Physics and Chemistry of the Earth 112 (2019) 175–186

Contents lists available at ScienceDirect

Physics and Chemistry of the Earth

journal homepage: www.elsevier.com/locate/pce

Assessment of lake surface dynamics using satellite imagery and in-situ data; case of Lake Ngami in North-West Botswana

Leokeditswe Mokgedi[b,*], Joel Nobert[a], Subira Munishi[a]

[a] Water Resources Engineering Department, University of Dar es Salaam, P.O Box 35131, Dar es Salaam, Tanzania
[b] PO Box 150044, Maun, Botswana

ARTICLE INFO

Keywords:
Lake surface dynamics
Data scarcity and remote sensing

ABSTRACT

The understanding of surface dynamics of Lake Ngami, a part of Okavango river system is hindered by paucity of data. The aim of this study was to assess the lake surface dynamics using satellite imagery and in-situ data.

Surface dynamics of Lake Ngami were monitored using remote sensing methods to complement the available inadequate in-situ measurements. Landsat imagery of the year 1979 to year 2016 were used. The Lake boundary was mapped using the Modified Normalised Difference Water Index (MNDWI), where use was made of Histogram thresholding segmentation method in extracting the water pixels. Remotely sensed actual evapotranspiration (ETa) was estimated using Simplified Surface Energy Balance (SSEB) Modelling Approach; while the satellite derived rainfall estimates were obtained from Tropical Rainfall Measuring Mission (TRMM) 3B43V7 satellite imagery product. Precipitation and potential evaporation data from meteorological stations were used to correct the bias of the satellite products. The SSEB method involved the estimation of evaporation fraction using the MODIS Land Surface Temperature and Emissivity 8-day product (MOD11A2) and GLDAS 0.25° Potential Evapotranspiration version 2.1 for the estimation of potential evapotranspiration.

The lake extraction process displayed good results with the average Kappa coefficient and overall accuracy of 0.93 and 96.6%, respectively. The maximum extent of Lake Ngami was observed in the year 2012 at 272 km^2. The ETa was found to be in range of 700 mm/year in dry regions to about 2000 mm/year in Okavango delta swamps. From the study, it was observed that after the 2009 flood-event, the precipitation occurring during the rainy season (October–March) at Angola Highlands had a positive relationship with the Lake Ngami surface area, with Pearson correlation of 0.70. Similar findings were noticed when the lake surface area trend was observed against the in-situ flow data at the Mohembo hydrometric station, which is the inflow of the Okavango delta. This suggests that since the floods of 2009, the precipitation in the Angola Highlands has a major influence in the surface dynamics of Lake Ngami.

1. Introduction

Hydrological data is very vital for water resources management. However, the data is not always readily available, either because of not being measured or limited accessibility (Muala et al., 2014). The decline of hydro networks has also been observed to add to challenges of acquiring accurate and representative hydrological data in river basins, particularly in the Sub-Saharan Africa. Equitable water allocation requires regular and accurate monitoring of water storage variation of the water sources, including rivers, lakes and reservoirs (Gomez-enri et al., 2008; Duan et al., 2013).

The challenge of estimating Lake volumes is complicated by the fact that, the Lake storage volume is a function of the balance between inflows (precipitation, inflows and groundwater seepage) and outflows (for example, groundwater percolation, withdrawals and evaporation) (Gomez-enri et al., 2008). It is not convenient to calculate the reservoir storage or volume variation from the flows and associated unreliability, therefore direct measurements of water levels in lakes and reservoirs are very important. However, many lakes and reservoirs have never been gauged, particularly in the developing countries (Duan et al., 2013; Deus et al., 2013; Gomez-enri et al., 2008). The conventional system of computing the volume of water stored in reservoirs or lakes is to estimate based on in-situ water levels measurements and bathymetry maps (Duan et al., 2013). The hydrological surveys that can be used to obtain bathymetry maps have been found to be time consuming, labour intensive and costly, therefore bathymetry maps are often not available or difficult to obtain (Duan et al., 2013).

Remote sensing techniques can thus be used to estimate water

* Corresponding author.
E-mail address: lmokgedi@gmail.com (L. Mokgedi).

https://doi.org/10.1016/j.pce.2018.12.008
Received 30 April 2018; Received in revised form 11 September 2018; Accepted 31 December 2018
Available online 03 January 2019

levels, surface area and storages in the open water bodies. Satellite imagery has been studied as a potential alternative of estimating water balance in lakes. Studies utilising satellite imagery have shown that this method can significantly estimate water variation in reservoirs and lakes with minimal errors (Duan et al., 2013; Deus et al., 2013; Muala et al., 2014). A good example is the estimated water volumes obtained by satellite techniques that were found to have a good correlation with in situ data for Lake Mead and Lake Tana with R^2 values above 0.95 (Duan et al., 2013). The analysis of lake dynamics of Lake Manyara in East Africa using MODIS surface reflectance product, employing MNDWI and histogram segmentation technique showed good application of remote sensing as a cost efficient method to study water resources (Deus and Gloaguen, 2013). Other studies have also combined satellite imagery and satellite altimetry to estimate the water volumes in the lake. A combined use of MODIS satellite imagery and radar altimetry data has also been used to estimate the water volume variations of Lake Victoria from 2000 to 2012 (Tong et al., 2016). Satellite gravimetric and altimetric data have also been used to examine trends in water balance of Lake Victoria, with satisfactory outcomes (Swenson and Wahr, 2009).

Understanding the lake water losses due to evapotranspiration (ET) is vital for monitoring of the water balance of the lake. Different assumptions are made during the estimation of ETa, based on the method employed. The conventional methods of ETa estimation include the use of Simplified Penman method (Villa Nova et al., 2006), Penman-Monteith method (Allen et al., 2006) and Bowen ration-energy balance method (Evett and Howell, 2000). Other conventional methods of evapotranspiration are lysimetres that measure ETa at a specific location (Nagler et al., 2013). Since the determination of Eta is not a straightforward thing, the majority of the methods are therefore indirect and based on equations and assumptions (Davids, 2005). Recently, Satellite method have been extensively employed for as a way of estimating ETa at regional and global scale. The satellite methods differ according to complexity and parameterisation, ranging from the simplest methods such as Simplified Surface Energy Balance (SSEB) (Senay et al., 2007). Model approach to complex methods such as Mapping Evaporation at High Resolution with Internal Calibration (METRIC) (Allen and Trezza, 2007; French et al., 2015). The Surface Energy Balance System (SEBS) model approach has been used in Upper Manyame catchment in Zimbabwe (Rwasoka et al., 2011) and Matebeleland in South western Zimbabwe (Timothy et al., 2015) with satisfactory outcomes. Therefore, the satellite approach has been observed to be a feasible method in the estimation of regional ETa.

The Lake Ngami, the interest of this research study, is an outlet of the Okavango Delta in Northern Botswana. In the recent past it has been a water security concern, mainly due to considerable changes experienced in the basin. The Lake temporarily dried from 1989 to 2004, the reasons of which have not yet been clearly understood, though its hydrodynamics are believed to be strongly attributed to the changing upstream basin land uses, especially the growing number of cattle population and grazing. Studies have indicated that the Lake goes through periodic desiccation (Shaw, 1985). The Lake, though an important source of livelihoods of the surrounding system, is a closed system and is regarded as an evaporation Lake (Shaw, 1985). Lake Ngami is a terminal part of one of the Xudum, which is one of the distributaries of the Okavango delta. The lake was a substantial water body during the 19th century and for a period of 80 years prior to 1983, the lake only dried for 2 consecutive years, five times (Wolski and Murray-hudson, 2006). However, the lake dried for a period of about 25 years, from 1989 until it subsequently filled during the Okavango delta flood of 2004. Since then the lake has swollen up with surface area of 51.9 km^2 in 2007 (Hancock et al., 2007). Lake Ngami is important to the economy of Botswana as it contributes to the tourism industry by being one of the Important Bird Areas in the semi-arid country. The travel and tourism sector contributed US$627.89 million (3.9% of GDP) to the economy of Botswana in 2016 and it is expected to increase by 5.1% per annum to US$1120.8million by 2027 (World Travel and Tourism Council, 2017). The lake also has an important role in the economy of the local people as it is one of the major sources of water for agro-pastoral farming and fishing, which are the major sources of livelihood in the area. Therefore, proper observation of the water variations of this water resource is vital considering the water scarcity state of the semi-arid country of Botswana. However, currently there's paucity of data at the lake with insufficient inflow data, water levels and evaporation unmonitored as well the lake surface area variation unobserved. This has thus prompted the application of remote sensing in the assessment of the lake dynamics.

This research project therefore assessed the extent to which satellite imagery can be used as a tool to monitor the dynamics of Lake Ngami. Specifically, the study attempted to map the rainfall and actual evapotranspiration from satellite data and eventually look into the probable causes of the surface area dynamics of the lake using earth observation techniques.

2. Methodology

2.1. Study area

The Okavango River is the Fourth-longest river system in southern Africa, running south-eastward for 1600 km with catchment area of 234,412 km^2. As shown in Fig. 1, the river originates at the Angola Highlands, discharging water to an endorheic basin, the Okavango Delta which is approximately 18,000 km^2 (McCarthy and Ellery, 1997). The Okavango River discharges flow into the Okavango delta during the southern hemisphere winter months from April to October, which is out of phase with the local rainy season which occurs from November to March (Meier et al., 2015). The flooding of the Okavango delta occurs progressively taking about six months to reach areas around Maun and Lake Ngami due to a flat terrain within Okavango delta with maximum flooding extent observed between August and September (Wolski and Murray-Hudson, 2005).

Lake Ngami is an endorheic lake in Botswana north of the Kalahari Desert 20°30′S 22°40′E. It was originally fed by Thaoge river (western distributary of the Okavango delta-Thaoge distributary), and was a substantial waterbody during the 19th century (Wolski and Murray-hudson, 2006). For a period of 80years prior to 1983, the lake only dried for 2 consecutive years, five times (Wolski and Murray-hudson, 2006). Currently, it is seasonally filled by the Kunyere and Nhabe River, effluents of the Okavango River system (Xudum distributary) flowing out of the western side of the Okavango Delta as shown in Fig. 1. During the Lake Ngami flooding of 2007 it was observed that the maximum flooding extent of the lake was 51.9 km^2 (Hancock et al., 2007). The annual precipitation in the lake catchment is around 460 mm/year with most of the rainfall occurring between November and March.

Although the lake has shrunk dramatically beginning from 1890, it remains an important habitat for birds and wildlife, especially in flood years. Lake Ngami is unique in Botswana and southern Africa with respect to birdlife. There is no other comparable birding area in the region (Hancock et al., 2007). Birdlife Botswana Organization has listed Lake Ngami as one of Botswana's 12 Important Bird Areas (IBAs). Even when dry, it has been observed to meet the criteria set by BirdLife International for qualification as an IBA, due to the presence of globally threatened and near-threatened species such as the Lesser Kestrel and Black-winged Pratincole, as well as numerous range-restricted and biome-restricted species such as the Kalahari Robin, Hartlaub's Babbler, and Burchell's Sandgrouse, among others (Hancock et al., 2007).

2.2. Lake water surface area determination

The steps that were followed for the surface area determination are shown in Fig. 2. The water surface area was delineated from Landsat MSS, Landsat ETM+ and Landsat 8 OLI imagery using indices between

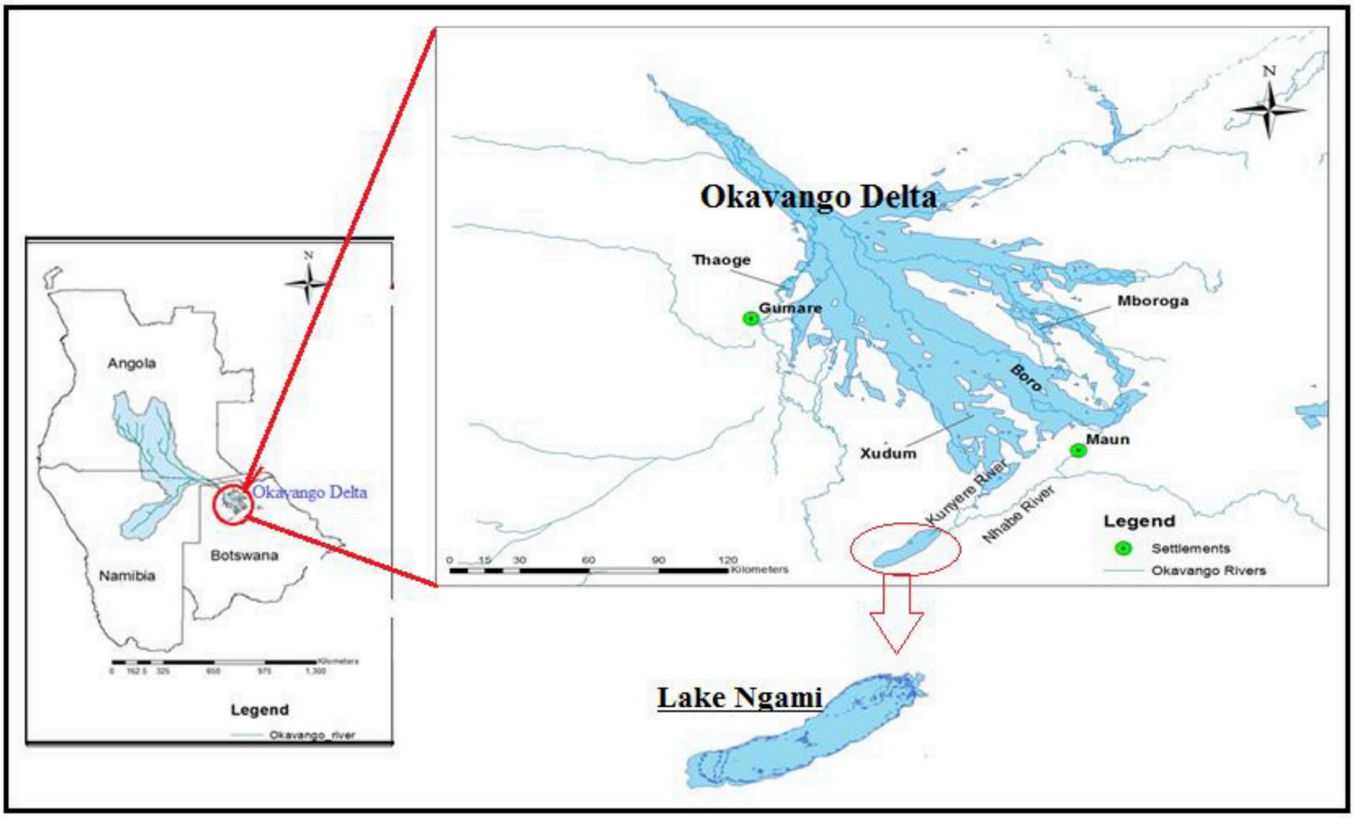

Fig. 1. Map showing Lake Ngami location within the Okavango River Basin and Delta.

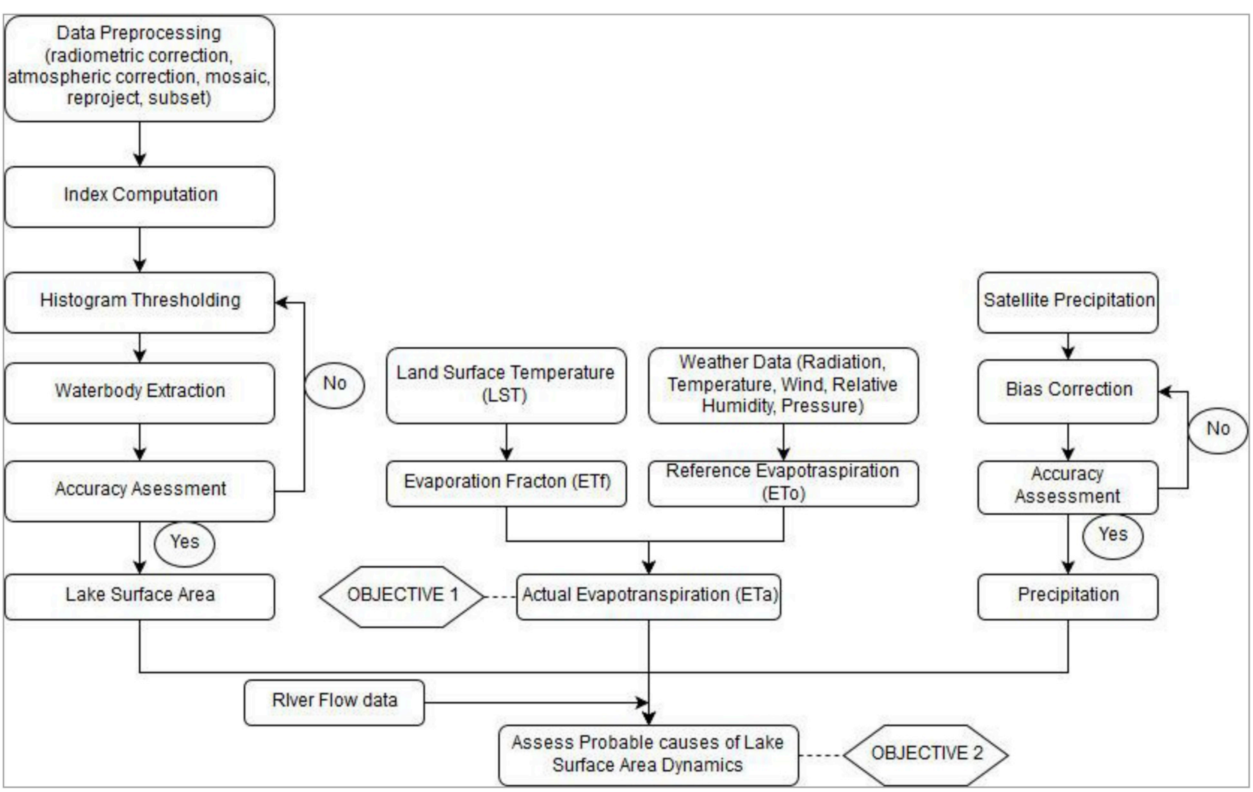

Fig. 2. Framework of the determination of lake surface area and probable causes of the lake surface area dynamics.

the years 1979–2016 on a spot basis. For 1979, Landsat MSS was used with Landsat ETM+ and Landsat 8 utilised from 2002 to 2016. However, Landsat 8 OLI imagery was only launched in February 2013 therefore it was only used for analysis post February 2013. Prior to index computation the Landsat imagery was pre-processed using ENVI 5.3 software. Image preprocessing included radiometric correction, atmospheric correction, mosaic and sub-setting.

For water surface extraction and analysis studies, the Normalised Difference Water Index (NDWI) (Muala et al., 2014) and Modified Normalised Difference Water Index (MNDWI) (Deus and Gloaguen, 2013) have been used. However, MNDWI has been found to produce better extracts of the water surface (Deus et al., 2013). For this study, the MNDWI index was used to extract Lake Ngami from Landsat Surface reflectance products.

The mathematical operation for MNDWI as obtained from Equation (1) (Xu, 2006) is;

$$MNDWI = \frac{G - SWIR}{G + SWIR} \tag{1}$$

G = surface reflectance of the green band (band 2 in Landsat products)
SWIR = shortwave infrared (SWIR) band (band 5 in Landsat products).

For this study the high resolution images from Google Earth platform were used for accuracy assessment. The kappa coefficient and overall accuracy were calculated for each image. The kappa coefficient, overall accuracy, error of omission, error of commission, users and producers accuracy were employed on the basis of error matrix (Li et al., 2013).

2.3. Actual evapotranspiration from Simplified Surface Energy Balance approach

The evapotranspiration rate was estimated using Simplified Surface Energy Balance (SSEB) Modelling Approach (Savoca et al., 2013; Senay et al., 2007). Combination of SSEB approach, remotely sensed Landsat imagery, MODIS Terra 1 km Land Surface Temperature and Emissivity Level 3 product, MOD11A2 imagery as well as Global potential evapotranspiration were used to estimate actual evapotranspiration. Landsat and MODIS satellite imagery were used to obtain the Land Surface Temperature (LST) employing ArcMap10.2 software platform tools. The LST data was used to obtain the evaporation fraction using Equation (2) from (Senay et al., 2007);

$$ET_f = \frac{TH - Tx}{TH - TC} \tag{2}$$

Where,

Tx = satellite observed Land Surface Temperature (LST) of each cell
TH = LST at idealized reference "hot" condition of the image for the same period where the lowest NDVI is observed
TC = cold reference pixel value where the highest NDVI is observed

The Global Land Data Assimilation Services (GLDAS) monthly potential evapotranspiration rate product, GLDAS 0.25° NOAH monthly Potential Evapotranspiration Rate product, was used to estimate the potential evapotranspiration. For use in the whole Okavango basin the evapotranspiration product was used as it was without any bias correction. This was done as the obtained evapotranspiration data was in Maun, which was not representative of the whole basin. However, zooming into the Okavango delta, the product was corrected for bias using the Class A pan evaporation rate obtained from Maun Airport Meteorological station prior to being used in the study. The bias correction was done using Variance Scaling method following a procedure for temperature bias correction as stipulated by (Fang et al., 2015).

Once the correction was completed, the actual evapotranspiration, ETa was estimated using Equation (3) recommended by (Senay et al., 2007);

$$ETa = ET_f \times ETo \tag{3}$$

2.4. Satellite derived precipitation

The TRMM combined monthly precipitation product (3B43-V7) which has a spatial resolution of 0.25° × 0.25° was used to estimate the precipitation at Lake Ngami and within the Okavango basin (Deus and Gloaguen, 2013). A rainfall threshold of 1 mm/month was set for the TRMM rainfall, thereby recording only rainfall events of 1 mm/month and above as recorded rainfall and those below as 0 (Tian et al., 2009). The satellite data was observed against data recorded from two raingauge stations, Maun Airport Meteorological station and Gumare Agriculture Station.

The satellite bias from gauged data was also observed based on the number of satellite rainfall months where rainfall was recorded and rainfall was observed at the gauge (Hit bias, H), satellite detected rainfall while no rain was recorded (False bias, F) and the number of months the satellite recorded no rainfall, rainfall was observed on the ground (Miss bias, M) and relative/percentage bias (Rbias). These information was ultimately used to determine the accuracy measures such as Probability of Detection (POD), that measures the accuracy of the product to detect rainfall and False Alarm ratio (FAR) (Cohen Liechti et al., 2012).

2.5. Probable causes of lake surface area variation

The regression and multiple-regression analysis of the precipitation, evapotranspiration and Okavango River flow at Mohembo (inflow into the Okavango delta) against the lake surface area was performed for a period of 10 years between the year 2003 and 2013. The multiple-regression analysis was done assuming non-linear conditions (logarithmic transformation) and linear conditions, at 90% confidence level, employing the Microsoft Excel software platform.

3. Results and discussion

3.1. Accuracy assessment of satellite derived lake surface area extraction

The accuracy assessment indicators shown in Table 1 were used to evaluate the accuracy of the image classification, employing a confusion matrix (Xu, 2006) and the multi-temporal high resolution images from Google Earth. The image classifications for all images showed satisfactory results with overall accuracy and Kappa coefficient ranging between 88.75% and 100% and 0.775 to 1, respectively. This was an indication that MNDWI could accurately extract the shallow water of Lake Ngami. Similar findings were observed in the extraction of a shallow Lake Manyara in Northern Tanzania employing MNDWI (Deus and Gloaguen, 2013).

3.2. Lake surface area trend

Fig. 3 shows the seasonal trend of the Lake Ngami surface area from Landsat imagery. It can be observed that the surface area of the lake reached its peak in October. This is possibly due to the floodwaters from Okavango delta that reached Lake Ngami about six months after the first floods are experienced in the delta around April. From this observation, the subsequent analyses of annual lake surface area extent variations were based on the month of October when it was assumed that the lake surface area had reached the maximum extent.

The Lake Ngami surface area trend was observed between the year 1979–2016 using Landsat satellite imagery. The lake was observed to

Table 1
Accuracy assessment of the lake extraction process.

Date	Landcover	Commission (%)	Omission (%)	Producers (%)	Users (%)	Overall accuracy (%)	Kappa coefficient
Oct-04	Non-water	4.76	0.00	100.00	95.24	97.5	0.95
	Water	0.00	5.00	95.00	100.00		
Oct-05	Non-water	14.89	0.00	85.11	100.00	91.25	0.825
	Water	0.00	17.50	100.00	82.50		
Sep-06	Non-water	0.00	5.00	95.00	100.00	97.5	0.95
	Water	4.76	0.00	100.00	95.24		
Sep-07	Non-water	0.00	0.00	100.00	100.00	100	1
	Water	0.00	0.00	100.00	100.00		
Apr-08	Non-water	15.22	2.50	97.50	84.78	91.25	0.825
	Water	0.00	17.50	85.00	100.00		
Aug-08	Non-water	15.56	7.50	95.00	84.44	88.75	0.775
	Water	5.71	17.50	82.50	94.29		
Oct-08	Non-water	2.44	0.00	100.00	97.56	98.75	0.975
	Water	0.00	2.50	97.50	100.00		
Oct-09	Non-water	0.00	0.00	100.00	100.00	100	1
	Water	0.00	0.00	100.00	100.00		
Oct-10	Non-water	0.00	5.00	95.00	100.00	97.5	0.95
	Water	4.76	0.00	100.00	95.24		
Oct-11	Non-water	0.00	0.00	100.00	100.00	100	1
	Water	0.00	0.00	100.00	100.00		
Oct-12	Non-water	0.00	0.00	100.00	100.00	100	1
	Water	0.00	0.00	100.00	100.00		
Oct-13	Non-water	3.23	0.00	100.00	96.77	98.33	0.9667
	Water	0.00	3.33	72.50	100.00		
Oct-16	Non-water	9.09	0.00	100.00	90.91	95	0.9
	Water	0.00	10.00	90.00	100.00		

have contained some water in 1979, and then followed by a dry period until the year 2004. The lake has never been completely dry since 2004 to date.

The Surface area of 57.14 km^2 was observed in 1979 followed by a dry period until 2004 when the lake filled up to 36.7 km^2 as shown in Fig. 4. Although analysis of the lake surface area for the years in between was not thoroughly done in this study, some studies suggest that the lake had last received water in 1989 (Wolski and Murray-hudson, 2006).

The drying of the lake was attributed to the blockage of relevant

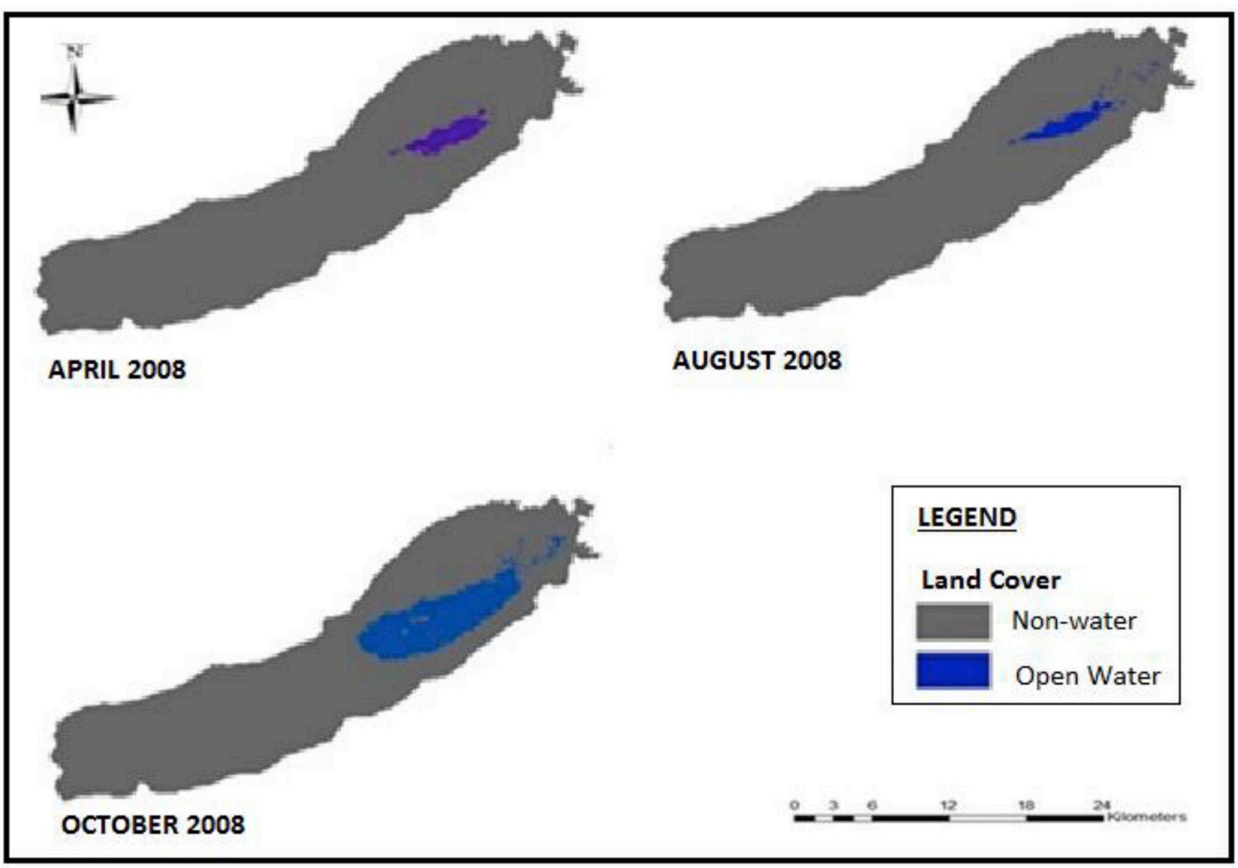

Fig. 3. Lake Ngami surface area seasonal trend.

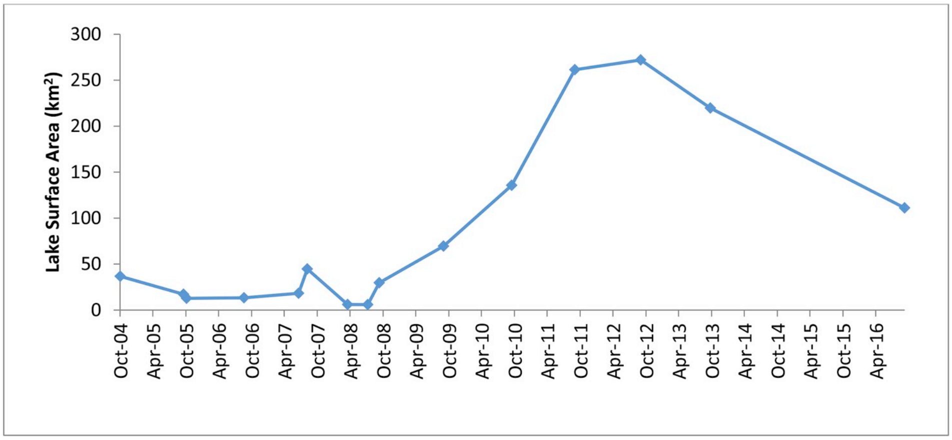

Fig. 4. Lake Ngami surface area trend.

channels in the Xudum distributary owing to the aggradation of the channel by sediments, floating debris and papyrus (Wolski and Murray-hudson, 2006). The channel blockages in the Okavango delta was described as being a result of an average accumulation of peat to heights of 5–6 m during the lifetime of a channel, which may make some channels ineffective in the conveyance of water leading to ultimate channel failure (McCarthy, 2006). Water is subsequently redirected to other channels leaving the blocked channel dry. This was observed during the analysis of inundation maps of Okavango delta, revealing that in 1997 a shift occurred in the distribution of the flood waters within the delta, with increase in inundated area of Xudum distributary (which flows to Lake Ngami) leading to a decrease in Thaoge distributary (Wolski and Murray-hudson, 2006). The 1997 shift in water distribution in the Okavango delta led to the subsequent filling of Lake Ngami in 2004 when the floodwaters became large enough to reach the lake (Wolski and Murray-hudson, 2006).

The Lake Ngami surface area started increasing properly in the year 2009 when lake surface area of 69.5 km^2 was observed in October of the year, subsequently reaching the highest of 272 km^2 in 2012 as shown in Fig. 4. The surface area in 2012 was observed to be the maximum extent of the lake thus far. The estimates closely resemble findings by Shaw (1983) who suggested that Lake Ngami surface area estimates varied from small pools close to the lake inlet (mouth of Lake River) to maximum extent of 250 km^2, with the length, width and circumference of 34.5 km, 8 km and 80 km, respectively. Therefore, the lake surface extent observed in 2012 was assumed to be the lake coastline. The filling of the lake during this period could be attributed to the 2009–2011 annual floods that were observed to have reached magnitudes last seen 20–30 years before (Wolski et al., 2014). This trend of annual maximum extent increase can also be observed in Fig. 5.

3.3. Satellite derived evapotranspiration

The Simplified Surface Energy Balance model was employed to estimate ET in the Okavango basin, and the Okavango delta using 1 km thermal data (MODIS) and the GLDAS 0.25° NOAH Monthly Potential Evapotranspiration Rate product.

3.3.1. Satellite derived evapotranspiration in Okavango Basin

The results indicated that water losses to the atmosphere were most prevalent in the Okavango delta relative to all other areas in the Okavango system. The highest evapotranspiration was observed in the some parts of the open water of Okavango delta at approximately 2500mm/annum as observed in Fig. 6. The observation closely resembled the observations from previous studies that estimated the average evapotranspiration in the delta at above 2000mm/annum (McCarthy, 2006). The actual evapotranspiration rate was spatially averaged for the entire basin in order to estimate the total water losses due to evapotranspiration for different temporal scales (monthly and annual).

From Fig. 7 it is noted that the highest evapotranspiration rates in the Okavango are observed from September to November, when the temperatures are found to be at the annual highest. The amount of evapotranspiration rates observed in September reach levels of 155 mm/month, and start decreasing in October until the levels reach all year lowest during the rainy seasons, where March has been found to have evapotranspiration losses of approximately 87 mm/month. The low evapotranspiration rates during the rainy season could be attributed to the high relative humidity and extensive cloud cover prevailing during those periods.

No bias correction or accuracy assessment was performed for the estimation of ETa in the Okavango basin as the only evaporation data accessible for the study was from a Class A pan based at Maun Airport Meteorological Station, which was not representative of the entire basin. However, for the intended purpose of the study the bias correction was not necessary.

3.3.2. Satellite derived actual evapotranspiration in Okavango Delta

The highest annual evapotranspiration of 1776 mm/annum was estimated in areas considered as permanent swamps within the Okavango delta as shown in Fig. 8. This is a significant reduction to the actual evapotranspiration observed before bias correction, which was approximately 2500mm/annum. The ETa was also found to underestimate the ETa found by previous studies (McCarthy, 2006; Farquharson et al., 1990). This could be due to the coarse pixels of the MODIS thermal data including losses from bare soils within the pixels that supposedly captured ETa from the swamps. However, the evaporation from this study were not far off from an estimated evaporation of 1900–2000mm/annum over open water in Botswana by (Farquharson et al., 1990).

It should also be noted that most of the Okavango delta is not open water but rather vegetated, meaning that some of the water is lost through transpiration rather than evaporation over open water bodies. This could be the attribution for the relatively lower actual evapotranspiration observed over the Okavango delta. The average actual evapotranspiration for the delta (including seasonal swamps) was observed to be approximately 1400mm/annum. This could be expected as the seasonal swamps are dry most of the time throughout the year, and only seasonally flooded by the inflow from the Okavango river (McCarthy et al., 2003; McCarthy, 2006). However, the estimated evaporation could have accounted for advection that has been observed to cool the air above waterbodies and also increase the humidity, thus making the ET relatively lower for open waterbodies.

It can be observed from Fig. 9 that the highest evapotranspiration

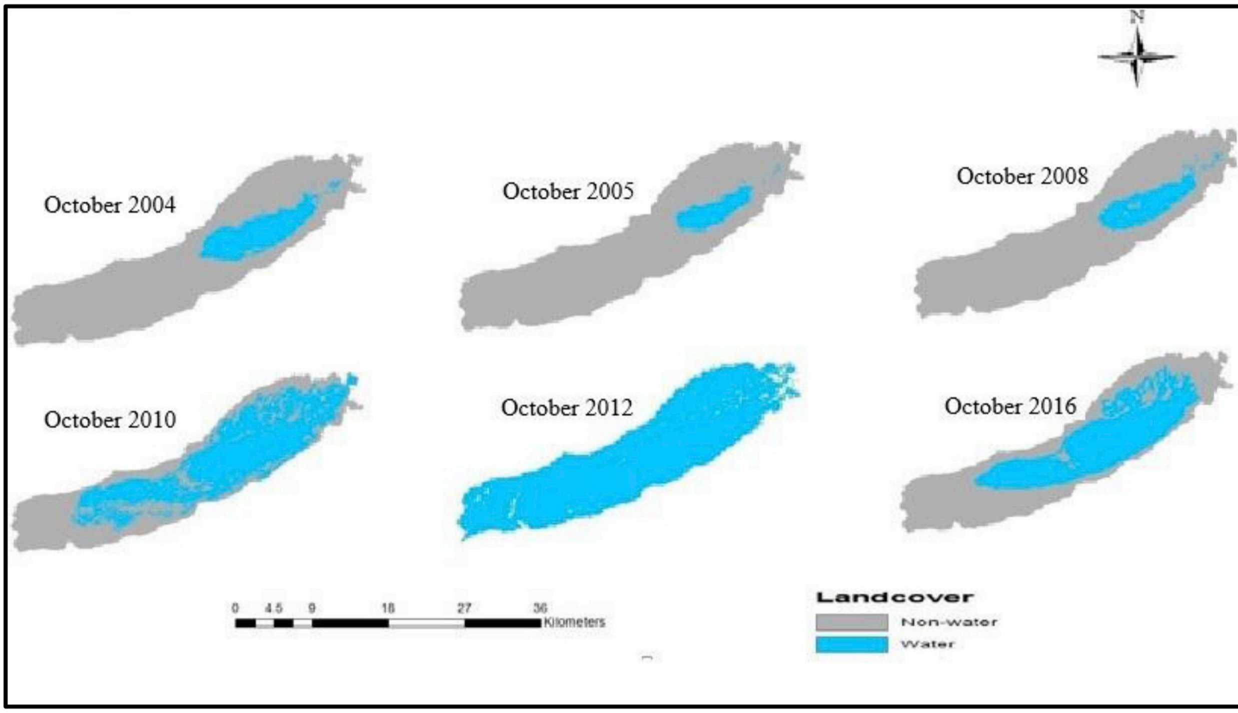

Fig. 5. Lake Ngami surface area inter-annual trend.

was observed during the hot period from September to November (144–157 mm/month). This could be due to an increase in temperatures and reduction in relative humidity in the atmosphere during the hot dry months just before the rainy season reaches the peak in December. The lowest observed actual evapotranspiration was observed in March where, approximately 87 mm/month of water is lost. This indicates that the raw GLDAS 0.25° NOAH Monthly Potential Evapotranspiration Rate used for the whole Okavango basin could capture the variation of the potential evapotranspiration, therefore proving its suitability for the intended purpose of this study in the Okavango basin.

3.3.3. Accuracy assessment of the SSEB model

Due to lack of ETa monitoring within the study area accuracy assessment was done using the Class A pan PET measured at Maun Airport Meteorological Station against the ETa observed at Lake Ngami. The evaporation fraction was hypothetically replicated at the same point where the Class A pan measurement was taken and hypothetically computing the ETa. A comparison was done between the Landsat derived evapotranspiration, with 30 m resolution and the MODIS derived evapotranspiration, with 1000 m resolution. Both methods underestimated the water losses, but Landsat derived ETa was found to

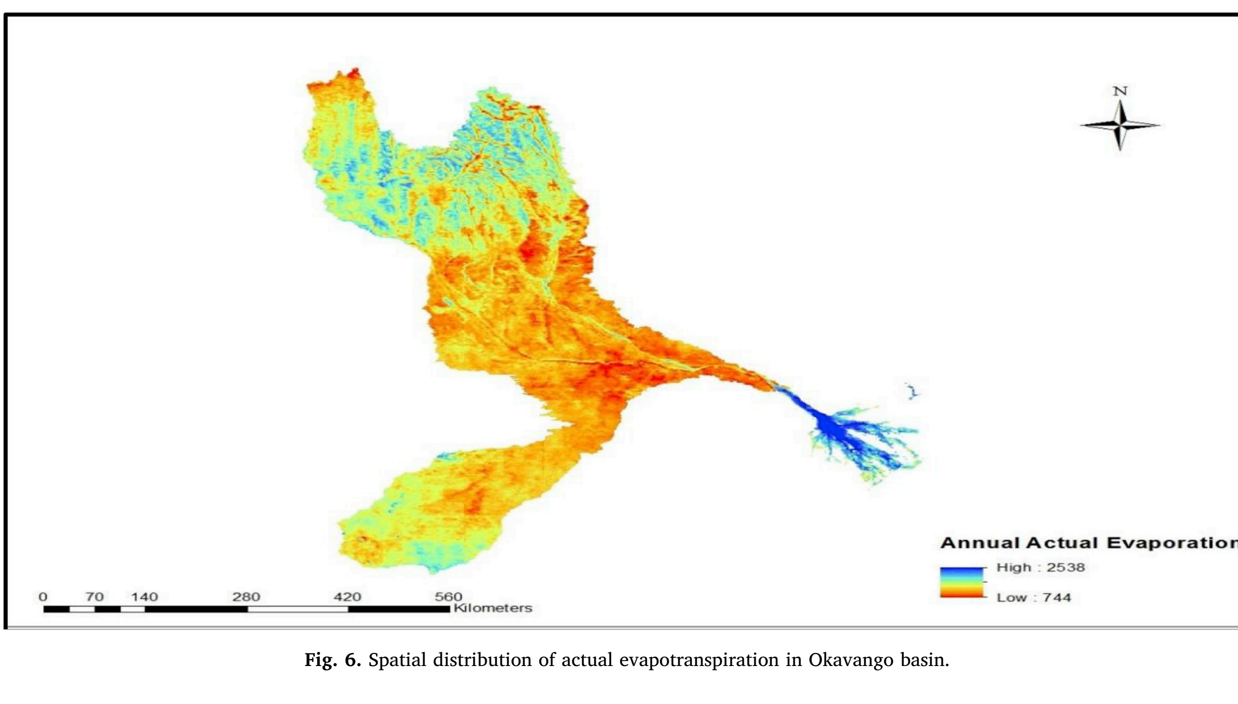

Fig. 6. Spatial distribution of actual evapotranspiration in Okavango basin.

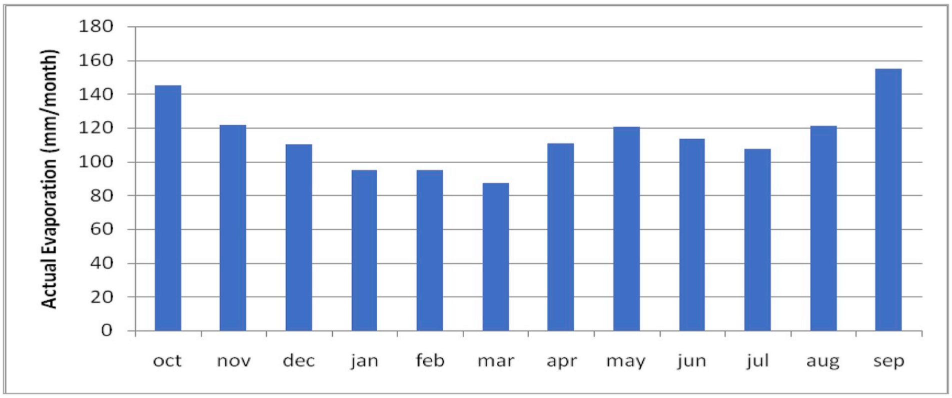

Fig. 7. Long term monthly average actual evapotranspiration in Okavango basin.

relatively represent the observed evapotranspiration better than the MODIS derived ETa. The R^2 values were found to be 0.79 and 0.72 for Landsat derived ETa and MODIS derived ETa, respectively, with RMSE values of 34 mm/month and 88 mm/month for the former and the latter, respectively (See Table 2). The RMSE of Landsat derived ETa and MODIS derived ETa were 15% and 38.7% of the observed mean, respectively.

The error is due to the underestimation of observed ET by both Landsat and MODIS thermal data. The large error of the MODIS derived ETa could be attributed to the resolution that could fail to capture the water pixels within the relatively small Lake Ngami. The other source of error could be that the MODIS LST and Emissivity product is averaged over 8 days, contrary to Landsat that captured the instantaneous LST. The GLADS PET product used in the study could have also contributed to the error as R^2 of only 0.75 was achieved even after the bias correction of the product. However, the results from both approaches were comparable with other data intensive models such as SEBS that have been used in the region (Rwasoka et al., 2011; Timothy et al., 2015). However, it should also be noted that the measured PET from Maun Airport Meteorological Station is observed over a relatively dry area, which fails to account for advection. Therefore, the observed PET may also be overestimating the actual evaporation over open waterbodies.

3.4. Satellite derived precipitation in Okavango basin and the delta

The Tropical Rainfall Measuring Mission monthly precipitation product, TRMM 3B43 version 7 was used to estimate precipitation in the Okavango basin and Okavango delta. No bias correction was performed on the satellite derived precipitation as observed rainfall data from the upstream sub-tropical central Angola and semi-arid Namibian parts of the basin were not obtained. However, for the case of the delta, two stations, Maun and Gumare were used to compute the bias employing the linear scaling method (Fang et al., 2015). From the study it was observed that no bias correction method made any significant improvements to the raw satellite data.

The annual rainfall distribution as shown in Fig. 10 indicates that the highest amounts of rainfall of approximately 1400mm/annum were observed in the Cubango area where the Okavango river headwaters originate. The lowest rainfall amounts of slightly above 200mm/annum were observed in Namibia. The rainfall in the basin has been observed to be positively correlated to elevation, with the Okavango Highlands receiving rainfall ranging between 700 and 1300mm/annum as also observed by (Baumberg et al., 2014). However, the spatial average rainfall of the Angola highlands which have been found to contribute most of the Okavango river flow was found to be 997mm/annum which closely matched estimates of about 900 mm by (McCarthy, 2006). In the Okavango delta, the observed rainfall has been estimated to the average of 490mm/annum with the range from 300 to 1000mm/annum (McCarthy, 2006). From Fig. 10 it can be observed that the rainfall decreases from north to south within the Okavango basin.

As shown in Fig. 11 the rainy season in the Okavango basin begins in October with some low rainfall but the highest rainfall is observed

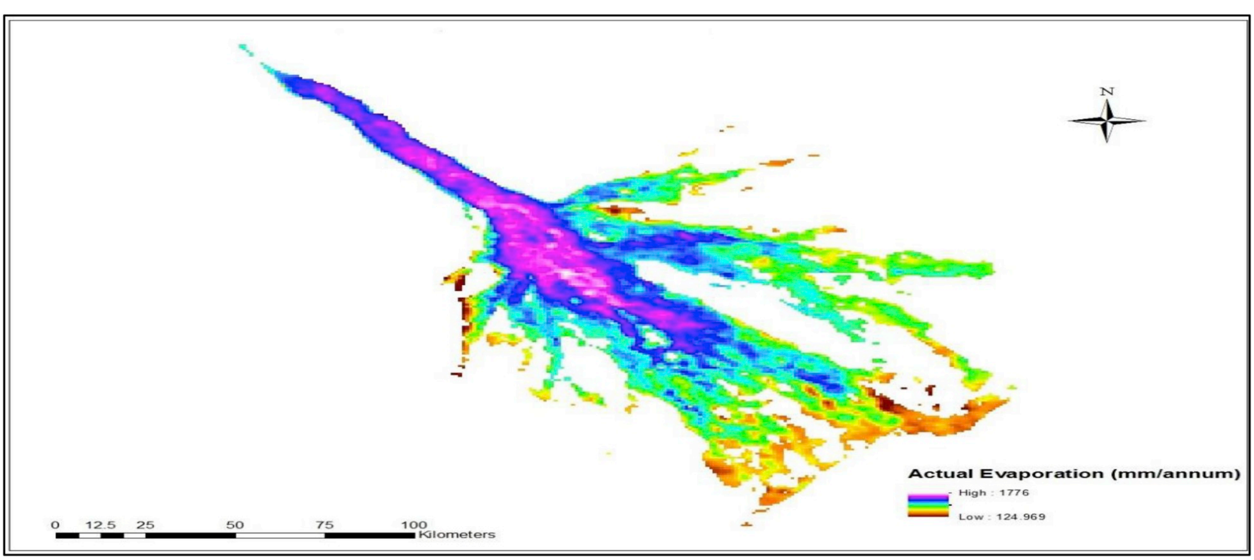

Fig. 8. Average annual actual evapotranspiration in Okavango delta.

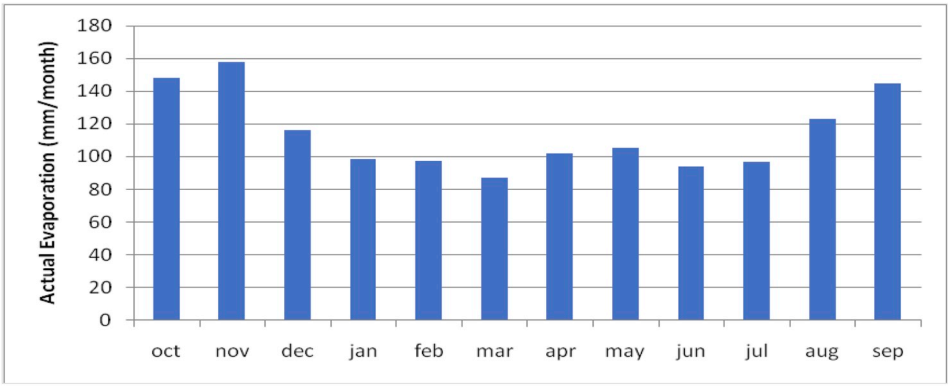

Fig. 9. Long term monthly evapotranspiration in the Okavango delta.

Table 2
Accuracy assessment of the SSEB model.

Date	ETo (mm/month)	$ET_{SSEB(Landsat)}$	$ET_{SSEB(MODIS)}$	Landsat error	MODIS error
Oct-04	300	277.73	195.85	22.27	104.15
Oct-05	324	321.10	241.80	2.90	82.20
Sep-06	207	228.96	125.47	−21.96	81.53
Jul-07	123	112.75	87.00	10.25	36.00
Sep-07	276	196.60	131.25	79.40	144.75
Apr-08	192	172.79	111.00	19.21	81.00
Aug-08	171	188.74	144.63	−17.74	26.37

between December and March, with January recording the highest rainfall of approximately 180 mm/month. Similar trends were observed by (Baumberg et al., 2014).

3.5. Probable causes of Lake Ngami Surface Area variation

The results for the analysis of the possible causes of Lake Ngami surface area dynamics indicated that the local and basinwide precipitation had very little influence on the lake surface variations with a p-value of 0.88 as shown in Table 3. This could be an indication that the regional climate change had no influence on the Lake Ngami surface area dynamics as indicated by (Shaw et al., 2003). However, from Fig. 12 it can be observed that on all occasions when there were significant changes to the lake surface area (2004, 2009 and 2011), there was increase in rainfall relative to the previous years within the Okavango basin (flood events).

The preliminary change detection, with t-statistic of 18.07 at significance level of 0.05, indicates that there was an increase in the rainfall within the Okavango basin since 2004. These findings could be an indication that the increase in rainfall post 2004 had an influence in the filling of the lake since 2004. However, in this study the relationship between the inter-annual surface variations of Lake Ngami and the inter-annual rainfall patterns is not clear before 2009. Previous studies that undertook an analysis of the inundation maps have suggested that in the year 1997 a shift occurred in the flooding patterns of Okavango delta distributaries, causing an increase in the inundation area of the Xudum distributary that is currently discharging water into Lake Ngami (Wolski and Murray-hudson, 2006).

It is further suggested that since 1997 the Xudum started receiving

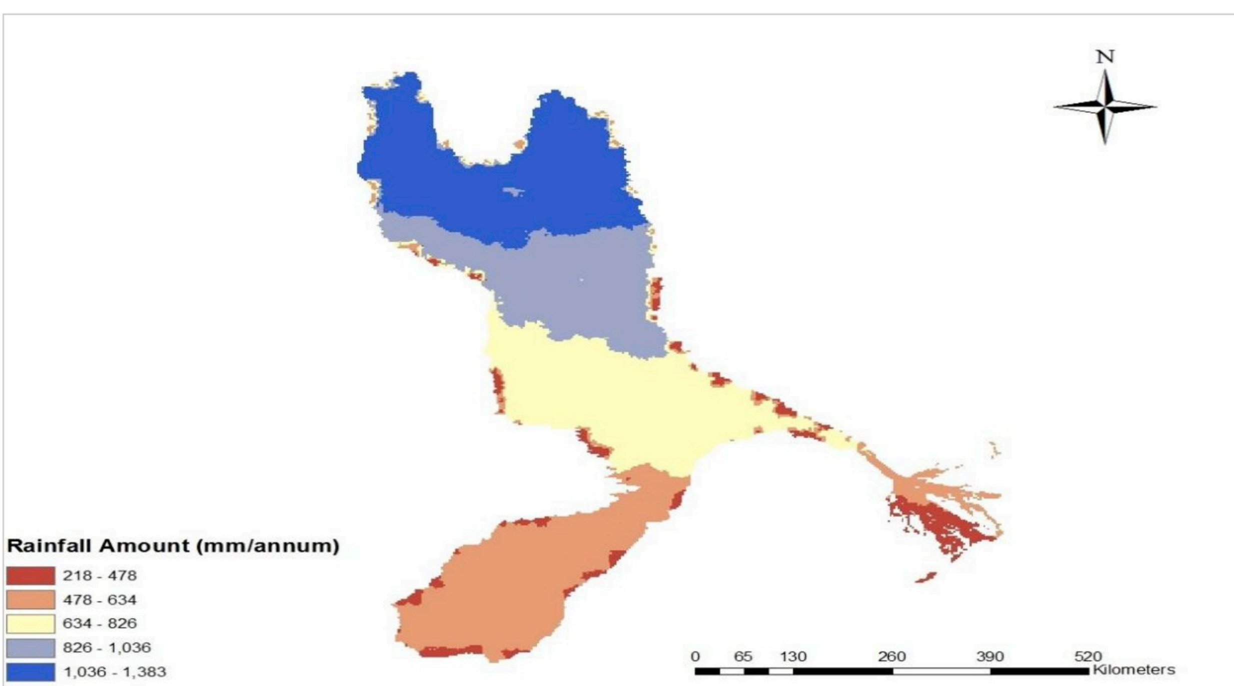

Fig. 10. Rainfall distribution in Okavango basin.

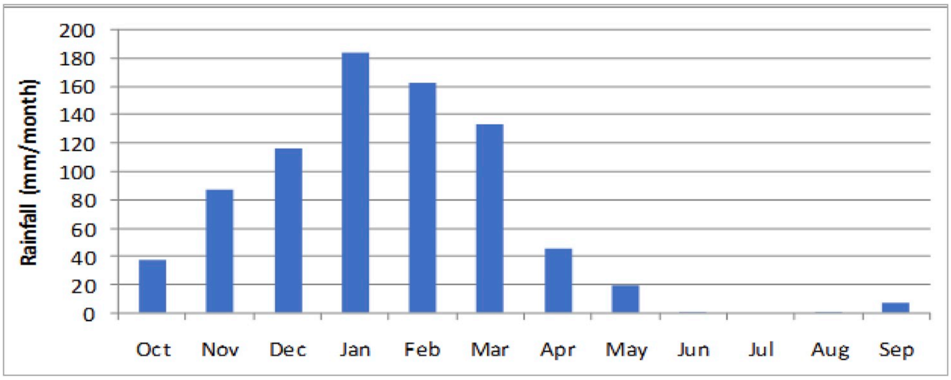

Fig. 11. Long term monthly rainfall in Okavango basin.

Table 3
Regression Analysis of the Probable causes of Lake Ngami Surface Dynamics.

Regression Statistics					
Multiple R					0.919298
R Square					0.845109
Adjusted R Square					0.721197
Standard Error					54.96439
Observations					10
ANOVA					
	Degree of Freedom	SS	MS	F	Significance F
Regression	4	82417.65	20604.41	6.820204	0.029391
Residual	5	15105.42	3021.084		
Total	9	97523.07			
Regression Coefficients					
	Coefficients	Standard Error	t-statistic	P-value	
Intercept	−1412.9	401.6776	−3.5175	0.016964	
Okavango Delta Precipitation	0.21676	0.148042	1.464177	0.203026	
Mohembo Flow	0.693694	0.304581	2.27754	0.071759	
Okavango basin Precipitation	0.033424	0.210808	0.158554	0.880225	
Okavango basin ETa	0.841541	0.235539	3.572822	0.015996	

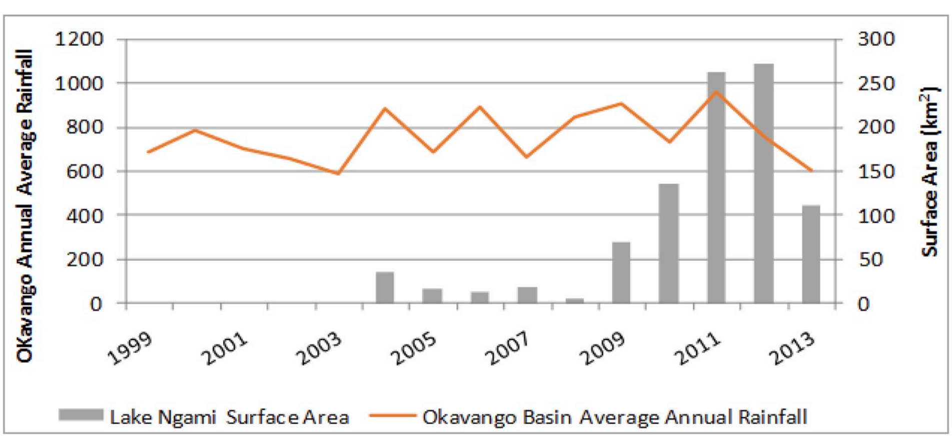

Fig. 12. Okavango basin annual rainfall and lake Ngami surface area.

more water but the flood waters were insignificant to reach the lake until the floods of 2004 (Wolski and Murray-hudson, 2006). Therefore, this could suggest that the distribution of water in the Okavango delta has a major influence on the Lake Ngami surface dynamics.

The findings observed about evaporation within the Okavango delta suggest a positive relationship between the lake surface area and evaporation with a Pearson correlation of 0.71. This observation could simply be a result of water availability being the driving force for both processes and not showing an influential relationship between the evaporation and lake surface area.

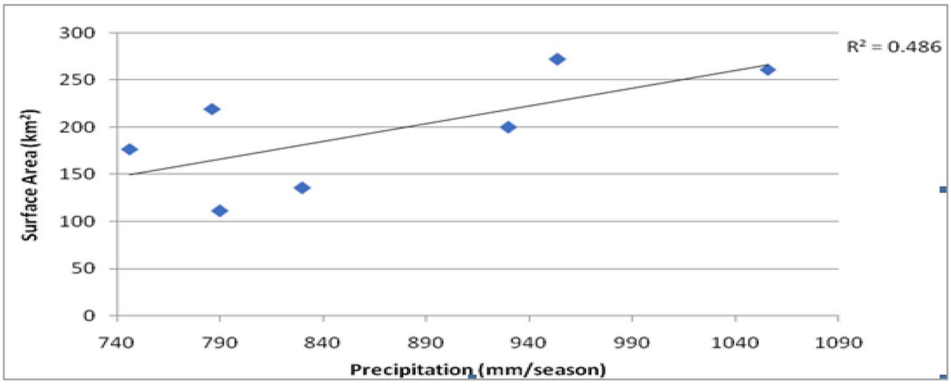

Fig. 13. Rainfall at Angola Highlands during Rainy Season (October–March) against Lake Ngami Surface Area post 2009.

3.6. Relationship between Angola highlands precipitation during rainy season (October–March) and Lake Ngami Surface Area post 2009

The runoff generated in the Angola Highlands during the rainy season (October–March) has been observed to contribute approximately 95% of inflow into the Okavango delta (Wolski et al., 2014). Therefore, a regression analysis of the rainfall occurring during the rainy season within the Angola Highlands against the Lake Ngami surface area was done. Prior to 2009 the regression results showed a poor relationship between the precipitation and lake surface area with a Pearson correlation of approximately 0. However, as shown in Fig. 13, the precipitation showed a positive relationship against the lake surface area with the Pearson correlation of 0.7 after the 2009 flood event. This result indicate that the rainfall from the Angola Highlands during the rainy season could be one of the major contributors to the lake surface variation after 2009 but prior to 2009 there were other factors that hindered the movement of floodwaters towards Lake Ngami.

The water levels and discharges for a particular site within Okavango delta system (which discharges water to Lake Ngami), have been observed to be influenced by complex interplay of flood-wave with local inputs, altered by channel-floodplain interactions, sedimentation and technical interventions both at site and upstream (Wolski and Murray-Hudson, 2005). Factors such as channel blockage and avulsion have also been observed to change flooding patterns within the Okavango delta (McCarthy et al., 2003). The change in flood inundation that subsequently led to the drying of Lake Ngami in the 1980s was observed to be caused by the Thaoge distributary failure due to blockage by papyrus (Shaw, 1983).

Neo-tectonic activities have also been attributions to the changes in water distribution patterns within the Okavango delta (McCarthy et al., 1993). Therefore, a lot of factors have been observed to influence the flooding patterns of Okavango delta, which may also influence the flooding extent of Lake Ngami. This abovementioned factors could be the attributions to the weak relationship observed between the surface areas of Lake Ngami against the variation of precipitation before 2009. However, the 2009 flood event could have cleared the path making the floodwaters from Angola Highlands to reach Lake Ngami with relative ease, hence the relatively stronger positive correlation between the precipitation and lake surface area dynamics post 2009.

3.7. Relationship between inflow at Mohembo (Okavango Panhandle) and Lake Ngami Surface Area

The inflow at Mohembo Hydrometric station showed some positive relationship against Lake Ngami surface area with the R^2 value of 0.33. This indicates that the inflow into the delta has some influence on the lake surface area. This could be a further indication that water availability in the Angola Highlands influences the surface area dynamics of Lake Ngami to some extent.

4. Conclusions

It can be concluded that remote sensing can be useful as a cheaper and convenient tool for monitoring lake surface area dynamics. The utilisation of the Modified Normalised Difference Water Index, which maximises the reflectance of water by using the green wavelength and minimise the low reflectance of SWIR by water bodies, proved to be applicable for segmentation of the lake in the study area. Histogram thresholding was also found to efficiently extract the shallow lake water pixels from the background land pixels. The accuracy of the lake extraction method was evaluated using the overall accuracy and the Kappa coefficient. The overall accuracy for the lake extraction process was found to range between 88.75% and 100%, with Kappa coefficients of 0.775–1.

The Simplified Surface Energy Balance modelling approach has been found to accurately estimate water losses due to evapotranspiration within the Okavango delta, employing 1 km thermal data (MODIS) and GLDAS 0.25° PET product. The accuracy of the model was assessed by replicating the evaporation fraction of Lake Ngami at Maun and hypothetically computing the actual evapotranspiration from the water body. The computed evaporation was compared to the Class A pan derived evaporation. From the evapotranspiration analysis it was found that the MODIS derived evapotranspiration had an R^2 and RMSE of 0.72 and 38%, respectively. This was less accurate than the results obtained from the Landsat derived evapotranspiration which had R^2 and RMSE of 0.79 and 15%, respectively. However, the overall results showed the method was comparable with other data intensive methods used in the region such as SEBS (Rwasoka et al., 2011; Timothy et al., 2015).

From this study it can be concluded that the rainfall variation at the Angola Highlands has a positive relationship with Lake Ngami surface area dynamics, post the 2009 flood events, showing Pearson correlation of 0.7. However, it could be concluded that prior to 2009 there were other factors that could have hindered the flow of water to the lake, which could have been cleared by the 2009 flood-event. The dynamics within the Okavango delta has also been observed to play a role. Factors such as sedimentation, channel blockage and avulsion have been observed to change flooding patters within the Okavango delta (McCarthy et al., 2003). Similar findings were observed previously where the filling of Lake Ngami in 2004 was attributed to the redistribution of floodwaters to the Xudum distributaries, which discharges water to Lake Ngami (Wolski et al., 2014). The possibilities of groundwater interactions having an influence on the Lake Ngami surface dynamics should also not be ruled out.

Acknowledgements

The support during data collection from the Department of Water Affairs and Department of Metereological Services in Botswana is highly appreciated. The author would also like to acknowledge financial support from Waternet which is based in Harare, Zimbabwe to undertake this study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pce.2018.12.008.

References

Allen, R.G., PEREIRA, L.S., RAES, D., SMITH, M., 2006. FAO Irrigation and Drainage Paper - Crop Evapotranspiration.

Allen, R.G., Trezza, R., 2007. Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC). J. Irrigat. Drain. Eng. 133 (4), 380–394.

Baumberg, V., Helmschrot, J., Steudel, T., Göhmann, H., Fischer, C., Flügel, W.-A., 2014. 'Assessing basin heterogeneities for rainfall–runoff modelling of the Okavango river and its transboundary management'. Proceedings of the International Association of Hydrological Sciences 364, 320–325.

Cohen Liechti, T., Matos, J.P., Boillat, J.L., Schleiss, A.J., 2012. Comparison and evaluation of satellite derived precipitation products for hydrological modeling of the Zambezi river basin. Hydrol. Earth Syst. Sci. 16 (2), 489–500.

Davids, G., 2005. SEBAL model with remotely sensed data to improve water-resources management under actual field conditions. J. Irrigat. Drain. Eng. 131 (1), 85–93.

Deus, D., Gloaguen, R., 2013. Remote sensing analysis of lake dynamics in semi-arid regions: implication for water resource management. Lake Manyara, East African Rift, northern Tanzania. Water 5 (2), 698–727.

Deus, D., Gloaguen, R., Krause, P., 2013. Water balance modeling in a semi-arid environment with limited in situ data using remote sensing in lake Manyara, East African Rift, Tanzania. Rem. Sens. 5 (4), 1651–1680.

Duan, Z., Universit, T., Education, W., 2013. Estimating water volume variations in lakes and reservoirs from four operational satellite altimetry databases and satellite imagery data. Rem. Sens. Environ. 134, 403–416.

Evett, S., Howell, T.A., 2000. The bowen ratio-energy balance method for estimating latent heat flux of irrigated Alfalfa evaluated in a semi- arid, advection environment. Agric. For. Meteorol. 103, 335–348.

Fang, G.H., Yang, J., Chen, Y.N., Zammit, C., 2015. Comparing bias correction methods in downscaling meteorological variables for a hydrologic impact study in an arid area in China. Hydrol. Earth Syst. Sci. 19 (6), 2547–2559.

Farquharson, F.A., Gash, J.H., Roberts, J., 1990. Report on a Review of Evaporation Estimation for the Okavavango Delta. Wallingford.

French, A.N., Hunsaker, D.J., Thorp, K.R., 2015. Remote sensing of evapotranspiration over cotton using the TSEB and METRIC energy balance models. Rem. Sens. Environ. 158, 281–294.

Gomez-enri, J., Alonso, J.J., Villares, P., Medina, C.E., Gomez-enri, J., Alonso, J.J., Villares, P., 2008. Water level fluctuations derived from ENVISAT radar altimeter (RA-2) and in-situ measurements in a subtropical waterbody ... Measurements in a subtropical Waterbody : lake Izabal (Guatemala)'. Rem. Sens. Environ. 112 (9), 3604–3617.

Hancock, P., Muller, M., Oake, K., 2007. Lake Ngami Important Bird Area Monitoring Report.

Li, W., Du, Z., Ling, F., Zhou, D., Wang, H., Gui, Y., Sun, B., Zhang, X., 2013. A comparison of land surface water mapping using the normalized difference water index from TM, ETM+ and ALI. Rem. Sens. 5 (11), 5530–5549.

McCarthy, J.M., Gumbricht, T., McCarthy, T., Frost, P., Wessels, K., Seidel, F., 2003. Flooding patterns of the Okavango wetland in Botswana between 1972 and 2000. Ambio 32 (7), 453–457.

McCarthy, T.S., 2006. Groundwater in the wetlands of the Okavango delta, Botswana, and its contribution to the structure and function of the ecosystem. J. Hydrol. 320 (3–4), 264–282.

McCarthy, T.S., Ellery, W.N., 1997. The fluvial dynamics of the Maunachira channel system, Northeastern Okavango swamps. Botswana'. in Water SA 23 (2), 115–125.

McCarthy, T.S., Green, R.W., Franey, N.J., 1993. The influence of neo-tectonics on water dispersal in the Northeastern regions of the Okavango swamps. Botswana'. in Journal of African Earth Sciences 17 (1), 23–32.

Meier, S.D., Atekwana, Eliot A., Molwalefhe, L., Atekwana, Estella A., 2015. Processes that control water chemistry and stable isotopic composition during the refilling of lake Ngami in semiarid Northwest Botswana. J. Hydrol. 527, 420–432.

Muala, E., Mohamed, Y.A., Duan, Z., Van Der Zaag, P., 2014. Estimation of reservoir discharges from lake Nasser and Roseires reservoir in the nile basin using satellite altimetry and imagery data. Rem. Sens. 6, 7522–7545.

Nagler, P.L., Glenn, E.P., Nguyen, U., Scott, R.L., Doody, T., 2013. Estimating Riparian and agricultural actual evapotranspiration by reference evapotranspiration and MODIS enhanced vegetation index. Rem. Sens. 5 (8), 3849–3871.

Rwasoka, D.T., Gumindoga, W., Gwenzi, J., 2011. Estimation of actual evapotranspiration using the surface energy balance system (SEBS) algorithm in the upper Manyame catchment in Zimbabwe. Phys. Chem. Earth 36 (14–15), 736–746.

Savoca, M.E., Senay, G.B., Maupin, M.A., Kenny, J.F., Perry, C.A., 2013. Actual Evapotranspiration Modeling Using the Operational Simplified Surface Energy Balance (SSEBop) Approach. U.S. Geological Survey Scientific Investigation, pp. 16p Report 2013-5126.

Senay, G.B., Budde, M., Verdin, J.P., Melesse, A.M., 2007. A coupled remote sensing and simplified surface energy balance approach to estimate actual evapotranspiration from irrigated fields. Sensors 7 (6), 979–1000.

Shaw, P., 1983. Fluctuations in the level of lake Ngami: the historical evidence. In: Botswana Notes and Records, vol. 15.

Shaw, P., 1985. The desiccation of Lake Ngami: an historical perspective. Geogr. J. 318–326.

Shaw, P.A., Bateman, M.D., Thomas, D.S.G., Davies, F., 2003. Holocene fluctuations of lake Ngami, middle Kalahari: chronology and responses to climatic change. Quat. Int. 111 (1), 23–35.

Swenson, S., Wahr, J., 2009. Monitoring the water balance of lake Victoria, East Africa, from space. J. Hydrol. 370 (1–4), 163–176.

Tian, Y., Peters-Lidard, C.D., Eylander, J.B., Joyce, R.J., Huffman, G.J., Adler, R.F., Hsu, K., Turk, F.J., Garcia, M., Zeng, J., 2009. Component analysis of errors in satellite-based precipitation estimates. J. Geophys. Res. 114 (D24).

Timothy, D., Shoko, C., Dube, T., Sibanda, M., Adelabu, S., 2015. Applying the surface energy balance system (SEBS) remote sensing model to estimate spatial variations in evapotranspiration in southern Zimbabwe. Trans. Roy. Soc. S. Afr. 70 (1), 47–55.

Tong, X., Pan, H., Xie, H., Xu, X., Li, F., Chen, L., Luo, X., Liu, S., Chen, P., Jin, Y., 2016. Estimating water volume variations in lake Victoria over the past 22 Years using multi-mission altimetry and remotely sensed images. Rem. Sens. Environ. 187, 400–413.

Villa Nova, N.A., de Miranda, J.H., Pereira, A.B., da Silva, K.O., 2006. Estimation of the potential evapotranspiration by a simplified penman method. Eng. Agrícola 26 (3), 713–721.

Wolski, P., Murray-hudson, M., 2006. Recent changes in flooding in the Xudum distributary of the Okavango delta and lake recent changes in flooding in the Xudum distributary of the Okavango delta and. South Afr. J. Sci. 102, 173–176.

Wolski, P., Murray-Hudson, M., 2005. Flooding dynamics in a large low-gradient Alluvial fan, the Okavango delta, Botswana, from analysis and interpretation of a 30-year hydrometric record. Hydrol. Earth Syst. Sci. Discuss. 2 (September), 1865–1892.

Wolski, P., Stone, D., Tadross, M., Wehner, M., Hewitson, B., 2014. Attribution of floods in the Okavango basin, southern Africa. J. Hydrol. 511, 350–358.

World Travel and Tourism Council, 2017. Travel & Tourism Economic Impact 2017 Botswana.

Xu, H., 2006. Modification of normalised difference water index (NDWI) to enhance open water features in remotely sensed imagery. Int. J. Rem. Sens. 27 (14), 3025–3033.