and execution are presented in Figure 18.

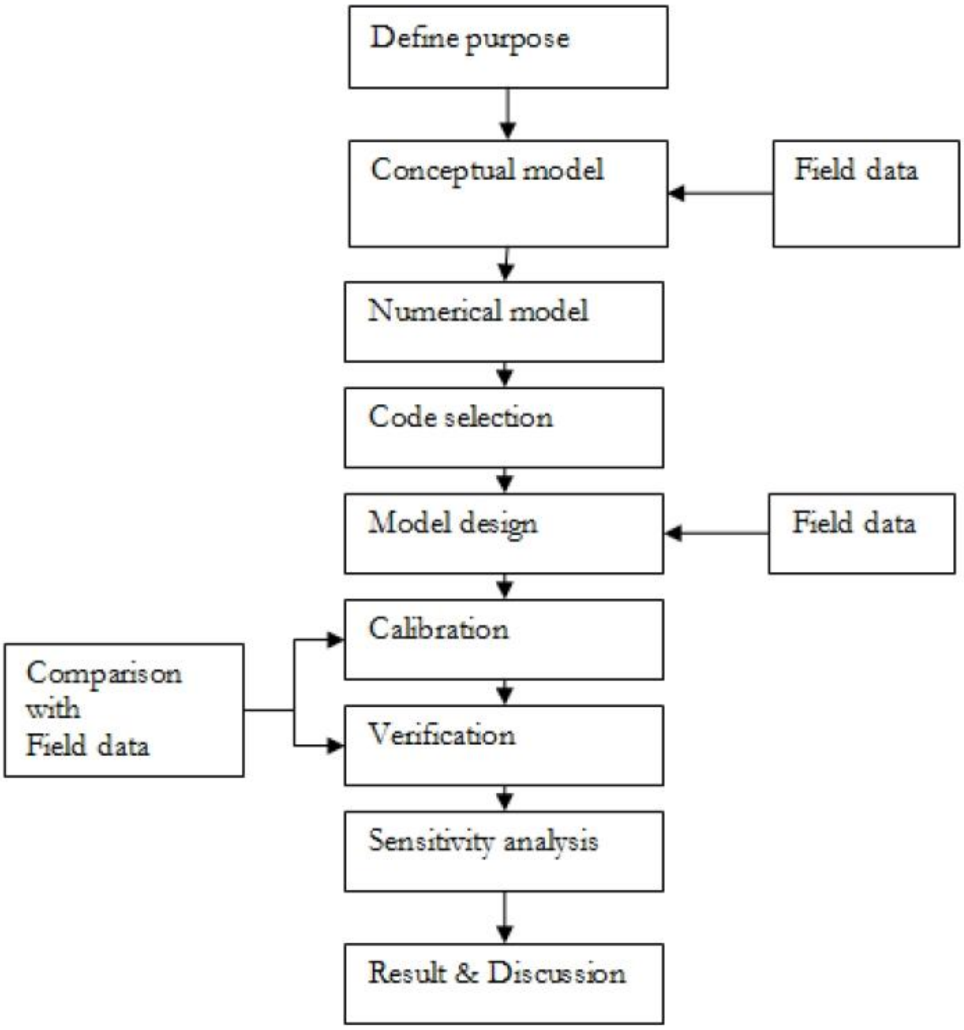

FIGURE 18. FLOW CHART OF THE MODELLING PROCESS (ADAPTED FROM ANDERSON AND WOESSNER, 2002)

Hydrogeological conceptualization of the study area

The hydrogeology of the study area has been reported in the two reports preceding this report. The study area is characterised by two main aquifers and a minor aquifer. The two most productive aquifer systems in the region are the shallow KwaMbonambi Formation and the deep Umkwelane and Uloa Formations (Weitz and Demlie, 2013; Jeffares and Green, 2012; Meyer and Godfrey, 1995; Meyer *et al*., 2001). These aquifer units have variable thickness (Botha and Porat, 2007; Porat and Botha, 2008) and is frequently exploited by the local community through hand dug and drilled wells (Meyer and Godfrey, 1995). Pumping tests undertaken in the KwaMbonambi Formation by Jeffares and Green (2012) revealed sustainable yields of between 190 and 1700 m^3/day. Meyer and Godfrey (1995) reported an average transmissivity of 1490 m^2/day and hydraulic conductivity range between 0.87 and 15.6 m/d for the same unit. The Umkwelane and Uloa Formations which constitute the main aquifer in the region (Jeffares and Green, 2012; Kelbe *et al*., 2013; Worthington, 1978), have reported sustainable yields of between 40 and 1500 m^3/day, and average permeability, transmissivity and storativity of 4.5 m/day, 116 m^2/day and 0.019 respectively (Jeffares and Green, 2012; Meyer and Godfrey, 1995). Worthington (1978) reported borehole yields of up to 25 l/s in areas where the aquifer layer is more than 20 m thick.

The Kosi Bay Formation, that separates the two main aquifers, is generally characterized by a relatively low yield and composed of silty sand and silt (Porat and Botha, 2008). As a result, it is generally considered as a leaky confined aquifer which acts as a storage reservoir to the underlying Umkwelane and Uloa Formations (Jeffares and Green, 2012). Hydraulic conductivity for the Kosi Bay Formation ranges from 4 to 5 m/d (Meyer and Godfrey, 1995).

The region is underlain by Cretaceous age siltstones of the St. Lucia Formation which is characterised by low yields and low permeability. Due to its impermeable nature, this regional Cretaceous unit is regarded as the hydrogeologic basement (bottom impermeable boundary).

The aquifer units overlying the Cretaceous basement are interconnected and have hydraulic characteristics that vary within small margin (Table 16). Thus, for the purpose of constructing a simplified model, these units are grouped as a single unconfined aquafer system having an averaged hydraulic property. These aquifers receive rainfall recharge from the top of the aquifer which averages about 12 % MAP. Runoff within the study area is very low and it is estimated to range between 2 and 5% of MAP.

TABLE 16. HYDRAULIC CHARACTERISTICS FOR THE AQUIFER UNITS WITHIN THE STUDY AREA (DATA FROM MEYER AND GODFREY, 1995; JEFFARES AND GREEN, 2012, AND OTHER VARIOUS SOURCES)

Aquifer name	Thickness (m)	K (m/d)	T (m2/d)	Borehole yields (L/s)
Sibayi/KwaMbonambi Formations	20-30*	0.87-15.6 (mean: ~5)	1490	0.5-5
Kosi Bay/Port	15-20*	4-5	-	2-10

Durnford Formations		(mean: 4.3)		
Uloa/Umkwelane Formation	5-20	0.5-25 (mean: 4.5)	116	5-25
St Lucia Formation	900	-	-	<1

Based measured groundwater level within and around the model area, the groundwater flow direction is indicated in Figure 15. A groundwater divide is identified west of Lake Sibayi's catchment which has helped to define the western model domain boundary. Groundwater flows from the groundwater divide towards the east, to the Indian Ocean. Groundwater level and associated flow direction, hydrochemical and environmental isotope data indicate that Lake Sibayi is a flow-through lake, with groundwater entering and exiting through parts of the lake bed.

Assumption made in the modelling Process

The following are some of the assumption made in developing the steady state model:

- An upper unconfined aquifer unit hydraulically connected to the underlying aquifer. Stressing the upper aquifer means that the stress propagates to the lower aquifer units accordingly.
- The Cretaceous sedimentary basement acts as an impermeable bottom model Boundary
- The system is initially at equilibrium, i.e. steady state conditions prevail despite changes that may exist.
- All the boundary condition defined for the model area are correctly conceptualized.
- Models are approximate representation of field situations and must be treated as such.
- Commercial Plantations pump some water from the saturated zone and hence can be approximated by abstraction wells

Model Domain and model design

A quasi-three dimensional model using MODFLOW GMS (Harbaugh et al., 2000) was constructed for 913 km^2 area that includes Lake Sibayi, its surface water and groundwater catchments (Figure 13). The model is designed as a single layer model bounded at the bottom by an impermeable boundary condition. The model domain is discretised into 410 rows and 421 columns with variable grid spacing where grid refinements were done for well cells. The total number of model grid cells is 172610, of which 111608 are active and 61002 are inactive. Lake Sibayi is represented inside the model domain with a zone of hydraulic conductivity having three orders of magnitude higher than the surrounding aquifer. Since the 1993 bathymetry of the lake was included to honour the bottom morphometry of the lake, the initial input area of the lake was based on that of 1993, which was 75.5 km^2.

The partial-differential equation of groundwater flow used in MODFLOW (Harbaugh and McDonald, 1996) is given by:

$$\frac{\delta}{\delta x}\left(K_{xx}\frac{\delta h}{\delta x}\right)+\frac{\delta}{\delta y}\left(K_{yy}\frac{\delta h}{\delta y}\right)+\frac{\delta}{\delta z}\left(K_{zz}\frac{\delta h}{\delta z}\right)-W=S_s\frac{\delta h}{\delta t}$$

Where, $\mathbf{K_{xx}}$, $\mathbf{K_{yy}}$, $\mathbf{K_{zz}}$ are the hydraulic conductivity values in the **x**, **y** and **z** axes; **h** is hydraulic head, **W** is a volumetric flux representing sources and/ or sinks of water; S_s is specific storage and **t** is time.

Model input and calibration

Model input

The hydrogeological conceptual model and water balance for Lake Sibayi formed the foundation of the numerical model. For simplicity and to establish a stable and robust steady-state model upon which the transient is to be based, the model was considered as a single layer model. The upper surface of the model was based on the recently captured SRTM 30 m (1 arc second) Digital Elevation Map (DEM) which had the bathymetry of the lake (Miller, 2001) embedded into it. The base of the model was assigned the elevation of the Umkwelane /Uloa and Cretaceous bedrock interface. The hydraulic characteristic of the aquifer layer was given the average of the values pertaining to the various hydrogeological units as indicated in Table 16. The High-K lake cells were given a horizontal hydraulic conductivity three orders of magnitude greater than that of the surrounding aquifer.

Boundary conditions

An essential component of any model is an appropriate set of boundary conditions to characterise the systems relationship with the surrounding system. In the case of the Lake Sibayi model, the boundary conditions will describe the exchange of flow between the lake and the various components of the external system. The model boundary represents the interface between the model area and the surrounding environment, and as such, need to be specified. The selection thereof is dependent on factors such as topography, hydrology and geology.

The northern, western and southern boundaries of the model domain were set as no-flow boundaries corresponding to the mapped groundwater divide. The eastern boundary along the Indian Ocean coastline is set as constant head boundary with a starting and ending constant head of 0 (zero) m amsl. The model bottom is constrained by the Cretaceous impermeable basement which is set at -45 m (45 m below mean sea level). The initial conditions was set as the ground surface elevation as defined by the DEM.

Sources and Sinks

The sources and sinks (input and outputs) were given for two zones, namely the aquifer and the lake cells. The sources to the aquifer is rainfall recharge which was estimated at 12% of MAP. The sources to the lake are precipitation on the surface of the lake, runoff from the lake’s catchment and groundwater inflow from the aquifer. The sinks for the aquifer cells are evapotranspiration, groundwater abstraction, drains through streams, groundwater flow to the lake and across the constant head boundary, while for the lake are evaporation, abstraction and flow through the aquifer to the ocean. Recharge, precipitation, runoff, evaporation, evapotranspiration and abstraction are pre-processed and input to the model. The rest are calculated by the model.

Model Results and discussion

Steady state model calibration

A very important process of groundwater flow modelling is the model calibration processes. In order a model to be used as a management tool, it must be established that the model can successfully simulate observed aquifer behaviour. Model calibration is simply stated as the processes where certain parameters of the model such as recharge and hydraulic conductivity are changed in a systematic way and the model is repeatedly run until the simulated solution matches field-observed or measured values within an acceptable level of accuracy. Two types of observed data were used in the calibration processes, namely groundwater level elevation from various wells within the model domain and observed lake level data for the year 2014. A total of 8 observation well and lake level at various points of the lake were utilized for calibration.

Automatic calibration techniques using the parameter estimation tool (PEST) was not successful. As a result, manual calibration was undertaken by repeatedly changing some of the model input parameters, mainly recharge and hydraulic conductivity. The result of the calibration was evaluated quantitatively (Anderson and Woessner, 2002) by expressing the average difference between simulated heads and measured heads using model calibration error statistics such as R2, mean error (ME), mean absolute error (MAE) and root mean square errors. The objective of the calibration is to minimize the errors. For all four calibration criteria, the respective minimum errors are all within acceptable limit and are presented in Table 17.

TABLE 17. STEADY STATE CALIBRATION ERROR SUMMARY

i. No.	ii. Evaluation Criteria	iii. Error value
iv. 1	v. Mean Error	vi. -0.683
vii. 2	viii. Mean absolute error	ix. 0.861
x. 3	xi. Root mean square error	xii. 1.295
xiii. 4	xiv. R^2	xv. 0.998

Scatter plot of measured against simulated heads was drawn to show the calibration fit (Figure 19). The scatter plot is virtually examined for point deviation from the best fit line. The best fit line along the scatter points have an R^2 value of 0.9977.

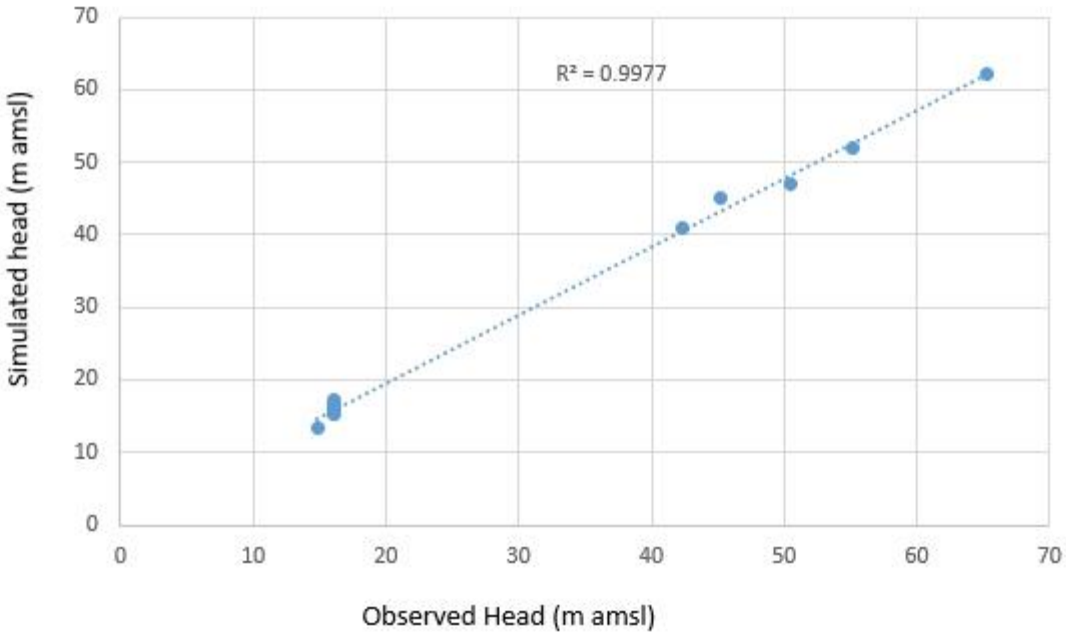

FIGURE 19. SCATTER PLOT OF OBSERVED VS SIMULATED HEAD VALUES

A further calibration check was made by observing the steady state model water budget results (Table 18). The steady state model water budget indicates a nearly zero percent discrepancy between the inflows and the outflows.

TABLE 18. STEADY STATE MODEL WATER BUDGET

Flow components	Inflow (m^3/day)	Outflow (m^3/day)
Constant head	0	107105.3
Evapotranspiration	0	39690
Aquifer recharge	254531.67	
Net lake flux	-	107735.5
Total	254531.67	254531.66
	Inflow – Outflow:	0.0036
	Percent discrepancy:	0

Calibrated model parameters

The steady state model was calibrated to present day condition of the model domain that includes modern day average precipitation of 936 mm/year, current land uses including unlicensed plantations, lake evaporation and abstractions. The optimum average horizontal hydraulic conductivity is 6.5 m/day and the recharge is 11.9% of MAP.

Scenario analyses

Six scenarios were selected for further simulations that indicate unlawful and lawful plantation coverages and changed climates. The various scenarios considered are shown in Table 19.

TABLE 19. THE VARIOUS SCENARIOS CONSIDERED IN THE MODELLING

Scenarios	Description
1	Current condition including existing unlawful plantations and other stresses
2	Current condition with only lawful plantations (unlawful plantations removed
3	Scenario 1 with a changed climate as expressed by a 10% decrease in rainfall amount
4	Scenario 2 with a changed climate as expressed by a 10% decrease in rainfall amount
5	Scenario 1 with a changed climate as expressed by 10% increase in rainfall amount
6	Scenario 2 with a changed climate as expressed by a 10% increase in rainfall amount.

Scenario 1

As stated above, the model was calibrated to present day conditions that include all plantations (lawful and unlawful), present day abstraction for the lake, evaporation and precipitations. The results of the simulation are presented in figures 20 and 21. Figure 21 shows the contour map of simulated aquifer heads and modelled lake extent. The simulated head contour map and lake area extent indicate observed present day conditions. The modelled lake area (blue) is compared against the 1993 lake extent (white outline) in Figure 21 to indicate how the area of the lake have reduced since then.

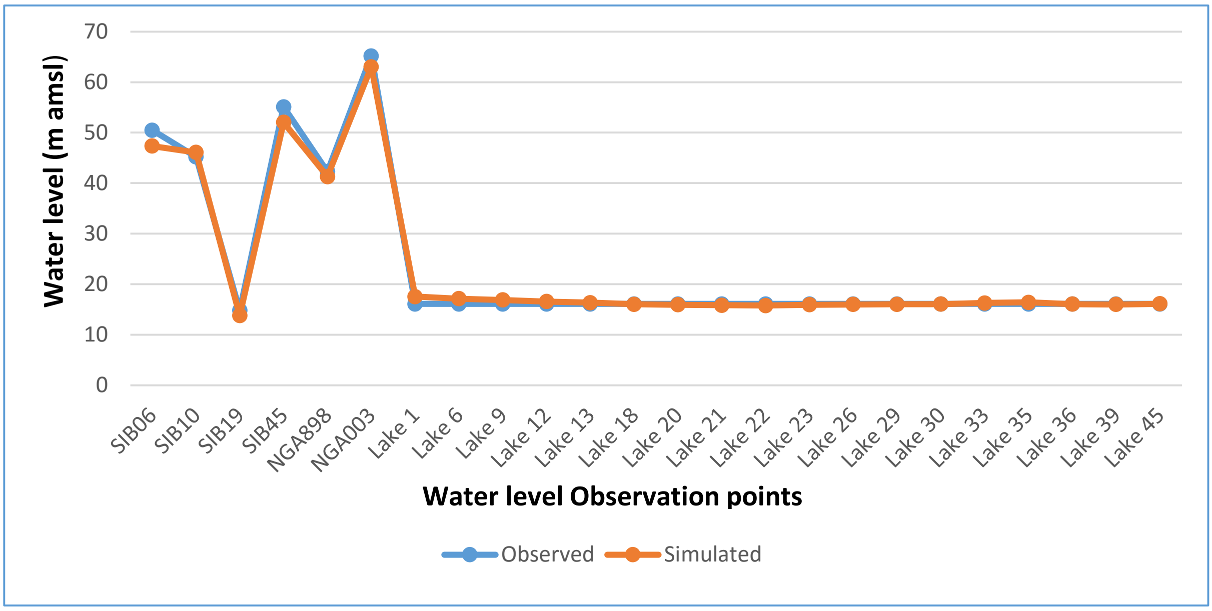

FIGURE 20. OBSERVED AND SIMULATED HEAD FOR THE VARIOUS OBSERVATION POINTS

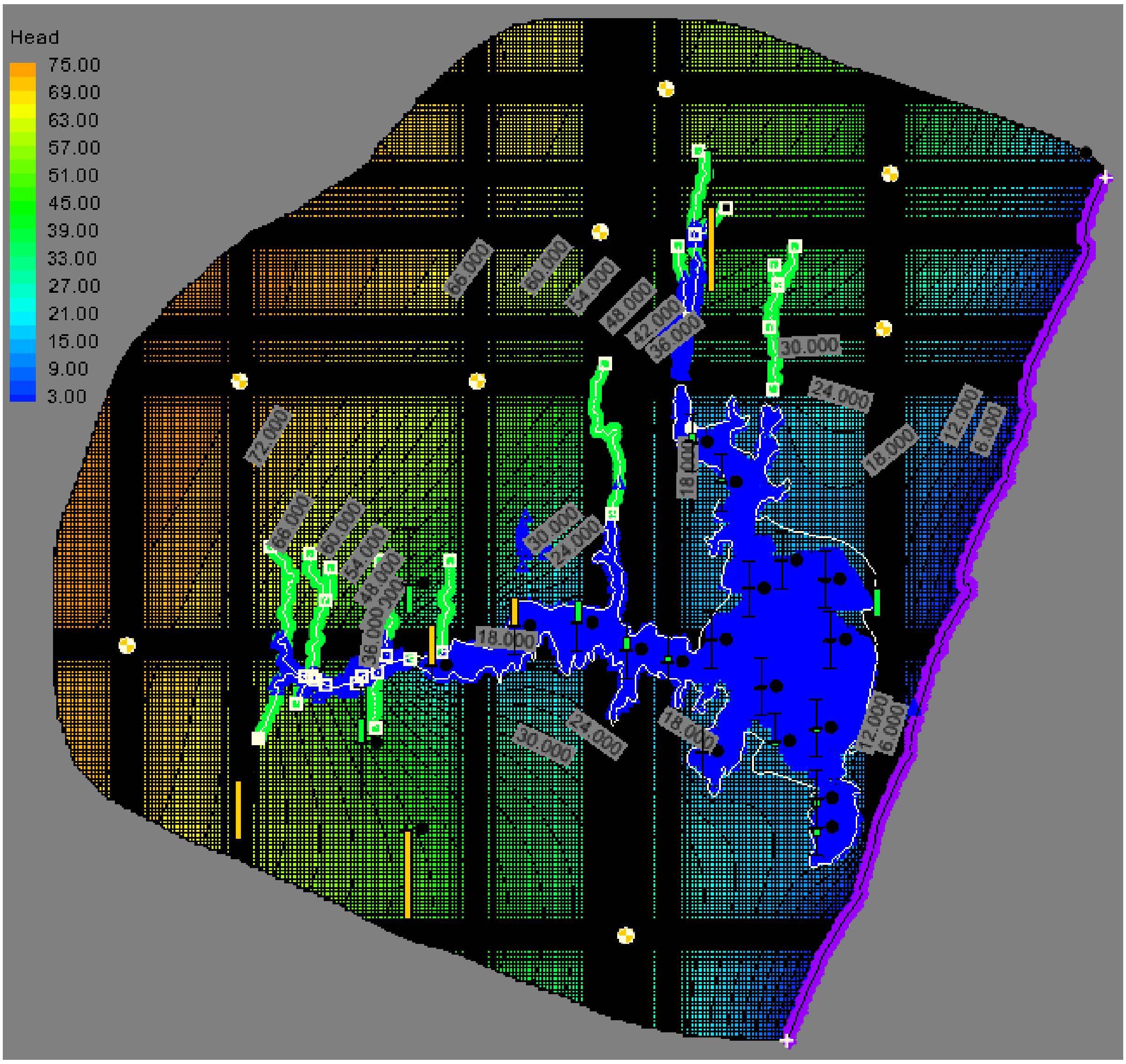

FIGURE 21. GROUNDWATER CONTOUR MAP AND LAKE EXTENT FOR SCENARIO 1 (STEADY STATE CALIBRATED)

Scenario 2

The model was simulated by removing the unlawful plantation but all other present day conditions unchanged. That means recharge, abstraction and evaporations are same as the first scenario. The result is presented in Figure 22. Removing of the unlawful plantation increased the average simulated head in the aquifer by 1.4 meter and lake level by 1.2 meters.

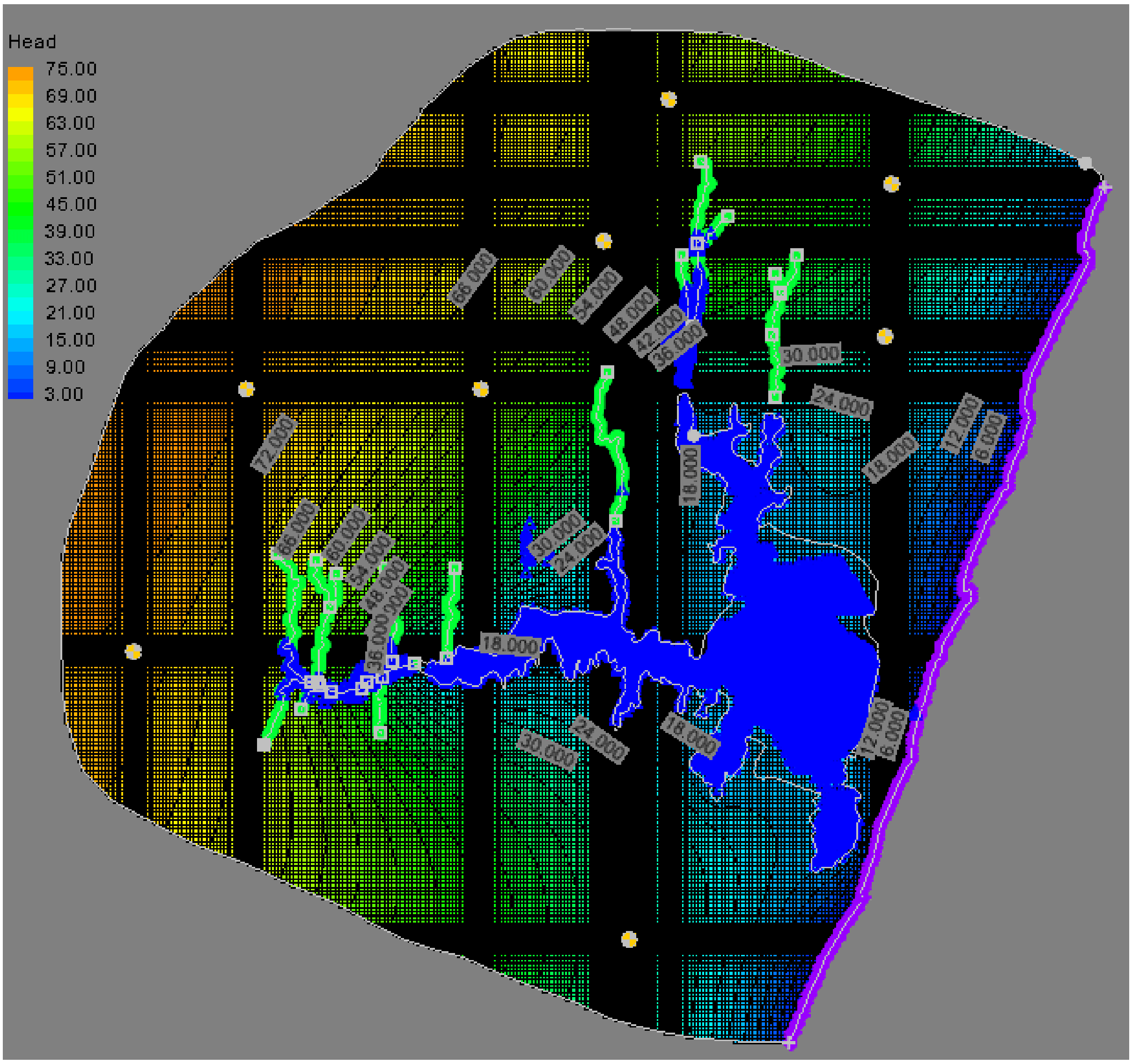

FIGURE 22. SIMULATED GROUNDWATER CONTOUR MAP FOR SCENARIO 2

Scenario 3

The model was run under a changed climate scenario by reducing the rainfall amount by 10% from the MAP, but keeping all the stresses at the current state. The resultant groundwater level and lake extent map is shown in Figure 23. The Simulation result indicates an average groundwater and lake level decrease of 4.7 and 5.38, respectively. This reduction in lake level is clearly shown on the lake extent in Figure 23.

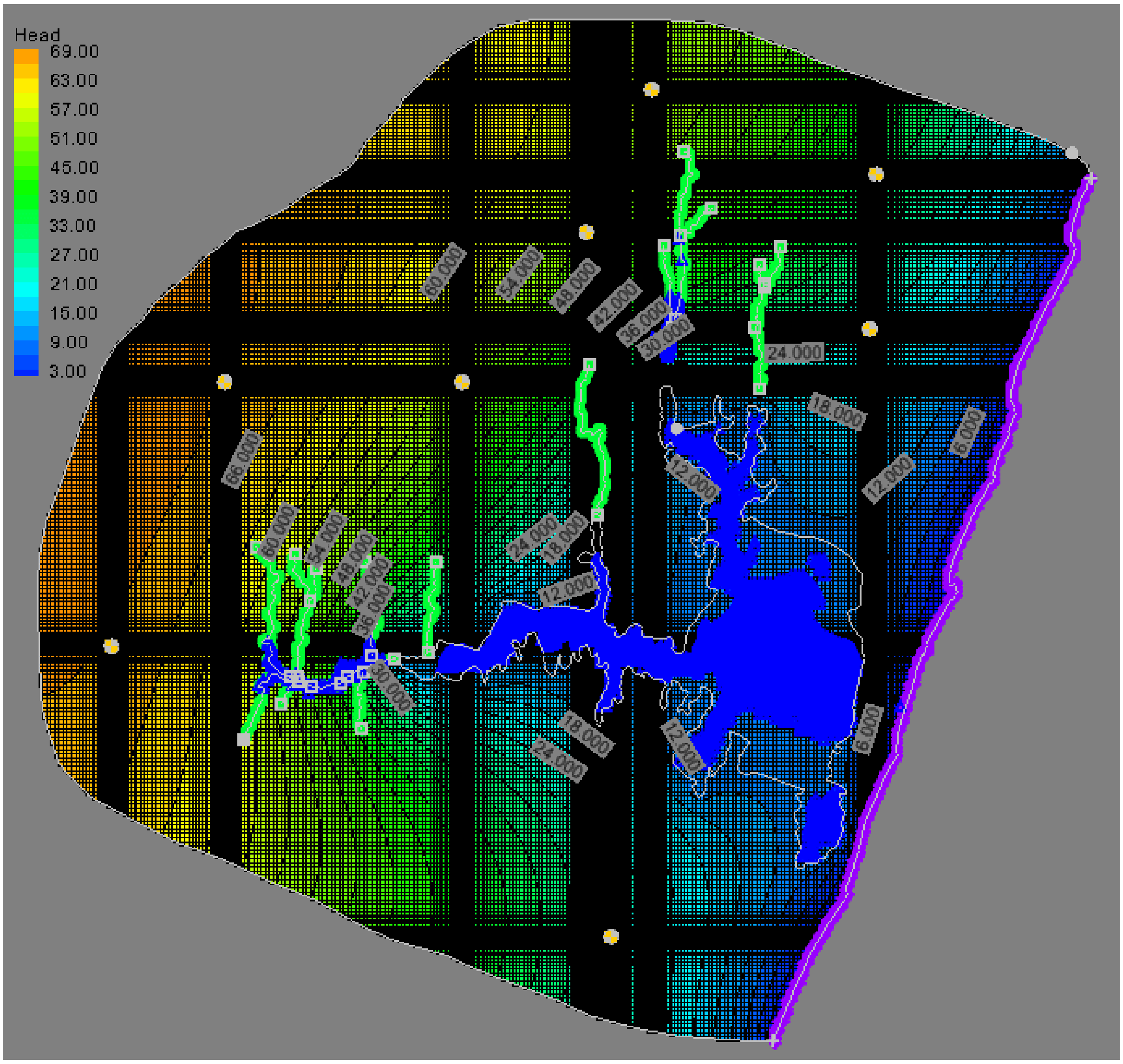

FIGURE 23. GROUNDWATER CONTOUR MAP AND LAKE EXTENT SIMULATED UNDER SCENARIO

Scenario 4

Scenario 2 was rerun under a changed climate by reducing the rainfall amount by 10% from the MAP, but keeping all the stresses same as scenario 1. The resultant groundwater level and lake extent map is shown in Figure 24. The Simulation result indicates an average groundwater and lake level decrease of 4.7 m and 5.3 m, respectively from scenario 1. This reduction in lake level is clearly shown on the lake extent in Figure 24.

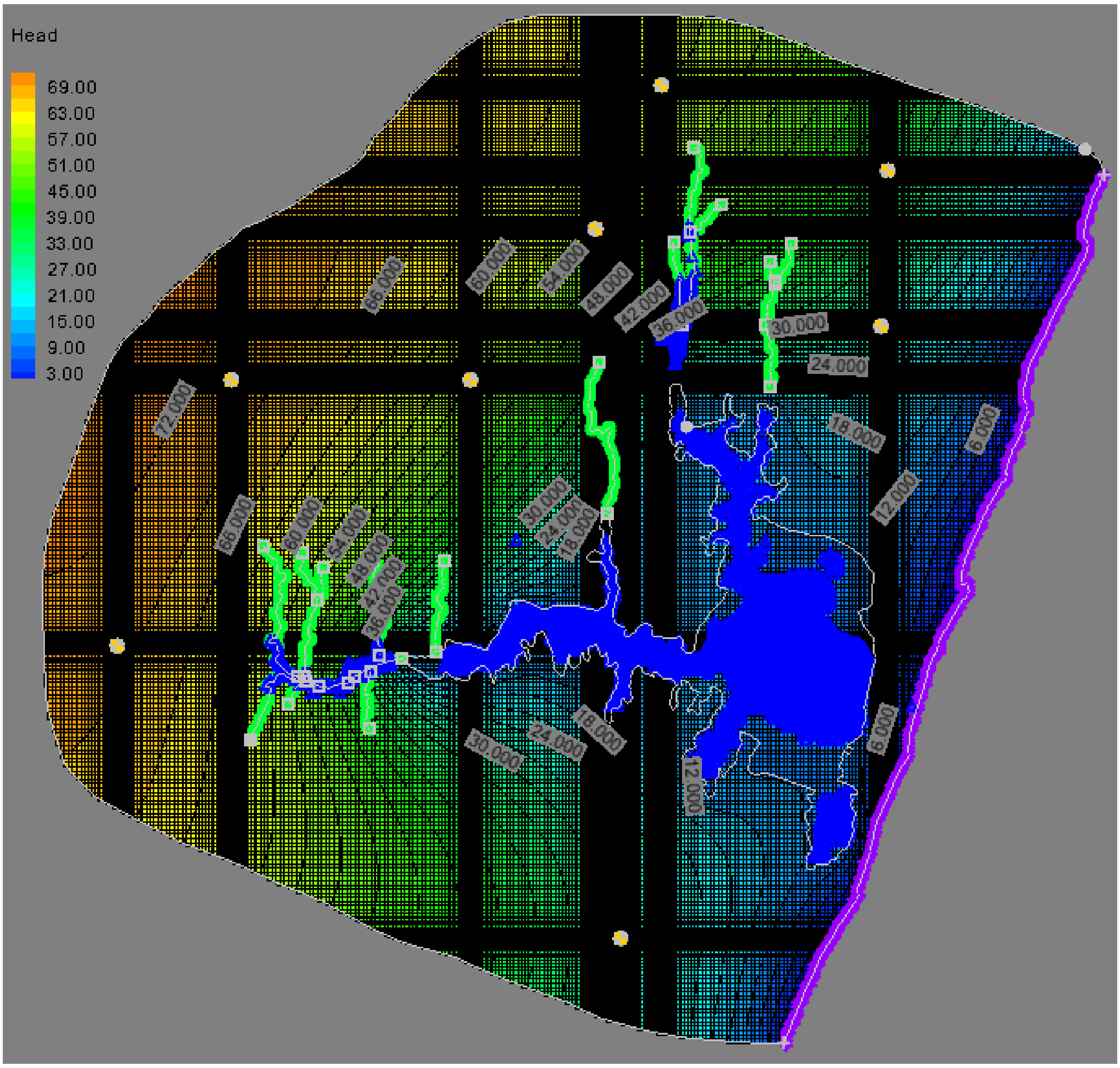

FIGURE 24. GROUNDWATER CONTOUR MAP AND LAKE EXTENT SIMULATED UNDER SCENARIO

Scenario 5

Scenario 1 was rerun under a changed climate scenario by increasing the rainfall amount by 10% from the MAP, but keeping all the stresses at the current state (scenario 1). The Simulation result indicates an average groundwater and lake level increase of 4.2 and 4.68 meters, respectively. As a result of the increase in groundwater level, a section of the far western side of the model domain has flooded cells creating some sort of lake/wetland.

Scenario 6

The last scenario was run by rerunning scenario 2 under a changed climate by increasing the rainfall amount by 10% from the MAP, but keeping all the stresses same as scenario 1. The Simulation result indicates an average groundwater and lake level increase of 4.16 and 4.6 meters, respectively from simulation results of scenario 2. As a result of the increase in groundwater level, a section of the far western side of the model domain has flooded cells creating some sort of lake/wetland.

Analysis of potential seawater intrusion as a result of reduced lake level.

By considering the simulation results of the worst case scenario, which is scenario 3 having an average lake level of 10.5 m amsl, a reverse particle tracking was undertaken from the coastline to inland. All flows are towards the ocean and seawater intrusion risk doesn't exist for all modelled scenarios including the worst case.

Model summary

Given the drought conditions that are affecting Southern Africa in general and the province of KwaZulu-Natal in particular, sustainable development of water resources, especially within the Lake Sibayi catchment is essential. A quasi-three-dimensional numerical groundwater flow model is calibrated using MODFLOW, with its various packages to understand the impact of land uses and climate change on groundwater and lake levels by running the calibrated model under various scenarios. The results show that removing the unlawful plantation increased the groundwater and lake levels by 1.4 meter and 1.2 meters on average, respectively (Table 20).

The sensitivity of the model to changes in hydrologic stresses that might occur due to potential climate changes was tested using the current plantation scenario. The result indicate that both groundwater level and lake stage changed substantially indicating that the system is very sensitive to climate forcing (i.e. changes in precipitation, evaporation and recharge rates). A reverse particle tracking was undertaken for the worst case model scenario results and no sea water intrusion was induced at a simulated lake level of about 10 meters.

TABLE 20. SUMMARY OF MODELED CHANGE IN GROUNDWATER AND LAKE LEVELS FOR VARIOUS SCENARIOS

Scenarios	Change in Groundwater level (m)	Change in Lake level (m)
1	-	-
2	1.4	1.2
3	-4.7	-5.38
4	-4.7	-5.3
5	4.2	4.68
6	4.16	4.6

4.3 Classification and Reserve for the Lake Kosi Bay Catchment

4.3.1 Location and catchment characteristics

The Kosi Bay Lakes Catchment covers the surface and groundwater catchments of the Kosi Bay Lakes system as shown in Figure 25. The area lies along the northern extreme part of the Zululand coastal plain of South Africa. The Kosi Bay Lakes system is an interconnected coastal lakes-wetland- estuary system composed of four main interconnected lakes. These lakes from north to south are called Makhawulani (Lake-1), Mpungwini (Lake-2), Nhlange (Lake-3) and Amanzimnyama (Lake-4). A broad channel (tidal flat) leading to an estuary opens to the Indian Ocean. Two smaller isolated Lakes located west and north of the main interconnected Lakes form part of the system.

The Kosi Bay Lakes System is located within the Usutu to Mhlathuze Water Management Area (WMA), specifically within the north-eastern corner of Quaternary catchment W70A. It is bounded in the west by the Pongola River drainage system, in the north by the Mozambique-South African Boundary, in the east by the Indian Ocean and in the south by the Lake Sibayi catchment. Due to the flat nature of the topography, highly porous Holocene cover sand, the numerous pans, swamps and marshes, the study area is characterised by an ill-defined drainage system.

Two perennial rivers, namely; the Gezisa and Sihadhla drain into Lake Amanzimnyama and Nhlange, respectively (Figure 24). The semi-perennial Ukhawe streams drains into the tidal flat from the northwest. The permeable nature of the cover sands, the relatively flat topography and shallow water table situations have resulted in a close relationship between surface waters (i.e. lakes, streams and wetlands) and the groundwater. This relationship is evident as the lake forms a surface expression of the groundwater (Meyer et al., 2001; Weitz and Demlie, 2014).

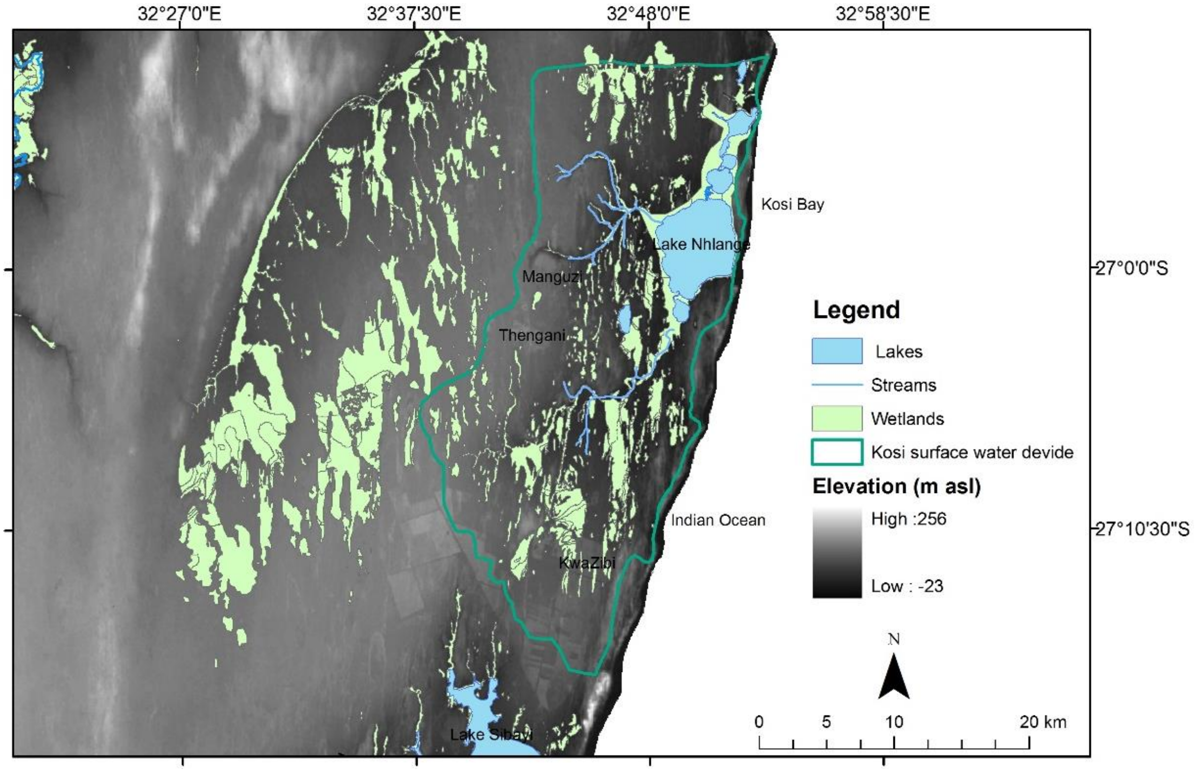

FIGURE 25. LOCATION AND DRAINAGE MAP OF THE KOSI BAY LAKES SYSTEM.

The main population centre within the study area is the town of Manguzi. The rest of the area are characterised by scattered rural population. The Kosi Bay Lakes system are the main water bodies that occupy the eastern section of the catchment, which is part of the iSimangaliso Wetland Park, an internationally significant wetland with RAMSAR convention listing (RAMSAR Site #528) (UNESCO, 1971).

The area is characterised by a chain of barrier lakes, lagoons and swamps, situated behind high vegetated dunes. The natural vegetation of the area consists of a mosaic of coastal thicket, Licuati sand forest, woodlands, woody edaphic grassland and patches of hygrophilous grassland, reed swamps and swamp forests (Matthews et al., 2001). Commercial plantations cover a substantial part of the southern Kosi Bay catchment (about 68 km^2) (Figure 26). The area is characterized by soil cover that is associated with the Maputaland Group dune sands including the dune cordon. Thus, the broad soil patterns can be described as deep, grey, structure-less and mainly non-calcareous sandy soils, which are excessively drained.

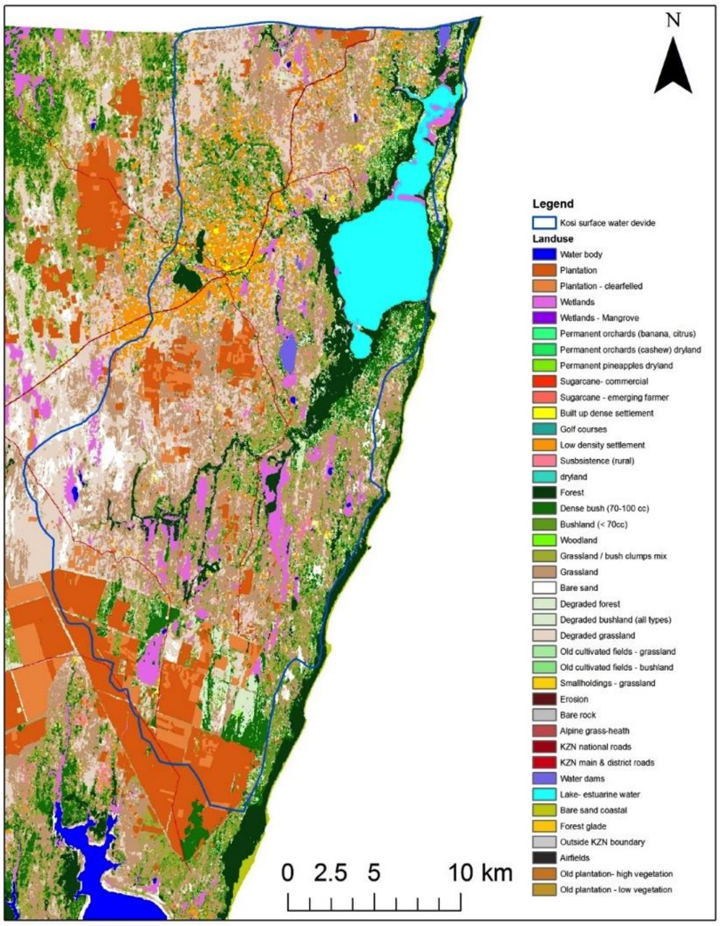

FIGURE 26. LAND USE AND LAND COVER MAP OF THE NORTH EASTERN KZN (MODIFIED FROM EZEMVELO KZN SPATIAL DATASETS, 2008).

4.3.2 Groudwater levels and groundwater flow directions

Groundwater levels measured within the Kosi Bay Lakes catchment during the course of this study were complimented with data from the Kwazulu-Natal Groundwater Resources Information Project (KZN-GRIP, 2013). These data (Figure 27) were used to construct a groundwater level contour map for the catchment (Figure 28). The results indicate that there appears to be a close relationship between water levels and surface topography and groundwater flows from west (along the western boundary of the lakes catchment) towards the Lakes. Because of the presence of numerous wetlands and pans, the regional flow pattern is somewhat distorted with flow lines directed towards the wetlands and pans and eventually to the lakes. Near the western catchment boundaries of the lakes, the groundwater elevation is around 70-80 m amsl (way above the stage of the Kosi Bay Lakes) from where it drops towards the coast to the altitude of the surface of the lakes. Groundwater levels and flow patterns are affected by the presence of the various wetlands and lakes

Based on the groundwater level map (Figure 28) and groundwater flow directions, the groundwater contributing area to the Kosi Bay Lakes has been delineated. It was observed that the surface water divide and groundwater divide don't coincide. The groundwater contributing area to Lakes is approximately 331 km^2 which is much lower than the 609 km^2 surface water catchment of the lakes.

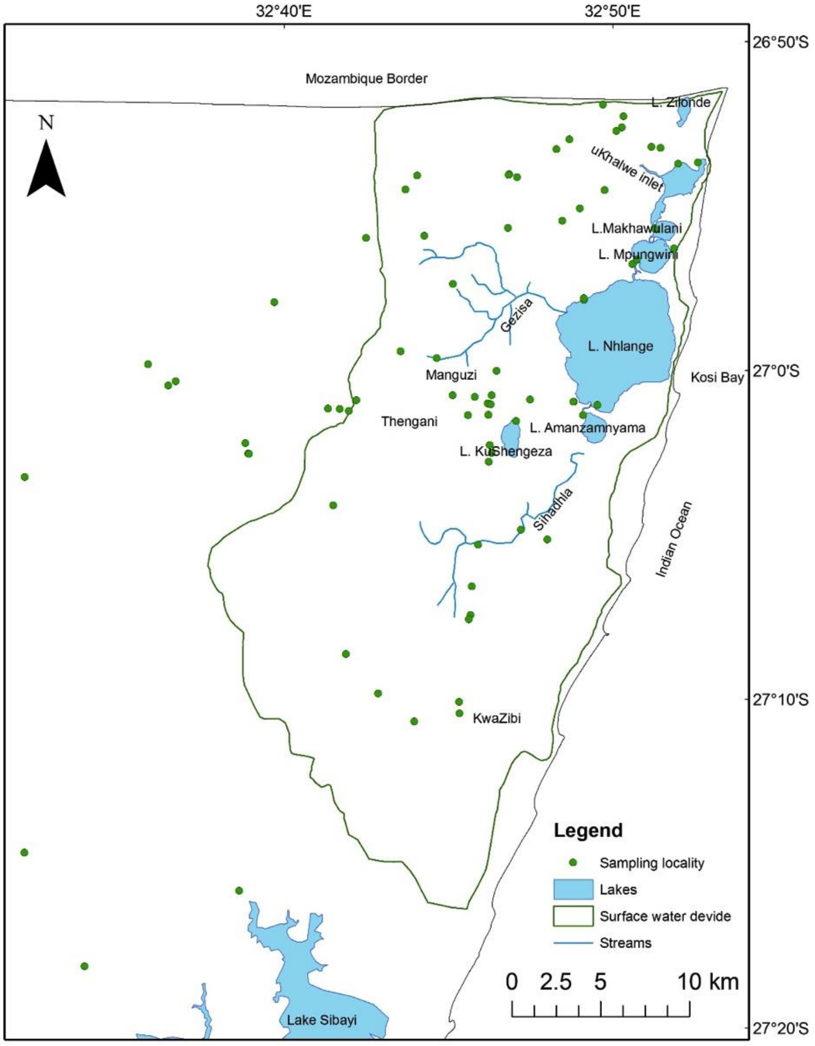

FIGURE 27. DISTRIBUTION OF BOREHOLES WHERE GROUNDWATER LEVELS WERE MEASURED.

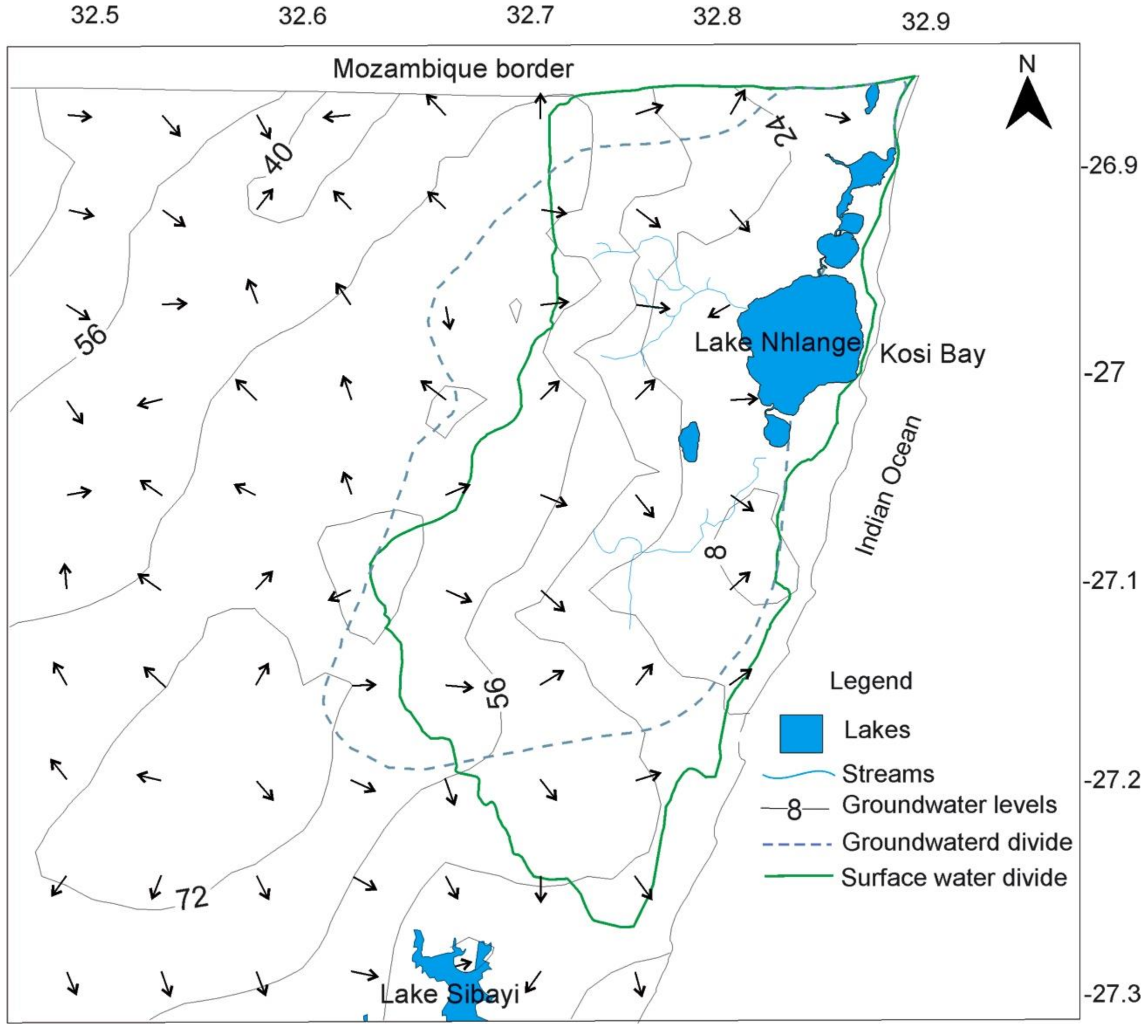

FIGURE 28. GROUNDWATER LEVEL CONTOUR MAP AND GROUNDWATER FLOW CONDITIONS FOR THE KOSI BAY CATCHMENT.

4.3.3 Groundwater recharge

Environmental isotope measurements within and around the study area show that the aquifers get recharged from rainfall. Most of this recharge is abstracted for various purposes and the remaining stored within the aquifers and discharges into the lakes, wetlands and to the sea.

For this study, the average chloride deposition measured from 1989-1992 at the Amanzengwenya and Phelindaba meteorological stations by Meyer *at al.,* (2001) were 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 (Figure 29). Isohyetal map (Figure 3) was constructed using a series of meteorological stations in KwaZulu-Natal and Mpumalanga to determine the rainfall at each of the points where groundwater chloride was determined. The result is 12% of the mean annual precipitation (MAP) or 112 mm/a.

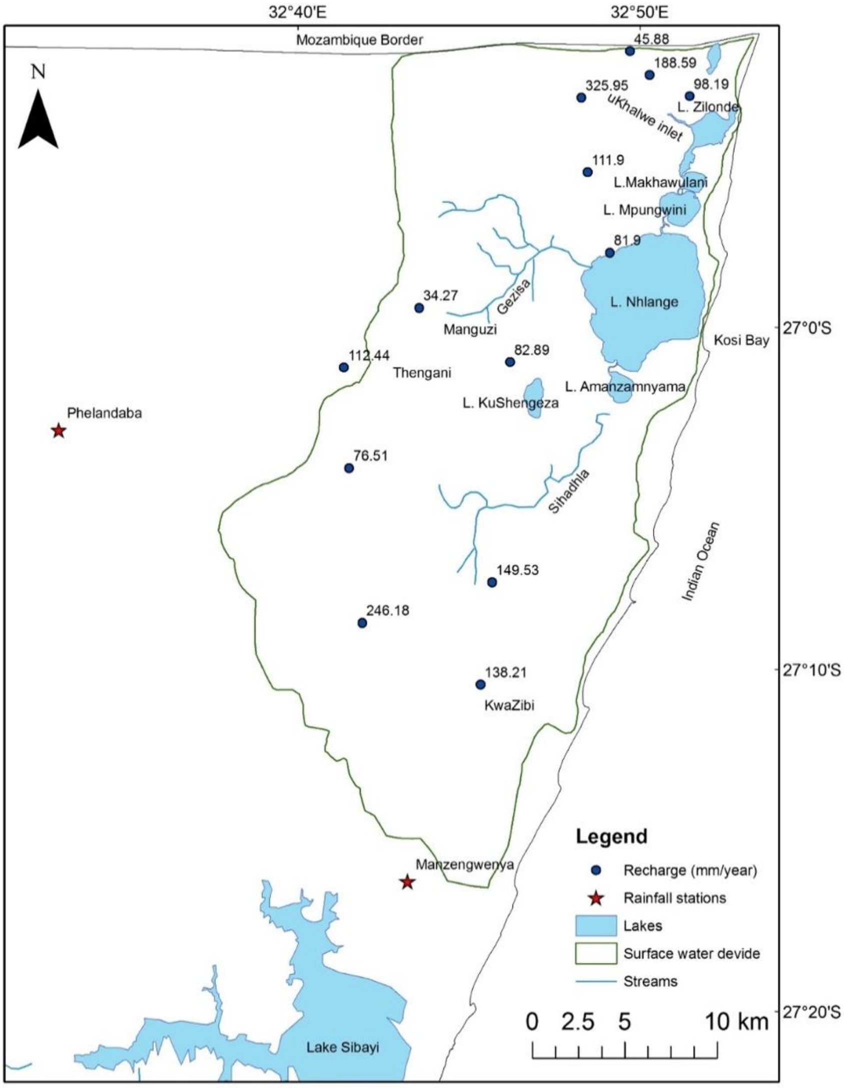

FIGURE 29. SPATIAL DISTRIBUTION OF GROUNDWATER RECHARGE WITHIN THE KOSI BAY CATCHMENT.

Based on this 12% recharge rate, average annual groundwater recharge volume for the Kosi Bay lakes catchment is 68.5×10^6 m^3/a.

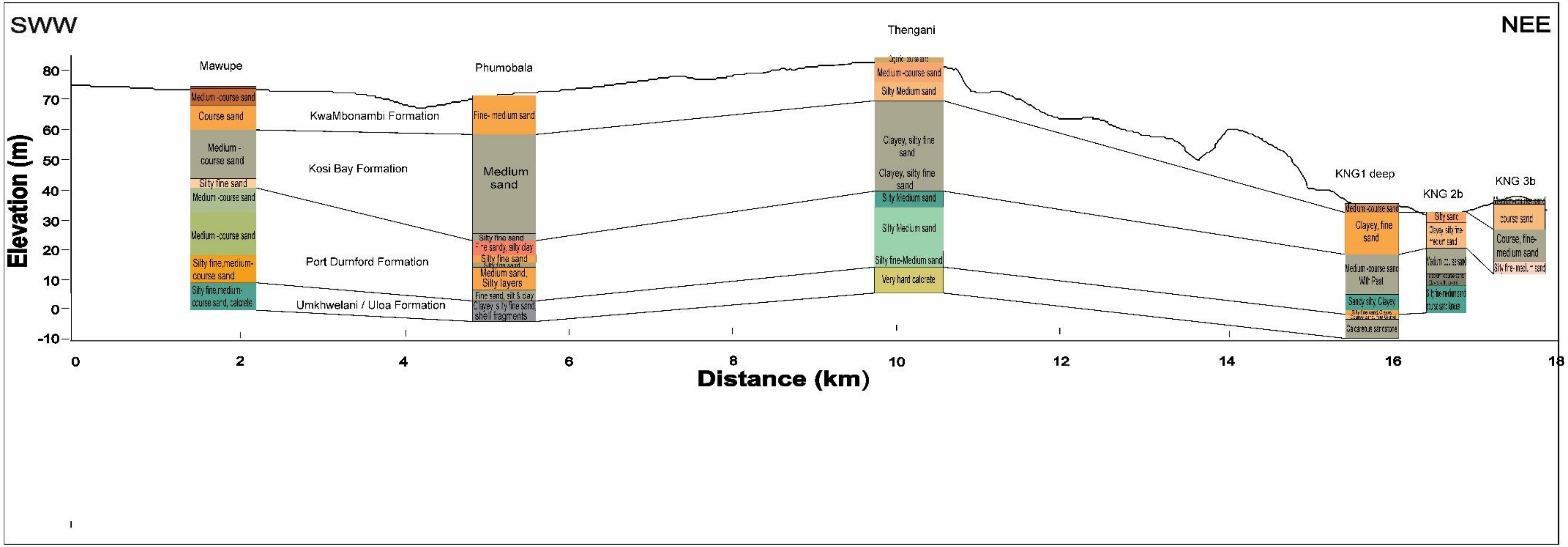

FIGURE 30. WELL TO WELL CROSS SECTION ACROSS THE KOSI BAY LAKES CATCHMENT SHOWING THE MAIN STRATIGRAPHIC UNITS.

4.3.4 Groundwater use, discharge and groundwater – surface water interactions

Groundwater in the area is discharged in the form of abstraction for domestic and agricultural use, natural evapotranspiration, forestry, natural outflow to the lake and ocean. Under no groundwater abstraction scenario from the system, the annual net groundwater recharge within the groundwater contributing area of the lakes and wetlands is expected to discharge to the lakes and wetlands. Groundwater flow directions and gradients (Figure 28) indicate that flow is towards the lakes and the Indian Ocean.

Groundwater use within the Kosi Bay catchment is limited to rural towns' water supply, small scale irrigation and water use by commercial forestry (Figure 31). The WARMS registered groundwater uses for the Kosi Bay catchment is 1645204 m^3/a, located mainly around the town of Manguzi. However, a brief hydrocensus undertaken in 2013 indicates many unregistered wells abstract groundwater mainly using shallow and intermediate depth wells. These wells are scattered throughout the region. Moreover, 546590 m^3/a WARMS registered abstraction take place from Lake Shengeza, and Gesiza stream and a total registered water use by forestry up until April, 2010 is about 6.5 x10^6 m^3/a. However, a minimum of 68 km^2 area of the catchment of the lakes is covered by commercial plantations which might use more than the registered groundwater use. The balance of the annual groundwater recharge that is left after groundwater abstraction is expected to be discharged into streams, wetlands, lakes and to the sea.

TABLE 21. GROUNDWATER USE BY VARIOUS SECTORS WITHIN THE KOSI BAY LAKES CATCHMENT

Groundwater use				
WARMS (Bores for domestic use) (Mm^3/a)	WARMS (only for Forest) (Mm^3/a)	Hydrocensus (estimated domestic use) (Mm^3/a)	Irrigation (Mm^3/a)	Total (Mm^3/a)
1.62	6.5	2.75	1	11.87

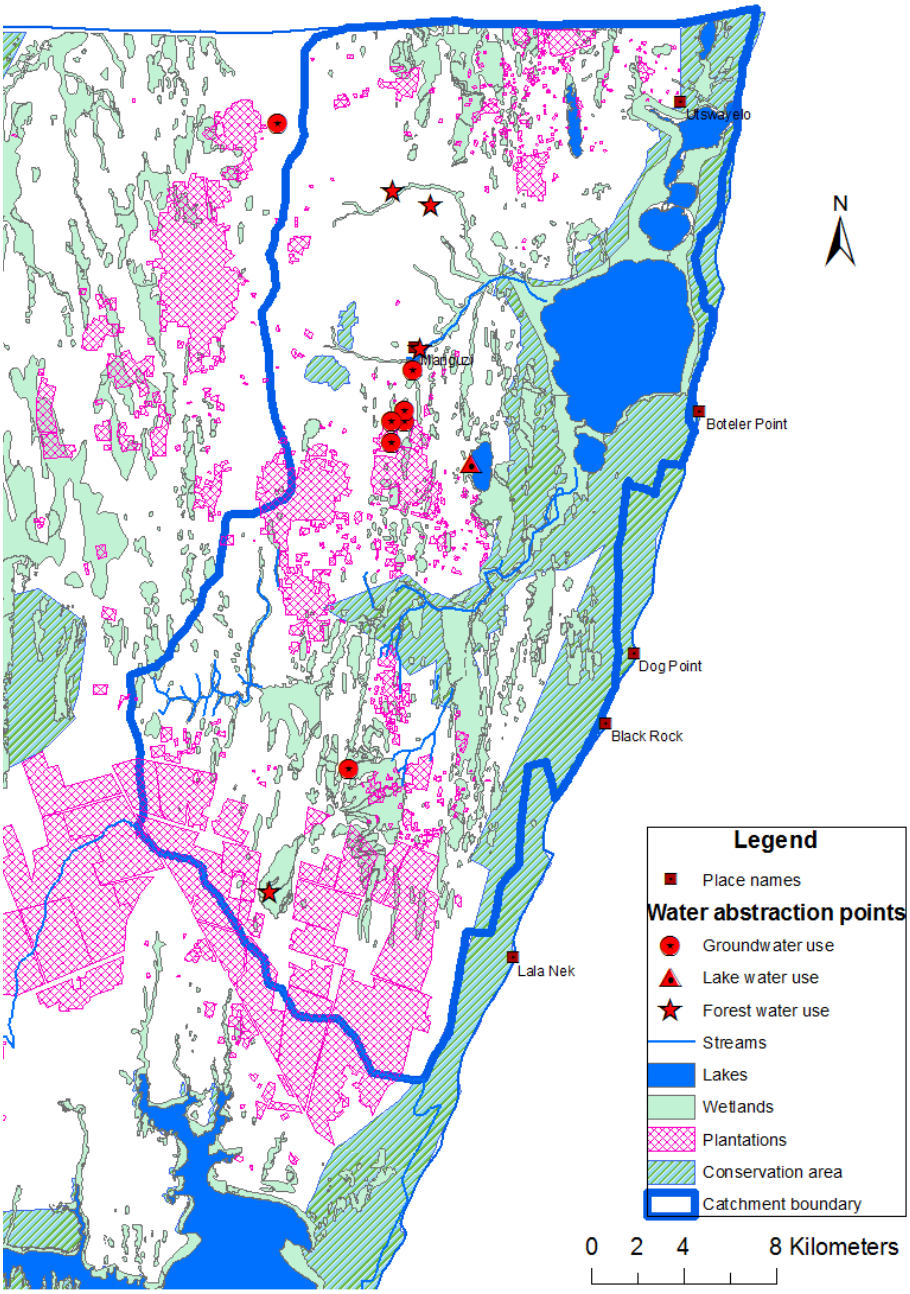

FIGURE 31. MAP SHOWING THE DISTRIBUTION OF REGISTERED WATER USE IN THE STUDY AREA.

It has been stated that shallow water level situations over most of the coastal plain results in the formation of numerous shallow lakes, pans and wetlands of different size throughout the area. These lakes, wetlands and pans are often the result of surface manifestation of the groundwater. The surface elevation of these lakes is merely a reflection of the local groundwater level. Isotopic and hydrochemical studies within the Lakes catchment indicated that not only lakes, pans and wetlands are groundwater fed, but streams sustain their flow from groundwater discharge (Figure 32). For instance the chemistry and stable isotopic composition of groundwater and Gezisa and Sihadhla streams (Figure 32) are similar indicating that its flow is supported from groundwater discharge. Groundwater contour map and associated flow direction indicates that the Lakes receive groundwater inflow from the western section where groundwater levels are above Lake stage and it losses water through groundwater to the coast in the eastern side of the lake where lake stage is higher than groundwater and sea levels.

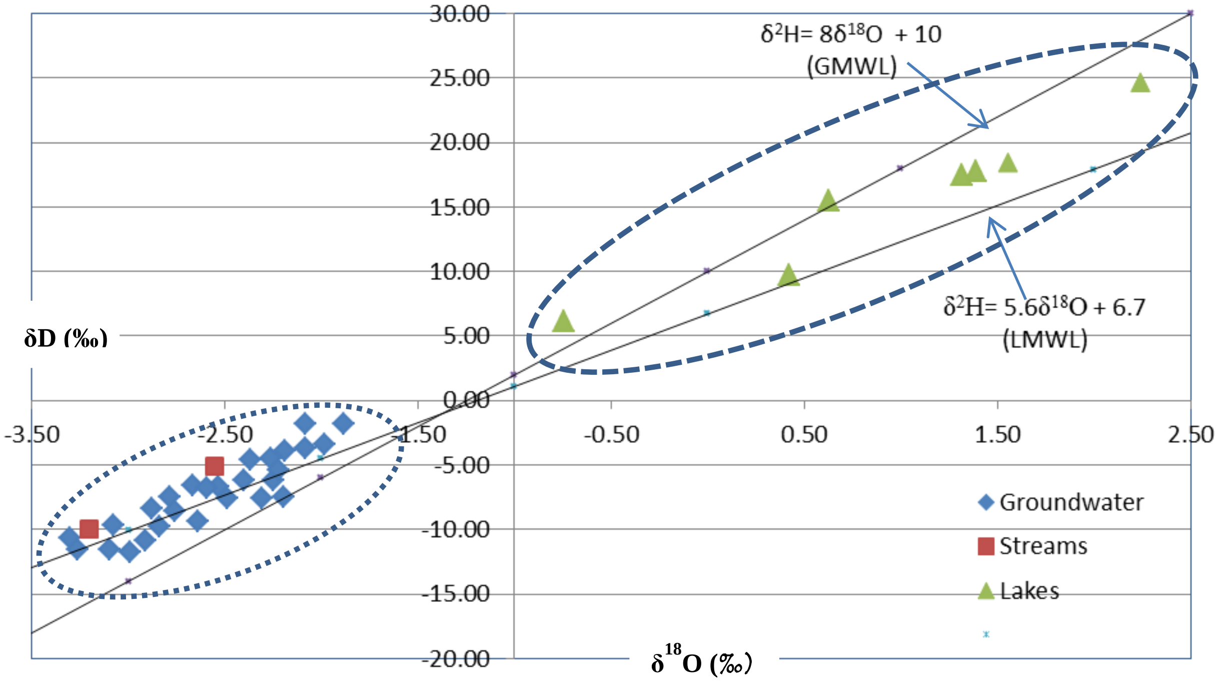

FIGURE 32. STABLE ISOTOPIC AND EC RELATIONSHIP BETWEEN GROUNDWATER, STREAMS AND LAKES INDICATING THEIR INTERACTION.

4.3.5 Water Balance for the Kosi Bay Lakes System

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 Kosi Bay Lakes system is a dynamic and open system where groundwater flows out through the dune cordon to the Indian Ocean. However, inflow and outflow through the Kosi mouth (estuary) is assumed to be same for the purpose of this study because of the following two reasons:

- During the 2013 field visit, the estuary was totally disconnected from the Ocean
- If an attempt is to be made to measure the flow through the estuary, monitored flow data is necessary but not available as yet.

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 about 42.6 km^2.

The overall conceptual water balance for the Lakes is given by the following equation:

$$\left[\left(\mathrm{PI} + \boldsymbol{R_{off}} + \boldsymbol{G_{in}}\right) - \left(\boldsymbol{E_0} + \boldsymbol{G_o} + \boldsymbol{Ws} + \boldsymbol{Wab}\right)\right] = \pm \boldsymbol{\Delta S}$$

Where:

P_l is precipitation on the surface of the lakes

R_{off} is surface runoff from the catchment to the lakes

G_{in} is groundwater inflow to the lakes

E_o is evaporation from the surface of the lakes

G_o is subsurface lake water outflow/seepage to the sea/Ocean.

W_{ab} is groundwater abstraction from the catchment

W_s is surface water abstraction from the catchment

ΔS is change in the storage of the lakes which will be reflected in the form of change in lake level.

All the inflow and outflow parameters used in the water balance analysis were either observed or estimated over a period from 1997-2015 and are tabulated as mean annual values.

***Precipitation* on the Lake s (P_l)**

The precipitation on the surface of the lakes is based on a long-term record from the Ingwavuma Kosi Bay and Ingwavuma Manguzi rainfall stations (SAWS, 2014) and the mean annual precipitation over the lakes is 937mm. The Kosi Bay lakes have total combined surface area of 42.6 km^2. The total amount of precipitation falling on the surface of the lakes is therefore 40*10^6 m^3/year.

Surface *runoff* to the Lakes (R_{off})

Since the streams that flow into the Lakes are not gauged and since not all surface water flow into the lake are channelized, the surface water runoff from the catchment to the lakes was estimated using the Runoff Curve Number (CN) method (USDA, 1986). This method is used 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 the main equation for the curve number method described by Woodward *et al.* (2002) for estimation of direct runoff from a rainfall event:

$$\boldsymbol{Q = \frac{(P - I_a)^2}{(P - I_a) + S}}$$

Where **Q** is the rate of runoff in mm, **P** is the average rainfall, **S** is the potential maximum retention in mm after runoff begins, and I_a is the initial abstraction in mm. The curve number method is described in detail among other in USDA (1986), Tripathi and Singh (1998), and Woodward *et al.* (2002). The runoff rate estimated for the Kosi Bay catchment is 5% of the precipitation. The total volume of runoff into the lakes is estimated at 33.5*10^6 m^3/year.

***Groundwater inflow* to the Lakes (G_{in})**

The western section of the lakes receives groundwater inflow from the catchment (Figure 26). Based on the groundwater contour map, the groundwater contributing area to the lakes (groundwater capture zone of the lakes) has been delineated. It is assumed that the net groundwater recharge within the groundwater contributing area enters the lake. This net groundwater recharge which discharges to the lakes is estimated from average recharge to the groundwater capture zone of the lake minus groundwater abstraction for domestic supply and evapotranspiration losses by commercial plantations (based on estimated evapotranspiration rates)) within the groundwater capture zone of the lakes. The total estimated annual groundwater recharge volume to the groundwater contributing area of the lakes is $37.3*10^6$ m^3. The total registered groundwater abstraction within the groundwater contributing area is $1.51*10^6$ m^3/year. However, more than 654 wells are captured in the KZN-GRIP data base having an average yield of 0.4 l/s. The estimated abstraction from these wells based on a 0.4l/s pumping rate pumped for 8 hrs/day is 7534 m^3/day or $2.75*10^6$ m^3/year. Moreover, 28.4 km^2 area of the capture zone of the lakes is covered by plantation with an estimated evapotranspiration rate of $15*10^6$ m^3/year. Taking these into consideration, the net groundwater inflow into the lakes is $18*10^6$ m^3/year.

Evaporation from the Surface of the Lakes (E_o)

Water loss from the lake through evaporation was calculated using the Penmann's equation (Penmann, 1948) from available meteorological data within and around the catchment. The equation combines the mass transfer and energy budget methods of evaporation estimation 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 the details of the step by step derivation of the equation and calculations are described in Shaw (1994):

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

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 incoming heat from the 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. The fourteen year average annual evaporation loss from the lake is estimated to be 1307mm. The total volume of water loss through evaporation from the lakes' surface is 56 $*10^6$ m^3/year.

Abstraction from Lake Shengaza

A total of 277400 m^3/year registered water is abstracted from Lake Shengeza for domestic use since 2008.

Lake *water outflow* (seepage) to the sea (G_{out})

Groundwater level contours and associated flow vectors, and data from the Sibayi catchment indicate that the Kosi Bay Lakes discharge groundwater through the dune cordon to the Indian Ocean. This seepage volume from lakes through the dune cordon (Groundwater outflow to the sea) is calculated using the following equation (Dupuit, 1863), assuming steady state conditions:

$$\boldsymbol{Q} = (\boldsymbol{Kxa}(\,\boldsymbol{h_0}^2 - \boldsymbol{h_1}^2))/\boldsymbol{2L}$$

where:

Q is the amount of ground water outflow to the sea
K is the hydraulic conductivity of the aquifer
a is the length of the seepage face
L is the length of the flow path (between the lakes and the coastline)
h_o - h_1 is the head difference between the mean lake stage and the sea surface above an impermeable cretaceous hydrogeologic basement unit.

This seepage rate was calculated using the following parameter values: **K** = 5 m/d, h_o = 70m calculated using the base of the aquifer (top of Cretaceous basement siltstone) as datum. h_1 = 50m, hydraulic head at the coastline calculated the same way as **h_o**. **L** is the horizontal distance between **h_o** and **h_1** and is about 1Km estimated using ArcGIS. The estimated seepage face along the coastline taken as straight line distance from the Kosi Bay mouth to Lake Amanzamnyama is 16 Km. The total seepage rate from the lake to the Indian Ocean is therefore, 96000 m^3/day or $35*10^6$ m^3/year.

The mean annual water balance components are summarized in Table 22. The water balance calculation gives nearly zero change in storage which is an indication of an equilibrium condition and makes the system very delicate.

TABLE 22. MEAN ANNUAL WATER BALANCE COMPONENTS FOR THE KOSI BAY LAKES (IN 10^6 M^3).

Precipitation on the lake	Surface runoff	Net groundwater inflow	Evaporation	Lake Abstraction	Seepage	±ΔS
40	33.5	18	56	0.3	35	0.2

This long term mean annual water balance of the lakes indicates that inputs are greater than that of the output parameters with a very small margin (positive ΔS). The water balance result appears to be supported by the long-term lake level records that show an increasing trend over time for the main lake (Lake Nhlange) (Figure 33). Moreover, the lake level fluctuation observed in Figure 32 appears to be controlled by precipitation inputs as it follows its trend.

Water Balance Scenarios

Six simple water balance scenarios were run for the Kosi Bay catchment so as to understand the impact of stresses on the Lake and groundwater systems. These scenarios are reference, current situation, lawful plantation use scenario and two more scenarios based on a changed climate scenario through 10% increase and decrease in rainfall. The current scenario (lawful and unlawful forestry) decreased the groundwater level by about four meters in seventeen years' time and removing the unlawful forestry improved the groundwater level by nearly 2 meters in seventeen years.

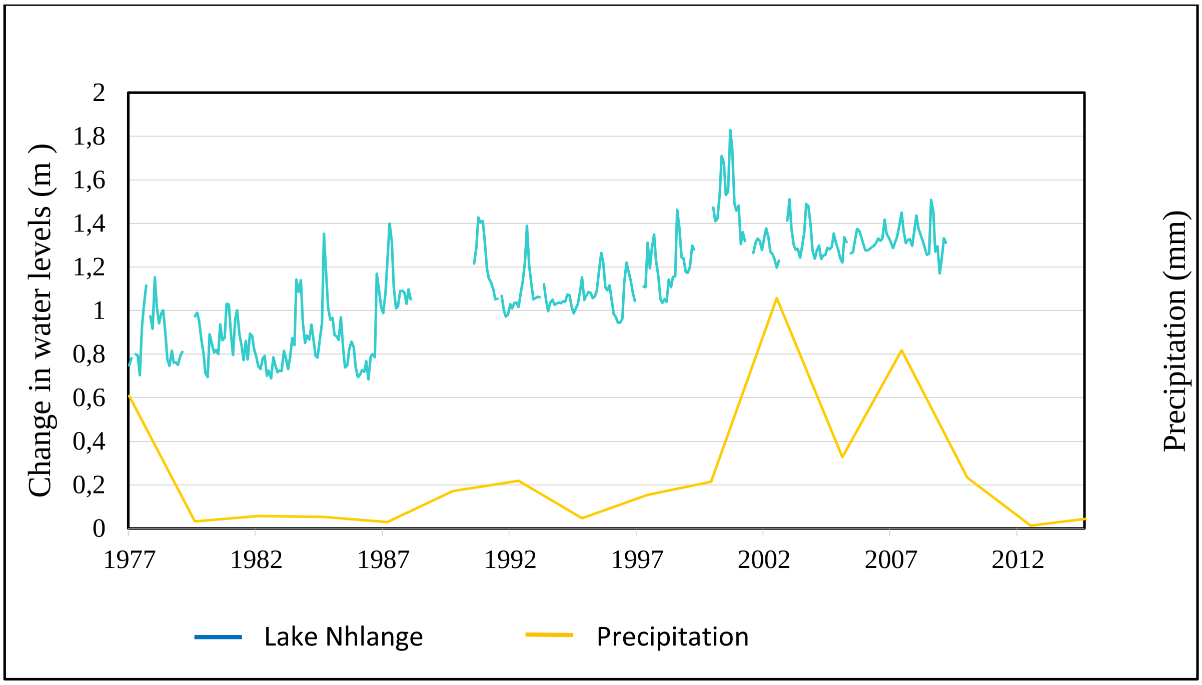

FIGURE 33. LONG TERM LAKE LEVEL CHANGES AT LAKE NHLANGE WITH MONTHLY PRECIPITATION FROM 1977- 2014 (LAKE LEVEL DATA FROM DWS AND PRECIPITATION DATA FROM SAWS, 2014).

4.3.6 Wetland Capture Zone Delineation for the Kosi Bay Lakes System

Wetlands are shallow ‘surface water’ bodies which are either permanently or seasonally wet and have been classified based on geometries (basin wetlands such as lakes, linear wetlands such as rivers and drains, and flat wetlands such as floodplains) and based on groundwater as discharge, recharge and flow-through wetlands (Davies et al., 2000). Wetlands may receive inflow from either surface water, groundwater or from both.

A surface water or topographic catchment or capture zone of a wetland comprises the areas that drain surface water and nutrients into the wetland and can be readily delineated based on conventional methods by referencing to contour maps and using digital elevation models. All wetlands have a surface water capture zone.

Groundwater capture zone of a wetland is the geographic extent of the land area from which recharge is discharged to the wetland. Only wetlands that are in direct hydraulic connection to a shallow unconfined aquifer have groundwater capture zone. It has been understood that the Kosi Bay wetlands are both surface water and groundwater driven.

There are several methods that can be used to delineate capture zone for wetlands, depending on the requirements of the user, and the limitations in hydrological data and the available resources. The main methods of capture zone delineation that has been described in US EPA (1987, 1994), Davies et al. (2000) and Townley and Trefry (2000) are Hydrogeological mapping, arbitrary geometric methods, analytical methods and numerical groundwater flow modelling methods. The capture zone of the Kosi Bay wetlands was delineated following the hydrogeological capture zone delineation method described in US-EPA (1987, 1994) because of data limitation. The method is based on available hydrogeological information and hence does have some level of certainty at the scale of the delineation. The method uses the surface water catchment, geological maps, and groundwater contributing areas generated from groundwater level measurements.

The area generally has a flat topography, with depression in between sand dunes where the main water table occurs very close to the surface, hence the distribution of the wetlands. Figure 8 and 28 shows that there is a groundwater divide between the Kosi Bay wetlands and those that lie to the west. The capture zone of the Kosi Bay wetland has an area of about 649 km^2 (Figure 34).

Since the main purpose of wetland capture zone delineation is to protect its ecological integrity, the capture zone delineated at a coarse scale and a more detailed and zoomed-in capture zone through community participation is recommended.

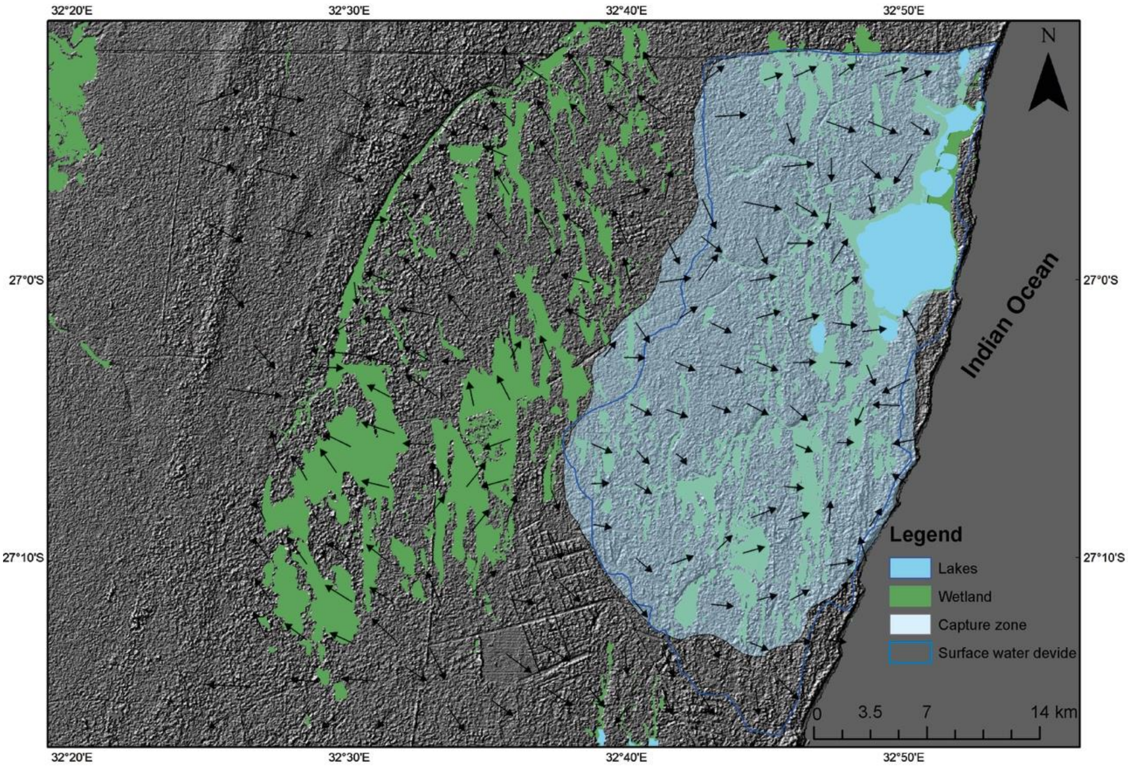

FIGURE 34. CAPTURE ZONE DELINEATED USING THE HYDROGEOLOGICAL MAPPING METHOD OF WETLANDS.

4.3.7 Delineated Capture zone and Water Balance for the Wetland area west of the Kosi Bay Lakes catchment

Hydrogeological capture zone delineation and an estimate of the water balance of the wetland located west of the Kosi Bay Lakes catchment have been undertaken. The western wetland system has similar hydrogeological setting to that of the Kosi Bay Lakes catchment except the fact that several lakes exist within the Kosi Bay Lakes catchment. As a result, the rate of precipitation, runoff characteristics, recharge rate, reference evapotranspiration rates for the western wetland are assumed to be the same as that of the Kosi Bay Lakes System.

Capture zone

Groundwater capture zone has been defined commonly as the total source area that contributes groundwater to a hydrogeological feature such as well or well fields, spring or groundwater-fed lakes and wetlands. The capture zone of the wetlands was delineated following the hydrogeological capture zone delineation method described in US- EPA (1987, 1994). The total capture zone area (Figure 35) of the wetland is 893 Km^2. The groundwater with this capture zone flows towards an approximately south-north striking line which is assumed to be the old flood plain of the Pongola River (Figure 35). The capture zone starts at the northwest boundary of the groundwater capture zone of the lake Sibayi system and continues into Mozambique to the north.

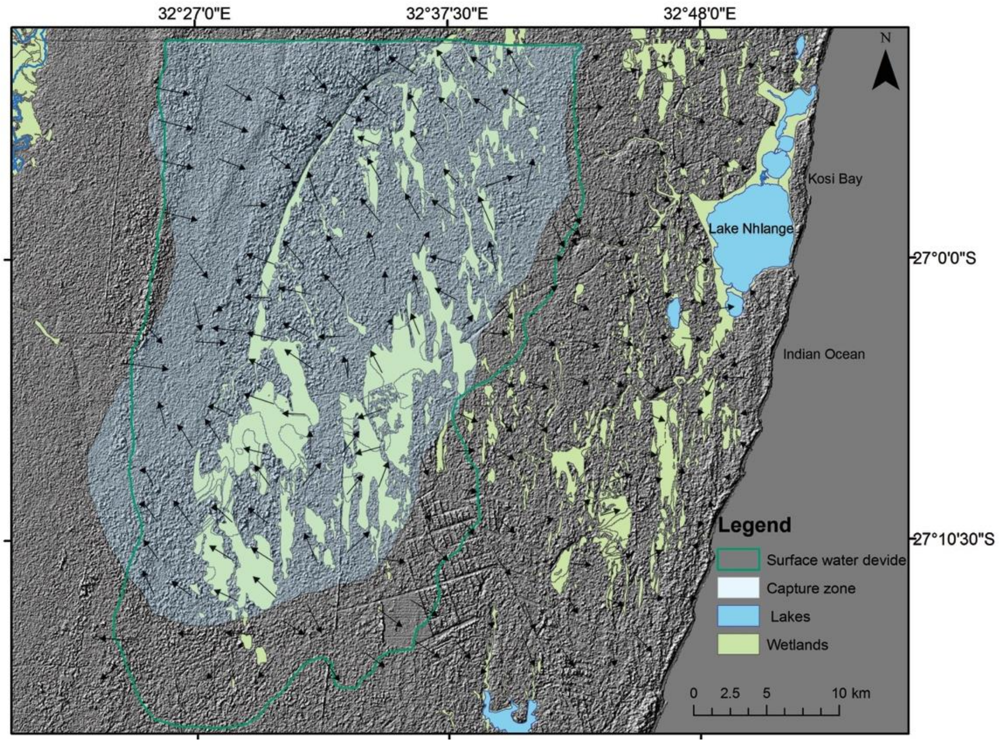

FIGURE 35. CAPTURE ZONE DELINEATED USING THE HYDROGEOLOGICAL METHOD FOR THE WETLAND LOCATED WEST OF THE KOSI BAY SYSTEM.

Simplified **Water Balance analysis for the Wetland area west of the Kosi Bay Lakes *catchment***

A simplified water balance analysis was undertaken for the delineated wetlands capture zone (893 Km^2 in area). The surface drainage of the wetland is estimated at 1128 Km^2. Like the groundwater flow direction, the surface water flows to the north towards Mozambique through interconnected wetlands and hence it is an open system, unlike the Sibayi and the Kosi Bay drainage systems. The simplified water balance for the wetlands is given by:

$$\mathbf{R_{gw} + SR_{off} - E_t - G_{ab} = \pm\Delta S}$$

Where $\mathbf{R_{gw}}$ is groundwater recharge from precipitation within the groundwater capture zone, $\mathbf{E_{tc}}$ is evapotranspiration from the wetland area, $\mathbf{G_{ab}}$ is groundwater abstraction through wells and plantations within the groundwater capture zone area, $\mathbf{SR_{off}}$ is surface water runoff which is very small and $\Delta\mathbf{S}$ is a residual of the water balance that includes any groundwater outflow to the north depending on prevailing hydraulic gradient (dependent on variations in the hydraulic head/or variations of groundwater level which eventually translates into the change in the extent of the wetlands) and surface water outflow to the north depending on water level in the wetlands.

It is assumed here that the wetlands are mainly groundwater dependent and a decline in the groundwater level leads to a decline in the extent of these groundwater dependent wetlands. Moreover, occasional storms increase the water level in the wetlands and generate surface water drainage to the north. Since the rate of precipitation decreases inland, the annual precipitation over the western wetlands is estimated from the isohyetal map (Figure 3) about 800 mm/year of which about 13% goes to recharge the groundwater.

The rate of runoff, if any, is very low and estimated to be between 1 and 2% of the precipitation and flows towards the wetlands and under extremely stormy events flows toward the north. The rate of evapotranspiration (**E_{tc})** from the wetland surfaces is assumed to proceed at the potential rate and is estimated at 1433 mm/year using the FAO Penmann-Monteith approach (Allen et al., 1998). This evapotranspiration rate is greater than the rate of precipitation, indicating that these wetlands are indeed groundwater dependent. This implies that the wetlands are sustained by groundwater inflow throughout the year and a bit of surface runoff during the wet season. About 32 Km^2 area of the capture zone of the wetlands is covered by plantation (Figures 31). The estimated evapotranspiration rate from these plantations is about 1060 mm/year.

The total estimated groundwater abstraction for various purposes based on 654 wells scattered within the wetland capture zone (KZN-GRIP data) which have an estimated average borehole discharge rate of 0.4 l/s (average borehole yield) pumped on average 8 hrs/day is 7534 m^3/day or 2.75*10^6 m^3/year. The overall estimated water balance is presented in Table 23 The water balance analysis gives a residual of about 12 million cubic meters of water per year which is assumed to discharge northwards both as groundwater and surface water discharge. However, it is important to note that all uncertainties (estimation error) in the water balance estimate is accumulated in this change in storage term.

TABLE 23. ANNUAL WATER BALANCE FOR THE WESTERN WETLANDS (10^6 M^3/A)

Surface water capture area (Km^2)	Groundwater Capture zone area (Km^2)	Plantation area (Km^2)	P (mm/year	R_{gw}	SR_{of}	E_{tc}	G_{ab}	±ΔS
1128	893	32	800	86	9	46	37	12

4.3.8 Water Quality

Groundwater and surface water quality analyses for the Kosi Bay catchments are presented in Figure 36. These samples were taken from the shallow (KwaMbonambi /Sibayi) and the deeper (Uloa) aquifer systems. The groundwater samples taken from the Kosi Bay catchments are characterized by low EC and low concentration of major ions. The groundwater quality data were compared to DWAF’s (1996) water quality class. The comparison indicated that the water conforms in almost all instances (more than 95% of the chemical parameters) to the “ideal water quality” category of DWAF. The highly saline Kosi Bay lakes and estuary samples plot at the end of an evolutionary trend of groundwater and stream samples. Except Lake Amanzimnyama, three of the Kosi bay lakes are saline. The Kosi Bay lakes have a salinity series that ranges from 102.4 mS/m for Lake Amanzimnyama, 482.9 mS/m for Lake Nhlange, 2167 mS/m for Lake Mpungwini, to 2460 mS/m for Lake Makhawulani, from south to north, respectively. The estuary had 1770 mS/m during the time of measurement (from 04 to 05 May 2013) indicating inflow of freshwater from surface and groundwater sources.

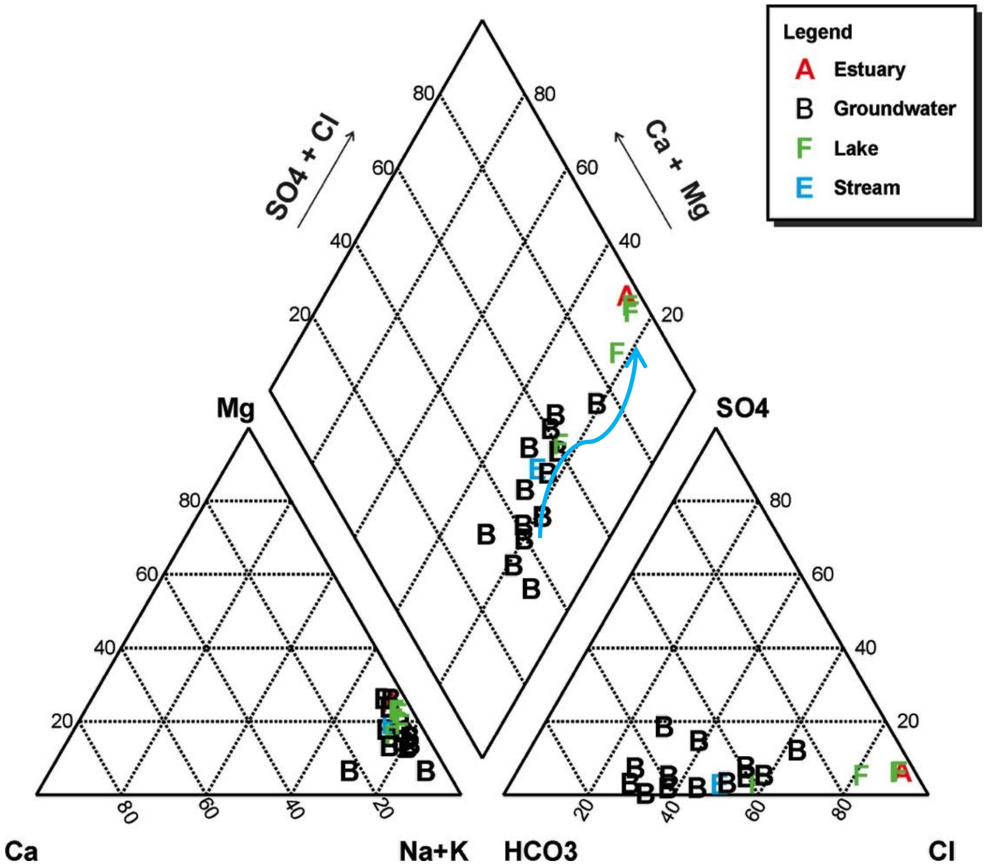

FIGURE 36. PIPER PLOT OF GROUNDWATER MAJOR ION CHEMISTRY DATA FOR THE KOSI BAY LAKES SYSTEM.

Tables 24 and Table 25 gives the water quality information for groundwater and surface water, respectively. Most of the water quality parameters for the Kosi Lakes are either within DWAF's "Marginal, Poor or unacceptable" water quality classes except Lake Amanzimnyama. All Lakes except Amanzimnyama are saline due to their interaction with the estuary. The poor water quality in these lakes is a natural process and is not related to anthropogenic pollution or stresses.

TABLE 24. GROUNDWATER QUALITY DATA FROM BOREHOLES WITHIN THE LAKE KOSI BAY CATCHMENT

Determinant	Unit	Borehole number										DWAF Water Quality Class				
		KB1	KB4	KB10	KB11	KB13	KB15	KB32	KB36	KB44	KB45	0	I	II	III	IV
												Ideal	Good	Marginal	Poor	Unacceptable
K	mg/l	0.64	0.36	8.56	4.62	0.05	0.74	0.92	0.89	0.87	0.28	<25	25-50	50-100	100-500	>500
Na	mg/l	13.8	17.49	56.17	54.37	21.35	21.92	17.05	15.5	14.6	20.8	<100	100-200	200-400	400-1000	>1000
Ca	mg/l	0.64	0.88	6.13	4.38	0.98	1.06	1.08	0.91	0.91	0.88	0-80	80-150	150-300	>300	ns
Mg	mg/l	1.44	1.55	7.69	7.79	0.82	2.98	1.45	2	79	3.01	0-70	70-100	100-200	200-400	>400
SO_4	mg/l	6.26	17.66	7.93	10.21	10.02	6.55	0.4	7.52	13.57	2.64	<200	200-400	400-600	600-1000	>1000
Cl	mg/l	32.5	2.49	141.5	137.3	28.8	56	36	39.3	0.09	42.8	<100	100-200	200-600	600-1200	>1200
Alkalinity	mg/l	36	12.8	57.3	44.4	23.2	14	24.4	9.8	11	23.2					
NO3-N	mg/l	0.04	2.86	8.56	1.02	0.47	0.36	0.04	0.41	0.6	0.37	<6	5¯10	10¯20	20-40	>40

Determinant	Unit	Borehole number										DWAF Water Quality Class				
		KB1	KB4	KB10	KB11	KB13	KB15	KB32	KB36	KB44	KB45	0	I	II	III	IV
												Ideal	Good	Marginal	Poor	Unacceptable
F	mg/l	0.03	0.03		0.06	0.03	0.02	0.01	0.03		0.02	<0.7	0.7-1.0	1.0-1.5	1.5-3.5	>3.5
Si	mg/l	1.8	2.7	9.9	6.9	3.6	2.8	2.7	2.9	2.5	3.2					
Fe	mg/l	0.1	0.09	0.03	0.16	0.73	1.73	0.33	0.04	0.09	0.17	<0.5	0.5-1.0	1.0-5.0	5¯10	>10
Mn	mg/l	0.01	0.008	0.23	0.03	0.006	0.04	0.02	0.01	0.03	0.004	<0.1	0.1-0.4	0.4-1.0	1.0-5	>5
EC	mS/m	8.6	10.2	37.4	34.1	11.2	14.9	11.1	12.2	11.4	13.2	0-70	70-150	150-370	370-520	>520
PH		5.7	5.83	6.76	7.2	5.7	5.8	5.6	5.12	5.85	5.95	6.0-9	5.0-9.0	4-100	3.5-10.5	<3.5 or >10.5

TABLE 25. LAKE KOSI BAY WATER QUALITY DATA

Determinant		Lake Sample ID					**DWAF Water Quality Class**				
		KB17	KB8	KB7	KB5	KB2	**0**	**I**	**II**	**III**	**IV**
	Unit	Amanzamnyama	Nhlange	Mpungwini	Makhawulani	Estuary	**Ideal**	**Good**	**Marginal**	**Poor**	**Unacceptable**
K	mg/l	7.04	32.45	149.94	173.42	147.05	<25	25-50	50-100	100-500	>500

Determinant		Lake Sample ID					**DWAF Water Quality Class**				
		KB17	KB8	KB7	KB5	KB2	**0**	**I**	**II**	**III**	**IV**
	Unit	Amanzamnyama	Nhlange	Mpungwini	Makhawulani	Estuary	**Ideal**	**Good**	**Marginal**	**Poor**	**Unacceptable**
Na	mg/l	165.3	830.9	4149.5	8443.3	4095.6	<100	100-200	200-400	400-1000	>1000
Ca	mg/l	14.94	36.9	152.9	194	173.8	0-80	80-150	150-300	>300	ns
Mg	mg/l	18.8	111	658	814	774	0-70	70-100	100-200	200-400	>400
SO_4	mg/l	31.9	204.6	11.28	1302	1154	<200	200-400	400-600	600-1000	>1000
Cl	mg/l	432	2378	12272	14084	12448	<100	100-200	200-600	600-1200	>1200
NO3-N	mg/l	0.93	1.43				<6	6¯10	10¯20	20-40	>40
F	mg/l	0.07	0.18	0.84	0.65	0.81	<0.7	0.7-1.0	1.0-1.5	1.5-3.5	>3.5
Fe	mg/l	0.24	0.2	1.44	2.05	1.82	<0.5	0.5-1.0	1.0-5.0	5¯¯10	>10
Mn	mg/l	0.001	0.005	0.007	0.005	0.02	<0.1	0.1-0.4	0.4-1.0	1.0-5	>5
EC	mS/m	102.4	482.9	2167	2460	4951	0-70	70-150	150-370	370-520	>520
pH		7.7	8.6	7.69	8.41	7	6.0-9.0	5.0-9.0	4.0-10.0	3.5-10.5	<3.5 or >10.5

Groundwater recharge: Groundwater recharge estimated for the Kosi Bay catchment is presented in section 4.3.3. The groundwater contributing area to the Lake's catchment differs from the Lake's surface water catchment area. Table 26 gives the volume of annual groundwater recharge to the Kosi Bay lakes surface water and groundwater catchments.

TABLE 26. GROUNDWATER RECHARGE INFORMATION FOR THE CATCHMENT

Mean annual recharge (MAR)	Surface water Catchment area excluding the lake	Groundwater contributing area excluding the lake (estimated)	Recharge volume within the surface water catchment	Recharge volume within the groundwater contributing area of the catchment
112 mm	609 Km^2	331 Km^2	68.2 Mm^3/a	37.07 Mm^3/a

Basic human needs (BNHs): The basic human need from groundwater is calculated based on the 2011 census population data for the Umhlabuyalingana Municipality. According to Census 2011, the Municipality has a population of 156736 and a pulsation growth rate of 0.9%. Assuming that half of this population lives within the Lake Kosi Bay catchment and depends on groundwater for their supply. Note that the town of Manguzi is highly dependent on groundwater. The basic human needs based on 0.9% population growth scenario is given in Table 27. Based on this growth scenario and taking 25 l/day/person water use, the total annual basic human needs is 876000 m^3/a.

TABLE 27. POPULATION DATA FOR THE MAIN POPULATION CENTRES IN THE CATCHMENT

Towns	2011 Census population	2040 projected Population
Manguzi and the areas around it	78368	96000
BHN (Mm^3/a)	0.72	0.88

Groundwater contribution to baseflow (EWR): No stream flow data is available for the small number of streams that drain into Lake Kosi Bay. Recent high level groundwater reserve assessment undertaken by Dennis et al. (2009) for the quaternary catchment W70A used the Pitman model among a suit of methods to estimate the groundwater contribution. Estimated groundwater contribution to baseflow for the catchment using various methods are given in Table 28.

TABLE 28. GROUNDWATER CONTRIBUTION TO BASEFLOW (MODIFIED FROM DENNIS ET AL., 2009). NOTE THAT THE VALUES ARE NORMALIZED BY AREA.

Groundwater contribution to baseflow							
GRDM Mm3/a	Hughes Mm3/a	Shultz Mm3/a	Pitman Mm3/a	vTonder Mm3/a	Min Mm3/a	Max Mm3/a	Herold Mm3/a
122.97	11.73	8.5	13.6	12.3	8.5	47.49	13.55

Water balance analysis for the Kosi Bay lakes catchment indicated a net groundwater flow of 18x10^6 m^3/a. This value is used as the Groundwater contribution to baseflow which eventually reaches the lakes.

Groundwater use: Groundwater use within the Lake Kosi Bay catchment is presented in Table 29 below.

TABLE 29. GROUNDWATER USE BY VARIOUS SECTORS

Groundwater use					
WARMS (Bores for domestic use) (Mm^3/a)	WARMS (only for Forest) (Mm^3/a)	Estimated Forest use based on forest area (Mm^3/a)	Hydrocensus (estimated domestic use) (Mm^3/a)	Irrigation (Mm3/a)	Total (Mm^3/a)
1.62	6.5	**15**	2.8	1	20.4

Groundwater quality: The groundwater quality within the Lake Kosi Bay catchment has been described in section 4.3.6 and presented in Table 20. The overall quality of groundwater within the catchment is within the DWAF's "Ideal" water quality class. Only few parameters fall within class I or "good" water quality class

4.3.9 Resource category

The present status category (PSC) is determined as based on at least the following three factors (Dennis et al., 2012):

- Based on observed environmental impact indicators
- Based on the level of stress of the groundwater units Index and
- Based on DWA water quality guideline for domestic use.

Few monitored groundwater level data around the Kosi Bay catchment indicates a decline in groundwater levels (Figure 37). However there is not groundwater level monitoring record within the Lake Kosi Bay catchment. Assuming that similar trend exists within the catchment, the groundwater is moderate used **(II) or B** (Localized low level impacts, but no negative effects apparent).

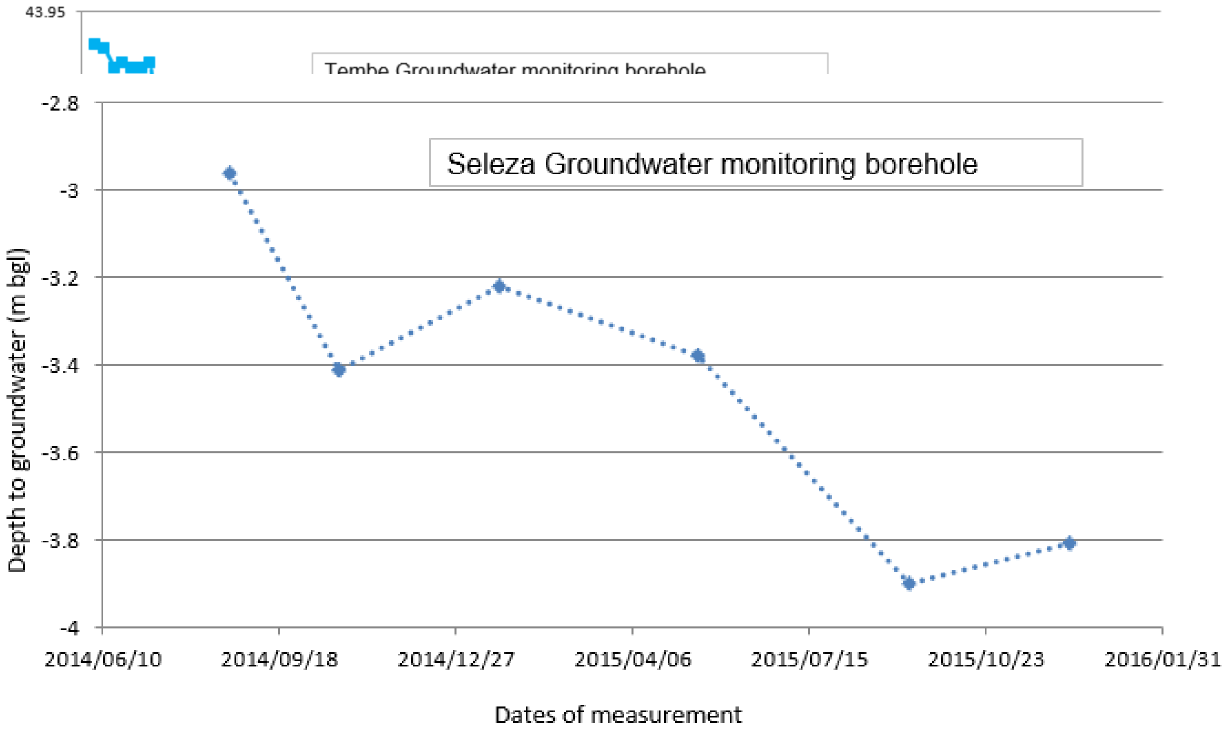

FIGURE 37. GROUNDWATER LEVEL DECLINE AROUND THE KOSI BAY CATCHMENT

Groundwater stress index: Stress index is a quantitative way of defining stress and can be calculated using the following abstraction to recharge relationship: The SI indicates the present status category (PSC) of the resource. The SI for the Kosi Bay catchment is 44%. Based on the calculated SI, the PSC for groundwater of the catchment is **II (moderately used) or D (moderately stressed**).

The water quality category for all the boreholes in the catchment based on DWA's water quality guideline is given in Table 30.

TABLE 30. PRESENT STATUS CATEGORY BASED ON DWA WATER QUALITY GUIDELINE FOR DOMESTIC USE

Present class	Description	Compliance (spatial/temporal)
I or B	DWA class 0 or 1 or natural background	95%

The final present status category for the lake Kosi Bay resource unit is II or C (moderated modified).

TABLE 31. GROUNDWATER RESOURCES CATEGORY FOR THE LAKE KOSI BAY RESOURCE UNIT

Groundwater resources categorization							
GRU	**Area (Km^2)**	**Recharge (Mm^3/a)**	**Groundwater use (Mm^3/a)**	**Stress Index, SI (%)**	**Present Category (SI)**	**Present category (Impact)**	**Present Category (quality)**
Kosi Bay	**331**	**37.1**	**20.4**	**44**	**II (D)**	**II (B)**	**I (B)**

4.3.10 Groundwater Reserve for the Kosi Bay System

The groundwater component of the reserve is the part of the groundwater resource that sustains basic human needs and contributes to environmental water requirements (EWR). To be able to quantify the groundwater component of the reserve, the volume of groundwater needed for Basic Human needs (BHN) and contributing to EWR needs to be quantified or known. The EWRs of the resource in question must consider the following:

- Groundwater contribution to baseflow in rivers
- Groundwater contribution to wetlands
- Groundwater contribution to springs and other groundwater –dependent ecosystems

Groundwater should only be allocated to users and potential users once the volume of groundwater that contributes to sustaining the reserve has been quantified and resource quality objectives (RQOs) have been met. The RQOs can be set based on both the reserve and the resource class. The groundwater reserve for the Kosi Bay catchment is summarized in Table 32.

TABLE 32. GROUNDWATER RESERVE FOR THE LAKE KOSI BAY CATCHMENT.

	Reserve				Allocation	
Baseflow (Mm^3/a)	**BHN (Mm^3/a)**	**Reserve (Mm^3/a)**	**Recharge (Mm^3/a)**	**Reserve (% of recharge)**	**Current use (Mm^3/a)**	***Allocable (Mm^3/a)**
18	**0.88**	**18.9**	**37.1**	**50.9%**	**20.4**	**None**

*__Note that only a maximum of 65% of recharge may be allocated due to its spatial and temporal variability__

5 MANAGEMENT OPTIONS AND RESOURCE QUALITY OBJECTIVES

Groundwater monitoring is an integral and important part of the management of water resources. Both Parson and Wentzel (2007) and Dennis et al. (2012) state that groundwater monitoring is simply aimed at quantifying the behaviour and response of groundwater systems to various controls and stressors such as recharge, discharge, abstraction, etc. The response of groundwater systems is typically manifested by variation in groundwater levels, a change in groundwater quality, or both. Analysis and interpretation of monitoring data and information enables the groundwater environment to be better understood and is therefore vital for sound and responsible groundwater resource management. Because of the fact that moderate yielding aquifers can have a significant contribution to water supply schemes, Dennis et al. (2012) proposed to combine the actual or potential importance of an aquifer and is the groundwater quality to arrive at a recommended monitoring class for all aquifers as shown in Figure 38 along with the recommended monitoring options.

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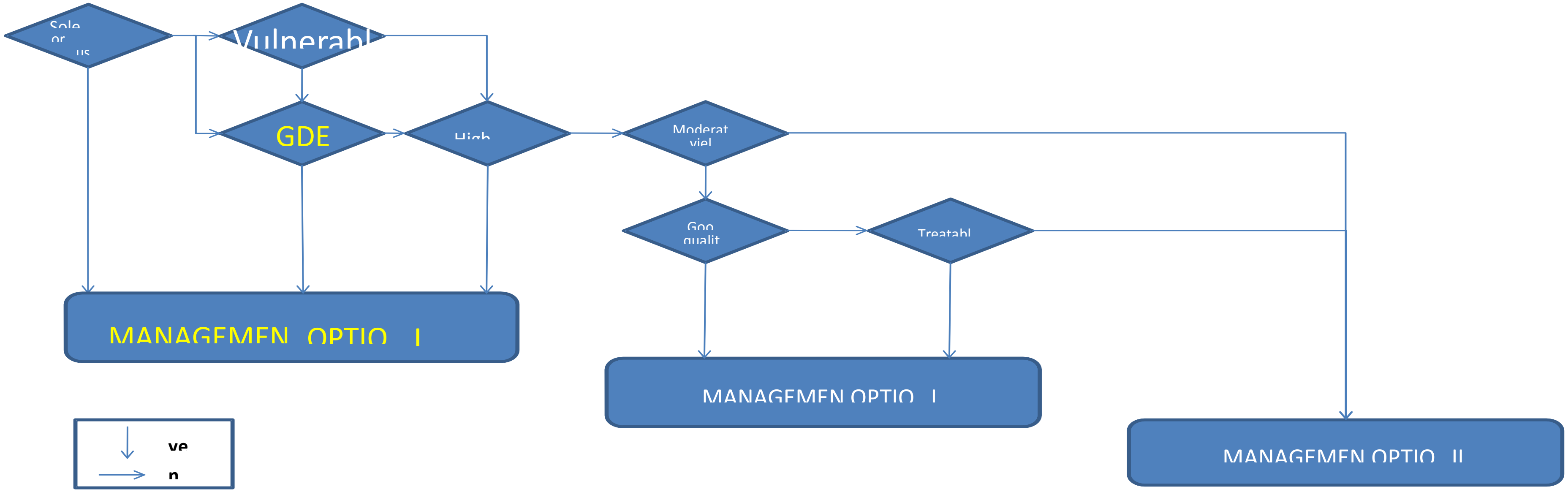

Management Option	Recommended Monitoring
I	Monthly monitoring of Groundwater level and Chemistry
II	Monitoring of groundwater levels and chemistry every 3 months
II	Monitoring of groundwater level and chemistry every 6 months

FIGURE 38. FLOW CHART USED TO DETERMINE THE RECOMMENDED AQUIFER MANAGEMENT CLASS (DENNIS ET AL., 2012)

5.1 Resource Quality Objectives

Resource Quality Objectives (RQOs) establish clear quantity and quality goals of a water resource unit to use it sustainably. According to Parsons and Wentzel (2007); Dennis et al. (2013), setting RQOs should consider the balance between the need to protect and sustain water resources, and the need to develop and use these resources should be ensured. RQOs are used to put classification and Reserve into practice by specifying conditions that will ensure that the class is not compromised and the Reserve can be met. RQOs need to have the following characteristics (Parsons and Wentzel, 2007; Dennis et al., 2012):

- They set limits that are simple and measurable
- They should reflect a balance between the need to protect and sustain the water resource, and the need to use and develop it.
- They provide goals within a management class and set the limits of acceptable impact
- They may be numeric or descriptive

Typical groundwater RQOs are related to groundwater level and gradients, groundwater quality, groundwater abstraction volumes, groundwater use activities that may impact the quantity or quality of a groundwater resource, aquifer structure and integrity, etc. that need to be maintained. These RQOs are set in consultation with stakeholders as part of the catchment visioning process, and can be implemented, among others, through land use planning and licensing conditions (Parsons and Wentzel, 2007; Colvin et al., 2004)

5.2 RQOs for the Lake Sibayi Resource Unit

The Lake Sibayi catchment is a groundwater driven freshwater lake catchment where the groundwater and the lake are moderately used mainly for commercial plantations and to a small extent for domestic and small scale irrigation purposes (Table 33).

TABLE 33. GROUNDWATER RESERVE AND CATEGORIZATION FOR THE LAKE SIBAYI SYSTEM

GRU	Area (km^2)	Recharge (Mm^3/a)	Groundwater to baseflow (Mm^3/a)	BHN (Mm^3/a)	Reserve (Mm^3/a)	GW Use (Mm^3/a)	Allocable (Mm^3/a)	Final Present Category	Management Option
Lake Sibayi	**612**	**63.7**	**39**	**0.61**	**39.6**	**24**	**None**	**II (C to D)**	**I**

- The lake and the eastern part of the water resource unit is covered by the iSimangaliso Wetland Park, where sometimes access to and data are limited
- The part of the catchment outside of the nature reserve is extensively covered by commercial plantation where a considerable amount of groundwater is pumped. This plantation groundwater use has impacted both on groundwater and the lake as indicated by lake and groundwater level decline.

- Further plantations within the catchment should be discouraged.
- The groundwater ecological reserve is very high, approximately 60% of the recharge. Therefore, all groundwater take activities within the groundwater contributing area of the lake needs to be monitored. Additionally, lake water abstraction should be closely monitored.
- The median lake level over a 30-year period should be ≥ 17.39 m amsl.
- Groundwater quality data is generally good but monitoring is recommended
- Further licences must be based on monitored data.

5.3 RQOs for the Lake Kosi Bay System

The Kosi Bay lakes catchment is a groundwater is also a driven lake –wetland-estuary system where the groundwater is moderately used mainly for commercial plantations and to a small extent for domestic and small scale irrigation purposes (Table 34).

TABLE 34. GROUNDWATER RESERVE AND CATEGORIZATION FOR THE LAKE KOSI BAY SYSTEM

GRU	Area (km^2)	Recharge (Mm^3/a)	Groundwater to baseflow (Mm^3/a)	BHN (Mm^3/a)	Reserve (Mm^3/a)	GW Use (Mm^3/a)	Allocable (Mm^3/a)	Final Present Category	Management Option
Lake Kosi Bay	**331**	**37.1**	**18**	**0.88**	**18.88**	**20.4**	**None**	**II (C)**	**I**

- The lake and the eastern section of the catchment of the water resource unit is covered by the iSimangaliso Wetland Park, where access is very limited and as a result data are limited
- The western and southern sections of the catchment that lie outside of the nature reserve is extensively covered by commercial plantation where a considerable amount of groundwater is being pumped. The plantation groundwater use has presumed to impact both the groundwater and the lake.
- Further plantation licensing within the catchment should be discouraged.
- The groundwater ecological reserve is very high, approximately 48% of the recharge. Therefore, all groundwater take activities within the groundwater contributing area of the lake needs to be monitored.
- There is no allocable groundwater left within the groundwater contributing area of the catchment.
- Groundwater quality data is generally good but monitoring is recommended.
- Groundwater and lake level monitoring needed.
- Further licences must be based on monitored data.

5.4 Recommended Monitoring requirements

The following monitoring recommendations needs to be implemented:

Groundwater:

- The Lake Sibayi and Kosi Bay system need at least three boreholes each dedicated to monitoring salt water intrusion: monitoring at least groundwater level and EC at a daily time step.

Lakes and estuary

- At least one lake level and EC monitoring station is need for each lake with a daily monitoring frequency.
- Flow and EC measuring station at the estuary mouth.

Recommended groundwater monitoring stations are given in Table 35 and Figure 39.

TABLE 35. RECOMMENDED MONITORING NETWORKS, PARAMETERS AND THEIR FREQUENCY FOR THE LAKES SIBAYI AND KOSI BAY CATCHMENTS

Monitoring No.	Longitude	Latitude	Point	Target	**Hydrodynamics	*Water quality	Monitoring Type	HYDSTRA NO.	GRU	Existing Type
1	32.83140	-26.86440	Existing (Kosi Bay)	Northeastern side	Daily groundwater level	quartely, EC automatic	Borehole	W7N0004	Kosi Bay	National
2	32.79600	-26.90300	New	Northern plantation	Daily groundwater level		Borehole	New	Kosi Bay	
3	32.87500	-26.93400	New	Salwater intrusion	Daily groundwater level	quartely, EC automatic	Borehole	New	Kosi Bay	
4	32.86100	-27.02600	New	Salwater intrusion	Daily groundwater level	quartely, EC automatic	Borehole	New	Kosi Bay	
5	32.81100	-27.16200	New	Salwater intrusion	Daily groundwater level	quartely, EC automatic	Borehole	New	Kosi Bay	
6	32.71900	-27.21200	New	Southern plantation	Daily groundwater level	quartely, EC automatic	Borehole	New	Kosi Bay	
7	32.74700	-27.03700	New	Central Plantation	Daily groundwater level		Borehole	New	Kosi Bay	
8	32.74900	-26.99100	New	Groundwater pumping	Daily groundwater level	quartely, EC automatic	Borehole	New	Kosi Bay	
9	32.67700	-26.94900	New	Western plantation	Daily groundwater level	quartely, EC automatic	Borehole	New	Kosi Bay	
10	32.60470	-27.08690	Existing (Sileza)	western boundary	Daily groundwater level	quartely, EC automatic	Borehole	W7N0003	Kosi Bay	National
11	32.51200	-27.23300	Western	Southwestern side	Daily groundwater level	quartely, EC automatic	Borehole	New	Sibayi	
12	32.56670	-27.40950	Mabaso	western side	Daily groundwater level	quartely, EC automatic	Borehole	W7N0007	Sibayi	Regional
13	32.64920	-27.45140	Mbazwana	Southern Plantation	Daily groundwater level	quartely, EC automatic	Borehole	W7N0008	Sibayi	Regional
14	32.66628	-27.41872	SIB02	Southern side	Daily groundwater level		Borehole	W7N0017	Sibayi	Regional
15	32.71400	-27.41900	New	Salwater intrusion	Daily groundwater level	quartely, EC automatic	Borehole	New	Sibayi	
16	32.73900	-27.34900	New	Salwater intrusion	Daily groundwater level	quartely, EC automatic	Borehole	New	Sibayi	
17	32.73810	-27.31940	Mabibi	Eastern side	Daily groundwater level		Borehole	W7N0002	Sibayi	Regional
18	32.71203	-27.29522	SIB01 a	Northeastern side	Daily groundwater level	quartely, EC automatic	Borehole	W7N0015	Sibayi	Regional
19	32.71194	-27.29527	SIB01b	Northeastern side	Daily groundwater level	quartely, EC automatic	Borehole	W7N0016	Sibayi	Regional

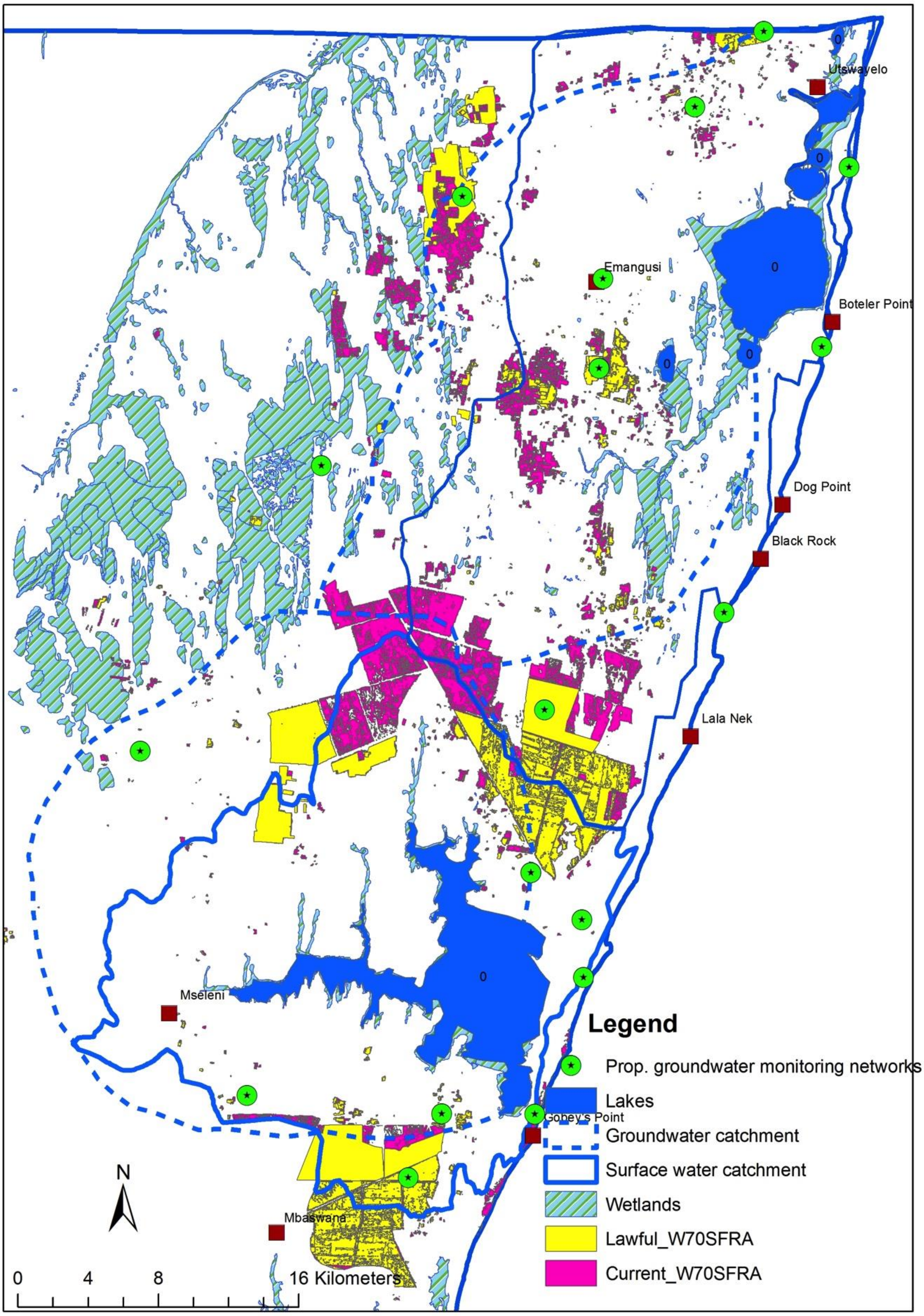

FIGURE 39. LOCATION MAP SHOWING THE RECOMMENDED GROUNDWATER MONITORING STATIONS/POINTS

6. SUMMARY

The Lake Sibayi and Kosi Bay catchments are situated within the extensive Zululand Coastal Plain primary aquifer system. The coastal plain aquifers are broadly categorized into three major aquifer units which are interconnected vertically and laterally. The groundwater system within these lakes catchment is intricately linked and interconnected within the lakes and wetlands, creating a groundwater fed lake and wetland system. The Lakes can be considered as the expression of the local ground water level in the area. Therefore, the lakes system should be managed together with the groundwater resources in the area, and should not be treated in isolation.

Groundwater generally flows from west to east towards the lakes and wetland and eventually to the coast line. Groundwater recharge for the area is estimated to be 12% of MAP or about 112 mm/a. The groundwater quality of the area is very good except few cases of high Fe content

The overall present status category of the groundwater resources in both catchments is II or C (moderated used or modified). The groundwater reserves are estimated at 50% and 62% of mean annual recharge for the Kosi Bay and Sibayi catchments, respectively. Based on the reserve calculation, no additional groundwater is available in both the Sibayi and the Kosi Bay catchments for allocation. It is recommended that further licensing needs to be considered only based on sufficiently monitored data

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