Lake Sibayi variations in response to climate variability in Northern KwaZulu- Natal, South Africa

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Abstract

The optimal management of natural resources like lakes requires understanding the relationship with other environmental elements. Remote sensing techniques using multi-temporal and multi-sensor images for change detection purposes are important in this regard. This study used a combination of approaches to detect changes in the lake surface area of Lake Sibayi in relation to changes in past climates. Delineation of the study area is achieved using WR2012 endoreic maps and Landsat satellite images from 1992 to 2016. Using data from eight meteorological stations past climate of the lake catchment was investigated. Thereafter, a multivariate correlation analysis is conducted to examine the relationship between the changes in the lake surface area and the changes in climatic (precipitation, temperature) variables and water levels. Results suggest that the lake surface area has decreased by 20% since 1992. There are significant changes in temperatures, while the annual rainfall totals declined significantly. The correlation between precipitation in the catchment and annual water level changes is 0.88. Statistically, significant increases in the water level and precipitation were experienced in 1993 and 2001. SPI analysis reveals that the study area is getting drier and the probability of recurrence of moderate dryness is 10%. The rate at which the lake is shrinking is not solely climatic related, as anthropogenic aspects are also responsible. To prevent further shrinkage of Lake Sibayi, it will be necessary to develop aggressive restoration policies and action plans aimed at maintaining inflows in the face of compounding climate change and water demand. Recommendations of the nature of further studies that can increase our understanding are included.

Keywords: Lake surface area variations, climate change, Lake Sibayi, change detection, SPI, PCI

1 Introduction

Lake surface area changes are sensitive to natural changes and consequently serve as proxies for disparities in local environments and variability of global climate. An understanding and evaluation of lake characteristics, including changes in spatial extent, are necessary to achieve sustainable management of water resources (Jawak et al. 2015). This is particularly applicable to a Lake Sibayi, which is a popular tourist destination, with developments around its catchment area that are affecting its hydrological characteristics. Hydrology has a strong link to the climate of a place. Floods, droughts, the water quality, ecosystem and sustainability of water resources are important issues in hydro-climatic interactions. To understand the interactions well and for optimal management of water resources, remote sensing technology and GIS have been used to investigate spatial changes of lakes (Fathian et al. 2016; Nsubuga et al. 2015; Liao et al. 2013; Ouma and Tateishi 2006). There are several change detection studies where satellite-based remotely sensed data are being applied, namely, the estimation of changes in the forestry areas and associated damages (Rasuly et al. 2010; Nel et al.2017a); and using Landsat and ICEsat data to investigate the response of inland lakes to climate change (Zewen 2012). Recently (Nel 2016; Nel et al.2017a) has modelled the trends of informal sand forest harvesting using remote sensing in northern KwaZulu-Natal, partly explaining the anthropogenic observations in the study area. Tiwari et al. (2009) used numerous data sources, including satellite images, aerial photos, and digital elevation models to determine lake area change. Lake area studies have transited from traditional methods of Lake Boundary extraction (Bianduo et al. 2009; Riordan 2006) to automated techniques that rely on density slicing using single or multiple spectral classifications (Bagli and Soille 2004). Space-borne remote sensing technology according to Liao et al (2013) provides an effective way to detect lake changes due to its vast coverage, multi-spectral information, and short revisit period. At the same time, (Alborzi et al. 2018; Arkian et al. 2016; Fathian et al. 2016; Delju et al. 2013; Parvin 2011; Delavar et al. 2008; Ghavidel and Zahedi 2007) have evaluated the meteorological factors influencing lake surface variations. However, less research has been carried out on the relationships between lake surface variations and climatic variables in southern Africa in combination with remotely sensed technology. The objective of the study is to investigate the effect of changes in climatic variables on Lake Sibayi's surface water area. First, we establish whether there are significant trends in temperature and rainfall now and in memory over the Lake Sibayi catchment. Secondly, we determine changes in the lake surface area. Thereafter we examine the long-term changes in rainfall and temperature in the lake's catchment and compare it with the surface water variations.

1.1 Study area

Lake Sibayi (sometimes referred to as Lake Sibaya) is a freshwater resource situated along the northern Kwa-Zulu-Natal coastline, within the uMkhanyakude District Municipality of South Africa. The lake forms part of the iSimangaliso Wetland Park and is of international importance (Combrink et al. 2011). The lake covers an average surface area of 58 km^2 and its catchment extends for approximately 450 km^2 (Weitz and Demlie 2014). According to Combrink et al. (2011), the amaThonga community occupies the surrounding land and lives on hunting, fishing and agro-pastoral activities. Figure 1 shows the location of Lake Sibayi, as well as the nearby meteorological stations and Table 3, gives the basic climatological characteristics and their correlation to the area series. A strong seasonal precipitation pattern is observed in the region with most of the rainfall occurring during the summer months, with over 40% falling in the first quarter of the year (see graph in Fig. 1). As Arkian et al. (2016) state in their work, surface water variations are attributed to changes in hydro-climatic conditions. These conditions are described in the section that follows.

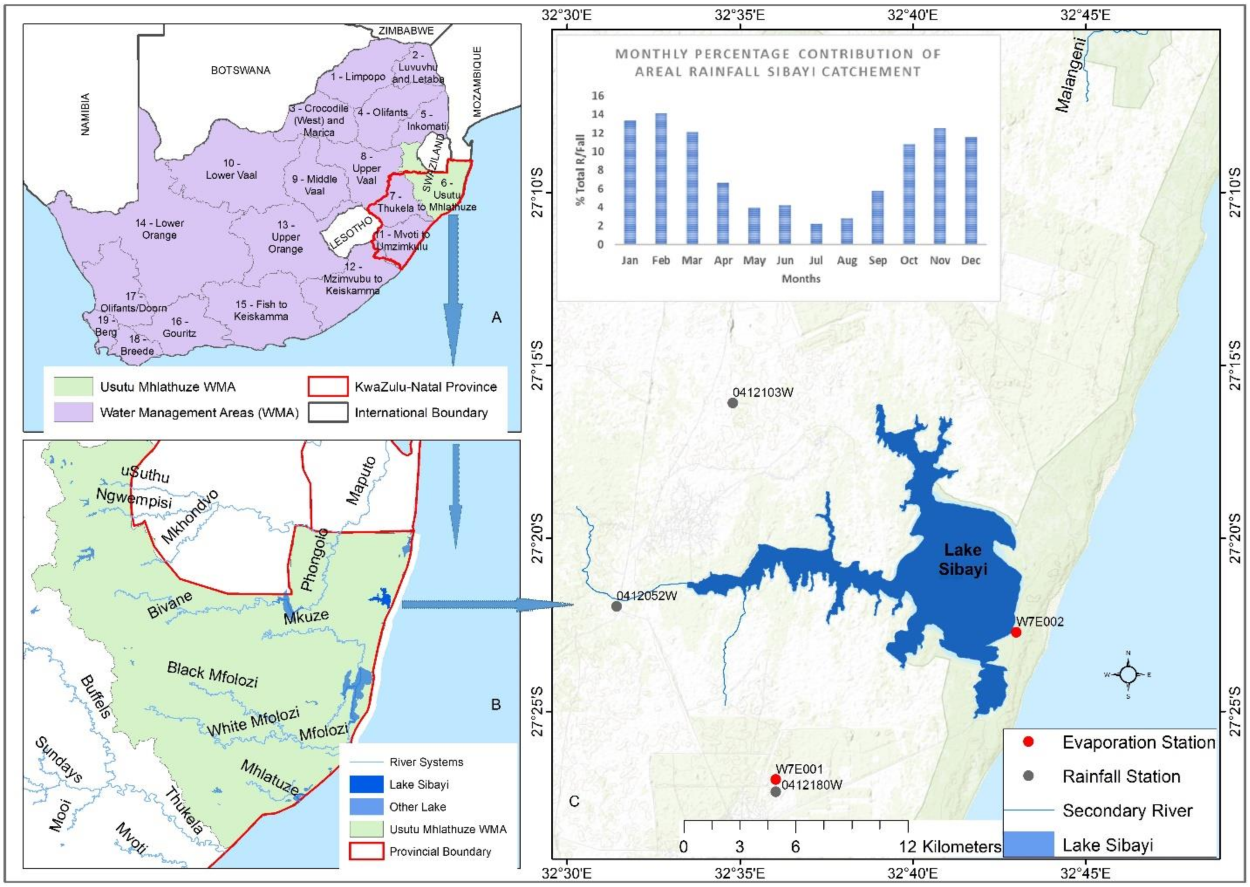


Fig 1. Showing locations of Usuthu-Mhlatuze water management area in South Africa (Map A), the position of Lake Sibayi in KwaZulu-Natal, Mkuzu sub-water management area is indicate in (Map B), (Map C) shows nearby meteorological stations used in the study, and the inset graph of monthly percentage contribution of areal rainfall in the catchment.

1.1.1 The hydro-climatology of Lake Sibayi

The lake is located in Area 6 of the Usuthu-Mhlatuze water management area, demarcated by the Department of Water Affairs (Figure 1, Map B) within the Mkuzu sub-water management area. Rivers flowing into the lake are the Mseleni, Kumzingwane, and Velindlovu. The lake is cut off from the ocean by a series of high north-south trending forested sand dunes, hence having no direct connection to the ocean. Detailed hydro-climatological information, the geological setting, and evolution of Lake Sibayi, which has resulted in the present morphology of incised channels, dendritic nature, shallow depression and coastal dune barrier development are well explained and illustrated in Combrink et al. (2011) and Weitz and Demlie (2014 and references therein). Important to note from their observations is that surface runoff, ground-water recharge and rainfall over the lake, have annually been balanced by evaporation and ground-water overflow to the sea, hence maintaining the lake levels of 20 m above the mean sea level. Determining whether the lake level changes is primarily due to human factors or climate variability according to (Alborzi et al. 2018) has implications for lake restoration strategies hence the study.

1.2 Data and analysis

1.2.1 Rainfall, temperature data, and mean characteristics

Monthly totals of rainfall data recorded at eight stations by the South Africa Weather Services (SAWS), within the Umhlabuyalingana Municipality in the Usuthu-Mhlatuze water management area are used in the study. It is important to obtain some insight into the homogeneity of the record and data quality. To achieve this, six homogeneity tests have been applied to normalized annual and seasonal series. Candidate stations that had more than 3% of missing data were omitted for analysis of the regional average total series. Neither was any treatment applied to the climatological series like in recent literature (Ngongondo et al. 2006; Nsubuga et al. 2014b) to overcome such a challenge. Because missing values do not cause a significant effect on the overall series and unwarranted biases. The Mbazwana Airfield, Swilleys and Phinda had short monthly data length, while False Bay station had the longest (Table 3). Annual and seasonal climate series for eight stations were investigated for homogeneity using six tests. Namely, Von Neuman ratio, cumulative deviations, worsely's likelihood ratio, Bayesian procedures, Mann Whitney and SNHT for a single test (Buishand 1982; Peterson et al. 1998b; Vincent 1998; Wijngaard et al. 2003; Sahin and Cigizoglu 2010; de Lima et al. 2010; Buishand et al. 2013; Nsubuga et al. 2014b). These tests are programmed in AnClim (v5.025), software, accessible from www.climahom.eu (Štěpánek 2008). For $\alpha = 0.05$ and $n = 30$, and the candidate stations were considered useful when three of the tests qualified the hypothesis. The eight stations were combined into a representative regional time series using the steps (1.i, ii, iii, iv) in Table 1 and have been used in the three-month time scale analysis. There are more benefits pointed out by Peterson (1998a) for studies using area averaged time series.

1.2.2 Area-averaged rainfall series

For this study, the original monthly precipitation series were standardised in order to minimise the highly diverse means and variability and the randomness of the convective process reflected in the individual station totals like in (Nicholson 1986; Arkian et al. 2016). Normalisation for each station was achieved by using Eq (1.i) while that of the region by using Eq (1.ii) (see Table 1). Partal and Kahya (2006) support the use of a regional average because it provides a time series that makes it easier to deal with an index series in a region like Lake Sibayi catchment. However, before using the climatological series with confidence for analysis and subsequent discussion, (Kraus 1977; Nicholson 1986; Türkeş 1996) suggest that one has to demonstrate that it adequately represents the region, thus the use of Eqs (1iii & 1iv, Table 1). In order to ensure that data is random and persistent free, autocorrelation (Von Storch and Navara 1995) was used to test for such randomness and independence using the equation in step 2.

1.2.3 Trend analysis

The popular Mann-Kendall (MK) test is applied on temperature and rainfall series to establish trends in observed data for the Sibayi catchment area. After the visual inspection of the climate plot, it was found necessary to investigate changes in mean and median, using the distribution free CUSUM test and the Rank-sum test respectively. All these tests are non-parametric and applicable to distribution-free data. The mathematical description of these statistical tests is found in (CRCCH 2005).

1.2.4 Standardised Precipitation Index

SPI in this study is applied to a normalised time series and calculated on a three- and 12-month timescale. SPIs of these time scales are usually tied to streamflow's, reservoir levels and even ground water levels at longer time scales (WMO 2012). According to Livada and Assimakopoulos (2007), large time scales can reflect on lake water levels and 30-year old datasets may be used. The definition of the index can be followed in Table 1, step 4 in (Edwards and Mckee 1997; Agnew 2000; Livada and Assimakopoulos 2007) and the *Standardized Precipitation Index User Guide* (WMO 2012). The advantage of using the SPI according to Arkian et al. (2016) is that it allows for the use of stations that cover different periods of recording or include gaps in individual months or years.

1.2.5 Precipitation Concentration Index

To understand the monthly heterogeneity of rainfall amounts and its temporal trends, a modified version of PCI by Oliver (1980) in Nsubuga et al. (2014c) was applied (Eq in step 5). The method of computing PCI and the way to interpret the calculated PCI series are explained in Michiels et al. (1992) and subsequent articles such as (de Luis et al. 2011; Valli et al. 2013; Iskander et al. 2014; Nsubuga et al. 2014c).

Table 1 Summary of the steps and associated equations used in data preparation and analysis

	Step	Process	Notes
1	Daily and Monthly rainfall data, obtained from SAWS	i) $M_{sy} = (R_{sy} - \overline{R}_s) / \sigma_s$ ii) $M_{ry} = (1/N_j)\sum_{s=1}^{N_s} M_{sy}$ iii) $v(time) = \frac{\sum N_j M_{ry}^2}{J-1}$ iv) $v(area) = \frac{n - \sum N_j M_{ry}^2}{n-J}$	Normalizing rainfall data series where N_j is the number of regional stations operating in the year *j* It has to be shown that the geographical variations of (M_{sy}) are small, compared to the temporal variations (Kraus 1977, Nicholson 1986, Türkeş 1996)

2	Test for randomness and persistence (von Storch and Navarra 1995)	v) $r_k = \dfrac{\sum_{i=1}^{N-k}(x_i - m)(x_i + k - m)}{\sum_{i=1}^{N}(x_i - m)^2}$	Where r_k is the lag- k autocorrelation coefficient, m is the mean value of a time series x_i , N is the number of observations, and k is the time lag.
3	Rainfall characteristics analysis	Mean and Percentage contribution to annual total rainfall.	Computed for monthly and seasonal time steps.
4	Quantifying rainfall deficit for various time scales (using SPI). (Agnew 2000, Livada and Assimakopoulos 2007)	$SPI = \dfrac{x_i - \bar{x}}{s}$,	Where x is the monthly meteorological variable, $\bar{x}$ is the 3-month mean value, with s as the standard deviation calculated from the whole time series of monthly values.
5	Evaluating the varying weight of monthly rainfall to the total amount of rainfall using PCI	$PCI = 100 \times \dfrac{\sum_{i=1}^{12} p_i^2}{\left(\sum_{i=1}^{12} p_i\right)^2}$	Where p_i is the rainfall amount of the *i*th month, calculated for each of the stations, year, and season under consideration. PCI values below 10 indicate a uniform monthly rainfall distribution in the year, whereas values from 11 to 20 denote seasonality in rainfall distribution.
6	Delineating surface water in Landsat ETM+/TM imagery.	$MNDWI_{L_{2,5}} = (P_{L_2} - P_{L_5})/(P_{L_2} + P_{L_5})$ (Xu,2006; ji *et al*,2009)	where P_{L2} and P_{L5} are the reflectance's of bands 2 and 5.

1.2.6 Lake area and water level data

A number of approaches applied in studies of this nature, on different images from divergent sensors, while extracting information on lakes as listed by Jawak et al. (2015). For this study, radiometrically and geometrically rectified Landsat images from USGS sites (http://glovis.usgs.gov/ and http://earthexplorer.usgs.gov/) that cover scenes (path 167, row 079) for the years 1992, 1998, 2004, 2013 and 2016 were acquired, particularly for the southern winter months of May, June, July, and August. Detailed information of satellite images processed in the current study is listed in Table 2. The study area (243km^2) was delineated by digitising, using the Usututo-Mhlatuze endoreic area shapefile extract for KwaZulu- Natal water management areas (Bailey and Pitman 2016). The daily mean surface water level data for Lake Sibayi (May 1966 to September 2016) was obtained from the Department of Water and Sanitation, Government of South Africa.

Table 2 Detailed information regarding satellite images used in the study

Satellite	**Sensor**	**Date of acquisition**	**Bands**	**Spatial Resolution**
LANDSAT 4	MSS	1992-06-15	1,2,3,4,5	60m
LANDSAT 5	TM	1998-06-24	1,2,3,4,5,7	30m
LANDSAT 5	TM	2004-05-23	1,2,3,4,5,7	30m
LANDSAT 8	OLI_TIRS	2013-07-03	1,2,3,4,5,6,7,8,9,10,11	30m
LANDSAT 8	OLI_TIRS	2016-06-25	1,2,3,4,5,6,7,8,9,10,11	30m

According to the present project aims and based on data availability, remote sensing tools ENVI 5.1, ArcGIS 10.3, were used during the image processing. Remote sensing provides effective information sources for the dynamic change of natural resources such as lakes. GIS has a strong function of data acquisition and editing, storage and management, processing and transforming, spatial analysis and statistics and so on. Subsequently, in the ArcGIS setting, digital layers are created, spatially analysed and final maps produced. Rate of change is derived from change maps for the changes occurring between 1992 and 1998, 1998 and 2004, 2004 and 2013, 2013 and 2016 and an overall change from 1992 to 2016 is reported.

Simultaneously, OriginPro.8.6, Trend 1.0.2, AnClim (v5.025) and Analyse-it tool in MS Excel are used in combination for analyses that followed.

2 Results

2.1 Data quality

Homogeneity tests revealed that rainfall stations (Mbazanwa Airfield, Swilleys, Phinda and Hlabisa SAP) were suspect and thus not used in trend analysis. The rejection of the four stations can be attributed to relatively shorter periods despite the method of transformation as explained in (Buishand 1982; Buishand et al. 2013). The surface water level data was considered suspect after failing the homogeneity tests, and therefore not analysed for trend. The literature could not guide us further on who has faced a similar problem and how they went about it. Probably more data on isostatic behaviour and outflow regulations that affect the water levels (Gronewold et al. 2013) could have provided insight but it was not available. The surface water level data has been used to support findings from other techniques. Based on the arguments of Peterson et al. (1998), the difference in trends between homogenised and unadjusted data can be enormous at individual stations and significant in regional analyses time series, hence the consideration.

2.1.1 Catchment area climatology

Table 3 Characteristics of monthly rainfall data which contribute to area climatology of the study area

Station Name	**Makatini**	**Mbazwana Airfield**	**Swilleys**	**Phinda**	**Sodwana Bay**	**False Bay Park**	**Hlabisa Mbazwana**	**Hlabisa SAP**
Station ID	04113232	04121486	N/A	N/A	03763027	03756884	04121800	03386682
Data length (months)	420	228	240	216	444	780	768	468
% Missing	1.2	2.1	45	3.2	49	2.05	2	9.6
Climatology mean total	591	719	388	721	565	734	973	869
Station's % contribution to reg. mean	10.6	12.9	7.0	13.0	10.2	13.2	17.5	15.6
Monthly correlation to area rainfall climatology series								
Jan	0.75	0.65	0.58	.67	0.55	0.57	0.57	0.46

Feb	0.73	0.62	0.61	0.62	0.49	0.68	0.73	0.56
Mar	0.78	0.74	**0.31**	0.73	0.63	0.77	0.80	0.40
Apr	0.70	0.53	0.41	0.71	0.61	0.61	0.64	0.36
May	0.72	0.25	0.47	0.47	0.56	0.84	0.81	0.74
Jun	0.77	0.71	**0.20**	0.77	0.60	0.84	0.83	0.42
Jul	0.78	0.57	**0.20**	0.67	0.62	0.60	0.67	0.44
Aug	0.71	0.62	**0.19**	0.63	0.45	0.85	0.64	0.51
Sep	0.85	0.74	**0.24**	0.74	0.63	0.81	0.79	0.54
Oct	0.82	0.70	0.45	0.67	0.69	0.55	0.62	0.51
Nov	0.53	0.82	0.52	0.79	0.80	0.63	0.72	0.60
Dec	0.78	0.66	0.43	0.74	0.64	0.51	0.57	0.41
Station monthly correlation to the mean area climatology	0.90	0.66	0.66	0.71	0.74	0.57	0.49	0.46

The correlation results, shown in Table 1, demonstrate that the mean regional climatic series adequately represents the area around Lake Sibayi. Notable differences are in the monthly series, especially for a station like Swilley, whose correlations are below 0.4 (bold in Table 3) in March, June, July, August and September. As argued by Nicholson (1986), the correlation of a series below 0.4 is not good for consideration in a regional climatic mean series. Using a regional average filters out the noise apparent at individual stations (Arkian et al. 2016). For the 12-month timescale analysis, three series (i.e. Mbazwana Airfield, Swilleys and Phinda) were eliminated because the series were short compared to the others and exerted a great influence on the regional climatology series.

Evidence from Fig. 2 shows that the catchment received above average rainfall from 1987 to 1991 and 1997 and 2000. The plot reveals a precipitation maximum in the year 2000 and a drastic decline in year 2002; thereafter, rainfall has been average year after year for six years. A personal conversation with Jeremiah Ndaba, a pensioner with KwaZulu- Natal Wildlife, revealed that by 1988, the time he started working around Lake Sibayi, the water levels were high. Historical data on the surface water levels also supports this (Fig.4). A closer analysis however reveals that, during this time there was a climatic event which climaxed in the year 2000 (see also figure 3). This event and associated tropical weather systems which moved over the northern provinces of South Africa is explained in (Dyson and Heerden 2001; 2002; Kruger 2006; Dyson 2009). From 2007, rainfall variability was high in the catchment. Various studies inform Kruger (2006) of the significant increase in extremes and inter-annual variability of precipitation over specific areas in South Africa.

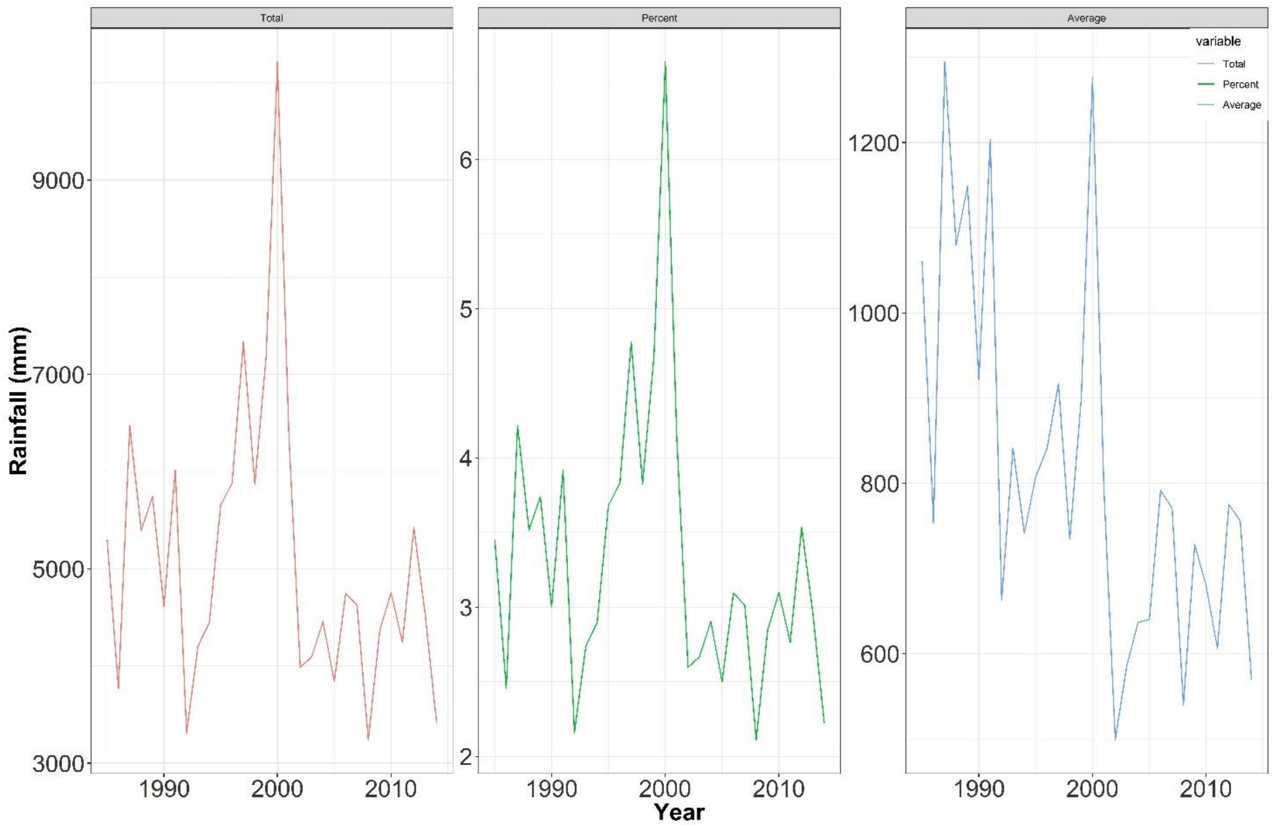


Fig. 2 Figure showing total, average and percentage contribution of rainfall for Sibayi catchment.

Using the SPI drought intensity classification scheme proposed by Mckee et al. (1995) and mentioned by Xie et al. (2013), the regional average climatological series plot shows that rainfall in the catchment is near normal. The catchment experienced a very wet year in 2000 (Fig. 3). We note that the SPI allows us to determine the rarity of a drought or an anomalously wet event at a particular timescale. For this location, negative intensity of -1.0 or less is evident in 1986, 1992, 2008 and 2014. It is hard to conclude that the catchment experienced serious drought as per (Mckee et al. 1995, WMO 2012) definition, because the sub-basin has been moderately dry. According to WMO (2012) SPI, allows the user to confidently compare historical and current climatic events and determine the probability of recurrence. This study concludes that moderate dryness (SPI value in the range -1.00 to -1.49) has a 10% probability of recurrence in the Sibayi catchment.

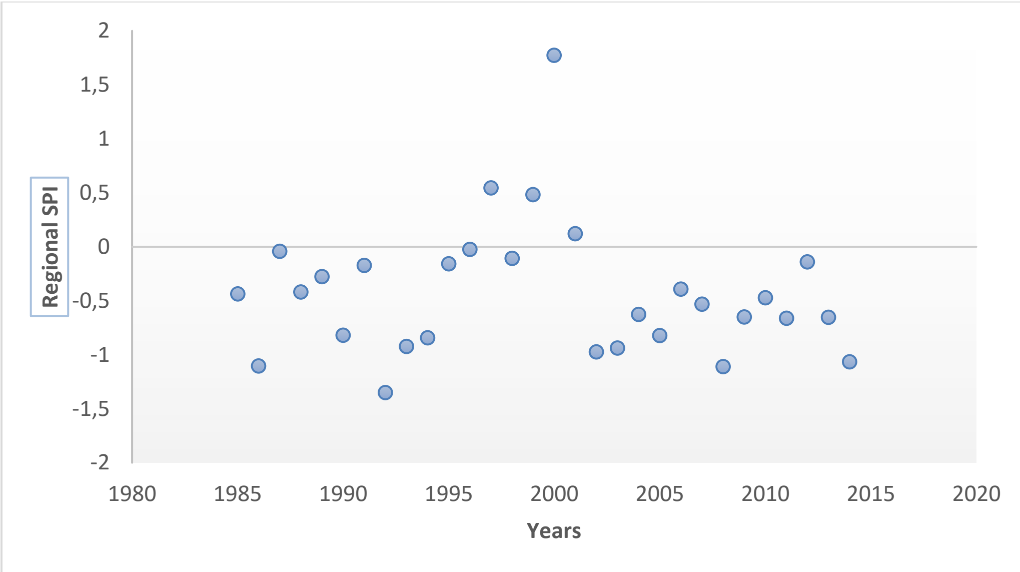


Fig. 3 Standardised annual precipitation anomalies for the Lake Sibayi catchment 1985 to 2014

Figure 4 shows consistency in SPI of the regionally average monthly values for the years under consideration and period 1987 – 2001 is captured as an unusual event in the area of study. The Mann-Kendall test on the same series shows a decrease in the rainfall (z statistic = –1.2) but not a statistically significant trend at 90%. The distribution-free CUSUM test indicates a statistically significant increase of rainfall in 2001 (at a < 0.1) and that rainfall in earlier years was higher than in later years. This is further confirmed by the Rank-sum test that shows that the median of 2000 to 2014 > 1985 to 1999 and that they are significantly different.

2.1.2 Trends in temperature and rainfall over the Lake Sibayi catchment

The areal temperature series were exposed to the Mann-Kendal trend analysis, which revealed that the average minimum temperatures (Ave.Tmin) and maximums of the minimum temperatures (MaxTmin) have experienced a significant decreasing trend, while the other series show trends that are not significant at the 5% confidence level (Table 4). A decreasing trend in the minimums is an indication of warming in the last 20 years. Further exploration of temperatures revealed that the maximums of the maximum temperatures (MaxTmax) have experienced a significant increasing trend at the 5% confidence level (Table 4) for Mbazwana and Makatini stations.

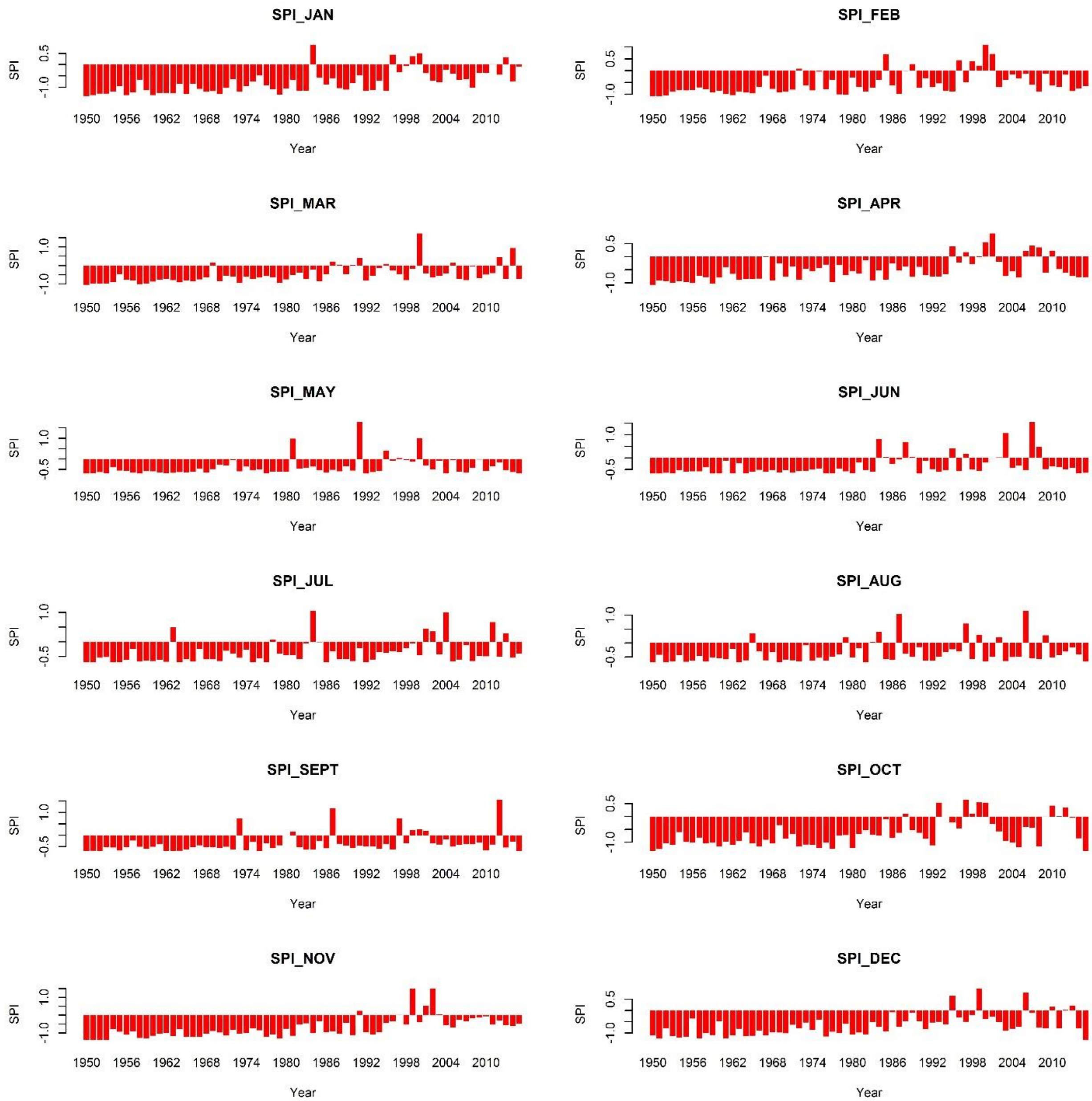


Fig. 4 Standardised regional average monthly precipitation anomalies for the Lake Sibayi catchment 1985 to 2014

Table 4 Trend (Z) values for Mbazwana and Makatini temperature series. Bold figures indicate Z-values that are statistically significant at the 5% level.

	Ave.Tmin	**Max.Tmin**	**Min.Tmin**	**Ave.Tmax**	**Max.Tmax**	**Min.Tmax**
Mbazwana	(Z= **-2.09**)	(Z= **-1.714**)	(Z= -0.735)	(Z= -0.91)	(Z=-0.105)	(Z= -0.84)
Makatini	(Z= -0.59)	(Z= -0.85)	(Z= -1.15)	(Z= **-2.23**)	(Z=-1.47)	(Z= -1.56)

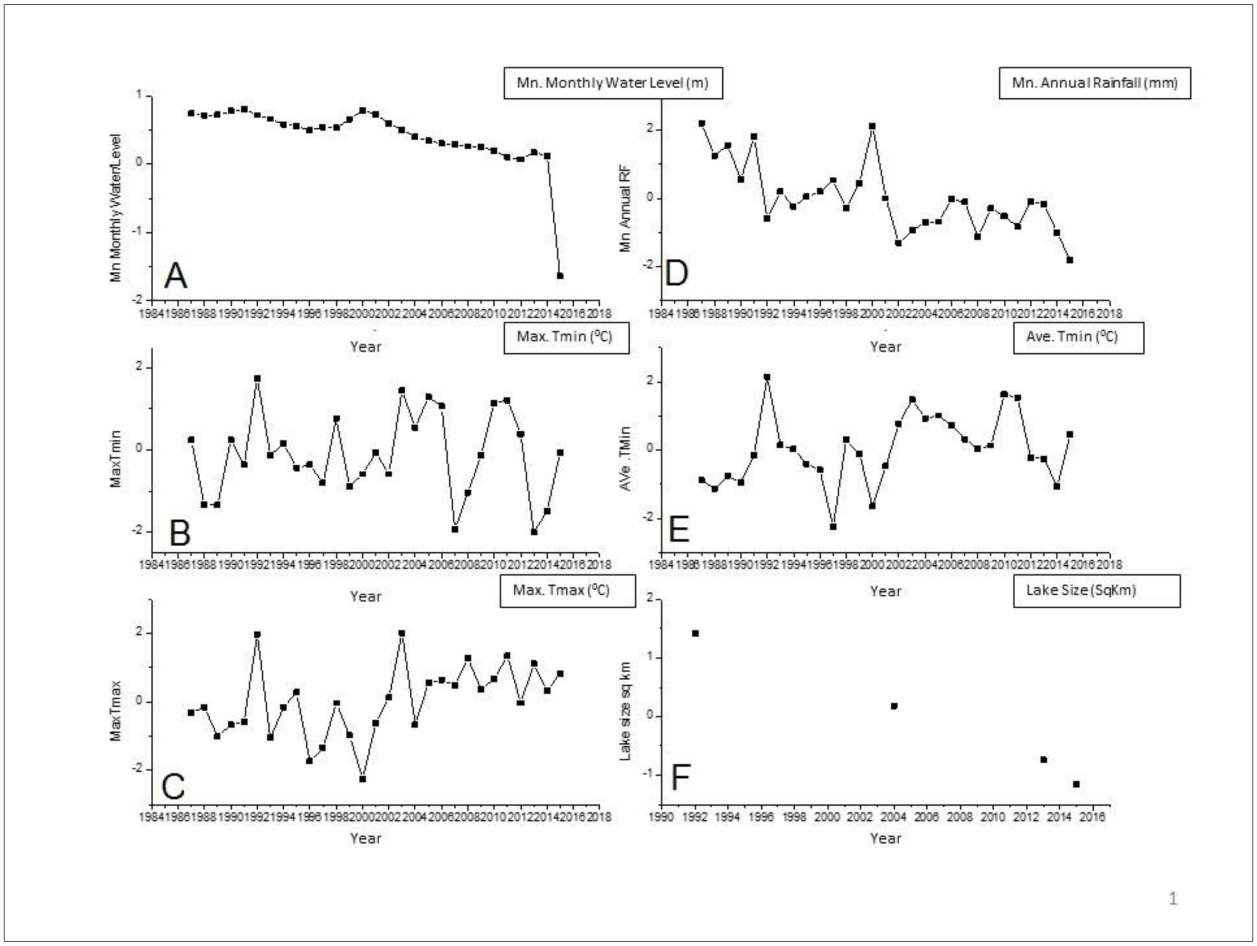


Fig. 5 Anomalies of variations in the annual mean water level(A), maximums of minimum temperatures(B), maximums of maximum temperatures(C), mean annual rainfall(D), average minimum temperatures(E) and the lake size of Sibayi(F).

An increased trend in the maximum temperatures coincides with the findings of (Kruger and Shongwe 2004; New et al. 2006; Kalumba et al. 2013) who indicated that temperatures were warming for southeast and West African countries.

The concentration of rainfall in a year is an important aspect of climate in water resources planning, especially when its distribution is balanced (Nsubuga et al. 2014c). The rainfall concentration can be well understood by using a statistically derived index (PCI) which quantifies the relative distribution of rainfall patterns. Seasonal concentrations for the study area was in the range of 11 to 21, except for the year 2002 which indicated a PCI of 9.4 – implying that the Usuthu-Mhlatuze area generally experiences a moderate to seasonal distribution. The temporal analysis of the study area reveals a PCI of 3.6, which is below 10, thus showing a uniform concentration for the period under analysis.

3 Lake area change

Lake Sibayi area has evidence of intra-annual and inter-annual variation between 1992 and June 2016. The delineated area of Lake Sibayi shrunk by 12.96 km, which is a 5% shrinkage in a span of 12 years (i.e. 1992 to 2004). By June 2016, the percentage area occupied by the lake was 24.23%. Changes in the percentage of the surface area over the years are illustrated in Table 5, and in images shown in Fig. 6 and 7 below.

Table 5 Percentage Change of water surface area of Lake Sibayi during the winter months of 1992 to 2016

Year and date of detection	Size (km^2)	Percentage area
1992 June 15	83.77	34.5
1998 June 24	73.16	30.11
2004 May 23	71.76	29.5
2013 July 03	62.50	25.72
2016 June 25	58.87	24.23

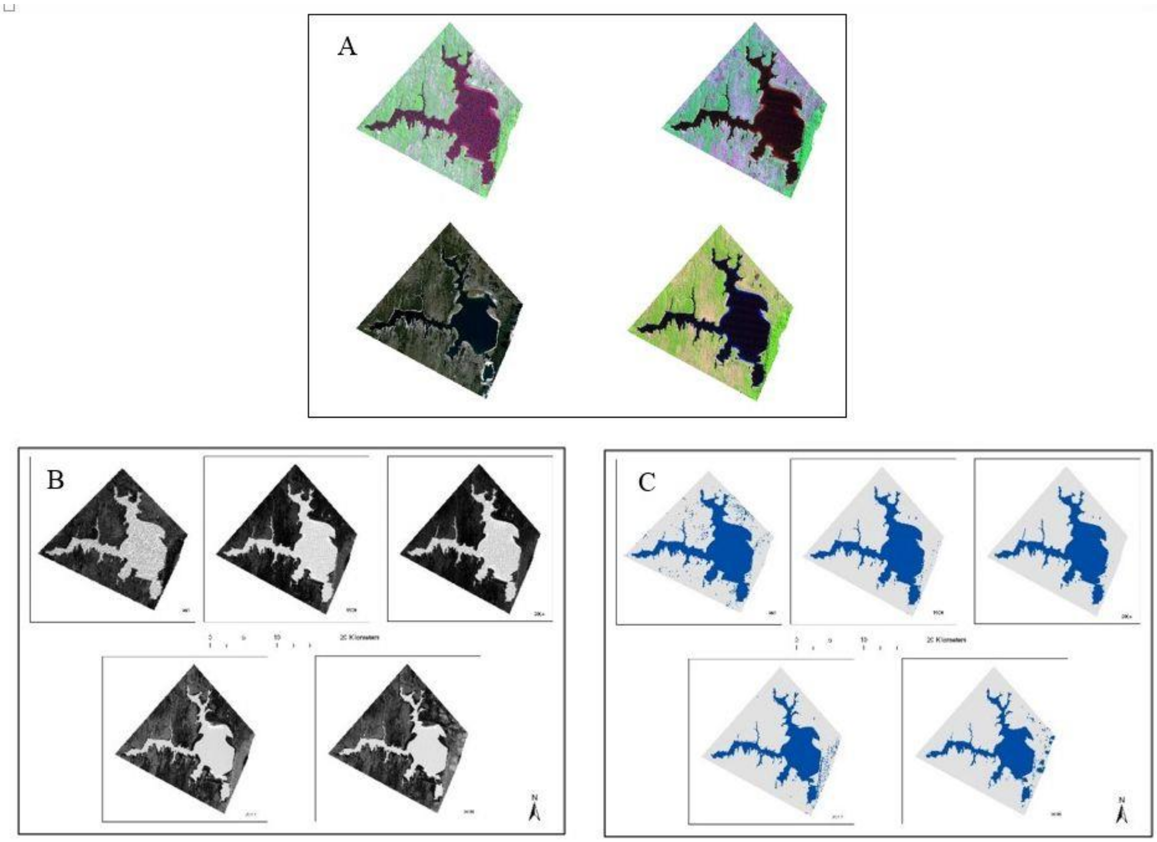


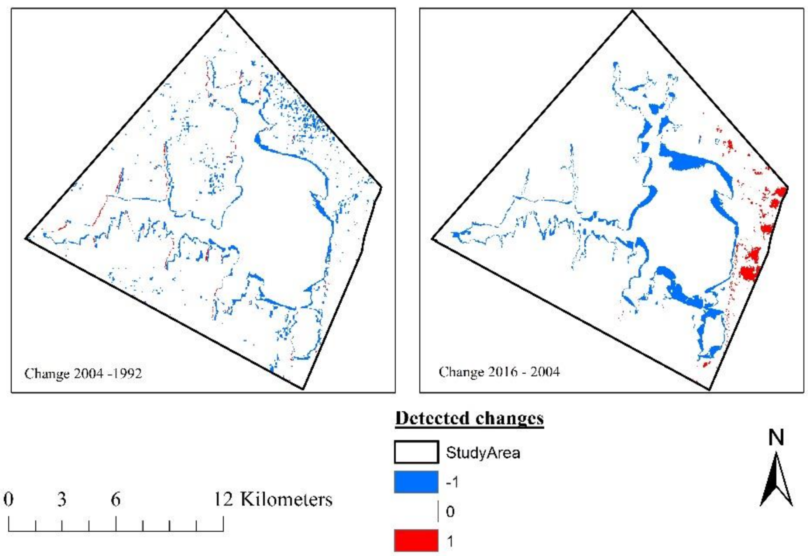
Fig. 6 Satellite output images prior to (A, B) and after calculating (C) change in the surface water area of Lake Sibayi sub-basin. Lake Sibayi sub-basin delineated images of 1992, 1998, 2004, 2013, 2016 using band combination 7,4,2 (A); the images in (B) have been enhanced by the MNDWI, while(C) shows reclassified images indicating a change in the surface water area.

3.1 The relationship between lake area changes, hydro-climate variables, and human activities

In order to support surface water management efforts and prevent Sibayi lake from deteriorating, it is important to know what has caused the recent shrinkage of the lake. Studies elsewhere in the world (Hassanzadeh et al. 2012; Fathian et al. 2015; AghaKouchak et al 2015; Shadkam et al. 2016) have indicated that a combination of climate variables, inflow reduction, climate variability and water resource use, can cause lake shrinkage. Some of these studies based their findings on assessing basin SPI, others were able to carry out simulations e.g on stream inflow and outflows. While (Fathian et al. 2015) was able to establish the magnitude of climate variables and thus determine their sensitivity on the resource. They come to a conclusion that climate change is at play. This study is not far from concluding that, the detected trend in this study is likely to belong to a long-term change in climate in the area. The main elements that relate to the water level change of a lake, according to Bian et al. (2009) are either direct (e.g. rainfall, ice, snow) or indirect (e.g. temperature, size of the lake, catchment area). Lake level fluctuations also depend on intra-and inter-annual hydrologic variability and water management practices in the lake basin (Alborzi et al. 2018). Reducing water levels according to Gronewold et al. (2013) can also be attributed to isostatic adjustments and outflow regulations.

The study finds that, water input into Lake Sibayi is a combination of precipitation in the surrounding catchment, which arrives as run-off, as well as that over the lake itself. To understand the variability, multi-decadal hydro-climate areal time series (rainfall, temperature, water level) from neighbouring gauge stations have been used in the study. For the sake of brevity, the discussion focuses on the mean annual trends in the past 35 years. The catchment does not have a broad hydro-climatic network, so long-term data was only available for two stations. By comparing long-term rainfall (1981 to 2015) and the mean annual lake surface water level (1967 to 2015) we assessed the relative contribution of these variables to the declining trend. The analysis revealed a decreasing trend for aveTmin and the maxTmin and an increasing trend in maximum temperatures which is in agreement with other studies that assessed temperature trends in south and eastern south Africa(Kruger and Shongwe 2004; Kalumba et al. 2013). Warming temperatures can favour an increase in the evaporation rate that may contribute to a reduction in lake size. The Cusum test indicates a statistically significant increase (at $a < 0.01$) in 1993 for the water levels whereas that of the rainfall in 2001 was not statistically significant. A Ranksum test on the medians of the two variables indicated that 1981 to 1997 is greater than those of 1998 to 2015. One would have expected to see a reflection of El-Nino rains of 2000 in the medians, but it is not the case, meaning that there could be other factors at play. Data shows that the lake levels do not recover after the years of very low rainfall – even after the extra-ordinary rains of the year 2000 in KwaZulu- Natal. The area experiences a strong seasonal rainfall distribution which coincides with what (Kruger 2006) have found for some areas in South Africa. For most lakes, inter-annual variability in rainfall according to Arkian et al. (2016) is not reflected in the lake level but in the annual change. A principal component analysis (PCA) revealed that the correlation over a 51-year period is 0.88, indicating that rainfall could explain the year-to-year variability of the lake levels. Coefficients are high for the first component (water level) and aveTmin (0.53). The second component (rainfall) has high coefficients with aveTmax and lake size. The estimated mean annual evaporation is between 1300 and 1400 mm. Weitz and Demlie (2014) discovered that the mean monthly and annual water balance of the lake is in the negative. Furthermore, the lake area has shrunk by 10.3% between 1992 and 2016. The extremely low lake levels in recent years is attributed to increased water abstraction by many economic activities that have sprung up (tourist related) and the reduced forest vegetation in the catchment (see also Nel 2016). Significant land use changes, for example, commercial forestry, subsistence agriculture and human settlements have occurred around the lake recently. This is visible on the 2013 and 2016 Landsat images (not shown here). Loss of vegetation can be attributed to wildfire presence and informal wood harvesting. Since the climate is not particularly responsible for the Lake's demise, there is evidence of anthropogenic aspects that could be at play, which (Nel 2016; Nel et al. 2017a) mentioned and a research team of the University of KwaZulu- Natal has identified. Ideally, the chance of preserving the lake will be high if human activities are the chief reason for water level decline because real actions to improve water management in the basin are known (Alborzi et al. 2018). The situation demands deep thought regarding the role of human activities now and in the future. As shown in Gaupp et al. (2015) looking at the past and future, one can establish the existing storage capacity so as to buffer intra- and inter-annual water variability and thereby mitigate resulting water scarcity.

Currently Sibayi catchment supports pastoralism, tourism and commercial forestry. Growing crops in this area is done at a subsistence level with a lot of difficulty. According to Nel (2016) there is extensive deforestation amidst commercial forestry. These pose a threat to the environment since human activities alter both variability and volume of river flows needed to maintain freshwater ecosystems (Gaupp et al. 2015). Forests can have a big role on the hydrology in the catchment. The development of tourism and growth in population (Nel et al. 2017a) implies increased abstraction of water from the catchment. Owners of tourist resorts are concerned about the sustainability of their livelihoods when water becomes scarce. There is evidence that tourist facilities owners drive long distances to find water for domestic use in tourism facilities. Alborzi et al. (2018) observe that any rise in demand e.g 5% above set values lead to lake level dropping below the ecological threshold. The question is how long will this lake support the needs of the rural communities? Is it necessary to shift to an ecosystem-based water management paradigm? How do we prevent the loss of tourism and potential public health effects due to windblown salt storms from exposed lake bed? This requires modelling the lake system and over all hydrology to establish the sustainability of this water resource in the future. A temporal trajectory that enables analysis of changes occurring over time, as well as analyzing the advancement of change over a determined period has been used by (Nel et al. 2017b) for forest harvesting in this area. Tree species that require low water intake should be investigated into. The fact that, rainfall variability, temperatures, and water withdraw are increasing, necessitates urgent intervention.



Areas indicated blue attached to (-1) value have experienced change (contracted).
Area denoted by (0) is the surface water which has changed during the period of investigation from 407.56 Km^2 in 1992-2004 to 201.24 Km^2 in 2004-2016.
Red colored areas (1) have experienced change (reclaimed) totaling 2.91 Km^2 in June 2016.

Pixel size: 30 x 30 m = 0.0009 Km^2

Value	**1992-2004**		**2004-2016**	
	Pixel count	**Area (Km^2)**	**Pixel count**	**Area (Km^2)**
-1	12958	11.66	16126	14.51
0	452847	407.56	223603	201.24
1	947	0.85	3238	2.91

Fig 7 shows observed changes between 1992 - 2004 and 2004 - 2016 of Lake Sibayi sub-basin's endoreic area.

4 Conclusions

This study has provided a level of understanding of the problem which may enable the need for synergistic efforts to revive a shrinking lake. Some of these direct and indirect main elements have been investigated in this study using a combination of techniques. It is evident that the area experiences a strong seasonal rainfall distribution, a decreasing trend in minimum temperatures, while an increasing trend in maximum temperatures is significant. Variations in temperature and precipitation strongly affect lakes as well as the environment of human beings (Liao et al. 2013). Despite the decreasing trend in rainfall, it cannot be used to argue that it is responsible for the fast decline of the lake. The outflows are more than the inflows in the lake, due to a decline in precipitation, increased temperatures, increased abstraction rates from the lake and its catchment, and change in land cover. Lake Sibayi is an exemplar in southern Africa of an emerging challenge related to unsustainable water management amidst growing demand and climatic changes. As we endeavor to inform the ongoing debate about the causes of Lake Sibayi shrinkage and plan restoration efforts, quantitative assessments of the basin's water resources and environmental water requirements necessitate further understanding. This can be done through modelling future changes, gathering valuable information in trends of water abstraction, quantity, quality and timing of water flows required to sustain freshwater and estuarine ecosystems, human livelihoods and well-being and surface water changes of Sibayi can be considered. Remote sensing techniques can still be used to investigate changes in land use and account for the changes observed. In understanding these changes appropriate measures can be implemented to prevent the increasing water scarcity and ensure that the associated ecological systems and community livelihoods are sustained. Re-establishing Lake Sibayi's ecological integrity will require aggressive restoration policies and action plans aimed at maintaining inflows in the face of compounding climate change and water demand in South Africa.

It is also recommended that further studies are conducted for increasing our understanding on environmental flow requirements, the effect of the changing lake geomorphology and geology, the effect of groundwater extraction, the potential effects of climate change on water scarcity, the sensitivity of infrastructure investments to a changing climate, the role of storage capacity in coping with intra and inter annual water variability etc. These can importantly contribute to finding a realistic solution for the Sibayi Lake socio-environment. The study is important for water resources monitoring and water resources management.

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