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Revisiting Hydrology of Lake Ngami in Botswana

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Abstract

Lake Ngami, an integral part of the Okavango Delta in Botswana, is a seasonal shallow lake that depends mostly on spills deriving from Boro River and rarely from Thamalakane River. In essence, the lake water is critical to the local population supporting the fishing industry, farming, livestock and tourism. This work attempts to revisit and to understand the hydrological conditions of the lake, which are of paramount importance for planning and development processes in the lake area. By referring to earlier historical publications and analyzing annual inflow of Okavango River at Mohembo in Botswana from 1932 to 2016, and annual outflow of Lake River to the lake at Mogapelwa from 1974 to 2016, three flooding regimes have been identified for the Lake Ngami namely wet, seasonal and dry. The hydrological data analysis has shown that the Okavango inflow directly influences the Lake River outflow which in turn determines the lake's three regimes. The findings show that the longest wet phase for the lake was from 1959 to 1972 and that the longest dry phase was from 1980 to 2003. Water depths measured at six accessible cross-sectional points along a distance of 39.3 km at higher water levels in September 2012 showed that the average depth of water in the lake was 3.508 m. Historical observations on the lake dimensions with water are varied. However, in September 2012 the volume of water determined for the lake was 974 Mm^3 occupying 277.7 km^2. Outflow volumes to the lake via Lake River and water levels in the lake from 1974 to 2016 provide further evidence to explain the lake regimes. The lake biodiversity has changed significantly since the early periods of 19th century. Water quality fluctuations in a given year are varied but can be improved through simple treatments such as boiling or chlorination. This study contributes to the understanding of the lake flow regimes and possible water allocations to the users.

Keywords: Lake Ngami; Hydrology; Okavango delta; Botswana; Water allocation

Introduction

The Okavango Delta's head flows originate in the south-eastern Province of Cuando-Cubango in the Angolan highlands as two rivers, namely the Cubango and Cuito. These rivers flow briefly through Namibia's Caprivi Strip by traversing a distance of 1500 km to form the Okavango Delta in the Kalahari Desert sands in Botswana. The delta is one of the largest "Ramsar Sites" in the world and it became the "1000th UNESCO World Heritage Site" in June 2014. The rainfall from 1932 to 2016 over the delta was a minimum of 217 mm and a maximum of 923 mm with ranges being 500-923 mm for 40 years; 700-923 for 5 years (1972-919 mm; 1974-923 mm; 1977-815 mm; 1989-711 mm; 2011-758 mm) and 217-499 mm for 40 years [1]. The Okavango Delta has five river systems viz., Selinda (Magweqgana) on the north of the Okavango River; Thaoge, Boro, Mboroga on the southern region; and Maunachira flowing to the east (Figure 1). The delta is a 12,000 km^2 endorheic wetland ecosystem and is an economically important hub of wildlife-based ecotourism and its basin is subject to persistent sequences of low and high flood years on multi-decadal time scales [2]. Lake Ngami is one of the most significant drainage base lakes of the Okavango Delta in the country and lies in the Ngamiland district. Transitions between decades of high and low flows in the delta impacts the ecosystem and its socio-economic activities in the lake area.

Lake Ngami plays an important role in the economy of northwest Botswana by way of supporting fishing, tourism, livestock watering and small scale subsistence pastoral/arable farming [3]. Historically, tourism around Lake Ngami primarily entailed birdlife viewing and photographing [4-6]. When the lake dries up, equally affected is the fisheries industry and food supplement to the local communities. Dry spells have had detrimental outcomes on local water supply, for both domestic and livestock watering. The Lake Ngami fisheries industry constitutes 85% men and 15% women and they would not have much revenue when the lake becomes dry [7]. Therefore, understanding the hydrology of Lake Ngami is important for planning purposes in order to address some of these issues outlined above.

Lake Ngami had substantial water levels when visited by European Travellers in the mid of 19th century [8]. Periodic records/observations of the lake water levels and inflow in the 19th century was irregular and scanty. Regular measurements and records of inflows and water levels of the Lake Ngami have been made since 1974 by the Hydrology Division, Department of Water and Sanitation (DWS) in the country. However, several travelers, administrators and engineers prior to 1974 observed the lake water conditions and reconstructed its history in 19th and 20th centuries using aerial photography and the then available satellite images [9, 10].

In the early 19th century, the lake used to receive more flood through the Thaoge River System [10], which ceased to flow into the lake after 1884 [11]. A build-up of vegetation blockages in the channel and changes in sedimentation could have led to the failure of Thaoge

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River [12-13]. The diversion of flow towards Boro River system via floodplain cross-channel as a result of blockages at Qaaxhwa Lagoon on Thaoge River (Figure 1) could be another factor contributing much of spills to the Kunyere River in high flood events through Matsibe River [14]. Stream discharge and water level measurements are important for understanding seasonal and inter-annual variability of inundation but in many cases the lack of regular monitoring is evident from data gaps.

A number of dates have been suggested for the cessation of flows in Thaoge River and hydrology of the Lake Ngami. Water did not pass beyond Makakung, 16 km north of the lake during 19th century [11]. Historical [10] and sedimentary analyses [15] indicate that the lake continues to experience cycles of flooding and desiccation. The analysis of hydrometric data for the lake from 1974 to 2016 has not been updated, interpreted and concluded. There is no record to show that water quantities have been determined at any point of time for the lake in flood events. Therefore, this paper attempts to revise the lake flooding regimes by considering the evidences and observations of earlier investigators to establish historical hydrology for the past 167 years (1849-2016) with particular reference to flooding events from 1974 onwards. The paper also presents the estimation of standing water in the Lake Ngami in the high flood of 2012 and water allocation to the users. This preliminary investigation provides insights that may be useful in developing methodologies to produce credible water resource development projects and to recognize the importance of low (or even no) flows linked to the natural community structure of riparian river-lake ecosystems.

Site Description, Data Used, Sources and Methodology

Site description

Lake Ngami has a complex shoreline ranging from the lake bed at 919 m to 945 m above mean sea level (msl). It is a shallow sedimentary basin bounded to the south-east by a low escarpment of Karoo and Ghanzi formation rocks along the Kunyere Fault line, which is an extension of the East African rift system [16]. To the southwest a sand ridge separates the Dautsa Flats from the lake basin, although both parts were inundated as part of a Greater Lake Ngami in the Holocene geological epoch [17]. To the north, abandoned Thaoge River system exists with sand ridges (near Kareng) (Figure 1). Various mineral deposits in the lake area are associated with the Ghanzi Formation, including coal and copper [18].

Since the failure of Thaoge River, Lake Ngami has been mainly fed by the Kunyere and Nhabe Rivers, both joining at Toteng, and flowing into the northeast extremity of the lake through a well-defined channel, the Lake River. The Lake River thus mostly derives its flow from the spills of Boro-Xudum-Matsibe systems via Kunyere River while Nhabe River empties into the Lake River from Thamalakane River in high flood events only (Figures 1 and 2).

Lake Ngami derives more than 90% of its water from Mohembo and the remaining ~10% could be from the precipitation. The flood waters typically arrive between June and July, peaking in late August. Waters then recede steadily between October and May of the following year. The behavior of the lake does not directly reflect the impact of long-term climate changes in the area, but the variation of the Mohembo inflow, which is dependent on periodic rainfall fluctuations in the headwaters of the Cubango and Cuito catchments in Angola. To a very limited extent, it also depends on local rainfall over the Delta and on changes of hydrological conditions within the Okavango Delta itself.

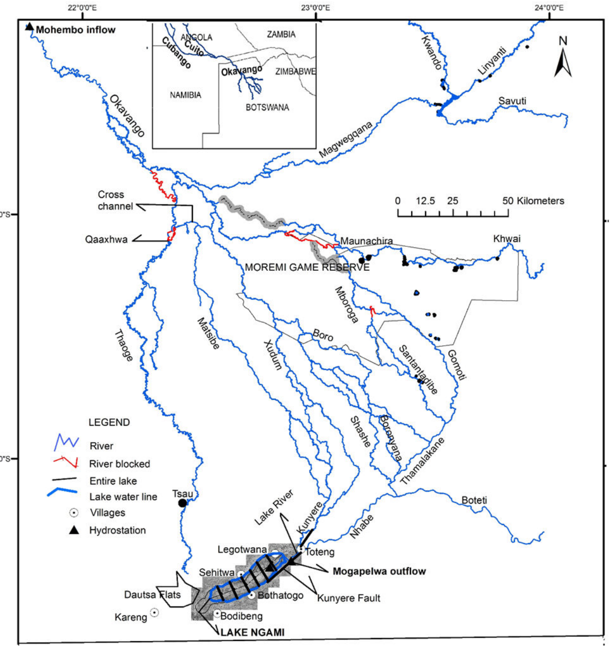

Figure 1: Map of the Okavango Delta showing its major inflow of Okavango River at Mohembo hydrostation and outflow at Mogapelwa hydrostation via Lake River with water area of Lake Ngami as of September 2012. Main distributaries of the delta are labeled.

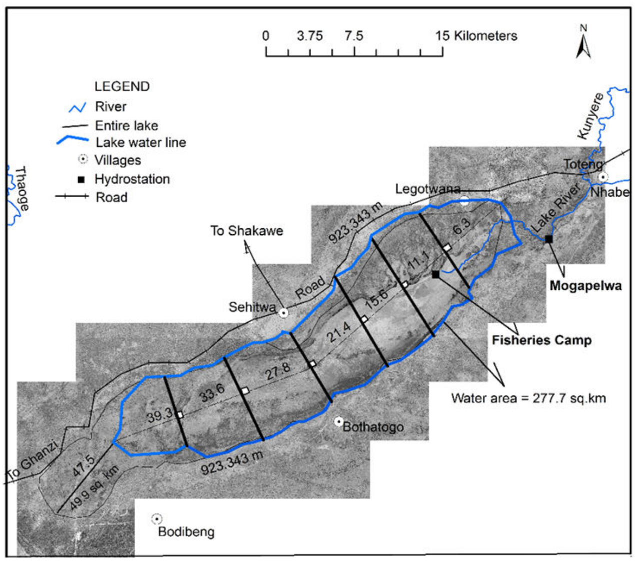

Figure 2: Area of water (277.7 Km^2) in Lake Ngami determined as of September 2012 by using 2002 aerial photographs with respect to total area. Water level contour was 923.343 m above mean sea level.

Total population around Lake Ngami is 6589 according to the 2011 population census [19]. Human settlement is concentrated in six main villages close to the lake with population sizes as follows: Sehitwa (2748), Kareng (1259), Bodibeng (778), Bothatogo (555), Toteng (902), and Legothwana (347) (Figure 1). This area generally lacks proper waste disposal and sanitary facilities. Therefore, pollution takes place around the lake area especially during wet seasons, also as a result of fishing and littering.

Data used, sources and methodology

Hydrometric data used in the present analyses were obtained from the Hydrology Division, DWS in Botswana. The data comprises water discharges (Q) at Mohembo hydrostation (inflow) on the Okavango River and at Mogapelwa (outflow) hydrostation on the Lake river including water levels (H) at Mogapelwa as well as at Fisheries Camp hydrostation in the Lake Ngami. Discharge measurements are undertaken using a current meter in natural channel cross-sections with the help of standard hydrological methods [20]. Water levels are read from staff gauges. Flow measurements are collected daily at Mohembo while in Lake River the hydro-data are collected 10 times or more on a monthly basis depending on the flood duration. The discharge data in cubic meters per second (m^3s^{-1}) was converted to million cubic meters (Mm^3). Fisheries Camp hydrostation is inaccessible in high flood events of the lake. The hydrological year is from October to September of the following year and for instance, hydrological year 1969/70 is presented as 1970 and so on.

Recorded historical flood events that took place in the 18th and 19th centuries were mostly from observations, rather than hydrometric measurements. In the absence of clear understanding of the Delta outflow to the lake, we have analyzed the hydrometric data for “Mohembo inflow” versus the “Lake River outflow to the Lake Ngami” by applying flow regime method to identify three flood regimes for the Delta and Lake Ngami.

- **Wet regime (a):** Inflow volumes of higher than 10000 Mm^3 at Mohembo together with transitional volumes of higher than 8000 Mm^3 in between the years if any is called “Wet regime”. The other factor considered under this regime is that the lake has to become wet for at least two years or more continuously, covering a larger part of its area.
- **Seasonal regime (b):** Years of inflow volumes that were between 8000 to 9999 Mm^3 are taken to constitute a “seasonal regime”. he lake would get a little water, mostly at the mouth of the lake to about a ¼ of its area.
- **Dry regime (c):** The years that had less than 8000 Mm^3 with years of transitional volumes of just higher than 8000 Mm^3 inflow has been termed as “dry regime”. Usually the lake would get very little or no water touching the lake and no flows in Lake River.

The inflow and outflow volumes for the duration of the flow periods for the three regimes, a, b, and c presented in Table 1, were averaged, and then plotted in Figure 3 for ease of interpretation. By taking into account the overall average flow volumes of a, b, and c between 1974 and 2016 for Mohembo and Mogapelwa (Figure 3), a probable outflow to the lake from the Lake River at Mogapelwa was calculated and extrapolated for 1932-1973 period using Mohembo inflow and is presented in bold (Table 1).

Monthly-wise discharges for the wet regime-a (1975 to 1979 and 2009 to 2015), seasonal regime-b (2004 to 2008 and 2016) and for the dry regime-c (1974, 1980 to 2003) were determined and presented (Figure 4). The long-term series of water levels between 1974 and 2016 at Mogapelwa on Lake River and water levels at Fisheries Camp in the lake are also shown (Figure 6).

Measurements and determination of lake water volumes

Six typical cross sections were laid along a distance of 39.3 km in the lake (Figure 2) in September 2012. The water depths were determined along each cross section at selected intervals in kilometers. The lake average width was calculated from the six cross sectional widths. For Lake River at Mogapelwa, the width and depth of the channel cross section at the highest water level (which was on 11th August 2012) was extracted from DWS-Hydrology data sheet. The deepest point along river cross section where gauge is installed at a hydrostation is called gauge zero and thus, the gauge zero for Mogapelwa on Lake River is 922.429 m above msl and 919.835 m above msl for Fisheries Camp in the Lake Ngami. The gauge zero above msl is used to compute the water levels for Mogapelwa and Fisheries Camp including for six cross sectionals of the lake obtain in September 2012 (Figure 5).

The water line along the perimeter of the lake as of September 2012 was determined by collecting GPS coordinates to map and determine the perimeter and water area using GIS ArcMap version 10.2. Similarly, using 2002 Delta aerial images the total probable perimeter and area of the entire lake was determined. A center line was drawn along the lake to determine its total length. The percentage area of water occupied in the lake was calculated with respect to its total area. The volume of standing water as of September 2012 in the lake was calculated using the formula:

$$V = A \times D,$$

Where V=Volume of standing water, A=Total water Area of the lake as of September 2012 and D=Average water Depths for the chosen six cross sections=277.7 × 3.508=974 Mm^3 (Table 2).

Results and Discussion

Hydrological scenario of the Lake Ngami

The available data were analyzed with the objective of improving and understanding long-term flood variations of Lake River and the Lake Ngami itself. The rate of Mohembo inflow of the Okavango River drives Mogapelwa outflow of the Lake River, which directly determines the duration of flooding in the Lake Ngami. Variable observations in water level in the lake for the period 1880 to 1983 have been summarized [10]. However, relying on the available information and data from 1849 to 2016, we arrived at three interpretations, which are presented here.

Period 1849 to 1931: Records for annual inflow at Mohembo and outflow for the lake at Mogapelwa are absent for 1849-1931 period (Table 1). However, several observations and anecdotal summaries in the period suggest different flood regimes for the Lake [9,10]. David Livingstone in one of his travels in Southern Africa reached the lake on 1st August 1849 and commented as saying that the lake was a “fine looking sheet of water” [21,22]. The lake was probably dry from 1881 to 1883 and more or less with continuous shallow water levels before and afterwards. Water reached 11 km downstream from Toteng between 1905 and 1909. Higher water levels presumably occurred beyond Sehithwa between 1898 and 1899 and from 1924 to 1926, while 1925 was considered the year with the highest water level of the 20th century. The lake was probably shallow after 1927.

Period 1932 to 1973: Only inflow data for Okavango River at Mohembo are available for the period between 1932 and 1973. In the absence of outflow data for Mogapelwa for the period 1932-1973, the data for 1974-2016 was used to extrapolate the outflow at Mogapelwa by taking into account of the Mohembo inflow (Table 1, see the numbers in bold). The computed and extrapolated data, thus, for the period 1932-1973 are corresponded to the lake flooding observed by the then travelers to the lake. The lake could have had considerable size of inundation at 10407 Mm^3 from 1932 to 1933, 10076 Mm^3 from 1942 to 1944, 10317 Mm^3 from 1946 to 1947, and at 10949 Mm^3 from 1950 to 1955 (Table 1). However, the lake water levels increased significantly with probable outflow of 436 Mm^3 in Lake River at average inflow of 12003 Mm^3 at Mohembo for 14 years from 1959 to 1972 (longest wet regimes for the Delta so far), reaching Bodibeng in 1968/69 [10]. The lake was seasonal in 1948 to 1949 and from 1956 to 1958 with water arriving the lake. In the dry years (1934-1941 and 1945), the average inflow at Mohembo was between 6103 to 8487 Mm^3 (Table 1). Satellite images show that by November 1972 half of the lake was with water, but by January 1973, lake dried with elevated ground portions.

Period 1974 to 2016: Measurements for outflow to the lake at Mogapelwa in Lake River started in 1973/74 (1974) hydrological year (Table 1). Inflow and outflow with three flooding regimes are presented in Figure 3. Water started reaching the lake from June 1974 and covered less than 11 km distance in September 1975 and from March 1976 water levels rose further to reach Sehitwa by 1979, which is supported by satellite images. The average outflow between 1975 and 1979 were 259 Mm^3 at Mogapelwa when inflow was 10783 Mm^3 at Mohembo (Table 1), although there was no flow between March and June in 1976. The lake would not dry if Lake River does not have flow for 3 to 6 months in a hydrological year when the antecedent flood at Mohembo is higher than 10000 Mm^3 in two consecutive years. However, Wilson [11] concluded that there were some fable stories of inconsistency about the wet and dry regimes of the lake between 1974 and 1979 [11,29]. The longest dry period so far for the Delta with intermittent little water at the mouth of the lake was between 1980 and 2003 (24 years) with average volumes of 23 Mm^3 outflow (Table 1). Lack of combined flows from the Boro, Boronyana and Shashe Rivers flowing into the Thamalakane and failure of Xudum system draining into the Kunyere River was responsible for the drying of the Lake Ngami for almost 25 years [23].

The most favorable wet regime for the Lake Ngami after a long time was from 2009 to 2015 with an average outflow of 523 Mm^3 in Lake River and average inflow of 10788 Mm^3 at Mohembo (Table 1). During this period, the Lake River had the highest outflow of 1101.3 Mm^3 (2010/11 hydrological year) (Figure 3). By September 2012, the water occupied 84.8% (Table 2) of the total lake area and water reached the Bodibeng Flats (Figure 2). The total cumulative volumes from 2009 to 2012 were 2643 Mm^3 excluding percolation and surface evaporation (Table 3). This high outflow happened with the support of Xudum and Kunyere River system as well as with additional flood from Nhabe River being fed by Boro spill (via Boronyana-Shashe Rivers) and Gomoti River (Mboroga distributary). Lake Ngami, thus, has frequently shifted between being a significant body of water with high productivity, to being dry wooded grassland holding only a few puddles of water in seasonal periods [15]. The lake was seasonal between 2004 and 2008 and 2016 with an average outflow of 102 Mm^3 at Mogapelwa (Figure 3). The year 2004 was exceptionally wet for the lake at 10740 Mm^3 (Figure 3) at Mohembo covering 27 km length of the lake but with moderate water levels fluctuating dramatically from year to year afterwards [21].

Duration	Mohembo inflow Range=(Min-Max) =Average Mm^3	Mogapelwa Outflow Range=(Min-Max) Average Mm^3	Lake Ngami condition
1849-1931: Lake Ngami flood is based on the observations and records-[9,10,15]			
Years	No measurements	No measurements	Summary of observations
1849	-	-	"Fine looking sheet of water" when Livingstone arrived at the lake on 1st August 1849.
1850-1853	-	-	Fluctuations from shallow to dry. Dry in 1951. Less water levels in July 1853.
1854-1855	-	-	Moderate water levels.
1856-1883	-	-	Decrease in lake size for nine years from 1856. From 1881 to 1883 desiccation seems probable.
1884-1896	-	-	Thaoge River ceased to run into Lake Ngami after 1884, drying from time to time.
1897-1899	-	-	Maximum levels of water reaching between Sehitwa and Bodibeng in 1898/99.
1900-1904	-	-	Water reached 11 km from Toteng from 1905 to 1909, except in 1910.
1905-1920	-	-	Water reached 11 km from Toteng, except in 1910.
1921-1923	-	-	No record, probably shallow.

1924-1926	-	-	Maximum levels of water reaching between Sehitwa and Bodibeng in 1925-highest levels of the 20th century.
1927-1929	-	-	No record, probably shallow lake.
1930-1931	-	-	Shallow lake
1932-1973: Lake Ngami flood is based on observations and records [8,9,15] Flood regimes "a, b, and c" for Mohembo inflow and probable extrapolated Mogapelwa outflows in bold.			
Years	Inflow data available	**No measurements,** **but probable outflow presented**	Summary of observations
1932-1933	(9209-11606) =10407-a	**(10407*391/10760)** **=378-a**	Shallow lake probably for considerable size in 1933. Inflow measurements started in 1932 at Mohembo.
1934-1941	(6103-8487) =7423-c	**(7423*37/7419)** **=37-c**	Little water in some years (1934-1936) and mostly dry.
1942-1944	(8565-12092) =10076-a	**(10076*391/10760 366-a**	Shallow lake, probably high water levels in 1943/44.
1945	=6847-c	**(6847*37/7419)** **=34-c**	No outflow to the lake.
1946-1947	(9405-11229) =10317-a	**(10317*391/10760)** **=374-a**	High flood resulted in more than half of the lake reaching over 20 km distance.
1948-1949	(8361-8811)-b =8586	**(8586*102/8550)** **=102-b**	Marginal water levels at the mouth of the lake.
1950-1955	(8596-13589) =10949-a	**(10949*391/10760)** **=398-a**	Moderate to high water levels covering more than 1/3rd of the lake.
1956-1958	(8194-8858) =8592-b	**(8592*102/8550)** **=103-b**	Water at the mouth of the lake.
1959-1972	(8738-16047) =12003-a	**(12003*391/10760)** **=436-a**	Inflow was 9108 Mm^3 in 1959, increased to maintain above 10000 Mm^3 from 1960 up to 1972 resulted in the highest water levels in 1968-69 between Sehitwa and Bodibeng. Longest wet period (14 years) in the history of the lake.
1973	=7412-c	**(7412*38/7419)** **=38-c**	Lake was drying with elevated ground portions in 1973 corroborated with satellite images.
1974-2016: Lake Ngami regimes "a, b, and c" for Mohembo inflow and Mogapelwa outflow			
Years	Inflow data available	Outflow data available	Summary of observations
1974	=7932-c	52 Mm3 in 1974-c	Measurements for outflow to the lake started from June 1974 at Mogapelwa by DWS
1975-1979	(9482-12050) =10783-a	(186-436) =259-a	Flow reached slowly to maximum levels between Sehithwa and Bodibeng in 1978/79. Mpho worked for Hydrology navigated Thaoge River 10 km downstream from Tsau village in January 1979.
1980-2003	(5331-10780) =7633-c	(0-196) =23-c	No outflow to the lake in 1980; water at the lake mouth in 1981, 1982-83, and in 1984; dried from 1985 to 1988, water at the lake mouth in 1989; dried from 1990 to 1998; became wet for approximately 7 km due to local rainfall over the Delta in 1999/2000 period; Dried from 2001 to 2003.
2004-2008	(7731-10740) =9014-b	(35-205) =95-b	Water covered approximately 27 km long and 6-8 km width in the lake with outflow volumes of 205 Mm^3 from the Lake River in 2003/04. Water was at the mouth of the lake for 1 to 3 months after 2005 and marginal levels in 2006/07.
2009-2015	(8255-13852) 10788-a	(109-1101) =523-a	Shallow lake of less than 3 km for 6 months in 2009, slowly water levels increased with moderate to significant outflow in 2011 at Mogapelwa

			resulted in increasing higher water levels by September 2012 beyond Toteng. Water levels started reducing from 2014 onwards.
2016	=8010-b	=109-b	Water area reduced in less than half of the lake, no flow for 5 months from January to May.
Note: Average volumes of "a" for wet, "b" for seasonal and "c" for dry regimes are presented in Figure 3 with long-term averages: Mohembo long-term average=9361 Mm^3; Mogapelwa long-term average=142 Mm^3			
Mohembo wet-a=10760 Mm^3		Lake Ngami wet-a=391 Mm^3	
Mohembo seasonal-b=8550 Mm^3		Lake Ngami seasonal-b=102 Mm^3	
Mohembo dry-c=7419 Mm^3		Lake Ngami dry-c=38 Mm^3	

Table 1: Historical record of Lake Ngami flood scenario from 1849-2016.

In summary, in long-time series of 85 years (1932 to 2016), the highest annual inflow at Mohembo was 16047 Mm^3 in 1967 followed by 15756 Mm^3 in 1962 and 13852 Mm^3 in 2011 (Figure 3). The least inflow in the period was 5331 Mm^3 in 1996. By applying 3-regime flow method for 85-year period for Mohembo inflow, it is likely that the Okavango Delta and the Lake Ngami could have had wet regime (a) for 36 years, seasonal regime (b) for 11 years and dry regime (c) for 35 years with an average inflow of 10760 Mm^3, 8550 Mm^3 and 7419 Mm^3 respectively (Figure 3). Therefore, one may conclude that the most probable scenario for the delta is the wet regime. In the period between 1974 and 2016, the average outflow of 391 Mm^3 at Mogapelwa on Lake River produced wet regime (a) for more than 3/4th of the lake area for 12 years (1975-1979 and 2009-2015); average of 102 Mm^3 resulted in seasonal regime (b) for 6 years (2004-2008 and 2016) with shallow water covering less than 1/4th of the lake. he average volumes of 38 Mm^3 outflow in Lake River resulted in either flood touching the lake or lake dry (1974, 1980-2003 for 24 years) (Figure 3). Interestingly, water reached beyond Sehitwa in 1968/69, 1978/79 and 2010/11 with consecutive higher levels in September 2012. Averages for monthly discharges determined from 1974 to 2016 provide further evidence and understanding for the three regimes for the Delta and the Lake Ngami (Figure 4).

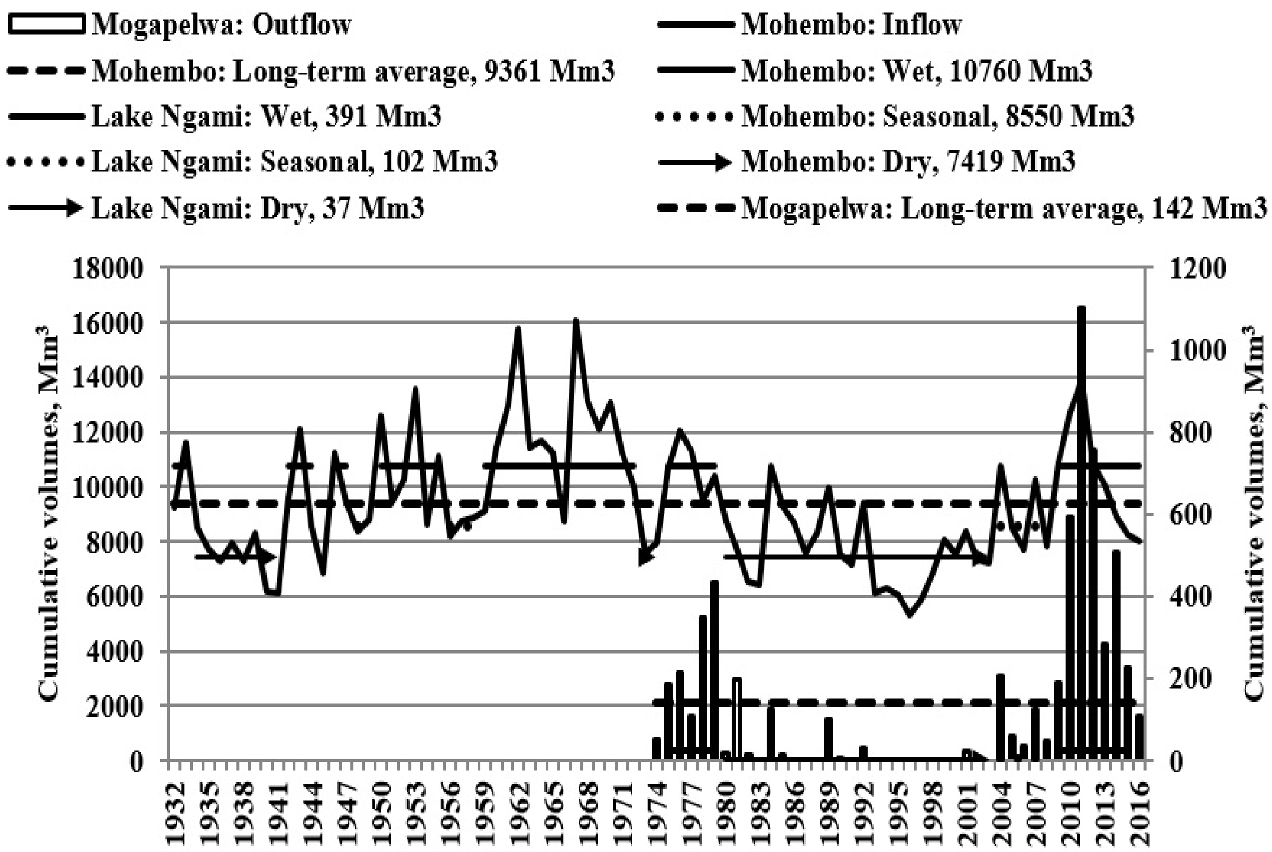

Figure 3: Graphical presentation based on the averages of "a" for wet, "b" for seasonal and "c" for dry regimes (Table 1) for Mohembo inflow from 1932 to 2016 and Mogapelwa outflow from 1974 to 2016. See Table 1 for explanation.

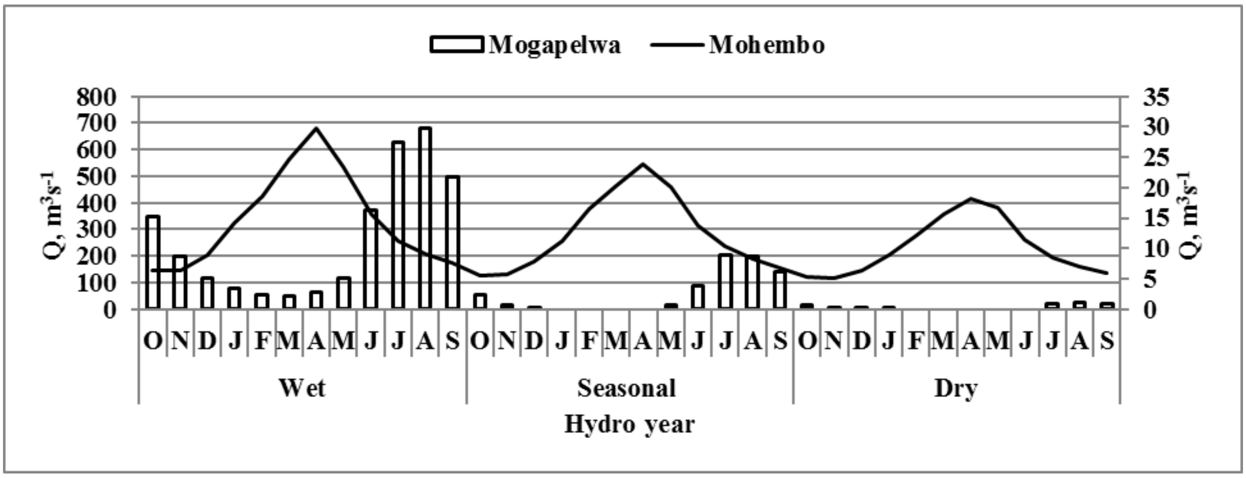

Figure 4: Monthly average flow discharges for the period 1974-2016 in wet, seasonal and dry regimes: Wet regime-a=1975 to 1979 and 2009 to 2015, Seasonal regime-b=2004 to 2008 and 2016 and for Dry regime-c=1974 and 1980 to 2003 (Table 1).

Lake size and shape

The lake was 34.5 km long and 8 km wide in high flood of 1969 [10]. However, other investigators presented different dimensions for the lake (Table 2), thus showing a degree of variability about the entire lake and flooded area in 19th century [10]. In our measurements, the entire length of the lake was 47.5 km with an average width of 7.15 km and a total area of 327.6 km^2 (Table 2). Dimensions of the lake may be difficult to ascertain because of low relief or sloping.

Lake river and lake Ngami water depths

Being ephemeral, the lake is liable to rapid fluctuations in both area and depth. The slope from Mogapelwa hydrostation on Lake River to Fisheries Camp hydrostation in the Lake Ngami is 2.594 m (calculated as the difference between Mogapelwa altitude 922.429 m above msl and Fisheries Camp altitude 919.835 m above msl). This allows the water to pass through smoothly from the Lake River to the lake (Figure 5). Average-maximum cross-sectional depth at Mogapelwa was 2.065 m on 11th August 2012 in the wet regime between 2009 and 2015. This is equivalent to 924.494 m (922.429+2.065=924.494 m) above msl. Similarly, average-maximum cross-sectional depth in the lake along the 4th cross section was at 4.050 m (919.835+4.050=923.885 above msl) in September 2012 between Sehitwa and Bothatogo villages (Figure 5) as compared to other average cross sectional depths. We suggest that greater depth along the 4th cross section is probably because of lowering of soil bed as a result of frequent transport use by the communities as well as other anthropogenic activities during dry conditions of the lake. Geochemical and diatom analyses of the soil cores collected and analyzed at the selected sites in the lake bed suggest that water levels were fairly high before 19th century [15]. However, accuracy for water depths, the time of the years of maximum flood must be considered.

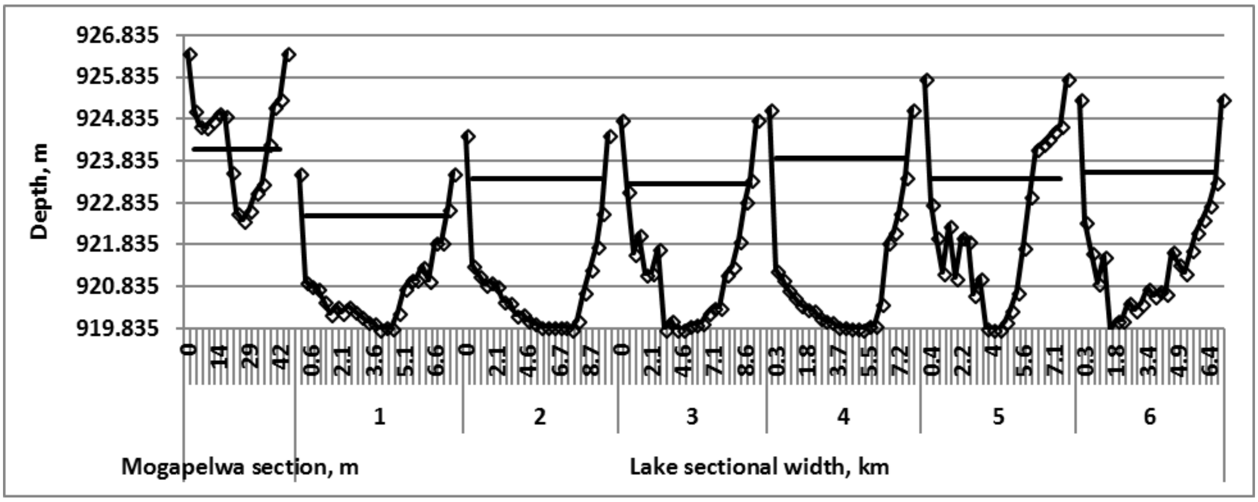

Figure 5: Cross sectional Lake River depths in meters above mean sea level at Mogapelwa on 11th August 2011, six cross sectional depths across the Lake Ngami and sectional average depths in meters above mean sea level as of September 2012. Water depths were computed for Mogapelwa at 922.429 m and 919.835 m above mean sea level for Fisheries Camp. Less average water depths indicate high altitude in the lake above mean sea level and vice versa.

Lake Ngami dimensions and water condition in September 2012							
Status	**Length, km**	**Width, km Min-Max**	**Perimeter, km**	**Total area, km^2**	**Water area, km^2**	**% Water area**	**Average depth, m**
With water	39.3	7.3-9.4 Average 7.9	89.7	-	277.7	84.8%	3.508
Entire Lake	47.5	5.6-8.7 Average 7.15	108.4 km	327.6	-	-	-

Dimensions of the Lake Ngami [10]			
Length, km	Width, km	Perimeter, km	Reference
-	-	70-75	[24]
-	-	90-100	McCabe, August 1852
30	14	-	Oswell, August 1849

57.5	12	115	McCabe, August 1852
	11.3-14.5	112.6	[25]
36-37	-	100	Chapman 1859
	10-12	-	Baines, December 1861
35	8	-	[26]

Table 2: Lake Ngami dimensions as of September 2012 as compared to earlier records [10,24].

The average depths of six cross sections of the lake in September 2012 was 3.508 m (Table 2), equivalent to 923.343 m (Figure 2) (919.835+3.508=923.343) above msl with a length of 39.3 km in a contour area of 277.7 Km^2 (Figure 2), average width of 7.9 km, circumference of 89.7 km (Table 2) and flood touching close to Bodibeng Flats (Figure 2). his is with reference to 923.5 m above msl presented by Shaw [8] in his 1968-1969 map with a lood extension of 250 km^2, length of 34.5 km, width of 8 km and circumference of 80 km reaching past Sehitwa damaging Moshu woodland on the Bodibeng Flats. The flood level of 923.7 m above msl [27] for the year 1925 was the highest in 19th century [28]. The September 2012 flood level of 923.343 m above msl (Figure 2) that passed beyond Sehitwa and Bodibeng is very much close to and testimony to the earlier observations. A study of a 30 km^2 diatomite at the eastern end of the lake basin indicated that a substantial freshwater lake of 932 m above msl was present throughout Holocene [15]. The subsequent decline can be attributed to episodic closure and rerouting of Okavango distributaries, particularly the Thaoge River, perhaps aided by anthropogenic activities. However, the dying of the lake is not indicative of regional climate change [8].

Fluctuations in water levels are correspondingly pronounced at the two stations (Mogapelwa and Fisheries Camp) in response to three water regimes on Lake River and Lake Ngami itself (Figure 6). Also, water levels at Mogapelwa on Lake River show stronger seasonal fluctuations than in Lake Ngami. This has been attributed to the effect of flow confinement in the rivers and the method of inflow surge into the river [12,29]. There is, however, a pronounced inter-annual variation in water levels and flow discharges on Lake River (Figure 7), which is influenced by the inflow pattern of the Okavango Delta. A rise in water levels in the lake in every hydrological year usually results from the previous hydrological year flood. The responses observed in reaches of the Lake River at Mogapelwa and at Fisheries Camp in Lake Ngami appear to display consistent pattern along the system. The data set presented in this study allowed for the characterization of differences in the three flood regimes and inter-annual dynamics in water levels and discharges reflect flood dynamics of Xudum-Kunyere floodplain-channel interactions that displayed on Lake River.

Water allocation

Mogapelwa outflow for 4 years=(2009+2010+2011+2012)	Standing water as of Sep 2012 =Area*average water depth)	Loss by percolation and evaporation, 2009 to 2012=(Mogapelwa Outflow - Standing water as of Sep. 2012)	Population, 6 villages	Average Household consumption @52.7 liters/person/day for 4 years)
(191.6+593.4+1101.3 +756.9)=2643 Mm^3	(277.7*3.508)= 974.2 or 974 Mm^3	(2643-974) = 1669 Mm^3	6589	(6589*52.7*365*4)=507 Mm^3

Table 3: Water allocations based on Mogapelwa outflow to Lake Ngami between 2009 and 2012.

Citation: Kurugundla CN, Parida BP, Buru JC, Paya B (2018) Revisiting Hydrology of Lake Ngami in Botswana. Hydrol Current Res 7: 301. doi: 10.4172/2157-7587.1000301

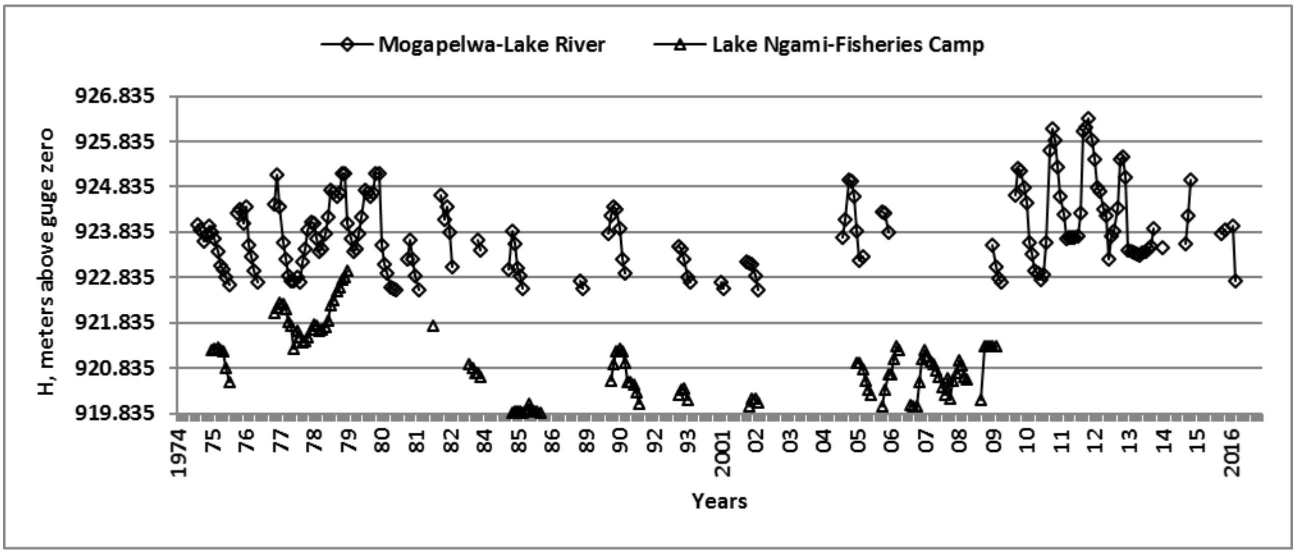

Figure 6: Long-term series of water levels from 1974 to 2016 at Mogapelwa (922.429 m above mean sea level) on Lake River and at Fisheries Camp (919.835 m above mean sea level) in Lake Ngami. Missing years represent either dry or with data gaps. Each year represents one hydrological year.

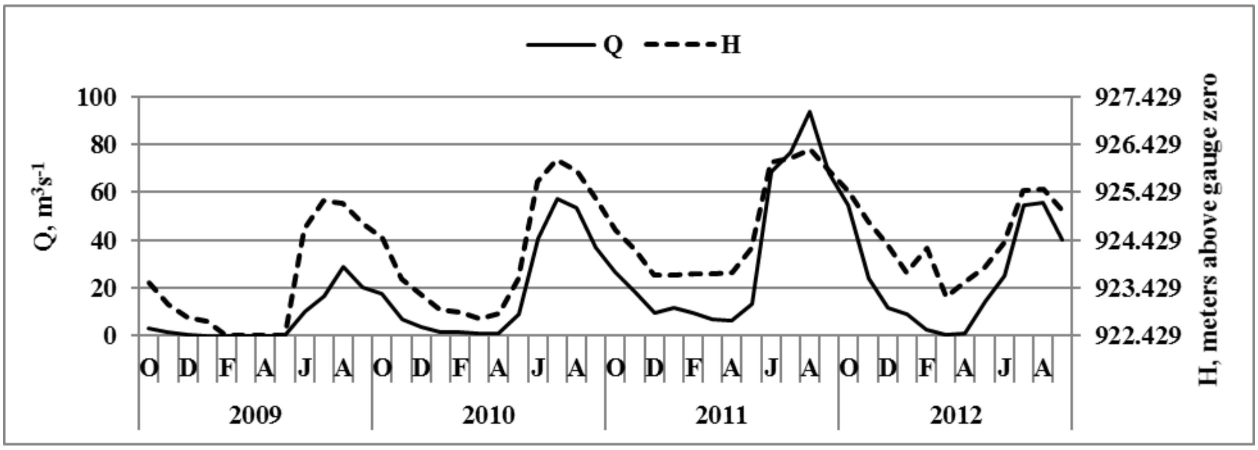

Figure 7: Monthly average water flow discharges (Q) and water levels (H) at Mogapelwa on Lake River between 2009 and 2016. Mogapelwa is 922.429 m above the mean sea level. Each year represents one hydrological year.

The total outflow from 2009 to 2012 in Lake River at Mogapelwa was 2643 Mm^3 (Table 3). It is also obvious that water loss by evapo-transpiration and percolation for the same period could have been higher at 1669 Mm^3 than the standing water at 974 Mm^3 as of September 2012. Such losses in water are probable because of the geographical location of the lake surrounded by vast area of land. National average for household water consumption estimated for 2014-15 was 52.7 liters per day [30]. By the per capita consumption, water available in the lake after domestic water supply for 4 years=difference between "standing water as of September 2012" and "household consumption for 4 years for 6589 population"=974-507=467 Mm^3 (Table 3). Volumes of 467 Mm^3 could have been available for allocation to other users such as livestock, farming and environment in 4 year period.

Biodiversity

Extensive reed beds and floating to submerged vegetation occurred in the lake until the turn of 19th century. The animals that were frequently found around the lake were kudu, buffalo, rhinoceros and hippopotamus [10]. Anderson [25] observed elevation of the southern side of the lake and the water fringed by extensive beds of reeds and rushes, which is not the case of the Lake Ngami today. The occurrence of aquatic vegetation in the lake has been detailed [31], and at four intervals in February, April, July and October between 2011 and 2012 in the Lake [32]. Plant species found in the lake water include: *Alternanthera sessilis* (L.) DC. *Lagerosiphon ilicifolius*Oberm. *Ludwigia stenorraphe* (Brenan) Hara, *Typha domingensis* Pers*, Najas horrida* A. Braun, *Nymphaea lotus* L., *Schoenoplectus corymbosus* (Roth ex Roem. and Schult.) J. Raynal, and *Potomegeton thunbergii*

Cham. and Schltdl. The lake-marginal species include *Eclipta prostrata* (L.) L., *Sesbania bispinosa*(Jacq.) W.F. Wight, *Sesbania brevipedunculata* Gillet, *Mollugo nudicaulis* Lam., *Chloris gayana* Kunth, *Amaranthus thunbergii* Moq., and *Xanthium strumanium* L. *Datura inoxia* Mill. Sub-species. *inoxia* just away from the margin of the Lake is toxic to livestock and cattle usually die from eating it. *Acacia arenaria* Schinz is fairly widespread, and it normally survives when the Lake dries but is killed in prolonged wet conditions. Indeed, thousands of water birds congregate at the Lake to nest as soon as the flood arrives from the Okavango Delta in winter, and they continue right through to the end of summer [4,6].

Water Quality

Water in the Lake is likely to be poor in terms of drinking quality, primarily because of its stagnant conditions, but can be treated through simple treatments such as boiling or chlorination [3]. Concentration of nutrients (Table 4) and bacteria levels (Table 5) are likely to fluctuate across the year by means of stagnation and dilution effects. As per the Botswana drinking water standards (BOS 32:2015), the permissible limits for coliforms is zero and hence treatment is required for potability [32].

pH	Electrical conductivity (µS/cm)	Dissolved Oxygen (mg/L)	Nitrates (mg/L)	Phosphates (mg/L)	Iron (mg/L)	Manganese (mg/L)	Flourine (mg/L)
6.26 -7.75	119.9-207.0	2.1-6.94	0.16-6.48	0.03-1.58	0.01-0.68	0.01-0.041	0.018-0.23

Table 4: Range of important water quality parameters (minimum to maximum) in Lake Ngami during small to high flood [32].

Total coliforms/100 ml	Faecal coliforms/100 ml	Faecal streptococci/100 ml
100-1820	10-270	300-395

Table 5: Range of faecal bacteria in Lake Ngami water (Minimum to maximum) during small to high flood [32].

There are approximately 622 hectares of arable land that appear to have been used for farming between 2009 and 2014 around the lake. Arable lands appear expanded along the southeastern margin in response to improved soil moisture conditions of high flood in 2012. However, in Legothwana and Sehitwa, fields were flooded and threatened between 2011 and 2013 [3].

Conclusion

From the available records and data analyses, it is certain that the Lake Ngami was mostly shallow, at times with moderate to high levels of water between 1849 and 1931. The probable longest wet regime-a, for the Okavango Delta and Lake Ngami was 39 years between 1932 and 2016 period. Surface water abstraction for domestic water supply in wet regime-a may not pose significant threats to the ecological integrity of the Lake Ngami. Under seasonal regime-b partial allocation may be practiced rationally for the users and the rest to the ecosystem requirement. Improving livelihoods on short-term to long-term basis and designating Lake Ngami as Wildlife Management Area is critical as the flooding regimes are highly variable in recent periods. Any planned land use activities will need to be adjusted accordingly to respond to the water resource availability that is altered by the hydrological variation of the lake.

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