

Three Decades of Shoreline Change Investigation over Lake Sibaya, South Africa, Using Landsat Imagery and Geospatial Methods

By

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PREFACE

The research contained in this thesis was completed by the candidate while based in the Discipline of Geography, School of Agricultural, Earth and Environmental Sciences, of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Westville Campus, South Africa. The research was financially supported by the Council for Geoscience, South Africa.

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Details of contribution to publications that form part of and/or include research presented in this thesis (includes publications in preparation, submitted, in press, and published and gives details of the contributions of each author to the experimental work and writing of each publication).

Publication 1: Kemp, F.K., Xulu, S., and Gebreslasie, M. (**Submitted**). Analysis of shoreline dynamics of Lake Sibaya in South Africa between 1986 and 2020 using Landsat series and DSAS algorithm. *Earth Science Informatics*.

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Dear Dr Kemp,

Your manuscript, "Analysis of shoreline dynamics of Lake Sibaya in South Africa between 1986 and 2020 using the Landsat series and DSAS algorithm", has now been assessed.

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Publication 2: Kemp, F.K., Xulu, S., and Gebreslasie, M. (**In preparation**). Climate and land use/cover changes in Lake Sibaya, South Africa: Assessing shoreline changes using remote sensing methods.

From the aforementioned manuscripts, my role included conducting all the data analysis work and contributing to the drafting of original drafts of the manuscripts under the guidance of my supervisors.

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ABSTRACT

Lake Sibaya has experienced a significant decline in shoreline changes over the past three decades, in part, due to land use/cover (LU/LC) changes and drier climate conditions. In response, this study examined shoreline changes of Lake Sibaya between 1986 and 2020, LU/LC changes surrounding it, and climate variability using Landsat data series, the Digital Shoreline Analysis System (DSAS) geospatial modelling approaches, and climate data. DSAS provides the unique ability to compute the rate of change statistics using a suite of metrics, but in this thesis, only two variables were used (Net Shoreline Movement (NSM) and End Point Rate (EPR)) to understand shoreline dynamics and predict the future shoreline position over the next decade. The Landsat analysis showed a reduction in Lake Sibaya's surface area from 70.7 km² in 1986 to 49.5 km² in 2020, while the DSAS analysis showed that the changes occurred at a NSM of -1338 m and an EPR average of ± 6 m/year. Clear, conspicuous retracted changes were observed near the planted forests of Mbazwana between the southeastern/western basins and Manzengwenya in the northeastern region of the northern arm. Shoreline projections for the future showed the lake would continue to shrink from 49.5 km² in 2020 to 39.1 km² by 2030. Field observations and photographs validated DSAS results of declining shoreline changes in the lake and further in the vulnerable edges. Regarding the LU/LC, the results showed an expansion of forest plantations from 155.2 km² in 1986 to 248.3 km² in 2020, while water bodies decreased considerably, as indicated above, with a clear increase of barren land from 129.3 to 210.5 km² over the 34 years, mostly the accumulation of sandbars in areas previously occupied by the lakes' water. The study established a link between the lake's surface changes and drier climate conditions during the extreme El Niño phases. During El Niño/La Niña events, the lake surface decreased/increased, with precipitation showing a significant decrease in the 2014/2016 intense drought period. During this period, higher temperatures were in the order of 32°C, and these conditions are believed to have caused further reduction in lake water levels. Overall, this research demonstrates how LU/LC change and drier climate conditions have interacted to shape Lake Sibaya's shoreline over the past 34 years and highlight the importance of integrated management approaches to sustaining this vital ecosystem. Further research is recommended to examine the development of diverse vegetation communities in dry areas of the lake as well as the intensification of illicit forestry practices in this catchment area and how these might impact the ecological function of this water resource.

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ACRONYMS

CHIRPS	Climate Hazards Group InfraRed Precipitation with Station Data
DSAS	Digital Shoreline Analysis System
DWS	Department of Water and Sanitation
EFTEON	Expanded Freshwater and Terrestrial Environmental Observation Network
EPR	End Point Rate
ETM+	Enhanced Thematic Mapper Plus
GEE	Google Earth Engine
GIS	Geographic Information System
GIT	Geographic Information Technology
ISO	International Organization for Standardization
LRR	Linear Regression Rate
LU/LC	Land Use/Land Cover
MNDWI	Modified Normalized Difference Water Index
NGI	National Geo-spatial Information
NDWI	Normalized Difference Water Index
SANLC	South African National Land Cover
NSM	Net Shoreline Movement
OLI	Operational Land Imager
RF	Random Forest
RS	Remote Sensing
SAEON	South African Environmental Observation Network
SAWS	South African Weather Service
SFRA	Stream Flow Reduction Activities
SPI	Standardized Precipitation Index
SWIR	Shortwave Infrared
TIRS	Thermal Infrared Sensor
UNESCO	United Nations Educational, Scientific and Cultural Organization
USGS	United States Geological Survey

CHAPTER 1

GENERAL INTRODUCTION

1.1 INTRODUCTION

In arid and semi-arid regions, inland lakes are an essential part of water resources (Bai et al., 2011; Yue et al., 2021; Zhan et al., 2022) as they increase the quality of life and provide numerous socioeconomic and environmental goods and services. However, due primarily to human activity and climatic changes, many lakes worldwide have seen significant declining changes in size in recent years (Coe and Foley, 2001; Schindler, 2001; Hampton et al., 2008; Ariztegui et al., 2010; Cui et al., 2013). These changes in lake size significantly impact the availability of freshwater supplies, which lessens the livelihood options and their value as well as ecosystem functionality (Cui et al., 2013). Similarly, in countries like South Africa, drier climate conditions and increased human activities have been reported also as causing declines in inland waterbodies such as freshwater lakes (Carnie, 2020). This is a serious cause for concern for an already water-limited country, as it is becoming prone to sporadic and occasionally long-lasting droughts and increasing population (Kohler, 2016).

South Africa's uneven groundwater and surface water distribution results from its geography and climate (Molobela and Sinha, 2011). It has an average rainfall of about 450 mm per year, thus generating reduced levels of runoff (the lowest proportion in the world) (Molobela and Sinha, 2011) and accessibility of surface water (Hüfner, 2000; Binns et al., 2001; Claassen, 2013). Globally, it is ranked the 30th driest country, with surface water resources supplying about 77% freshwater, 19% groundwater, and 14% recycled water. Further, agriculture consumes the most considerable amount of water in the country, totalling 67% (Louw, 2021). Much of the rural population living in South Africa relies on water from inland water bodies such as lakes for their basic needs. This results from the country lacking economic development and infrastructure to supply rural communities with water. Even though water is important in overall human development, it is among the most mismanaged resources, principally in the context of developing countries like South Africa (Reddy, 2002).

Lake Sibaya, a freshwater inland water body in South Africa, provides multiple ecosystem services and goods, similar to many other inland water resources, and has indispensable natural

environment purposes. The northeast coast region where the lake is situated has become vulnerable to recurrent drier climate conditions such as droughts, and intensification of commercial timber plantations known as streamflow reduction activity (SFRA), together acting as the main factors contributing to the lake drying up over the past decades (Carnie, 2020). Previous work by UNEP (2001) reported that since 1990, widespread deforestation and cultivation in the lake's catchment area increased eutrophication and erosion in most drainage lines feeding the lake system, adding to the lake's receding complexity. Also, Whitelaw and van Rensburg (2020) found that the lake retreated because water was extracted for human use in adjacent Sodwana, Mbazwana, and Mseleni communities by various water users. In light of the aforesaid, an assessment and knowledge of the lake features, like modifications to its size, are necessary to manage water resources strategically and sustainably.

Studying lake shoreline changes is of great importance for sustainable development strategies as it provides a point of reference for estimating the effects created in lakes due to climate change and human activities (Mason et al., 1994; Chaudhari et al., 2018; Yang et al., 2020; Peng et al., 2021). Recent evidence by Bamunawala et al. (2021) suggests that the combined impacts of anthropogenic influences (urbanization) and climate change (such as temperature and precipitation) will cause 90% of global shorelines to retreat. Consequently, there is an urgent need to implement appropriate planning and management tools to safeguard the lake's sustainable development for present and future use (Adu-Boahen, 2017). Hence, using methods that provide accurate, timely, and cost-effective information is vital. Previously, monitoring shoreline changes was done using traditional ground survey methods (Aedla et al., 2015), which were laborious. Now, remote sensing has a noteworthy role in spatial data acquisition.

Remote sensing systems measure radiation reflected or radiated from the Earth's surface using sensors installed on platforms like satellites or aeroplanes. This allows spatial data to be captured, retrieved, analyzed, stored, and visualised (Durduran, 2010). Due to optical imagery's accessibility and interpretability, remote sensing has transformed the collecting of geographical data from an economic standpoint (Ozesmi and Bauer, 2002). The diverse ways that different surface materials interact with wavelengths are a fundamental aspect of remote sensing. These images are frequently used for shoreline mapping owing to this feature, which makes the combination of visible and infrared bands especially helpful for mapping the geographical distribution of water and land (DeWitt and Weiwen Feng, 2002). Additionally, multitemporal, multisensory, and multiband images are now available due to developments in remote sensing

technology, greatly enhancing digital analysis capabilities. These advancements have enabled scholars to examine changes in space and time, offering valuable perspectives on changes brought about by both natural and man-made phenomena (Chopra et al., 2001; Kalivas et al., 2003; Ma et al., 2007; Sidle et al., 2007; Pilgrim et al., 2014; Zhang et al., 2015).

The modified normalized difference water index (MNDWI), according to Xu (2006), is a good index for effectively mapping alterations in lake shorelines. Hence, multiple studies have successfully analyzed changes in lake shorelines using the MNDWI derived from high-resolution images. These include Santra et al. (2011), who effectively characterized shoreline changes and predictions alongside the Junput Coast of West Bengal in India, using Landsat 7 ETM+ and IRS LISS IV images. Also, Nsubuga et al. (2017) used Landsat and the MNDWI to identify changes in the Lake Kyoga sub-basin water surface area.

1.2 STATEMENT OF THE RESEARCH PROBLEM

Lake Sibaya is South Africa's largest offshore natural freshwater lake. On 28 June 1991, the lake was awarded RAMSAR status as a Wetland of International Importance (ISimangaliso Wetland Park, 2022), particularly as a waterfowl habitat (SA Ramsar Sites, n.d). In 1994, the water surface was declared a Nature Reserve under the KwaZulu Nature Conservation Act (Whyte, 1999). Surrounding Lake Sibaya is a densely forested iSimangaliso Wetland Park, which has been recognised as a UNESCO World Heritage Site since 1999. It is categorised as an important Bird Area by Bird Life SA, having 279 bird species, supports more than 20,000 waterfowl, maintains a varied group of zooplankton, 43 species of terrestrial and 15 species of aquatic molluscs as well as flora and fauna endemic to SA (Kock, 2017; SA Venues, 2022; South African Tourism, 2022). The amaThonga people also occupy the eastern shoreline of the lake for centuries, and they survive primarily on it for fishing, hunting and agro-pastoral projects (Bruton and Allanson, 1980).

In 2021, The South African Environment Observation Network (SAEON), in collaboration with the Department of Science and Innovation (DSI), and the National Research Foundation (NRF), had Lake Sibaya enlisted as an Expanded Freshwater and Terrestrial Environmental Observation Network (EFTEON) terrain where ecosystem research will be conducted (one of only six in the country). Moreover, the groundwater catchment was selected as a central focus region for EFTEON's long-term scientific observations (SAEON, 2023).

Lake Sibaya, however, has been declining over the last few decades. This is caused by aspects such as the pressure of human development and the intensification of commercial forestry. Additionally, there is further stress imposed upon the lake waters from unlicensed commercial forestry plants outside the property, even though licenses are no longer being issued (Department of Forestry, Fisheries and the Environment (DEFF), 2024). The climate also has a solid connection to the hydrology of the place, with droughts, floods, ecological and water resource sustainability, and water quality being significant concerns in hydro-climatic relationships. Consequently, lake spatial variations have been studied using the geographic information system (GIS) and remote sensing technologies in order to fully comprehend the interactions and ensure the best possible administration of water resources (Carnie, 2020; Department of Water & Sanitation (DWS), 2016; Kock, 2017; Nsubuga et al., 2019; SAEON, 2023). Yet, Nsubuga et al. (2019) established that little research has been done using remotely sensed technologies to examine the connections between climate factors and lake surface changes in southern Africa. So, a study that explores the extent and where the lake is drying up is paramount as this will help the management of the lake and surrounding area. Fortunately, Landsat, with its long history of over four decades and 30 m spatial resolution, holds much capacity to address these requirements.

1.3 RESEARCH AIM AND OBJECTIVES

This study aims to analyze three decades of shoreline changes over Lake Sibaya, South Africa, with Landsat data series and DSAS geospatial tool from 1986 to 2020. The study also aims to investigate the influence of climate change and LU/LC change on Lake Sibaya dynamics over the study period. To achieve these aims, the following objectives are pursued:

1. To quantify and map historical shoreline changes using Landsat data series
2. To analyze shoreline changes using the DSAS tool and forecast future changes into 2030
3. To examine the relationship between shoreline changes and LU/LC and climatic patterns

1.4 THESIS OUTLINE

Chapter One discusses the introduction, statement of the research problem and the aim and objectives. Chapter two is the first manuscript of the thesis. It looks at the decade changes in Lake Sibaya using Landsat imagery and the DSAS tool. Statistical values and rates at which

the lake changed are discussed, and the predicted future shoreline details are also included. The lake's vulnerable edges are also identified. Chapter three is the second manuscript of the thesis that looks at how climate change and LU/LC changes affect the lake shoreline and its surrounding region. In this regard, the main causes of the lake's deterioration and increasing shoreline susceptibility are examined. Overall, both manuscripts' introductions, methods, results, and discussion are deliberated. Finally, chapter four concludes with the main characteristics highlighting the study, its limitations and recommendations that address the research problem. Recommendations for future studies are also pointed out.

CHAPTER 2

ANALYSIS OF SHORELINE DYNAMICS OF LAKE SIBAYA, SOUTH AFRICA, USING A 1986–2020 LANDSAT IMAGE SERIES AND DSAS ALGORITHM

ABSTRACT

Lake Sibaya is the largest nearshore freshwater lake in South Africa. It is ecologically and socioeconomically linked to the human development agenda in the northeastern coastal region of the country. It is part of the iSimangaliso Wetland Park, the country's first proclaimed World Heritage Site and the only water resource serving surrounding areas. However, Lake Sibaya is reportedly drying up rapidly for various reasons (e.g., commercial forestry), yet the extent and pattern of this drying have hitherto not been quantified. In this paper, the Landsat satellite data series, Modified Normalized Difference Water Index (MNDWI), geographic information system (GIS), and the Digital Shoreline Analysis System (DSAS) algorithm were used to analyze the changes in the shoreline of Lake Sibaya between 1986 and 2020. The DSAS measured the rates of shoreline displacement in terms of erosion by computing a number of statistical parameters, including net shoreline movement (NSM) and end point rate (EPR). The study results indicate that Lake Sibaya displayed significant retracting changes, from 70.7 km² in 1986 to 49.5 km² in 2020, with noticeable erosional changes in the southeastern basin and northern arm regions. This occurred with a net shoreline displacement of –1338 m and an end point rate of –39 m/year, averaging ± 6 m/year. The results projected further lake retreat from 49.5 km² in 2020 to 39.1 km² in 2030. Vegetation growth was observed on sandbanks separating the southeastern basin from the central system, threatening to isolate these systems entirely. Fieldwork images and observations corresponded with the DSAS results that indicated a reduced lake shoreline. The reductions were more in the sensitive areas created by commercial forestry plantations. Improved rainfall is expected to reconnect these basins because they rely heavily on groundwater recharge and precipitation. Otherwise, activities served by the southeastern basin will be affected. The study recommends further research to accurately quantify the levels of abstraction by different users, including fine-scale mapping of planted forests surrounding this lake.

Keywords: Lake Sibaya, DSAS, Landsat imagery, shoreline evolution, remote sensing, MNDWI, change detection

2.1 INTRODUCTION

Lake Sibaya is the largest nearshore freshwater lake in South Africa; it was formerly an estuary wholly separated from the sea by the gradual formation of forested coastal dunes (Allanson, 1979) on the northeast coast of KwaZulu-Natal Province. The lake is part of the iSimangaliso Wetland Park (Obura, 2012), the country's first proclaimed World Heritage Site, with various wetlands comprising its biodiversity. Like many inland waters, Lake Sibaya provides a variety of ecosystem goods and services and has essential functions in the natural environment. It is an attractive tourist destination, yet its hydrological features are impacted by various developments in its catchment area (Nsubuga et al., 2019). Lake Sibaya is often the only water source for certain animals during drought periods (Weitz and Demlie, 2014). Beyond its socioeconomic and ecological importance, the lake holds important global and national significance (CEPF, 2010), and is a vital site for scientific research. Concerns over the long-term sustainability of its water resources are raised by its receding shoreline and oscillating water levels. Acknowledging its significance for climate change research and environmental monitoring, the Expanded Freshwater and Terrestrial Environmental Observation Network (EFTEON) recently selected it as one of six essential landscapes across the nation to host ecosystem research projects (Feig, 2018).

As part of the sustainable management of water resources, regularly monitoring lakes and marking shoreline changes are essential. This approach is necessary seeing as global lake levels are declining (Dereli and Tercan, 2020), and in much of Africa, where the difficulty of monitoring lakes is challenging even with the best-funded monitoring programs (Ballatore et al., 2014). This task is even more critical in a water-scarce country such as South Africa, where water resources must be managed sustainably (Snaddon et al., 1998). The commonly used procedure for assessing the dynamics of coastal areas and inland waterbodies is shoreline change analysis, a sensitive and robust indicator of the vulnerability of these systems to natural and human-induced forces (Genz et al., 2007).

A shoreline is an interface between a waterbody and land, the movement of which is a complex process associated with changes in precipitation, evaporation, runoff, and human land-use activities and their interactions (Temiz and Durduran, 2016). Therefore, shoreline change detection is crucial for providing a spatiotemporal analysis of freshwater resources to aid in formulating protection strategies (Duru, 2017). Many tools are utilized for shoreline change analysis. In the past shoreline change evaluations were done using traditional field methods

and based on direct comparisons with preexisting maps (Burningham and Fernandez-Nunez, 2020). However, there were limited estimates of precision and uncertainty available at the time. Thus, in the 1970s, advances in computer technology witnessed a complete change in methods of studying shoreline change, largely centered on geographic information technology (GIT). Hitherto, concerted research efforts have been reflected in the growing number of shoreline change studies, most of which use remote sensing and other geospatial tools to understand the dynamics of inland waters against various natural and anthropogenic pressures (Ankrah et al., 2022).

Remote sensing, particularly Landsat products, is an indispensable data source for shoreline extraction due to their longevity, free access, and good coverage with a 30-m ground sampling distance (Li et al., 2022), hence their selection for this study. Several studies have exploited Landsat data to characterize inland waterbodies (Pekel et al., 2016; Adu-Boahen, 2017; Hovsepyan et al., 2019; Ramsayer, 2021; Yue et al., 2021; Yao et al., 2023). The basis for determining the shoreline using remote sensing is the spectral difference between the waterbody and the surrounding land area (McFeeters, 1996), and its accuracy depends on the sensor's native resolution and how the position is mapped (Smith et al., 2021). A growing number of studies have effectively examined shoreline changes in many lakes using the modified normalized difference water index (MNDWI; Xu, 2006) based on Landsat data. For example, Tao et al. (2015) used multiyear Landsat imagery from 1987 to 2010 on various lakes on the Mongolian Plateau and reported rapid losses resulting from variations in precipitation, mining and agricultural practices. Similarly, using machine learning and Landsat imagery over the period 1984 to 2019, AI-Mashagbah et al. (2021) found that the repercussions of climate change and activities via humans caused the Dead Sea to shrink. Also, Ogilvie et al. (2018) examined the long-term effects induced by humans and changes in climate on water levels and shoreline dynamics, and found that they changed the shoreline significantly, resulting in habitat loss and erosion. So, for the preservation and sustainability of wetlands, estimating shoreline change rates utilizing remote sensing technology has emerged as an active area of research (Bouchahma and Yan, 2014; Bacino et al., 2020; Valderrama-Landeros et al., 2020). To measure shoreline changes using remotely sensed data, several methods are available, including a cell-to-cell comparison of binary images and the Digital Shoreline Analysis System (DSAS) extension in ArcGIS software (Bouchahma and Yan, 2012; Rezaee et al., 2019).

In this paper, the aim is to determine the historical shoreline changes in Lake Sibaya between 1986 and 2020. Then a Landsat image time series and the DSAS geospatial tool were used to identify vulnerable shores. Then two statistical variables, namely, Net Shoreline Movement (NSM) and the End Point Rate (EPR) were used for the calculation of net distance and rate of change. Additionally, the DSAS is utilized to predict future shoreline changes for the next ten years (up to 2030). The novel contribution in this paper is to determine the extent of shoreline displacement and identify vulnerable edges of Lake Sibaya, as there is no research yet that has tracked shoreline evolution in Lake Sibaya.

2.2 MATERIALS AND METHODS

2.2.1 Study area

This study was conducted at Lake Sibaya on the northeast coast of South Africa (Figure 2.1). The lake is the country's most extensive natural coastal freshwater system and covers an area of nearly 70 km² (Combrink et al., 2011) at 20 m above sea level (Stager et al., 2013). It has an average depth of 13 m with a maximum of 43 m (Bowen, 1978). Lake Sibaya was once an estuary before it was separated from the Indian Ocean by the gradual formation of a coastal forest dune (Allanson, 1979), yielding no straightforward surface discharge to the sea. Rather, the water equilibrium of the lake is preserved by an interplay of precipitation, evaporation, groundwater inflow, surface runoff, and underground seepage to the sea (Nsubuga et al., 2019).

This region has a subtropical climate with warm summers characterized by average daily temperatures ranging from 21.0°C to 32.1°C and mild winters ranging from 10.9°C to 26.4°C (SAWS (South African Weather Service), 2018). It receives less precipitation in winter, which is the dry season (April to September), and more in summer (wet season) most of which falls between October and March, with pronounced spatial and temporal variations (Ramjeawon et al., 2020). The hydrology of Lake Sibaya is greatly impacted by the land use activities that surround it. Particularly during dry seasons, the growth of commercial *Eucalyptus* plantations has caused groundwater levels to drop, altering the lake's natural water balance SAEON (2024). Additionally, the hydrological cycle has also been changed by increased agricultural activity and deforestation in the catchment, which has resulted in increased sedimentation, decreased groundwater recharge, and increased surface runoff. These changes modify both the lake's water availability and quality, highlighting the necessity of managing the area's land and water resources sustainably (Weitz and Demlie, 2014; Smithers et al., 2017; SAEON, 2024).

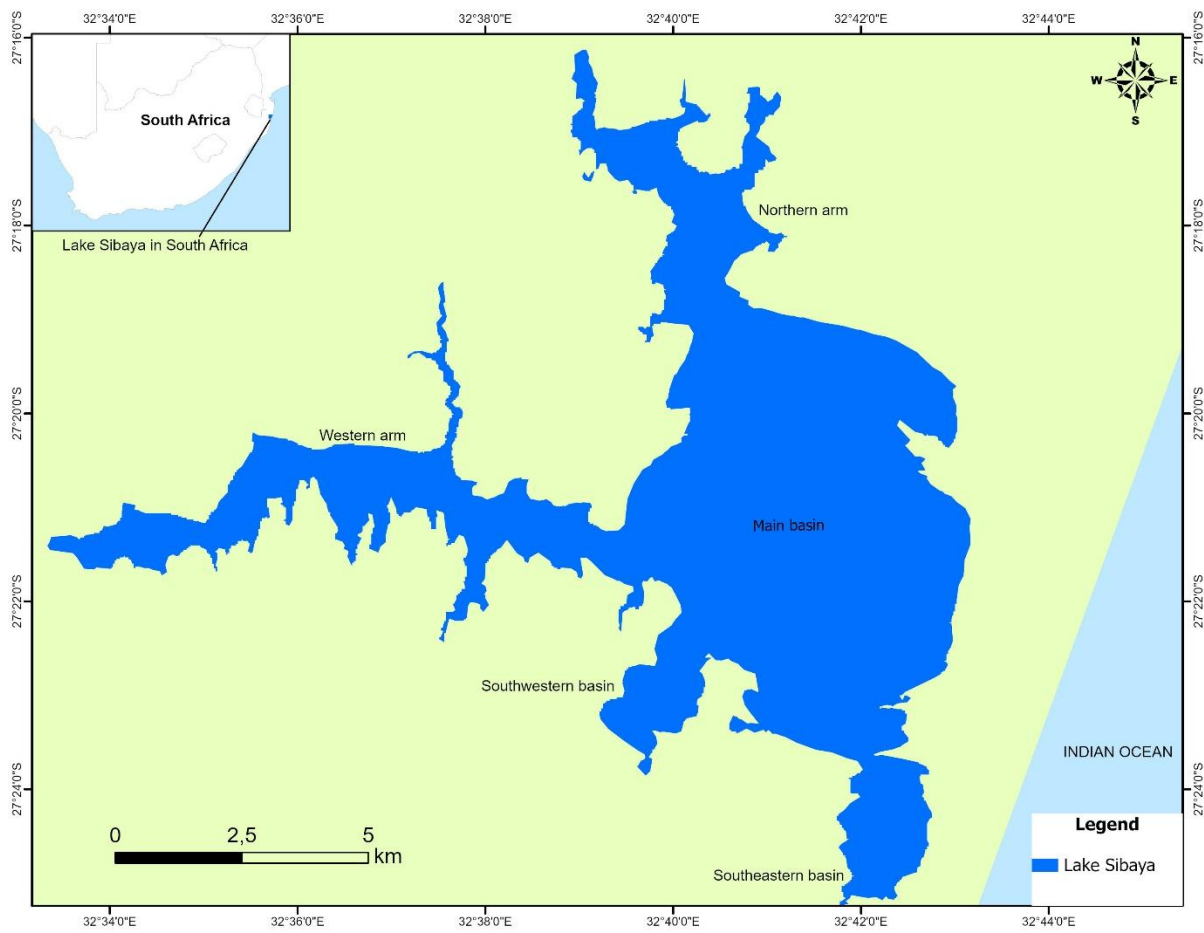


Figure 2.1 Location of Lake Sibaya on the northeast coast of South Africa.

2.2.2 Landsat data and shoreline extraction

In this study, a time series (1986–2020) of Landsat satellite data products was downloaded free of charge from the United States Geological Survey (USGS) online portal: <http://earthexplorer.usgs.gov> (accessed August 03, 2023). The images were obtained as Level-2 Surface Reflectance Products (L2SP), with corrections for atmospheric effects. Radiometric adjustment and atmospheric correction techniques were then used to retrieve the surface reflectance values of each image, guaranteeing constancy across the multiple acquisition dates for precise shoreline change analysis.

The images were mainly acquired from winter (dry season) as this season provides a clearer boundary, whereas the greatest amount of water is captured in wet-season images. However, not all images required for the analysis could be obtained during this season due to the absence of cloud-free, high-quality images for the dates needed. Hence, available cloud-free images (March and December) close to the study period season were selected. Using this method,

hydrological inconsistencies were considered, since Lake Sibaya has fluctuating water levels caused by groundwater recharge and seasonal rainfall. The seasonal variations aided in differentiating between natural shoreline changes and long-term recession. This method enhanced accuracy, ensured temporal uniformity, and enabled shoreline positions to be cross-validated under various hydrological settings. The characteristics of Landsat data are summarized in Table 2.1.

Table 2.1 Specifications of Landsat imagery used in the study.

Satellite	Sensor	Image date	Scene ID
Landsat-5	TM	14 Nov 1986	LT05_L2SP_167079_19861114_20200917_02_T1
		02 Jun 1990	LT05_L2SP_167079_19900602_20200915_02_T1
		12 Mar 1995	LT05_L2SP_167079_19950312_20200912_02_T1
		25 Mar 2000	LT05_L2SP_167079_20000325_20200907_02_T1
		24 Apr 2005	LT05_L2SP_167079_20050424_20200902_02_T1
		20 Dec 2009	LT05_L2SP_167079_20090505_20200827_02_T2
Landsat-8	OLI/TIRS	23 Jun 2015	LC08_L2SP_167079_20150623_20200909_02_T1
		20 Jun 2020	LC08_L2SP_167079_20200620_20200824_02_T1

For shoreline detection, the remote sensing methods rely on the spectral differences between water and land in the electromagnetic spectrums of visible and shortwave infrared channels. So, a modified normalized difference water index (MNDWI; Xu, 2006) image was generated from each Landsat image using the Green band and SWIR band in ArcMap. The MNDWI is calculated as the reflective difference between the green (Green) and shortwave infrared (SWIR) bands of the electromagnetic spectrum over their sum (Equation (2.1)).

$$\text{MNDWI} = \frac{\text{Green} - \text{SWIR}}{\text{Green} + \text{SWIR}} \quad (2.1)$$

To extract the waterbody while maintaining shoreline accuracy, a threshold was applied to classify non-water and water areas using the reclassifying tool, and then a raster-to-vector (polygon) conversion was implemented. Furthermore, smaller patches of water polygons surrounding the lake border were manually erased and fragmented polygons dissolved to create a clean geometry. Following this, the shoreline was manually drawn using the image and polyline editing tools after which the polyline geometry of Lake Sibaya was saved for each date. Each polyline with a corresponding Landsat imagery was then overlaid and visually inspected the boundary on-screen to ensure the accuracy of the shoreline extraction results.

This exercise was extended with false-color Landsat imagery, following Verpoorter et al. (2012) observation that most lake boundaries match well with false-color images. The shorelines derived from each image date were validated visually on Google Earth Pro using the respective Keyhole Markup Language (KML) files and their conformity with Table 2.1 was cross-checked. Shoreline deviations were evaluated qualitatively rather than quantitatively to assure consistency due to possible variations in geographic resolution and acquisition dates.

For lake area and water data, many methods can be used, using various sensors whilst the information on lakes is extracted (Jawak et al., 2015). In this study, polylines were converted to polygons in ArcMap, and the area in km² for each year of interest was calculated, and graphs displaying the results were generated. The average monthly data (1986–2020) for surface water was obtained from the South African Environmental Observation Network (SAEON).

2.2.3 Shoreline change detection

Digital Shoreline Analysis System (DSAS) V5.0 extension developed by the United States Geological Survey (USGS) was used within the ESRI ArcGIS (ArcMap 10.6) environment to analyze shoreline changes (Himmelstoss et al., 2018). DSAS provides a unique opportunity to compute the rate-of-change statistics necessary to understand shoreline dynamics and to forecast a decade or two of shoreline possibilities. Its importance as a scientific tool to quantify spatial and temporal variations in shoreline changes has been described previously by Mondal et al. (2020). For the purposes of this study, the historical shoreline positions of Lake Sibaya for the years 1986, 1990, 1995, 2000, 2005, 2009, 2015, and 2020 were imported into the DSAS system.

In the DSAS, transects were set to cast at a maximum search distance of 1800 m from the baseline, transect spacing of 200 m, smoothing distance of 1000 m, and default uncertainty of 10 m. The shoreline threshold was set at 6 for statistical values, and the confidence level was set at 90%. The accuracy of shoreline change detection and computing efficiency were balanced in the selection of the DSAS settings. In places that were fast receding, a maximum search distance of 1800 m guaranteed coverage of substantial shoreline movements. While preserving computational efficiency, a transect spacing of 200 m offered sufficient resolution for identifying localized alterations. In order to minimize short-term shoreline variations and highlight long-term patterns, a smoothing distance of 1000 meters was used. Potential positioning mistakes resulting from seasonal variations in water level, georeferencing

problems, and image resolution were taken into consideration by setting a default uncertainty of 10 m.

The horizontal changes in the shoreline and rates of change were subsequently established. These metrics included (a) the Net Shoreline Movement (NSM), which indicates the distance between the oldest and newest shorelines, and (b) the End Point Rate (EPR), which is the distance of shoreline movement between the oldest and the newest shoreline positions divided by the time-lapse and is one of the most widely used methods in shoreline change research studies carried out globally (Himmelstoss et al., 2018).

2.2.4 Future shoreline

The EPR model is often the foundation for forecasting future shorelines (Esmail et al., 2019). According to Nandi et al. (2016), many recent studies have confirmed the EPR as the most effective statistical method for forecasting future temporal changes in shoreline dynamics. A statistically determined collection of Linear Regression Rate (LRR) values is used by the Kalman filter to more precisely anticipate the location of the future shoreline (Yan et al., 2021). The subsequent shoreline positions are approximated with time by combining historical shorelines. By then updating the rates and uncertainties, the Kalman filter reduces the difference between the modelled shorelines and those observed (Long and Plant, 2012). These updated data forecast the shoreline position for each subsequent period. The predicted shoreline is displayed along with an uncertainty band since the shoreline uncertainty reflects the measurement inaccuracy (Himmelstoss et al., 2018).

Based on the calculated statistical data, the DSAS beta model was able to forecast the shoreline for the year 2030. According to Himmelstoss et al. (2018), it is crucial to remember that not all data types, localities, and shoreline change patterns are appropriate for this forecasting tool. When determining the feasibility of using this tool to project an anticipated shoreline position, users must consider the parameters and constraints of their data. In the case of this study, we used high-resolution satellite imagery and georeferenced historical shoreline records with adequate temporal intervals for precise shoreline delineation. The projection algorithm that was applied was the End Point Rate (EPR) for the effective detection and quantification of shoreline changes. These characteristics guaranteed accurate shoreline analysis, as they took into account a variety of scenarios and corresponded with our user expertise and study requirements. The shoreline change analysis and future projection is summarized in Figure 2.2.

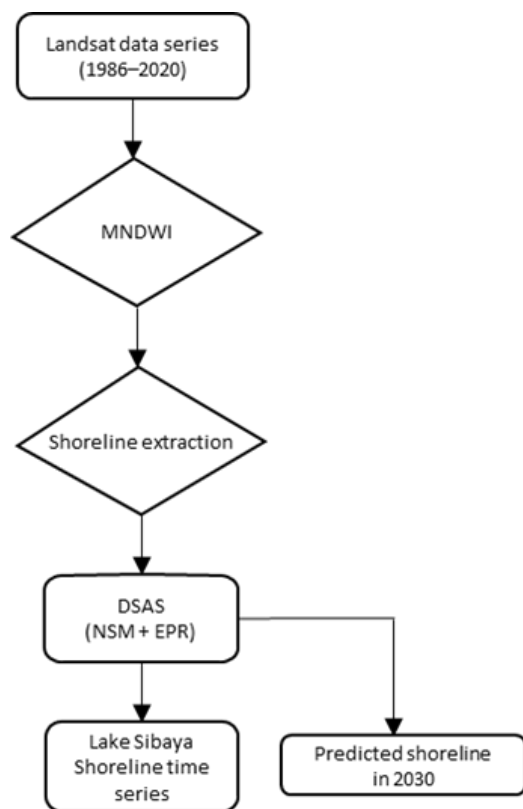


Figure 2.2 Flow chart summary of DSAS and remote sensing-based shoreline change analysis method.

2.2.5 Field observation

To validate the DSAS results and offer context about the environmental factors impacting shoreline alterations, field observations were carried out [October 2023]. Photographs were taken at important locations to record vegetation increase, planted forests, and exposed sandy banks. This time period was chosen because it was relevant to [water level variations, optimal visibility of shoreline characteristics, and post-dry season circumstances]. The northeastern region, the northern arm, and the southeastern basin, were among the specific sites that were chosen due to their closeness to the lake's drainage basin and their influence on water levels (refer to Table 2.1 for region locations and names).

2.3 RESULTS

2.3.1 Spatio-temporal changes of Lake Sibaya over the 1986–2020 period.

The spatio-temporal changes in Sibaya Lake are presented in Figure 2.3(a), which shows the surface cover (polygons), and in Figure 2.3(b), which shows the lake boundaries (polylines) for each recorded year. The results in Figures 2.3(a) and (b) show a considerable receding trend,

particularly at the base of the northern arm and in the southeastern and southwestern basins. Over time, the cordon-like system is progressively closing between the central and southeastern basins and became more apparent after 2015, resulting in the separation of these basins. The ominous appearance of plant patches (i.e., *Juncus oxycarpus*) and the expansion of sand between these basins point to their complete separation. Relatively small, but noticeable, changes occur over the western arm of the lake.

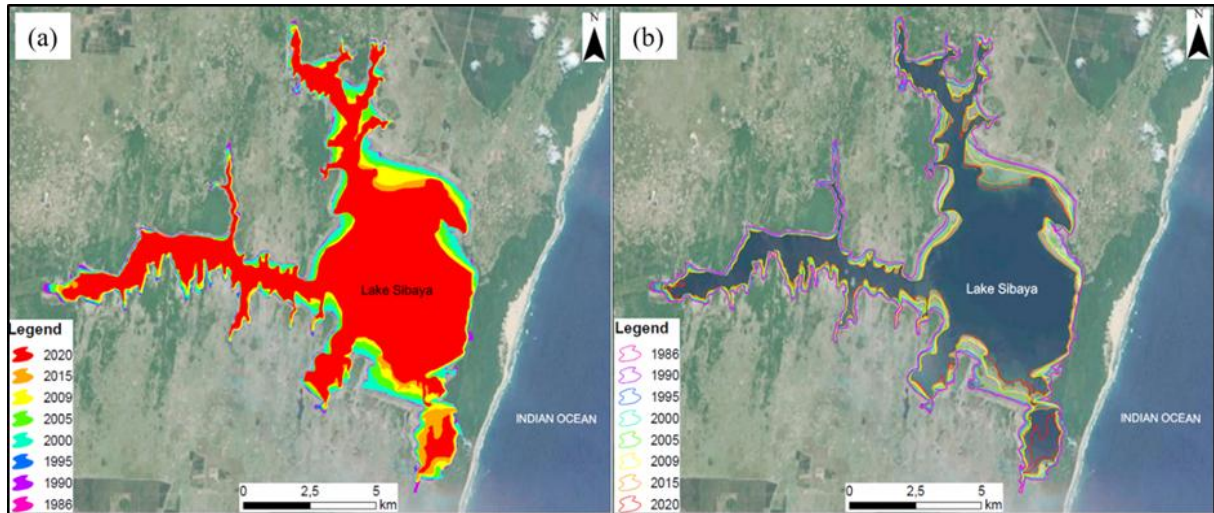


Figure 2.3 Spatial areal changes of Lake Sibaya between 1986 and 2020: (a) areal changes, (b) boundary changes. (Source of background image: National Geo-spatial Information (NGI), 2020).

Figure 2.4 shows the surface area changes over the lake in each sampled year as well as the average recorded lake level data from SAEON. It had the largest area in the earlier years of the study period, with 70.7 km² in 1986, which increased to 71.1 km² in 1990. In 1995, the area decreased to 66.7 km² and recovered in 2000. From the mid-2000s, the lake exhibited a steady downward trend from 61.9 km² to its lowest level (49.5 km²) in 2020. This implies that Lake Sibaya suffered a surface area decrease of 32.5% between 1986 and 2020. As expected, the net average yearly water level followed the same pattern, dropping from 19.1 m amsl to 14.7 m amsl over the study period (Figure 2.4).

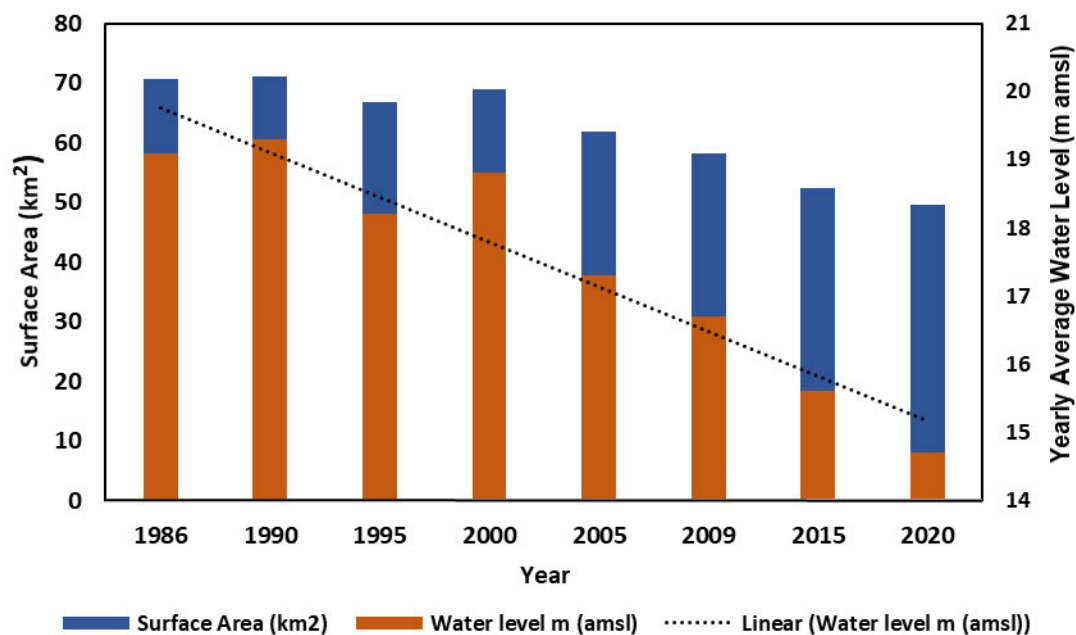


Figure 2.4 Water surface area and yearly average water level of Lake Sibaya (1986–2020).

2.3.2 Shoreline change analysis between 1986 and 2020

The analysis of the shoreline movements is based on 465 transects along Lake Sibaya between 1986 and 2020, summarized in Table 2.2, Figure 2.5 and Figure 2.6. As shown in Figure 2.5, the lake shorelines exhibited high variability between the recorded years and generally displayed a net receding pattern. The land-to-lake shift varied between -10 m and -1338 m over the study period, with the most extended shoreline displacement (NSM) reaching -1338 m in the southwestern basin, followed by -1119 m at the base of the northern arm (Figure 2.5).

Table 2.2 Statistical quantification of shoreline movement.

No. of Transects	Metric	Max	Min	Avg.	Net erosion (%)	Max erosion
465	NSM (m)	-1338	-	-201	99.6	-
	EPR	0	-	-6	99.6	-39
	(m/year)					

Figure 2.6 presents the EPR changes. It shows a receding pattern between the southeastern and southwestern regions, including the northeastern region of the northern arm. Statistically, the EPR is -39 m/year, with an average of -6 m/year. Both methods also yielded similar results regarding the retreat patterns along the shoreline over the study period. Little change is observed in the western arm and east of the central basin.

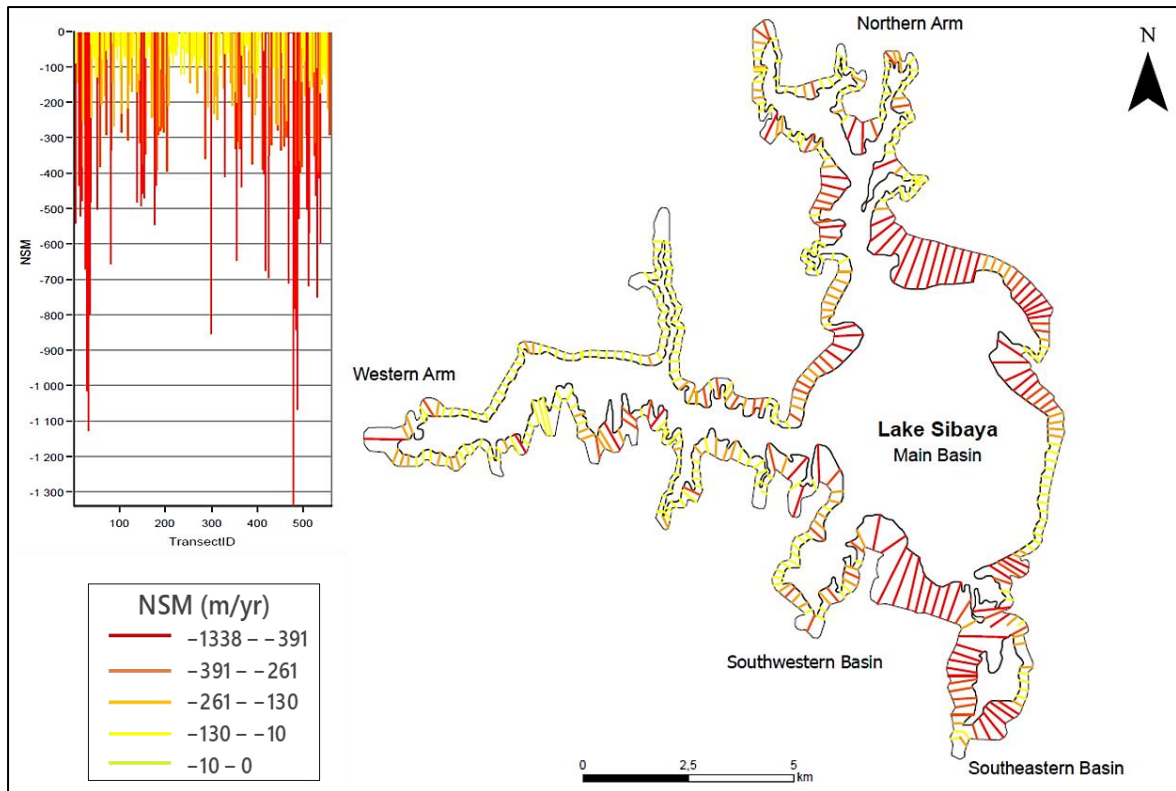


Figure 2.5 Net Shoreline Movement (NSM) over Lake Sibaya (1986–2020).

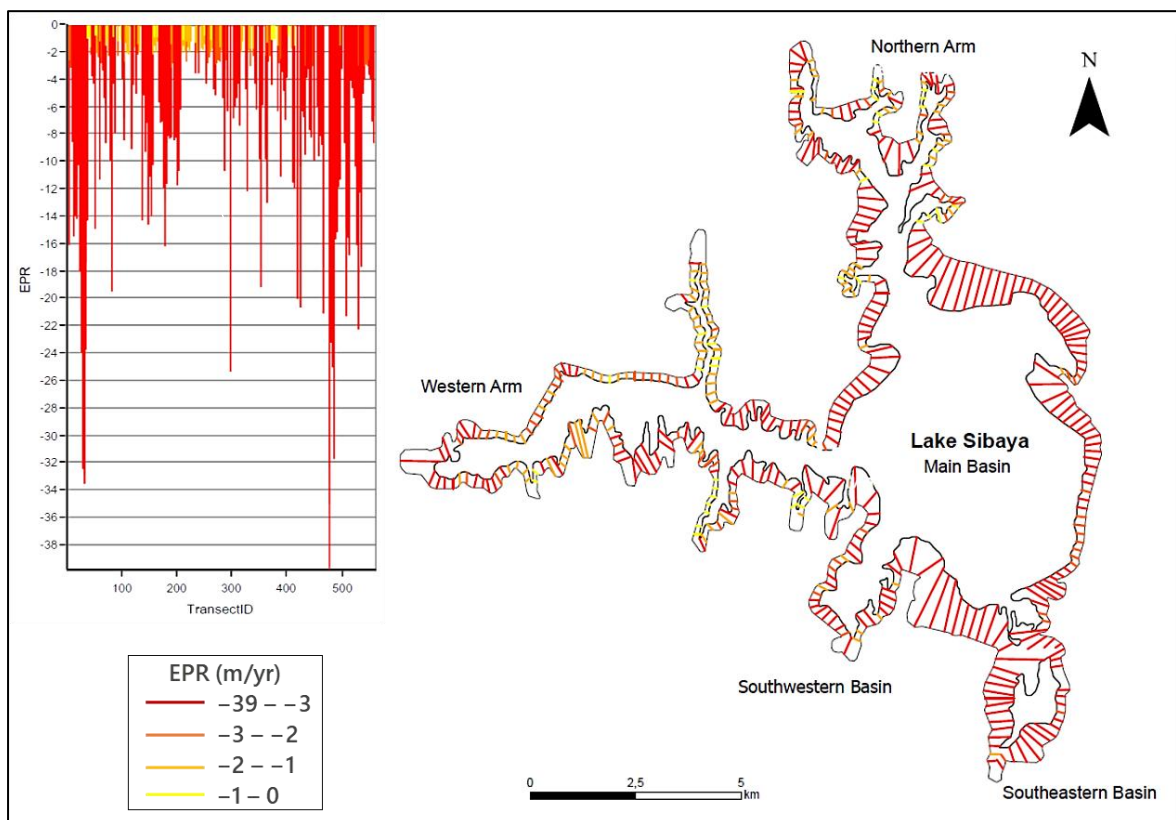


Figure 2.6 End Point Rate indicating the rates of shoreline changes per year.

2.3.3 Prediction of shoreline change in Lake Sibaya for 10 Years

Based on the shoreline statistics of the period 1986–2020, the year 2020 was used to forecast the shoreline for the year 2030. This was done to indicate where the shoreline could be in the next decade and where the most vulnerable edges of concern need immediate attention. In Figure 2.7, the prediction analysis of this study points to a further decline in the lake surface area from 49.5 km² in 2020 to 39.1 km² in 2030. The projection focuses on the most severe case, predicting lake recession trends seen after 2000 and into 2030.

This strategy was selected since the lake's extent has been steadily decreasing since 2000, due to below-normal precipitation and human pressures like water abstraction and commercial forestry. This result corresponds with Everson et al. (2019), SAEON (2023), and Weitz and Demlie (2014), who stated the region's water depletion is caused by a combination of forestry expansion and below-average rainfall. Based on the 1986–2000 trends, we did not consider a recovery scenario, given that lake levels at that time were largely driven by favourable regional climatic conditions that are no longer common, and recent data show that the lake is still under stress, which makes a recovery scenario less representative of the current and expected conditions.

A substantial amount of change (receding) is notable at the base of the northern arm and the region between the southeastern and southwestern basins. As previously mentioned in section 2.3.1 results, the separation of the southeastern basin from the central system is complex and represents an exciting test of the DSAS tool for lakes with breaching shorelines.

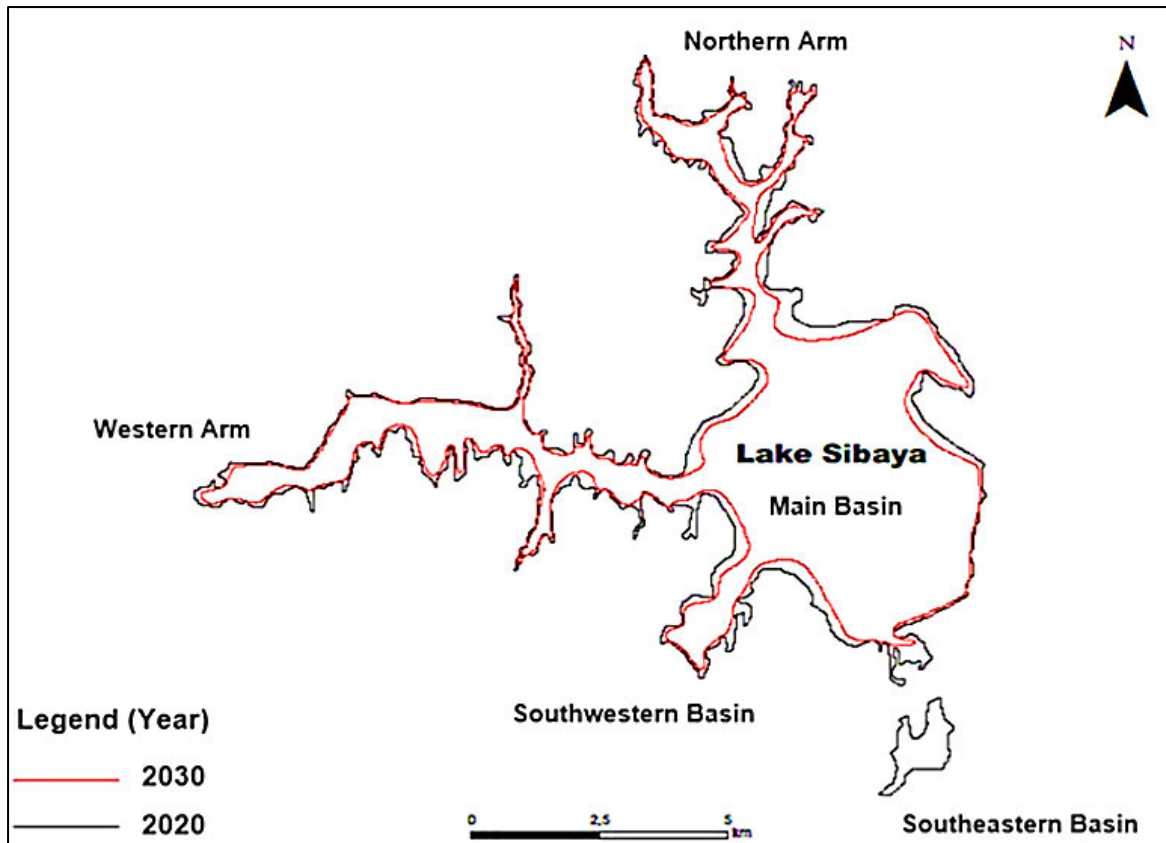


Figure 2.7 Predicted shoreline of 2030.

2.3.4 Shoreline change verification

The DSAS result and the fieldwork observation of Lake Sibaya match. The results displayed a generally dwindling shoreline and major erosional changes occurring in the areas of the lake closest to the forested plantations, causing vulnerable edges. Corresponding to this finding, in Figure 2.8 (a) displaying the overview of erosional changes along the shoreline, (b), (c) and (d) showing a few factors contributing to the declining changes in lake water levels. In Figure 2.8 (b), the planted forests (encircled in yellow) in the northern arm and northeastern region are in close proximity to the lake catchment area. Hence, their vicious rooting systems' easy accessibility to the lake's catchment region subsurface, drawing large volumes of groundwater. Due to these mentioned factors, reduced water levels and sensitive regions have developed on the edges of the lake in the vicinity of these forested plantations. As a result, the shoreline dynamics have been further altered by the exposing of dry, sandy banks where opportunistic vegetation, including grasses and shrubs, has begun to grow.

Figure 2.8 (c) demonstrates the considerable loss in water levels with a complete separation of the main basin from the southeastern basin. Dry ground covered with plant species such as

Scirpus littoralis, *Juncus oxycarpus* and grass covers this open space. This correlates with DSAS results, having shown a complete separation in this region after 2010. In Figure 2.8 (d), a water abstraction pipe (feeding the Mbazwana community), once previously submerged under water is now exposed on the banks of the lake as a result of retracted water levels. This is a serious issue as an abstraction for the mentioned Mbazwana community is directly linked to the southeastern basin. So, there could be drastic implications for all ecosystems the southeastern basin supports, should the entire system continue declining to where it completely disappears as suggested by DSAS future predictions. Overall major erosional changes are occurring in the shoreline of the lake and more so in the regions of the commercial plantations, and this is evident where key erosion is occurring based on the DSAS results.

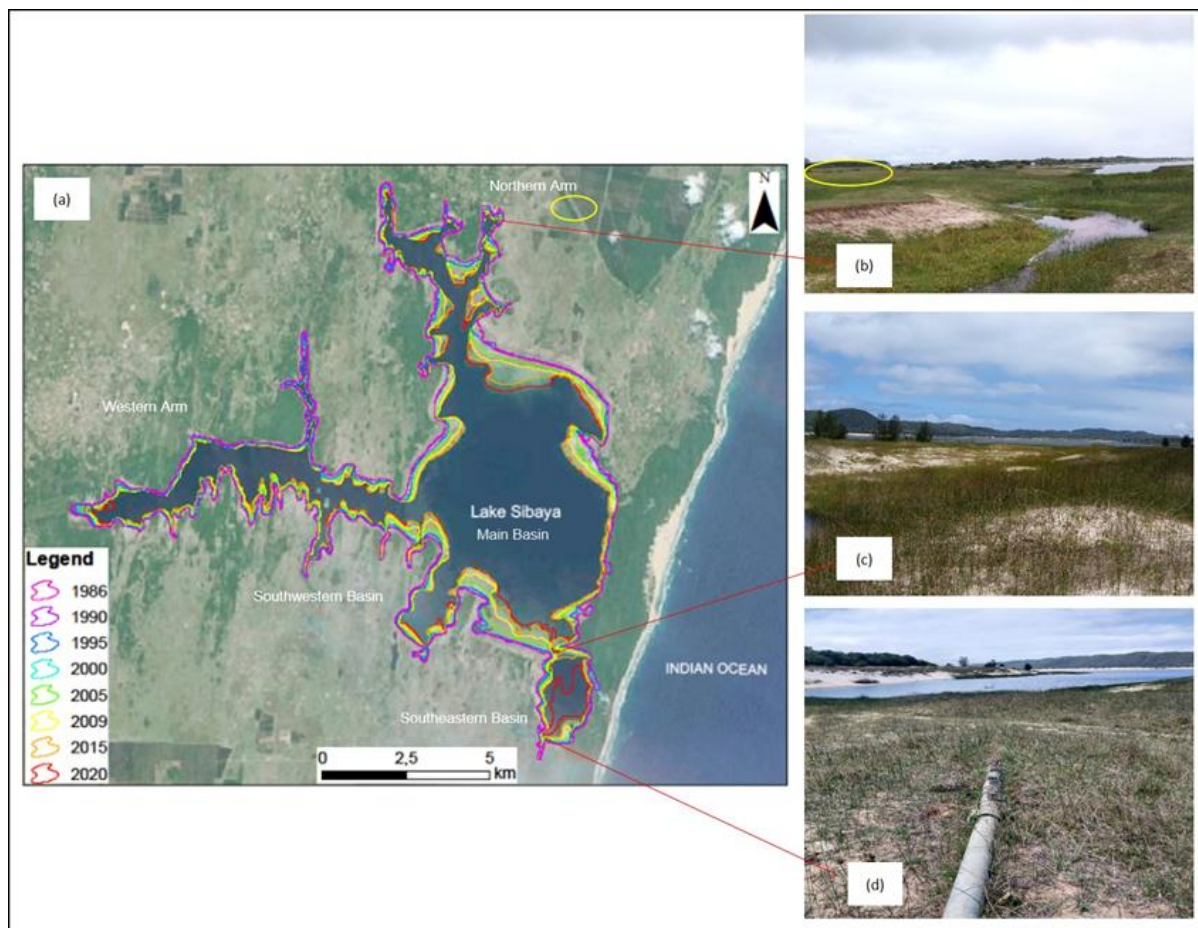


Figure 2.8 Shoreline erosion and most affected regions in Lake Sibaya: (a) Overview of the erosional trends along the shoreline (*Source of background image: National Geo-spatial Information (NGI), 2020*); (b) Close proximity of the Manzengwenya planted forest to the lake (highlighted by the yellow ring) and eroded banks due to reduced water levels; (c) Complete separation of the main basin and southeastern basin; (d) Visible water extraction pipe supplying the Mbazwana community on dry, eroded banks. *Photographs taken in October 2023.*

2.4 DISCUSSION

The study of shoreline dynamics at Lake Sibaya using Landsat series and DSAS analysis between 1986 and 2020 has allowed the characterization of the changes over 34 years. The results show that Lake Sibaya experienced the greatest shoreline changes at the base of the northern arm and between the southeastern and southwestern basins, with a maximum NSM of $-1\,338$ m at an average of -201 m and an average EPR of -6 m/year. Principally, the lake area decreased from 70.7 km^2 to 49.5 km^2 during this period, corresponding to a loss of 30%. These results show a decline in surface area in line with the reported results by Nsubuga et al. (2019), (83.7 km^2 in 1992 to 58.8 km^2 in 2016, a significance of 29.7%). These findings are also consistent with work done by Smithers et al. (2017), who reported an approximately 35% decrease in the water level of Lake Sibaya since 2001, which, in part, could be attributed to the impact of commercial forestry plantations, and ten years of significantly lower-than-average rainfall from 2001 to 2011. Additionally, Mpungose et al. (2022) established that over the past two decades, Lake Sibaya's water levels have decreased significantly, exposing large areas once flooded. Though, surrounding systems such as Lake St. Lucia and local dams have gradually improved since the recent 2015/16 drought, Lake Sibaya has not and continues to deteriorate (Carnie, 2020).

The comprehensive dwindling trend of the lake shoreline further displayed that during the study period, the lake reached its lowest water level record in history in 2015, separating the main basin from the southeastern basin, and exposing a sandbar between the two (Figure 2.9). The sandbar gradually enlarged, suggesting the persistent shoreline retreat, highlighting shifts in the rates of sediment transportation and deposition, which are associated with decreased water levels and reduced supply due to human-induced and/or climate variables. These sedimentary dynamics are important in coastal freshwater lake systems such as Lake Sibaya, where ecological balance is maintained through interactions between the hydrology of the lake and shoreline morphology (Whyte 1999). The newly formed sand dune appears to be important as it potentially protects the main water body from the Ocean, even though it places activities of the southeastern basin under threat. This modification occurrence resembles the development of the dune cordon that separates the Lake Sibaya estuary from the Indian Ocean (Whyte, 1999). The results of this study corroborate previous work (Carnie, 2020; Ramjeawon et al., 2020). The separation between these basins reached a point of no return in 2015.

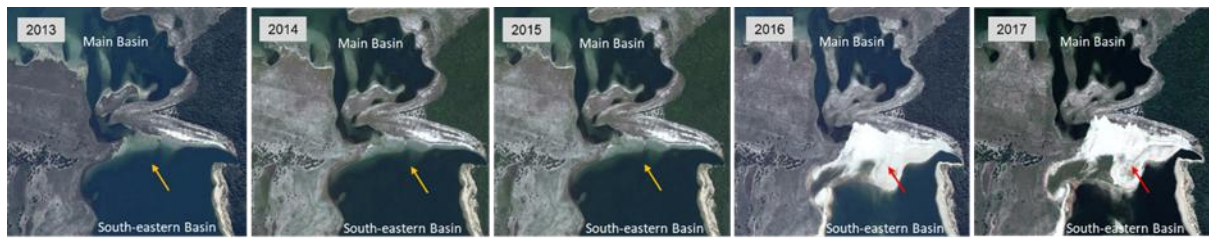


Figure 2.9 Satellite imagery depicting the evolution of the main basin separating from the southeastern basin before and after 2015, with arrows indicating the development of the sandbar. (Source: Google Earth Pro).

The prediction analysis of this study also confirmed further retraction from 49.5 km² in 2020 to 39.1 km² in 2030 and the complete separation of these systems. So, for the reconnection of these two systems, the region needs to encounter more or less sufficient rainfall to replenish the lost surface area. This would need to be calculated as the year 2010 (58.1 km²), when the basins had not fragmented, minus the year 2020 (49.5 km²) where the study period ends, accounting for an overall difference of 8.6 km². Several studies have attributed this decline to the interaction of drier climatic conditions and forestry expansion, which has led to conflicts over water resources between people and livestock and economic activities such as issuing commercial forestry licenses (SAEON, 2023).

The threatening changes to Lake Sibaya are not uncommon, as many lakes worldwide are experiencing dwindling changes caused by increasing human- and naturally-induced disturbances (Han et al. 2024). For example, Lake Chad in Central Africa drastically diminished by over 90%, from 24597 km² in 1963 to 1317 km² in 2017 (Ikusemoran et al. 2018). Also, the Aral Sea in Central Asia reduced by more than 90% from 68478 km² in 1960 to 9285 km² in 2020 (Krapivin et al. 2019; Zonn et al. 2020; Li et al. 2021). Similarly, Lake Urmia in north-western Iran has declined by 88% since 1972 (AghaKouchak et al. 2015), with (Khorshiddoust et al. 2022) displaying it retracted from 3100 km² in 1988 to 1262 km² in 2018. In South Africa, and the context of Lake Sibaya, SAEON (2023) established that the lake shrunk in size by 25% from 119 km² in 1990 to 89 km² in 2020. According to studies by Miller (1998) and Weitz and Demlie (2014), the lake's surface area decreased dramatically to an average of 56 km². However, Smithers et al. (2017) did a thorough analysis of Miller's (1998) and Weitz and Demlie's (2014) findings and established the lake reduced by 35%, from 93 km² in 2001 to around 69 km² in 2017.

Taken together, the shoreline change analysis provides insights into the declining lake water levels, primarily reflecting the changes caused by natural and human activities within the lake (Temiz and Durduran 2016). Similarly, in this study, Landsat and DSAS data allowed us to quantify and understand the changes in Lake Sibaya between 1986 and 2020 and the expected changes by 2030. The results suggested important issues for lake and land management. Such as, the lake's decreasing surface area lowers its capacity to store water, increasing the likelihood that neighbouring communities would flood during severe weather events. Moreover, the ecological ramifications are also concerning because the southeastern basin's separation from the main basin may lead to a major loss of habitat and a decline in biodiversity. In order to overcome these obstacles, shoreline monitoring should be combined with geological and hydrological research to create adaptable lake conservation methods. Thus, unlike conventional techniques, DSAS provides a systematic framework for detecting shoreline changes over time, offering data on spatial patterns of change that are crucial for understanding the interplay between sedimentation, water levels, and lake characteristics. The results of the present study highlight how crucial it is to combine shoreline monitoring with other environmental assessments in order to generate management plans that will effectively preserve Lake Sibaya and comparable systems around the world.

2.5 CONCLUSION

This paper presented the analysis of shoreline changes in Lake Sibaya from 1986 to 2020 using Landsat data series and the DSAS tool, with predictions for the state in 2030. The results revealed a robust retreating pattern of the shoreline, especially in the northeastern arm and between the southeastern and southwestern basins. The most significant shoreline displacement (NSM) is -1338 m and the most considerable shoreline displacement (EPR) is -6 m/year between the southwestern and southeastern basins. This retreating shoreline movement led to the separation of the southeastern basin from the main system in 2015, during one of the extreme drought events in South Africa. Lake Sibaya shoreline was predicted to further decline over the next 10 years. These systems are expected to be temporarily reconnected during good rains. The vegetation on the sandbars separating these systems is developing rapidly, posing a further threat of permanent separation. Further research is needed to understand these implications and other underlying factors involved in this retreat. Integrating Landsat and DSAS data provides a unique opportunity to understand the shoreline variability of Lake Sibaya. Continued advances in sensor technology are expected to add additional value in the

future. The next Chapter will examine the climate and LU/LC changes affecting Lake Sibaya's shoreline using remote sensing techniques.

CHAPTER 3

CLIMATE AND LAND USE/COVER CHANGES IN LAKE SIBAYA, SOUTH AFRICA: ASSESSING SHORELINE CHANGES USING REMOTE SENSING METHODS

ABSTRACT

Lake Sibaya, a freshwater body positioned along the northeast coast of South Africa, has been in decline from 1986 to 2020, and several factors have been partially identified that threaten its lifespan. Thus, an investigation is made in this paper to gain an understanding of the dynamics of the lake in response to changes in Land use/cover (LU/LC) and climatic changes in the area. Specifically, this paper examined the influence of climate change and LU/LC changes on the shoreline reduction of Lake Sibaya. The paper expands on the previous research by using Landsat-derived images, the Modified Normalized Difference Water Index (MNDWI) and the Random Forest (RF) classifier from 1986 to 2020 to understand the changes in the main classes surrounding the lake. The results of the study indicate that over the study period, extreme climate events were exhibited, with drier/wet (El Niño/ La Niña) conditions associated with the retreat/expansion tendency of Lake Sibaya. The intensification of planted forests from 155.2 km² in 1986 to 248.3 km² in 2020 is notable over the study period, corresponding to a reduction in lake water levels from 70.7 km² in 1986 to an alarming 49.5 km² in 2020. Around the 2014–2016 period, temperatures increased to around 32°C, and rainfall decreased to around 568.2 mm, contributing to the lowest lake water levels. Bathymetric and volumetric results show that the lake is mainly affected on the outer, shallow shores, making it more susceptible to erosional changes in these regions. Taken together, the changes brought on by these natural and climatic factors are believed to have influenced the decline of the lake's surface area. The outcomes of this study show that Lake Sibaya's configuration is shrinking and converting to a point where if protective plans are not put in place, the lake might not be able to recover once it has gone beyond its threshold.

Keywords: Lake Sibaya, Landsat, climate change, Remote Sensing, Land use/ cover change

3.1 INTRODUCTION

Inland lakes worldwide contain roughly 87% of the planet's liquid surface freshwater (Gleick, 1995; Verpoorter et al., 2014). These lakes offer vital ecological services beneficial to human populations, including climate mediation, flood mitigation, water storage, and nutrient cycling (Rinke et al., 2019). They also provide educational opportunities, wildlife habitats, water supply, and aesthetics (Beeton, 2002; Brönmark and Hansson, 2002; Tiner, 2005). Though, several lakes worldwide are dwindling or vanishing, and the overall state of the remaining lakes is getting worse, principally due to anthropogenic factors, including excessive reclamation, water contamination, and poor management practices, alongside natural phenomena like climate change and soil erosion (Xie et al., 2010; Mitsch and Gosselink, 2015). So, these changes affect the availability of freshwater, weakening the lakes' economic value and ecosystem functionality (Cui et al., 2013).

Numerous global climate change scenarios and impact assessments have recorded declines in lake water levels and other visible changes (Coe and Foley, 2001; Schwartz et al., 2004; Ma et al., 2010; Mohammed and Tarboton, 2012; Shadkam et al., 2016). Ma et al. (2010) emphasized the importance of monitoring a lake's water level as it is a fundamental sign of its stability. Coe and Foley (2001) and Ma et al. (2010) highlight the role water management techniques play in influencing lake water levels, while Mei et al. (2015) ascribe changes to inter- and intra-annual hydrologic variability. So, recognizing the primary drivers of lake changes—whether human activity or climate change—is essential for developing effective lake restoration strategies.

In South Africa, Lake Sibaya serves as a vital natural freshwater resource that sustains nearby communities and offers essential ecosystem services (iSimangaliso Wetland Park, 2022; SA Ramsar Sites, n.d). However, there are uncertainties regarding the stresses facing the lake due to climate change and LU/LC changes. Research by Bruton and Allanson (1980), Weitz and Demlie (2014), and Nsubuga et al. (2019) reports that over the past few decades, the region has experienced notable shifts in precipitation, with some years witnessing below-average rainfall and others experiencing intense precipitation events. Additional studies by Carnie (2020), Ramjeawon et al, (2020), and SAEON (2023) have established that Lake Sibaya's surface area and water levels have been declining in the previous decades due to human-induced stresses, climate change and LU/LC changes.

To preserve this critical freshwater body, it is vital to understand the precise effects of these factors, as debates about their relative reputation persist. Moreover, determining the reasons for historical and spatial changes in the lake is important for its sustainable management. Consequently, examining water body dynamics using precise data is critical for effective water resource management, helping estimate the water needed to sustain the surrounding ecosystems' natural state (Hagenlocher et al., 2019). Although conventional field techniques offer greater spatial precision, they require significant time and money (Dereli and Tercan, 2020). Fortunately, remote sensing technology provides a solution for monitoring and analyzing shoreline changes due to LU/LC and climate change in freshwater bodies. It offers several advantages regarding labour, time, and expense (Liu et al., 2013; Natesan et al., 2013). Remote sensing methods have been extensively and successfully applied to monitor lake changes caused by both natural and human factors globally (Lyon and McCarthy, 1995; Wright and Gallant, 2007; Junhong et al., 2008; Wang et al., 2008; Bai et al., 2011).

Therefore, the purpose of this paper is to analyze the relationship between the historical shoreline changes in Lake Sibaya over the period 1986–2020 with climatic variables and LU/LC changes. With an emphasis on these variables, the study seeks to determine the primary forces influencing shoreline dynamics in the lake, offering insight into the relative impacts of climatic and LU/LC factors. Such an analysis is essential for guiding the sustainable management of water resources and guaranteeing the ecological and socioeconomic functions of Lake Sibaya are preserved over the long term.

3.2 MATERIALS AND METHODS

3.2.1 Study area

Situated on South Africa's east coast is Lake Sibaya (Figure 3.1) (Ward and Kyle, 1990; Combrink et al., 2011; Humphries and Benitez-Nelson, 2013; Stager et al., 2013). The classified image used was acquired from the South African National Land Cover (NLC) dataset, obtained from the Department of Forestry, Fisheries and the Environment (DFFE) https://egis.environment.gov.za/sa_national_land_cover_datasets. This dataset was selected as it provides an authoritative and comprehensive land cover classification for South Africa, and it served as the foundation for the classification of the Lake Sibaya study area. According to Ward and Kyle (1990), Combrink et al. (2011) and Miranda and Perissinotto (2012), there are five primary divisions within the lake: the main basin, southeastern basin, southwestern basin, northern arm, and western arm. The lake averages a depth of 13 m, a maximum depth of 41 m,

and an average surface size of 65 km² (Pitman and Hutchison, 1975). Lake Sibaya has a water level of ± 20 m higher than the mean sea level and a bottom of ± 21 m lower than the mean sea level. The lake is isolated from the ocean by a coastal dune cordon that runs north-south and varies in height from 64 to 172 mm above mean sea level (amsl) (Miller, 1998).

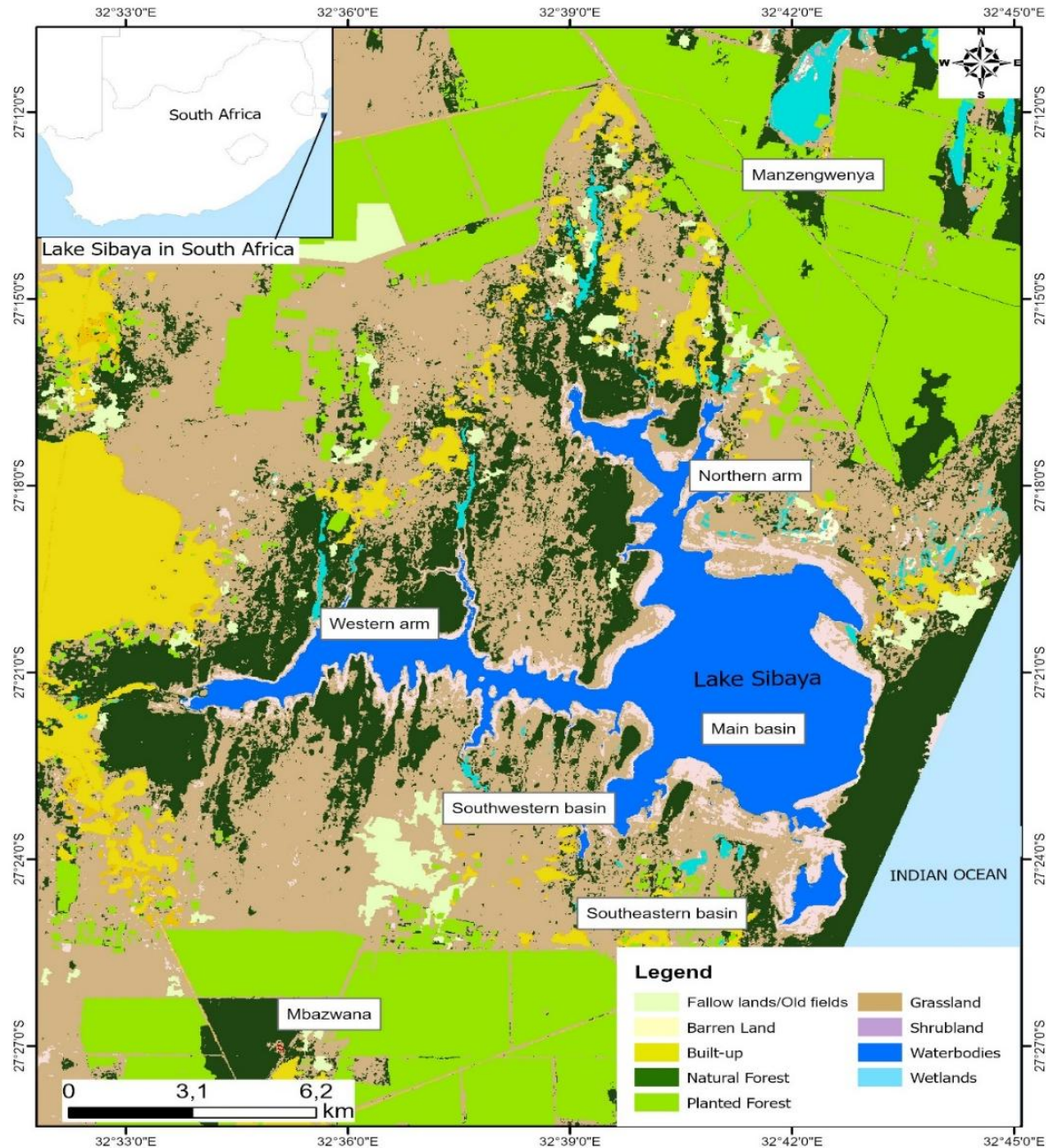


Figure 3.1 Lake Sibaya's location on South Africa's northeast coast.

The lake is situated on a level coastal plain with minimal surrounding terrain rising higher than 100 m above sea level. However, a crucial groundwater aquifer beneath the region's mainly barren and sandy soils has supported the local population and the environment surrounding Lake Sibaya for millennia. The lake, a component of this aquifer, nearly perfectly reflects the

groundwater table, which is significant to the area (Carnie, 2020). The lower water table, relatively flat topography, and sandy catchment substrate all contribute to the intimate interaction between the lake's surface waters and the groundwater. The region is referred to by Midgeley et al. (1994) as a local endorheic area since surface water drainage does not exit the watershed.

Warm summers and a humid subtropical climate characterize the northeastern coastal region of South Africa, controlled by the southern subtropical high-pressure belt (STHP) (Hunter, 1988). Mean monthly temperatures range from 19°C to 27°C (Smithers et al., 2017). The region receives rainfall from both mid-latitude and tropical weather systems. The area exhibits a significant seasonal precipitation pattern, with summertime experiencing tremendous rain. The average annual precipitation (MAP) rises from roughly 700 mm/year on the catchment's western edge to approximately 1000 mm/year near the shore. The Lake Sibaya region has significant potential evaporation rates, which peak in the summer. With significant regional and temporal changes, it receives greater precipitation in the summer (wet season), which primarily occurs between October and March, and less in the winter (dry season, April to September) (Ramjeawon et al., 2020).

The land use activities surrounding Lake Sibaya (Figure 3.1) have a significant impact on its hydrology. The expansion of commercial *Eucalyptus* trees has lowered groundwater levels, especially during dry seasons, changing the lake's natural water balance SAEON (2024). Increased agricultural activity and deforestation in the catchment have also altered the hydrological cycle, leading to decreased groundwater recharge, increased sedimentation and increased surface runoff. These alterations alter the lake's water quality and availability, underscoring the need for sustainable land and water resource management in the region (Weitz and Demlie, 2014; Smithers et al., 2017; SAEON, 2024).

3.2.2 Landsat data extraction

Worldwide, free georeferenced imagery and image processing is provided by the United States Geological Survey (USGS). Hence, this data source was selected to download Landsat-5 and 8 images in this study. The Landsat program is the most extended initiative (since 1972) to collect repeating (every 16 days) multispectral imagery of the Earth's surface (USGS, n.d). To provide precise surface reflectance values, the images were acquired as Level-2 Surface

Reflectance Products (L2SP) that were geometrically and radiometrically corrected to take into consideration the effects of aerosols, ozone, and water vapour.

Images were selected for the dry season as the water level is more stable, images have fewer clouds, and the contrast between water and vegetation is clearer. However, due to the scarcity of cloud-free images, gaps in the historical satellite record, and the rare return durations of older sensors such as Landsat 5, it was difficult to obtain satellite photographs completely from the same season. Consequently, a few images were chosen from periods near the intended season. The analysis could take on inconsistencies as a result, especially when comparing seasons. In order to overcome this, the study concentrated on long-term shoreline dynamics rather than short-term seasonal changes, and pre-processing and normalization techniques were used where feasible.

To guarantee the accuracy and consistency of the images to be used during the analysis process, pre-processing was applied to the Landsat 5 and 8 imagery used in this study. In order to concentrate the investigation and maximise computer efficiency, the Lake Sibaya shapefile was added to establish the study area boundary. This allowed for a zone that was much more focused, reducing the computational load and data. Zonal statistics were further incorporated to examine changes within Lake Sibaya's boundary, making certain that the findings accurately represented spatial differences inside the lake as opposed to the surrounding regions. These procedures guaranteed consistent, high-quality data that could be used for change detection, facilitating the detection of small changes in the landscape of the area over time. By limiting the research to this particular region, we were able to concentrate our efforts on the most important areas, which decreased data noise and increased the precision of our findings. Table 3.1 displays a summary of Landsat image properties.

Table 3.1 Landsat imagery specifications used in the study area.

Satellite	Sensor	Image date	Scene ID
Landsat-5	TM	14 Nov 1986	LT05_L2SP_167079_19861114_20200917_02_T1
		02 Jun 1990	LT05_L2SP_167079_19900602_20200915_02_T1
		12 Mar 1995	LT05_L2SP_167079_19950312_20200912_02_T1
		25 Mar 2000	LT05_L2SP_167079_20000325_20200907_02_T1
		24 Apr 2005	LT05_L2SP_167079_20050424_20200902_02_T1
		20 Dec 2009	LT05_L2SP_167079_20090505_20200827_02_T2
Landsat-8	OLI/TIRS	23 Jun 2015	LC08_L2SP_167079_20150623_20200909_02_T1
		20 Jun 2020	LC08_L2SP_167079_20200620_20200824_02_T1

3.2.3 Multi-temporal land cover classification using random forest

In the field of remote sensing, random forest (RF) is being employed extensively in large-scale, multi-category, multi-feature LU/LC mapping (Li et al., 2020; Rodriguez-Galiano et al., 2012; Talukdar et al., 2020) due to its high classification accuracy of complicated remote sensing images and processing speed (Pal, 2005; Rodriguez-Galiano et al., 2012; Du et al., 2015). Also, RF has significantly lower sensitivity to training data quality and overfitting (Belgiu and Drăguț, 2016; Hemmerling et al., 2021) and removes the necessity for tree pruning (Wei et al., 2021). Due to these benefits, RF was chosen as the classifier for this study.

To construct a decision tree (fundamental classifier), RF uses aggregate guided sampling (bagging) of training data. This represents a collection of distinct base classifiers (Mellor and Boukir, 2017) that are used in assigning a class when combined into a set (prediction) by voting (for categorical data) or averaging (for constant variables) (Breiman, 2001) to the response variable. As each decision tree is built in RF, a subset of predictors chosen randomly from the model (*mtry* parameter) is assessed at each node (split point) to separate the training data into progressively homogeneous subsets. The predictor variables are then used to split the training data to maximise data consistency. The number of decision trees (base classifiers) in the RF set is indicated by the (*ntree*) parameter.

This study used the Random Forest algorithm in Google Earth Engine (GEE) to classify LU/LC. The GEE platform was selected as it is a free cloud computing platform to manage and interpret large geographic datasets (Wagle et al., 2020). GEE gives users access to various earth observation products, such as the historical record from Landsat. Apart from the pre-processed

imagery that is available, users can import and modify other machine-learning approaches that have been deployed (Gorelick et al., 2017; Amani et al., 2020; Tamiminia et al., 2020).

Lake Sibaya boundary shapefile was imported into GEE. Image collections of Landsat-5 for the years 1986, 1990, 1995, 2000, 2005, and 2009, and Landsat-8 for 2015 and 2020 were selected. These images were filtered further to be cloud-free or have less than 10% cloud cover, mosaicked with median composite, and the required bands selected 1–5 and 7 (Landsat 5) and 2–6 and 7 (Landsat 8). Training points on the various classes of water, planted forest, natural forest, barren land, and grassland were collected from Landsat 5 and 8 satellite images. Training points were merged and stored into one variable. The training dataset was created by sampling regions using band pixel value. There were 100 trees set, and the number of predictor variables at each node was determined by taking the square root of the model's input variables (Gislason et al., 2006) which in our instance was 70% and 30% split. 100 trees were selected for the classification model because it is usual practice to use an ensemble method to avoid overfitting and improve model robustness. The RF classifier was created, and the images were classified.

The varying objectives of each image is the reason for the disparity in land cover classes between Figure 3.1 (9 classes) and Figure 3.2 (5 classes). While Figure 3.2 concentrates on the five most pertinent classes (water, planted forest, natural forest, barren land, and grassland) for change detection around Lake Sibaya, Figure 3.1 displays the total land cover classification schema. By capturing spatial linkages and class transitions, Figure 3.2's increased spatial scope facilitates a better understanding of land cover changes.

3.2.4 Accuracy assessment

For every classification performed by the RF classifier, an accuracy measure was carried out using a confusion matrix that indicated the overall accuracy (OA), user's accuracy (UA) and producer's accuracy (PA), as indications. Congalton and Green (2019) state that the overall percentage of classification (OA) is the percentage of units that are correctly classified to the total number of units. In contrast, PA and UA represent the accuracy of single-class classification (Story and Congalton, 1986). The PA and UA refer to the proportion of correctly classified units to validation units and all classified units in a class, respectively, and correctly classified units to all classified units.

$$PA = \frac{A}{A+B} \times 100 \quad (3.1)$$

where, A is the number of pixels that were accurately classified, and B is the number of pixels that were inaccurately classified.

$$UA = \frac{C}{C+D} \times 100 \quad (3.2)$$

where C is the number of pixels that were accurately classified, and D is also the number of pixels that were accurately classified. The overall classification (OA) accuracies were determined by the following equation:

$$OA = \frac{A+D}{A+B+C+D} \times 100 \quad (3.3)$$

The *Kappa* coefficient was also selected with the confusion matrix for the assessment of the accuracies of both the land cover map and reference data. *Kappa* coefficient is computed based on the error matrix using the following equation (Lillesand et al., 2015):

$$\kappa = \frac{N \sum_{i=1}^r x_{ii} - \sum_{i=1}^r (x_{i+} \cdot x_{+i})}{N^2 - \sum_{i=1}^r (x_{i+} \cdot x_{+i})} \quad (3.4)$$

where

r = number of rows in the error matrix

x_{ii} = number of observations in row i and column i

x_{i+} = total of observations in row i

x_{+i} = total of observations in column i

N = total number of observations included in matrix

For the various classes' reference points, 10 were used for Water, Barren Land, Natural Forest, and Planted Forest, while 24 were used for Grassland. Grassland required more points as it covers a larger portion of the area under study and this sample size improves its statistical reliability. The South African Land Cover (SANLC) 2021 dataset was used as a reference map to further validate these classes (Figure 3.1).

3.2.5 Surface area variations

A comparison was examined between the areal extent and the Standardized monthly Niño 3.4 signals to denote a link between the region's shoreline changes and El Niño (La Niña)-related climate change. This was done to establish if the lake surface area increased during La Niña or declined during El Niño periods. The Niño 3.4 Sea Surface Temperature Anomaly allows users to track the evolution of the ENSO phase and is an effective tool (reliable gauge) for seasonal

weather forecasting (Copernicus EU, 2023). One of the most frequently employed indices to characterize El Niño and La Niña episodes is the Niño 3.4 index (Trenberth, 2016). The Standardized monthly Niño 3.4 data and graph were created from the Climate Data Guide from 1986 to 2020. Then, similarities were established between the two.

3.2.6 Analysis of climate parameters

Precipitation patterns are indicative of climatic change. For this purpose, the Climate Hazards Group Infrared Precipitation with Station data (CHIRPS) established by the U.S. Geological Survey (USGS) was used. An exclusive compilation of global precipitation statistics, consisting of *in situ* station data and satellite images with a 5 km resolution, to create real-time, grid-like, precipitation data sets since 1981. Commencing from 2014, these datasets are openly available (Funk et al., 2015). The basis for our decision is on Katsanos et al. (2016), who discovered CHIRPS and rain gauges have good agreement compared to Tropical Rainfall Measuring Mission (TRMM) estimates, which tend to miscalculate precipitation. According to studies led by Moses et al. (2022) in southern Africa, the Eastern Cape province of South Africa (Mahlalela et al., 2020), and the northwest of the country (Thoithi et al., 2021), CHIRPS correlated significantly with observations over the examined regions. The gridded data employed in this study, offer consistency, completeness, spatial representativeness and long-term continuity of climatic conditions throughout the study area.

In this study, the shapefile of Lake Sibaya was imported into Climate Engine. Precipitation data was retrieved for the period 1986 and 2020. In addition, a two-variable graph was created to display precipitation and temperatures in the region over the study period and determine a link between the two. The TerraClimate dataset was selected for the temperature variable as this dataset combines monthly temporal data from 1958 to the present with a fine spatial resolution (4 km (~1/24° per pixel)).

In the study, the Standardized Precipitation Index (SPI) designed by McKee et al. (1993) was then utilized to quantify drought changes over 30 years. The formula for quantifying rainfall deficit for various timescales is given by (Equation (3.5)).

$$SPI = \frac{X - \mu}{\sigma} \quad (3.5)$$

Where X is the monthly climate variable, μ is the mean value over 12 months, and σ is the standard deviation derived from the entire yearly value time series.

SPI was used to measure periods of drought and normal conditions, as well as wet periods from 1986 to 2020 around Lake Sibaya. These time spans reflect how drought affects the availability of various water supplies. Not only does the index calculate various time scales, but it also assesses drought severity and provides early warning of drought (WMO, 2012). According to Arkian et al. (2018), SPI has the advantage of enabling the use of stations that span a variety of recording periods or include gaps in different years and months. Additionally, it enables the user to compare past and present climate occurrences and calculates the likelihood of repetition (WMO, 2012).

The SPI values (Table 3.2) display the classification system McKee et al. (1993) used to describe drought intenseness resulting from the SPI. The basis for calculating the SPI for any locality is obtaining the continuing precipitation dataset for a preferred time frame. After that, the historical dataset is matched to a distribution of probabilities, which is then transformed to a standard deviation to ensure the mean SPI for the selected periods is nil. (Edwards and McKee, 1997). Negative values specify less than average precipitation, while positive SPI values specify greater than median precipitation. Drought, as determined by the SPI, begins when it is equal to or less than -1.0, ends when the value becomes positive.

Table 3.2 SPI values, Precipitation Regime and Anomaly.

Range of SPI Values	Precipitation Regime	Anomaly
2.0+	Extreme wet	Positive
1.5 – 1.99	Very wet	Positive
1.0 – 1.49	Moderate wet	Positive
-0.99 – 0.99	Normal	None
-1.0 – -1.49	Moderate dry	Negative
-1.5 – -1.99	Severe dry	Negative
-2 and less	Extreme dry	Negative

This study used the CHIRPS dataset in GEE to establish the various SPI ranges and precipitation regimes for Lake Sibaya. The selection of GEE was based on Heydari et al. (2024) outcome that to measure drought accurately, the gamma distribution parameters for the SPI are derived using precipitation data from the CHIRPS dataset, which is processed in GEE. For capturing the long-term trends and climate change, a 12-month scale for 30 years was used.

Wind data for this research was obtained from the “interactive” Vortex (<https://vortexfdc.com/> accessed 10 August 2023) and Global Wind Atlas (GWA) (<https://globalwindatlas.info/en/> accessed 10 August 2023) online portals. The GWA has been effectively assessed against other

products, notably South African, demonstrating similarities and high accuracy (Gruber et al., 2022).

3.2.7 Examination of bathymetric data and lake elevation

In this research, the Space Shuttle Radar Topography Mission (SRTM) was downloaded one arc-second (30 meters) South African data from USGS EarthExplorer for the region's elevation. SRTM was selected as it captures one of the planet's most precise digital elevation models (GISGeography, 2017). An elevation map for the study area was then created by mosaicking the raster file, clipping it to the exact extent with the Lake Sibaya shapefile and selecting the appropriate colour ramp. Bathymetric data was derived according to Miller's (2001) most recent bathymetric data, which proposed that the lake's maximum depth was measured at 41 metres. So, using both Miller's (2001) bathymetric and SRTM elevation data, similarities between the two were established.

3.2.8 Investigation of lake-level data

From 1986 to 2020, lake-level data were obtained from SAEON and the Department of Water and Sanitation. Inconsistencies in the data resulted from DWS not having readings for particular months. Updated lake water level data was supplied by (van Rensburg et al., 2024).

3.3 RESULTS

3.3.1 Random forest classifier for multi-temporal land use classification

Figure 3.2 and Table 3.3 display the results of the area changes from land use/cover image classification from 1986 to 2020. Five dominant land use/cover classes were established. The statistics indicate that lake water surface area declined from 70.7 km² (14%) in 1986 down to 52.4 km² (11%) in 2015 and further reduced to 49.5 km² (10%) in 2020, indicating significant changes occurred after 2010. Planted forests expanded from 155.2 km² (10%) in 1986 to 248.3 km² (16%) in 2020. Natural forests expanded from 250.3 km² (11%) in 1986 to 288 km² (13%) in 2020. Barren land increased from 129.3 km² (9%) in 1986 to 210.5 km² (14%) in 2020. Grasslands decreased from 741.6 km² (15%) in 1986 to 560.2 km² (11%) in 2020.

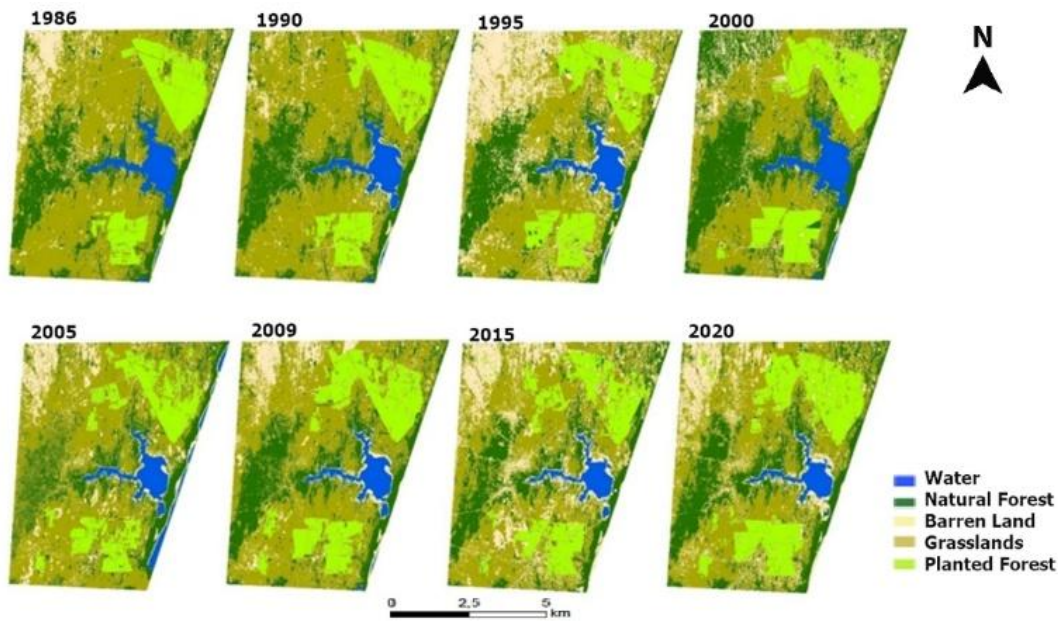


Figure 3.2 Land use/cover classification over Lake Sibaya.

Table 3.3 Statistical values of Land use/cover area changes (km²)

Year	1986	1990	1995	2000	2005	2009	2015	2020
Water	70.7	71.1	66.7	69	61.9	58.1	52.4	49.5
Planted Forest	155.2	173	195.2	236.1	216.1	171.7	179	248.3
Natural Forest	250.3	273.1	246.2	401.3	271.1	235	253.7	288
Barren land	129.3	103.4	334.3	121.9	148	160.2	266.9	210.5
Grassland	741.6	732.2	513	515.9	657.7	711.6	603.7	560.2

3.3.2 Performance evaluation and accuracy of random forest algorithm

In Table 3.4 the results show an Overall Accuracy of 91% and a Kappa coefficient of 88%, which means it has a very high agreement. The Kappa coefficient for water (0.975 = 98%), natural forest (0.974 = 97%), barren land (0.894 = 90%), grassland (0.765 = 77%) and (0.975 = 98%). The highest reliability came from Water, Natural Forest, and Planted Forest ($\kappa \approx 0.97$), while Grassland has the lowest Kappa ($\kappa = 0.765$), suggesting more misclassification occurred here.

Table 3.4 Confusion matrix of *in situ* measurements versus image interpretation.

Image interpretation	In situ measurements						Total
		Water	Natural Forest	Barren Land	Grassland	Planted Forest	
Water		10	0	0	0	0	10
Natural Forest		0	10	0	0	0	10
Barren Land		0	0	9	1	0	10
Grassland		0	1	3	19	1	24
Planted Forest		0	0	0	0	10	10
Total		10	11	12	20	10	64
Overall Accuracy = $58/64 = 0.90625 = 90.63\%$ Expected Agreement = $910/4096 = 0.2222$ Kappa Coefficient = $\text{Overall Accuracy} - \text{Expected Agreement} = 0.879 = 87.9\%$							

3.3.3 Variations in surface area

In Figure 3.3, we show the surface area changes over the lake in each sampled year. The surface covered an area of 70.7 km² in 1986 and expanded to 71.1 km² in 1990. This was followed by a decrease to 66.7 km² in 1995. Subsequent to this, a declining trend was witnessed from 61.9 km² in 2005 to 52.4 km² in 2015, its lowest water level (49.5 km²) in 2020. Overall the lake surface area decreased by 32.5% over the period 1986 to 2020. One of the most precise results of our study is the striking resemblance of lake surface variations to ENSO signals, with peaks (retreats) during the La Niña (El Niño) periods (Figure 3.4).

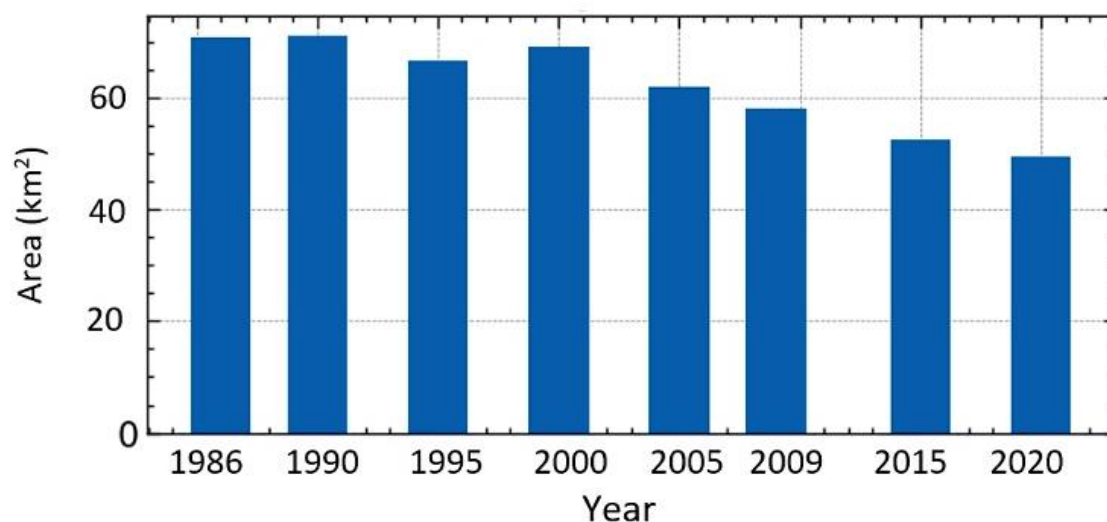


Figure 3.3 Water surface areas for Lake Sibaya calculated by using Landsat-derived MNDWI.

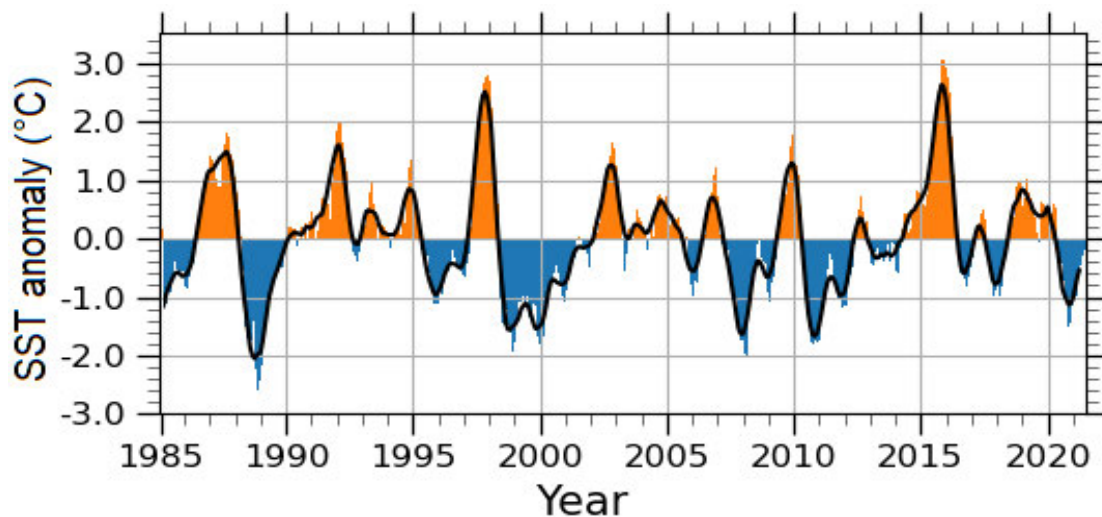


Figure 3.4 Standardized monthly Niño 3.4, showing warm (red) and cold (blue) phases of abnormal sea surface temperatures in the tropical Pacific Ocean from 1986 to 2020.

3.3.4 Climate parameters analysis

Figure 3.5 designates the graphs of the two variables with precipitation symbolized by bars and temperature shown as a line for the periods (1986, 1990, 1995, 2000, 2005, 2010, 2015 and 2020). Statistics of Figure 3.5 are presented in Table 3.5. Figure 3.5 shows a fluctuating precipitation trend throughout the study period, with blue bars symbolizing periods of increased rainfall and the red bars the inverse. In 1986, about 606 mm of rainfall was received, which increased to 1191.1 mm in 2000. Succeeding 2000, a severe decline was seen to 631 mm in 2005, followed by a minor increase to 756.5 mm in 2010. After 2010, an elongated decline was seen, with the worst being 568.2 mm in 2015. Overall, the statistical summary average precipitation was 28 mm/year.

The Lake Sibaya region experienced above-normal temperatures after 2010, with even higher readings occurring around 2014 to 2016. The highest temperatures averaged between 29°C to 32°C were recorded in December, January, and February. Generally, when temperatures were high, rainfall was low.

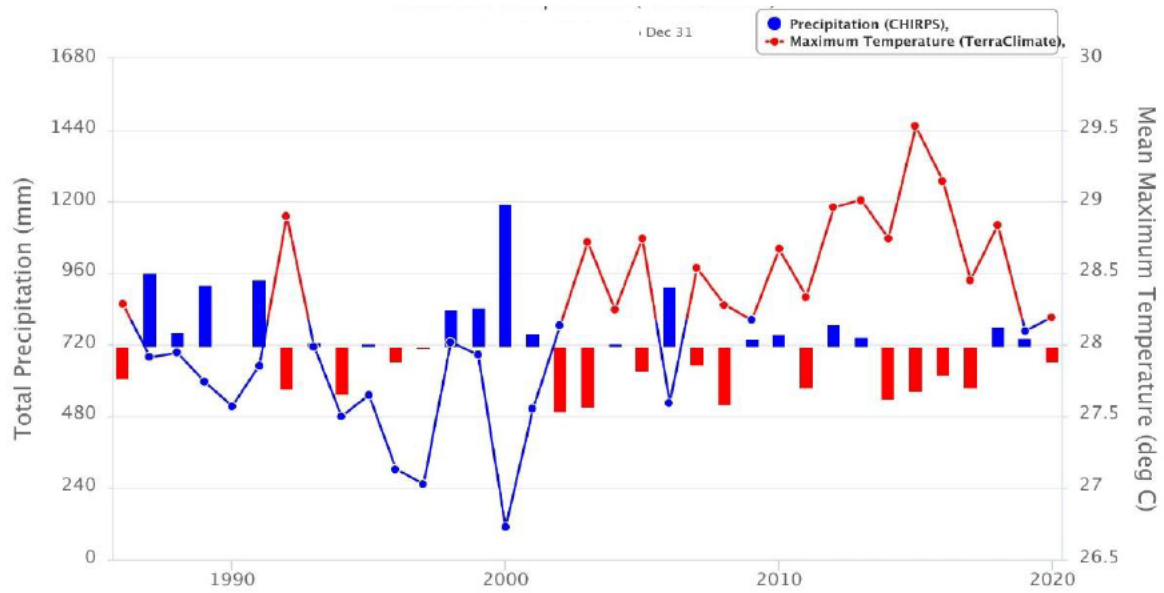


Figure 3.5 Comparison of precipitation in region and mean/max temperature (1986 – 2020).

Table 3.5 Summary of precipitation and temperature statistics (1986–2020).

Year	Precipitation (mm)	Annual Average Precipitation (mm)	Month and Highest Temperature (°C)
1986	606	28.3	Jan / 31
1990	718	28	Jan / 31
1995	723	28	Feb / 32
2000	1191.1	27	Dec / 29
2005	631	29	Feb / 32
2010	756.5	29	Feb / 31
2015	568.2	30	Dec / 32
2020	719.4	28.2	Jan / 32

Figure 3.6 displays the vegetation drought valuation using SPI with a Probability function using GEE and CHIRPS precipitation values (Table 3.5). The calculated SPI for each study period year was 1986 (−0.685), 1990 (−0.109), 1995 (−0.083), 2000 (3.236), 2005 (−0.557), 2010 (0.089), 2015 (−0.880), and 2020 (−0.102). The year 2015 showed the driest period in the recorded dataset. This image indicates how drought periods have affected the lake over the last 30 years.

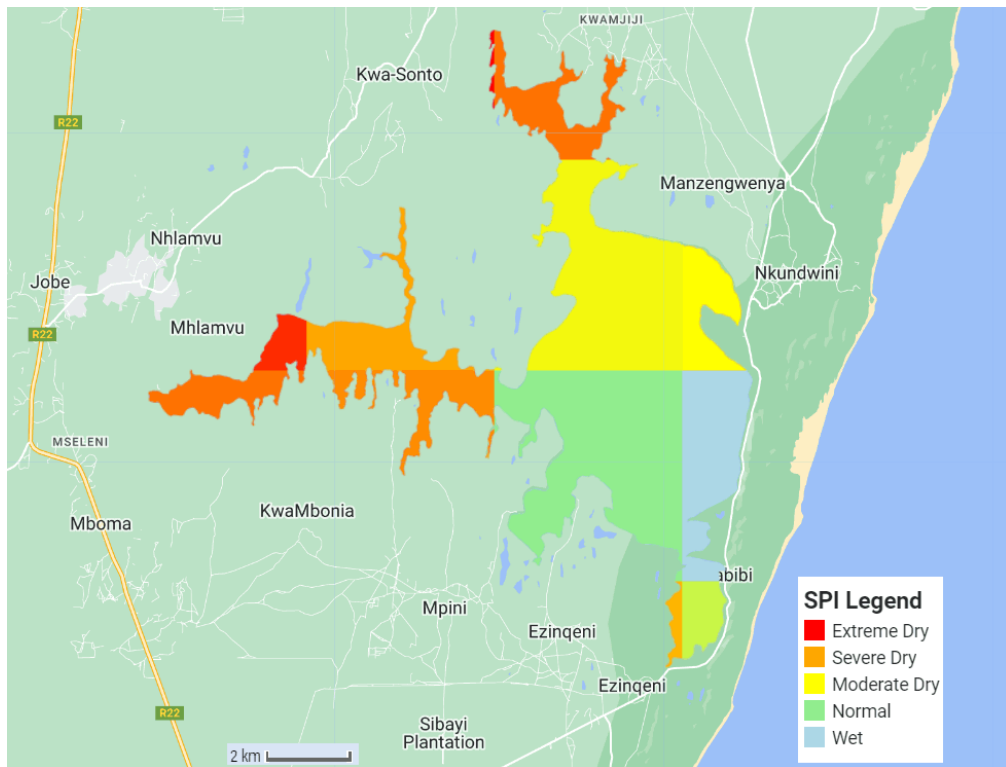


Figure 3.6 SPI results from GEE for the years 1986 to 2020.

The wind conditions over Lake Sibaya from 1986 to 2020 are presented using a wind rose, which characterizes the mean wind dynamics over 6 months at an altitude of 100 m (Figure 3.7(a)). Winds from the south, south-west, north and north-east blow over large parts of the lake at an average of 7 m/s. Strong winds, as indicated by the Wind Index (Figure 3.7(b)), are common in summer and somewhat calmer during winter. Wind-generated currents drive the sedimentary processes within the lake (Miller, 1998).

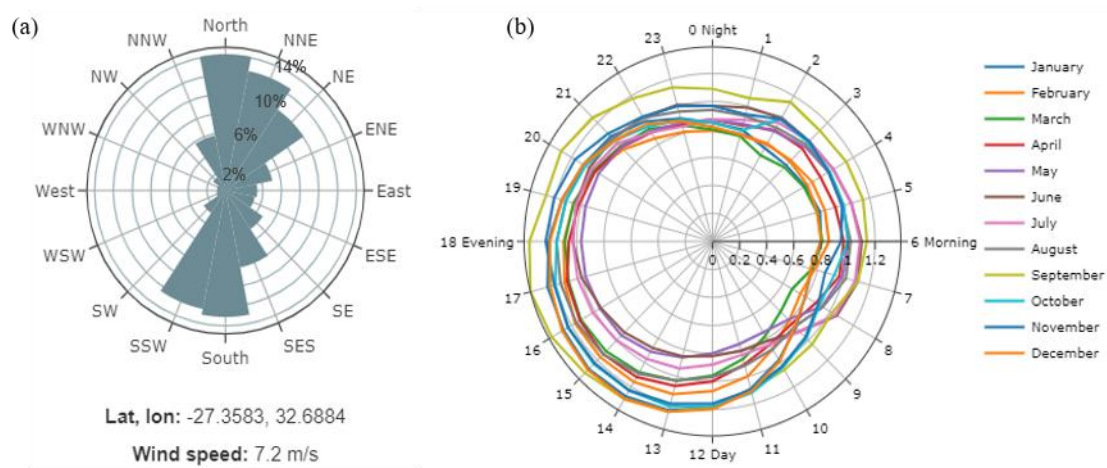


Figure 3.7 Wind rose to show wind direction (a) and hourly-monthly radar wind plot (b) over Lake Sibaya.

3.3.5 Lake elevation and bathymetric data examination

As seen in Figure 3.8(a), Lake Sibaya is an enveloped system with a lower elevation averaging 20 m and increasing elevation on all sides, with a dune corridor (up to 167 m) separating it from the ocean. The sandy subsoil surrounding the lake limits runoff from the surface, and the water levels in the lake are primarily sustained by groundwater recharge (Pitman and Hutchison, 1975).

The bathymetric analysis of Lake Sibaya in Figure 3.8(b), reveals significant changes in water depth distribution over the study period. The interpolated depth model indicates a general reduction in water levels, with previously deeper areas showing a marked decrease in depth. Similarly, Carnie (2020) mentioned that Lake Sibaya lake level dropped from around 20 m amsl in 2001 to around 16 m amsl in 2014, the lowest recorded record over a span of five decades. These results are consistent with the overall decrease in lake surface area.

Spatial patterns of depth change demonstrate that shallower regions along the lake margins have expanded, resulting in a progressive loss of deeper water zones. The most noticeable depth reductions are found in the northern arm, and southern regions of the lake, indicating a stronger influence of land use changes, groundwater abstraction, or climate variability in these areas. According to DWS (2014), many small-to-medium-sized groundwater systems are pumped from the watershed, such as the many hand pumps that draw water from the shallow aquifer for household use. Water withdrawal from the lake started in June 1975 and has increased over the years, with the total withdrawal being $2.8 \times 10^6 \text{ m}^3$ per year in 2014.

Considering the water-human requirements reserve of 25 litres per person per day (NWA, 1998), approximately 1.35 million m^3/a is abstracted for domestic use (Kelbe et al., 2014). Furthermore, a study conducted by the Department of Water & Sanitation (DWS, 2016) established that groundwater in the catchment was primarily used for forestry, which was roughly 6.9 million m^3/year by July 2010, irrigation on a small scale (1.5 million m^3/year), and supplying rural water (1.5 million m^3/year). Various studies have also tried to understand the abstraction levels of Lake Sibaya (Weitz and Demlie, 2015, 2014; Smithers et al., 2017; Everson et al., 2019; Nsubuga et al., 2019; DWS, 2014). However, information on the confidence of these hydrological study results still needs to be tackled.

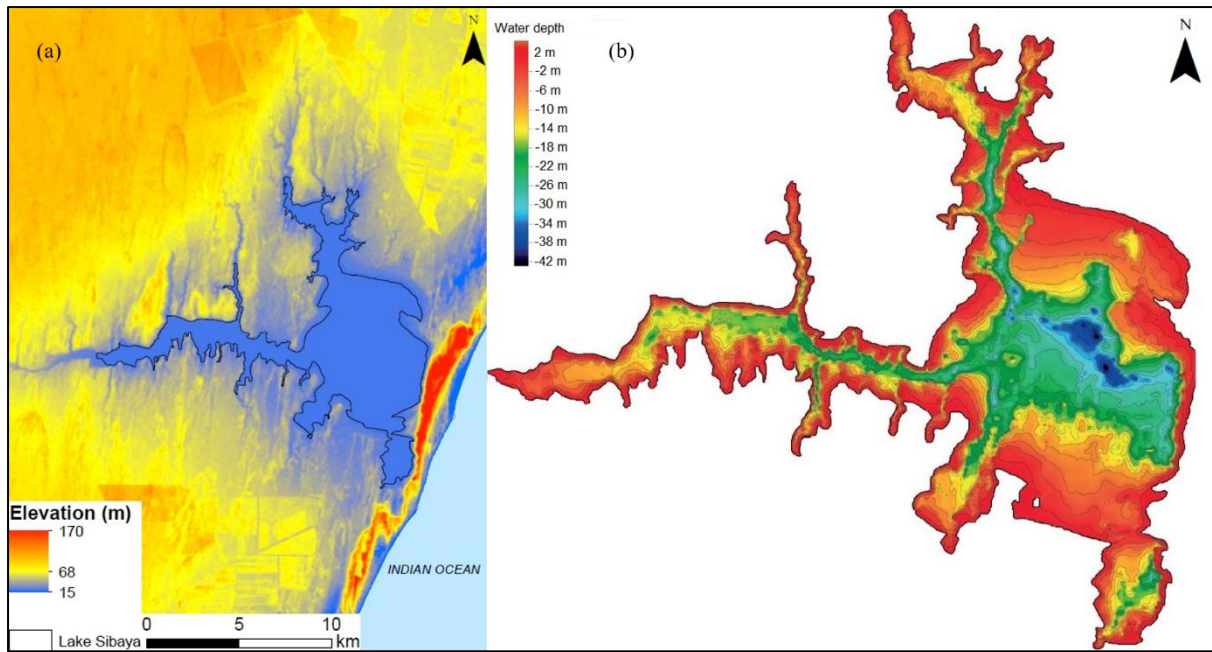


Figure 3.8 Lake Sibaya in an enveloped landscape (a) difference in elevation (b) and the variation of water depth.

Lake Sibaya is relatively shallow on the shore and more substantially deeper in the interior (>40 m) of the main basin (Figure 3.8(b)). Also, shallower water (<16 m) is represented by colours on the warm end of the spectrum: red, orange and yellow. The deepening of the water (>17 m) is indicated by cooler colours that shift through green, light blue and finally into dark blue.

3.3.6 Lake level investigation from 1986 to 2020

Figure 3.9 displays Lake Sibaya's initial water level data received from SAEON at the onset of this study. The trend line shows a fluctuation in water levels from 1986 to 2000. From 2000, water levels progressively declined to the lowest around 2014 to 2016. Even though water levels increased from the 2016 recordings, they have not filled up to surpass the 1986 readings, so Lake Sibaya levels have generally declined over the past three decades. Work carried out by the Department of Water & Sanitation (DWS), in 2016, identified the non-equilibrium state in Lake Sibaya's mean annual water balance elements (in 10^6 m^3): Precipitation on the lake surface (52.5), surface runoff to the lake (4.3), net groundwater inflow (39), lake evaporation (84), seepage from the lake (11.9), abstraction from the Lake (2.8) and change in storage around (-2.9). Together, these factors demonstrated that the system's storage changed negatively between 1980 and 2013. Thus, signifying a decline in the lake levels with major retracting

changes seen since the 2000's. Largely, the study indicated that the average water level decreased from 18.89 m amsl in 1980 to 15.89 m amsl in 2013.

Table 3.6 Statistical results display that the lake reduced from an average of 19.4 m amsl in 1986 to 15.6 m amsl in 2015 and further to 14.8 m amsl in 2020. Inconsistencies in the data are displayed during specific periods throughout the three decades. These results were subjected to change by SAEON while the study proceeded, as Lake Sibaya's water level database was being updated.

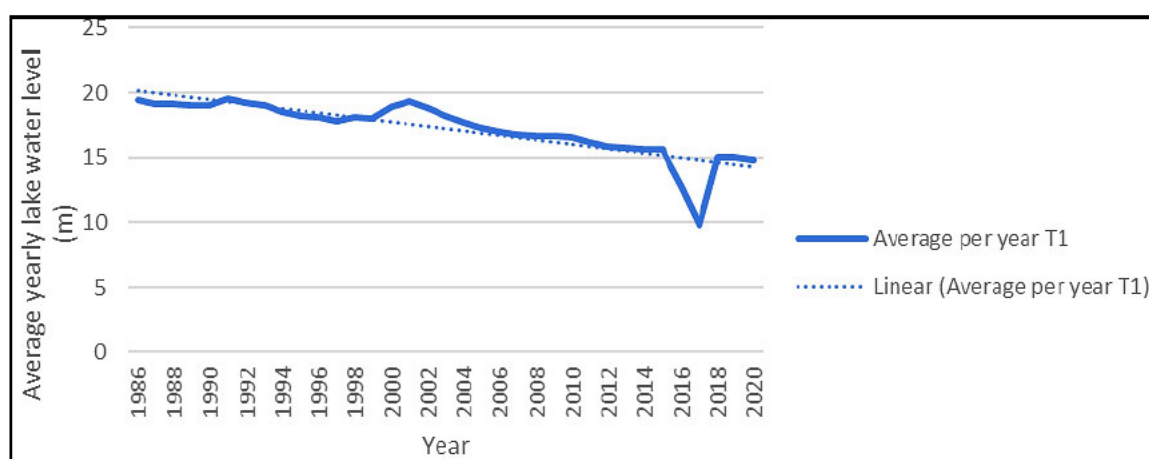


Figure 3.9 Yearly water level and linear water level data for Lake Sibaya.

Table 3.6 Lake water level annual average statistics

Year	Average lake level (m amsl)
1986	19.4
1990	19.1
1995	18.2
2000	19.0
2005	17.3
2009	16.6
2015	15.6
2020	14.8

3.4 DISCUSSION

The results of this study demonstrated that Lake Sibaya exhibited a more significant extent in 1986 (70.7 km²) when its shoreline covered more ground than it did in the subsequent years up until 2020 (49.5 km²). Both climate (natural) and LU/LC (human-induced) changes led to a decrease in the lake's surface area. Studies such as Kock et al. (2019) supported this by concluding that human-induced factors like forestry and rural development caused declining

changes in Lake Sibaya. Humphries and Benitez-Nelson (2013) also attributed dwindling changes in the lake to land clearance and human settlement, altering nutrient and sediment build-up rates over the last 250 years and not natural factors. In contrast, Miller (2001) found that retracting changes in the lake area were principally attributed to natural factors like lake level fluctuations, sediment availability, and wind-generated currents. Also, Walther and Neumann (2011) established that natural factors such as shifts in vegetation due to human activities and climatic variations rather than solely natural causes were responsible for retracting changes in the lake.

3.4.1 Human-induced factors

The natural terrain surrounding Lake Sibaya has been changed by agricultural development and urbanization (Combrink et al., 2011), which has also decreased the area's ability to preserve water. Weitz and Demlie (2015) established that due to changes in land use and increased water consumption, residential areas and tourism growth substantially affect Lake Sibaya's water levels. Lake levels are declining because of increased water usage and changed hydrological dynamics due to urbanization and tourism (Smithers et al., 2017). Also, lower groundwater recharge rates have resulted from the replacement of natural vegetation with plantations of *Eucalyptus* and *Pinus* trees and infrastructure such as residential development and tourism, and roads and pathways, which decreases precipitation infiltration into the soil (iSimangaliso Integrated Management Plan 2022-2031, 2021). The quantity of water that filters into the aquifers that replenish the lake is thus decreased by deforestation and other changes in land cover, which also increase surface runoff.

The densely populated plantations of *Eucalyptus* and *Pinus* lie adjacent to Lake Sibaya (Smithers et al., 2017). This enables their extensive root systems to draw large amounts of water from the lake's subterranean catchment area, thus affecting regions closest to them and creating sensitive zones. Further exacerbating the effects of these plantations on the reduction of the lake's surface area and water levels is their staggering expansion over the past three decades from 155.2 km² in 1986 to 248.3 km² in 2020. According to Allanson (1979), commercial plantations of *Pinus* and *Eucalyptus* that started in the 1950s make up most of the region's modified land use. Pagella et al. (2013) specified that land-use patterns significantly shift due to *Eucalyptus* plantations. Everson et al. (2019) and Ramjeawon et al. (2020) elaborated on this and stated that since 1985, forestry has doubled with a switch from *Pinus* to water-intensive *Eucalyptus* plants. Although *Eucalyptus* may have favourable short-term

economic effects (Nunes et al., 2019), it frequently has adverse long-term effects on the ecosystem, including higher fire risks, depleted water supplies and decreased biodiversity (Sunder, 1993). So, in countries like South Africa, with its water resource “crises”, extra caution is required to counteract these effects as DWS (2018) also declared that it could have a 17% water shortage by 2030.

Concerns about the environmental and social impacts of extensive *Eucalyptus* planting for industrial and social forestry purposes have been voiced worldwide. The hydrological impacts of afforestation are one of this study's main discussion topics. In essence, the concerns by Shiva et al. (1982) and, Shiva and Bandyopadhyay (1985) concentrate on the idea that *Eucalyptus* trees are voracious water consumers who will eventually deplete water supplies. Moreover, in the Nyalazi plantation on the western shores of Lake St Lucia, Brites (2013) established that mature *Pinus* plantations less impacted the groundwater environment. On the other hand, over the course of 13 years, the *Eucalyptus* species demonstrated a notable influence by causing the groundwater table in the plantation area to drop by 10 to 16 metres, or an average of one metre annually.

3.4.2 Natural factors

Lake Sibaya's precipitation and temperature trends were investigated for 34 years, indicating that precipitation levels decreased and temperatures increased, thus contributing to the surface area retreat. Precipitation patterns using CHIRPS data showed an increase from roughly 600 mm in 1986 to 1100 mm in 2000, then decreased to a concerning rate around 500 mm during the 2014/2016 period. Correspondingly, it was determined that two of the leading natural factors contributing to Lake Sibaya's reduction were prolonged drought, particularly South Africa's worst-hit drought of 2014–2016, which was more intense than that of the 1940s (De Jager, 2016), and irregular rainfall (Nsubuga et al., 2019). These factors affected the local groundwater table, and precipitation served as the lake's only recharge source (SAEON, 2023). Furthermore, a study conducted by SAEON (2024) found that the region's precipitation patterns have changed due to climate change and additionally reflect broader international trends (Trenberth, 2011). This has immensely affected the area's hydrology over the previous few decades. These problems will worsen as rainfall fluctuates, making the lake ecosystem more vulnerable.

The lake's maximum temperatures increased from normal (26°C–28°C) before 2010 to its highest (28°C–32°C) around the 2014–2016 drought period. This trend correlates with Nsubuga et al. (2019), who investigated variations in Lake Sibaya caused by climate change and variability and found that maximum temperatures increased in the region from 1996 to 2016. Also, according to observed climate statistics, the annual mean temperature over the lake has been steadily growing over the past 40 years, consistent with the pattern of global warming (Lindsey and Dahlman, 2023). Similarly, global statistics revealed that the 2015 El Niño event led to 2015 being the most hot year on record (Tollefson, 2016). Likewise, increasing temperatures accelerated the pace of evaporation, which further reduced the surface area. Temperature and precipitation variations frequently impact water resources, affecting all industries that rely on water resources directly or indirectly (Estrela et al., 2012). It is thus seen that these climatic factors directly influence lake shaping. Correspondingly, Wang et al. (1998) recognized that temperature and precipitation have the most significant effects on lakes of all climatic parameters.

The ENSO phenomenon largely influences temperature and rainfall in southern Africa (Kruger, 1999; Anyamba et al., 2002). For this reason, Lake Sibaya surface area variations against Niño 3.4 signals were examined, and a link was established between the two. A more robust pattern of retreat was observed during the drier El Niño periods and recovery during the strong La Niña phases. A study by Rouault and Richard (2003) found that South Africa experienced severe droughts that began during a mature El Niño era. The droughts of 1982–1983, 1991–1992, and 1994–1995 seemed to have been the most severe over the preceding 30 years, with the 1991 to 1992 drought being considered the worst on record (Baudoin et al., 2017). Another corresponding study was done by Agri SA (2016) and Xulu et al. (2018), whose findings indicated that the current drought of 2014–2016 was both more severe and protracted than the 1991–1992 episode. Jawak et al. (2015) noted that natural changes impact changes in lake surface area and can, therefore, be used to compensate for disparities in local and global environmental variability.

This research further specifies that Lake Sibaya has a shallow littoral zone, and as you move to the centre of the lake, it deepens. According to Miller (1998), volume and depth beyond 24 m decrease slowly due to restricted areas of greater depth. This makes the larger shallow surface area more sensitive to high temperatures that heat it and cause higher evaporation rates in these regions, thus contributing to the decline of surface area and water level. Lake Sibaya

can shrink due to increased evaporation rates from rising temperatures (Nsubuga et al.; 2019). Additionally, the region's strong winds and high temperatures generate higher evaporation as more water is heated. Strong winds at Lake Sibaya blow mainly in summer, affecting climatic processes occurring over the lake and even changing its morphology. Sedimentary processes influenced by changing water levels and wind-driven currents shape Lake Sibaya's morphology through infilling and shoreline progradation processes connected to the lake segmentation process (Miller, 1998).

Lake Sibaya's average lake water levels initially displayed a decline from 19.4 m amsl in 1986 to 14.8 m amsl in 2020. However, van Rensburg et al. (2024) improved the data quality of these water levels, as displayed in Figure 3.10, by using data from several sources; a new water level record for Lake Sibaya was created to rectify discrepancies found in earlier research conducted by Meyer and Godfrey (2003) and Smithers et al. (2017). Two collaborative infield survey missions by DWS and NRF-SAEON supported this, surveying the region's lake-level gauging stations and boreholes about a standard elevation baseline. Lake water levels were identified to initially have an average of around 19.11 m amsl in 1986, 16.66 m amsl in 2009 and down to 14.66 m amsl in 2020. Corresponding with this lake level decline was Pitman and Hutchison (1975), who recorded low lake level data of 16.20 m amsl in December 1935 and found this low level occurred again in 2011 with a gradual decline succeeding this.

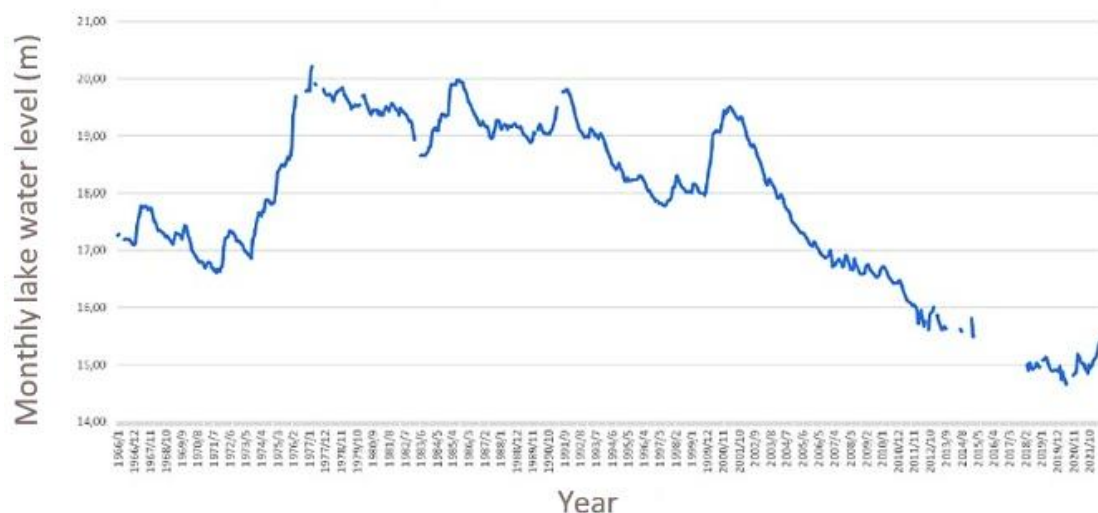


Figure 3.10 Lake Sibaya corrected monthly level data (source: van Rensburg et al., 2024).

Overall, the intricate interactions between anthropogenic activities and climatic change between 1986 and 2020 directly contributed to Lake Sibaya's depletion. Human activities like introducing invasive species, altered land use, and water abstraction further stress the lake's

delicate ecosystem as climate conditions like drought and decreased rainfall worsen. Hence, effective management techniques—such as limited water abstraction, sustainable land use, and conservation initiatives—are essential to reducing these detrimental effects.

Without intervention, the current decline might have severe ecological repercussions and result in more biodiversity losses. This work has demonstrated the effectiveness of using Landsat data and GIS tools to evaluate climate variables and changes in LU/LC that reduce the area and water levels of Lake Sibaya. Future research must incorporate cross-validation and more efficient ways to mitigate erosive processes and safeguard the shoreline, particularly in response to climate-related and human issues.

3.5 CONCLUSION

This study examined climate and LU/LC variations in Lake Sibaya from 1986–2020 to detect significant factors contributing to its decline using remote sensing techniques. The findings demonstrated that fluctuations in climatic patterns, including changes in temperature and precipitation, combined land use/cover modifications such as expanded agricultural operations and deforestation, had a major impact on the lake's shoreline stability and hydrology. The results demonstrated that over 34 years, the water surface area of Lake Sibaya decreased by 21.1 km², from 70.7 to 49.5 km². So, due to the lake being enclosed, with shallow banks, any small changes in its depth can severely affect its spatial extent.

Overall yearly average precipitation declined, making groundwater the only source sustaining lake water levels in the absence or reduction of rain. Drought periods increased and lasted for extended periods, while temperature increased, and both can be attributed to changing climate. As these changes occurred, desertification occurred on the lake banks, and regions of water abstraction, as this is dominant in semi-arid environments. So, as the lake retreated, dunes enlarged and allowed plant species to grow in these regions, causing further implications. Forested plantations are seen as significant contributors to the lake level decline, and more so in the regions where they are planted, creating sensitive areas. The study also established that Niño events positively correlate with changes in the lake shoreline. Thus, the retreat trend in lake level caused by climatic variations and land-use/cover changes have a strong statistical link.

Based on the results of this study, temperatures are anticipated to continue increasing and

precipitation decrease in the region. Therefore, future studies should incorporate remote sensing methods to understand changes occurring in inland water bodies such as lakes as this will contribute positively to understanding their changes in an additionally accurate, efficient and cost-effective manner. Thus, decision-making regarding the sustainable management of these water bodies is enhanced.

CHAPTER 4

SUMMARY, CONCLUSION AND RECOMMENDATIONS

4.1 INTRODUCTION

The assessment and conclusions of the research findings are made in this Chapter. The conclusion drawn here tracks the structure of the purpose of the thesis. As a result, in the first section, each research objective is reviewed and evaluated. The study's findings are then drawn, and the final section provides recommendations and suggestions for further research.

4.2 AIM AND OBJECTIVES REVIEWED

4.2.1 Aim reviewed

This study aimed to analyze three decades of shoreline changes over Lake Sibaya, South Africa, with Landsat data series and the DSAS geospatial tool from 1986 to 2020. The study also aimed to investigate the influence of climate change and LU/LC change on Lake Sibaya dynamics over the study period.

4.2.2 Objectives reviewed

In this section, each objective is revised to reveal how they were addressed through the results generated.

Objective 1: Quantify and map historical shoreline changes using Landsat data series (1986–2020)

To extract historical shoreline changes, Landsat images acquired in 1986, 1990, 1995, 2000, 2005, 2010, 2015, and 2020 were extracted from the USGS EarthExplorer portal. The images for each year were classified using the MNDWI index to separate water and land and then converted from raster to vector in ArcMap to maintain shoreline accuracy while extracting the water body. Then, the polygon geometry of Lake Sibaya was saved for each year. To verify the accuracy of the shoreline extraction results, each polygon was then overlaid with corresponding Landsat images and the boundaries were visually inspected on the screen. To further verify the accuracy of shorelines, polygons were converted to polylines, then converted to KML files, exported to Google Earth Pro and overlaid on matching year boundaries, which visually matched more or less accurately. A decline of lake area from 70.7 km² in 1986 to 49.5

km² in 2020 was noticed. Using Landsat imagery, the study effectively examined shoreline changes over a 34-year span, offering a thorough grasp of how Lake Sibaya's shoreline has changed over time.

Objective 2: Analyze shoreline changes using the DSAS tool and forecast future changes into 2030

The Digital Shoreline Analysis System (DSAS) was used to analyze shoreline changes over 34 years. DSAS enabled the calculation of rate-of-change statistics from the desired historical shoreline positions. It afforded the calculation of the rate of change, supplied the statistical data needed to evaluate the rates' robustness, and comprised a beta model that assisted with calculating future shoreline prediction for a decade. DSAS indicated that the shoreline significantly declined over the study period, and this occurred with a net shoreline movement of -1338 m and an end point rate of -39 m/year, averaging ± 6 m/year. These retracting changes were seen the most in the regions of the northern arm near Manzengwenya commercial forested plantations and in the southeastern basin towards the Mbazwana plantations. Additionally, the expansion of barren land around the lake further displays this retreat. The future shoreline was also predicted to continue declining from 49.5 km² in 2020 to 39.1 km² in 2030, and additionally in the vulnerable regions of the lake that the study identified, with the southeastern basin ultimately diminishing. Fieldwork verification using photos and visible observations was done, and they matched DSAS results displaying these dwindling changes.

Objective 3: Examine the relationship between shoreline changes in relation to LU/LC and climatic patterns

Landsat images acquired for the years in study (1986–2020) were classified using Random forest to establish the dominant land cover classes and quantify their areal extent of change. Sample datasets were selected from different points within the study area, and then the RF model was trained with the data and applied to classify the entire study region. Five main land-cover classes (water bodies, planted forests, grasslands, natural forests and barren land) were established. Noticeable results over the period 1986 to 2020 included: water bodies decreasing significantly from 70.7 km² to 49.5 km², planted forests expanded from 155.2 km² to 248.3 km², grasslands decreased from 741.6 km² to 560.2 km², natural forests had slight expansion changes from 250.3 km² to 288 km², and barren land increased dramatically from 129.3 km² to 210.5 km² over the three decades. The User, Producer and Overall Accuracy were also calculated. RF had an overall accuracy of 91% and Kappa coefficient of 88%.

Precipitation and temperature are two crucial climatic variables that affect hydrological patterns. For this reason, the Lake Sibaya shapefile was imported into the Climate Engine platform, and precipitation using CHIRPS and temperature using TerraClimate data was retrieved between 1986 and 2020 to establish the relationship between the two. It was established that when precipitation increased, such as that of the year 2000 (1191.1 mm), the temperature dropped (29 °C), and vice versa, when precipitation dropped (568.2 mm in 2015), the temperature increased (32 °C). When these precipitation and temperature changes occurred, like increased/decreased, the lake's surface area expanded/declined. Also, a link was established between surface area changes and ENSO signals, with peaks (retreats) during the La Niña (El Niño) periods.

The study effectively investigated changes in land cover/ use surrounding Lake Sibaya, demonstrating the ways in which both natural and human causes have impacted the dynamics of the lake. Shoreline changes were associated with changes in agricultural growth, vegetation and urbanization, providing details on how these variables might have influenced the changes that were detected. The study further determined the possible effects of climate change on Lake Sibaya dynamics, including variations in temperature, precipitation patterns, and water levels. Although climate change's impact was evaluated, more research may be necessary to directly link certain climatic factors to shoreline alterations.

4.3 GENERAL CONCLUSION

The study found that Landsat, with its multispectral imaging and moderate (30 m) spatial resolution, together with the MNDWI index that uses its SWIR and Green band to separate water from land in the images, work well together to assess changes in the shoreline of lakes, and allow for easy assessment of climate variables and land-use/cover that are causing these changes. Added to these two is that the DSAS tool further enables the examination of shoreline change using two critical variables –NSM and EPR to calculate how much of the shoreline has changed, where these changes are occurring and at what rate. DSAS also allows for future shorelines of up to two decades to be predicted using its beta model. These GIS and remote sensing techniques allow for a much clearer understanding of an event occurring that does not physically require a person to be in the area of interest to do the study, as they can be done remotely. This is a tremendous benefit, particularly in isolated or difficult -to-reach areas. They are cheap and do not waste much time on assessments like traditional field surveys, especially

when handling vast areas or gathering extensive data. However, some ground-truthing may still be necessary, depending on the sensor or image resolution. DSAS displayed that the lake shoreline declined dramatically over the study period with a NSM of -1338 m and an average of ± 201 m/year, with EPR occurring at -39 m/year with an average of ± 6 m/year. Vulnerable Edges were established in the regions close to the planted forests of Manzengwenya and Mbazwana.

Further, extracting the Landsat images from 1986 to 2020 allowed for the area to be classified using the machine learning algorithm Random Forest. In this way, we establish the five main land cover classes (planted forests, natural forest, barren land, water bodies, and grasslands), view how they have changed, and calculate their actual extent of change. The accuracy of the classification was 91%. From these findings, water bodies decreased alarmingly while planted forests expanded at a very high rate. Planted forests are causing the most effects in the regions near the lake where they were grown (the northeastern arm and between the southeastern/western basin). Climate Engine was used to download precipitation data using CHIRPS and temperature using TerraClimate data. Precipitation in the region decreased, and temperature increased over the study period, with the most effects occurring during the 2014/2016 period due to the drought around that time. Data such as Lake Bathymetry, elevation, and wind were also assessed. To some extent, all climate variables under study contributed to the lake dwindling over the 34 years.

4.4 LIMITATIONS OF THE STUDY

There were multiple limitations in this study. The examination of inter-annual variations was hampered by temporal gaps in cloud-free data, and fine-scale shoreline changes may have been missed by the 30-meter spatial resolution of Landsat imagery. Boundary precision may have been impacted by the sensitivity of shoreline extraction techniques to seasonal variations and water level fluctuations. Insufficient hydrological and land-use data limited the ability to attribute shoreline retreat to particular factors such as development, or tourism. Further factors that might have affected the accuracy of the results were the DSAS algorithm's assumptions, the lack of localized climatic data, and the restricted validation with in-situ measurements.

In addition, in Lake Sibaya's case, no other studies have calculated the statistics and rates at which the shoreline was reduced. This is due to limited work being done using remote sensing techniques and tools like DSAS in the region, so much referenced work needed to be sought

from international work similar to this study. When compared to coastline studies, little research has been done on mapping inland water bodies, which also made it more difficult to find relatable work, especially regarding declining lakes using DSAS.

4.5 RECOMMENDATIONS

Considering the findings of the research thesis, the recommendations listed below are suggested:

It may be possible to uncover interannual shoreline variation through the analysis of a variety of time intervals using existing data from satellites. In order to develop prospective planning and protection policies, it is essential to thoroughly quantify the water consumers within the surrounding regions of the lake. It involves fine-scale tracking of unauthorised planted forests. Identifying changes in morphology and researching the growth of vegetation on banks are crucial. It is vital to investigate groundwater variability as this will shed some light as to why the smaller bodies of water in this area are recovering, whereas Lake Sibaya is not, thus looking into studies such as van Rensburg et al. (2024) who attempted to rectify water level record inconsistencies could assist.

Eucalyptus and *Pinus* plantations should be discouraged, and they ought to be replaced with eco-friendly, resilient and fast-growing tree species. Examples are the *Populus* (Mapuru et al., 2023) and *Grevillea* species, as well as related (leguminous) shrubs and trees that provide similar goods and services (Desta et al., 2023). According to Ngubane (2005) and SA Forestry Online (2012), an alternative management regime, "small grower" woodlots can be contrasted to large-scale commercial forestry operations such as Tembe TA, Mabasa TA, and Mbila TA/TMM Forestry. TMM Forestry has a proven track record of enabling researchers and is interested in exploring alternatives to *Eucalyptus* plantations. A few *Eucalyptus* compartments are being changed to *Macadamia*, adding more landscape-level "experimental" layouts. The current vast groves of cashew plantings on the Coastal Cashews farm provide another helpful comparison. On this farm, they have openly embraced SAEON operations and promoted using research tools and long-term observations. They support EFTEON activities in the region and on the farm, investigate commercially viable alternatives, and offer more experimentation opportunities. The lake system provides an invaluable hydrological test site with significant social and ecological consequences (EFTEON, 2021).

Furthermore, regions where the lake has retreated are seen to have *Syzygium cordatum* “Waterberry” trees fast expanding along the dried-out lake areas, and this is also a problem as they are also water-loving trees. Further research studies may examine how to prevent the invasion of such vegetation growing on the lake's borders after the water has retreated past specific zones. This can be achieved by employing remote sensing and geospatial tools to perceive to what extent these trees have grown and what strategies can be used to mitigate the widespread effect of these trees. These trees may lead to higher evapotranspiration levels along the border of the lake and, thus, higher evaporation rates of lake water. Also, some regions have increased cyanobacteria (photosynthetic tiny organisms), rendering the lake water unfit for human consumption and its species. More water abstraction from these tree-rooting systems will occur from the lake, further reducing the lake levels and putting the entire ecosystem under intense pressure. Therefore, the hydrological and biological balance of the lake must be preserved.

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