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 $3/4^{th}$ 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 $1/4^{th}$ 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).

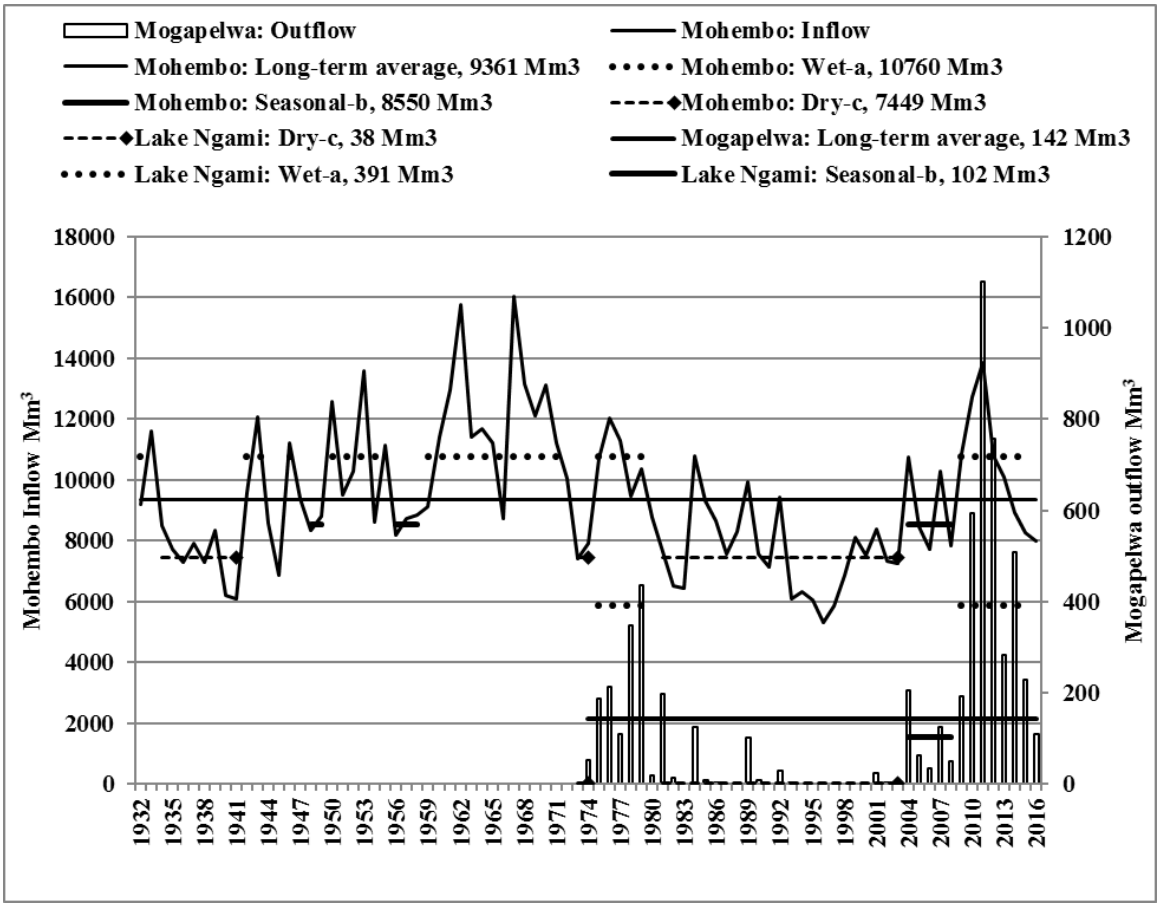

Figure 3: Graphical presentation based on the averages of "a" for wet, "b" for seasonal and "c" for dry regimes (Table 1) for Mohembo inflow from 1932 to 2016 and Mogapelwa outflow from 1974 to 2016. See Table 1 for explanation.

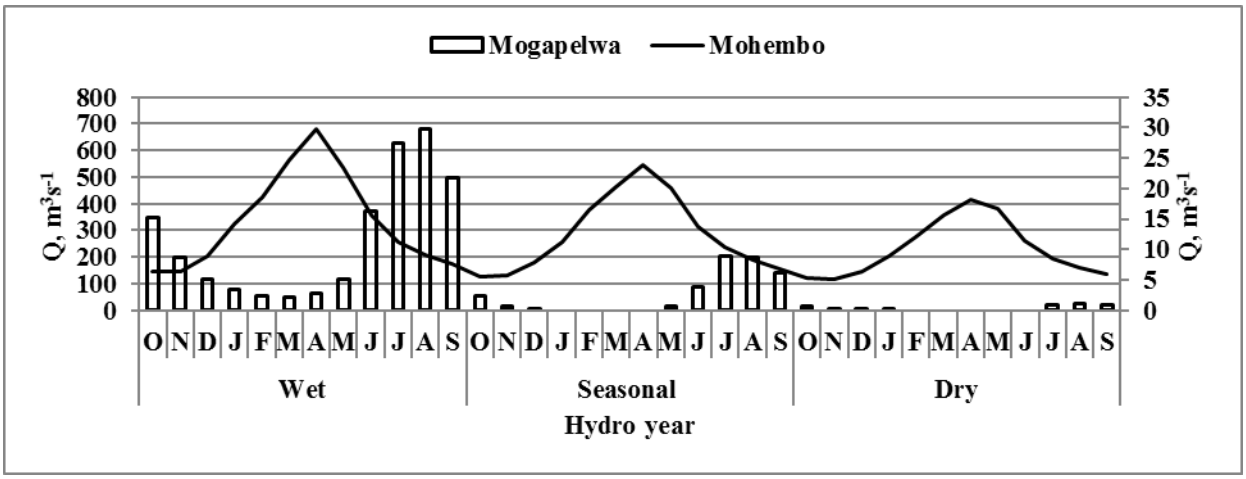

Figure 4: Monthly average flow discharges for the period 1974-2016 in wet, seasonal and dry regimes: Wet regime-a=1975 to 1979 and 2009 to 2015, Seasonal regime-b=2004 to 2008 and 2016 and for Dry regime-c=1974 and 1980 to 2003 (Table 1).

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.

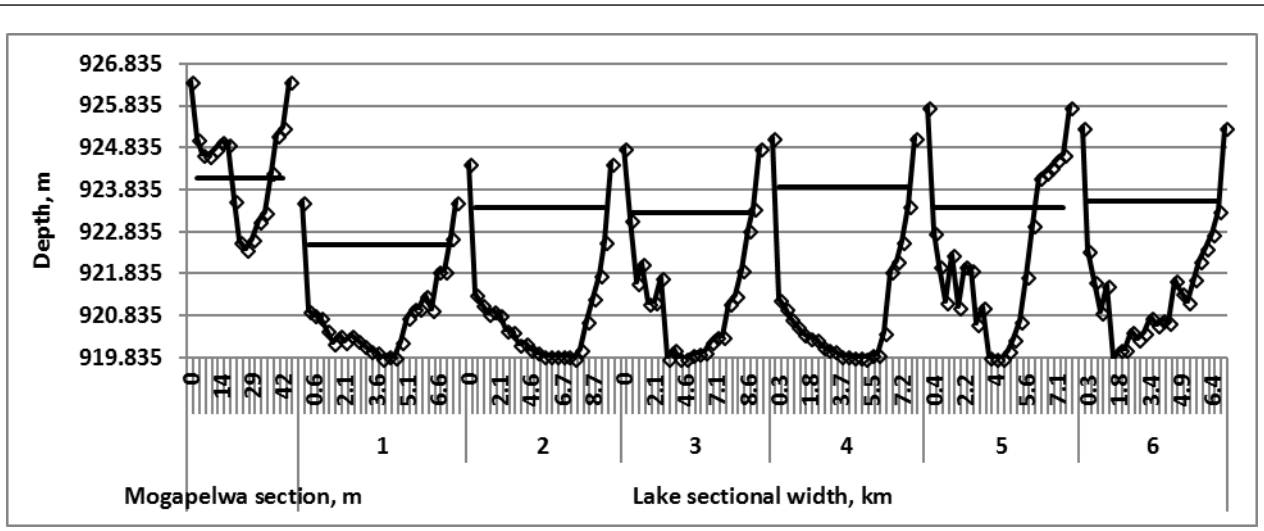

Figure 5: Cross sectional Lake River depths in meters above mean sea level at Mogapelwa on 11th August 2011, six cross sectional depths across the Lake Ngami and sectional average depths in meters above mean sea level as of September 2012. Water depths were computed for Mogapelwa at 922.429 m and 919.835 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). This is with reference to 923.5 m above msl presented by Shaw [24] in his 1968-1969 map with a flood 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.

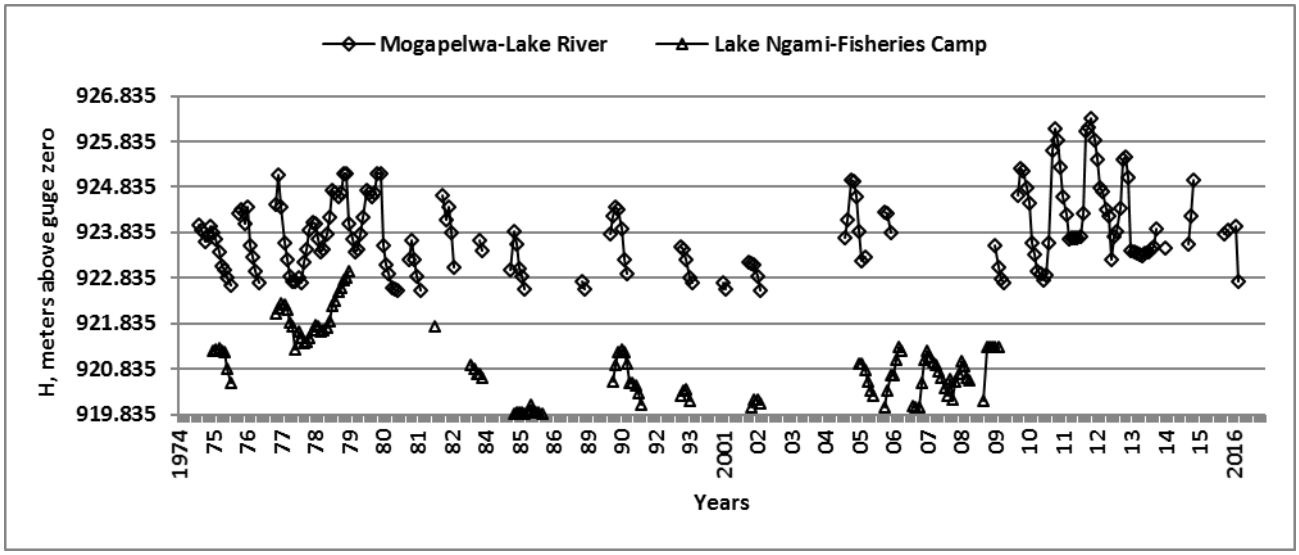

Figure 6: Long-term series of water levels from 1974 to 2016 at Mogapelwa (922.429 m above mean sea level) on Lake River and at Fisheries Camp (919.835 m above mean sea level) in Lake Ngami. Missing years represent either dry or with data gaps. Each year represents one hydrological year.

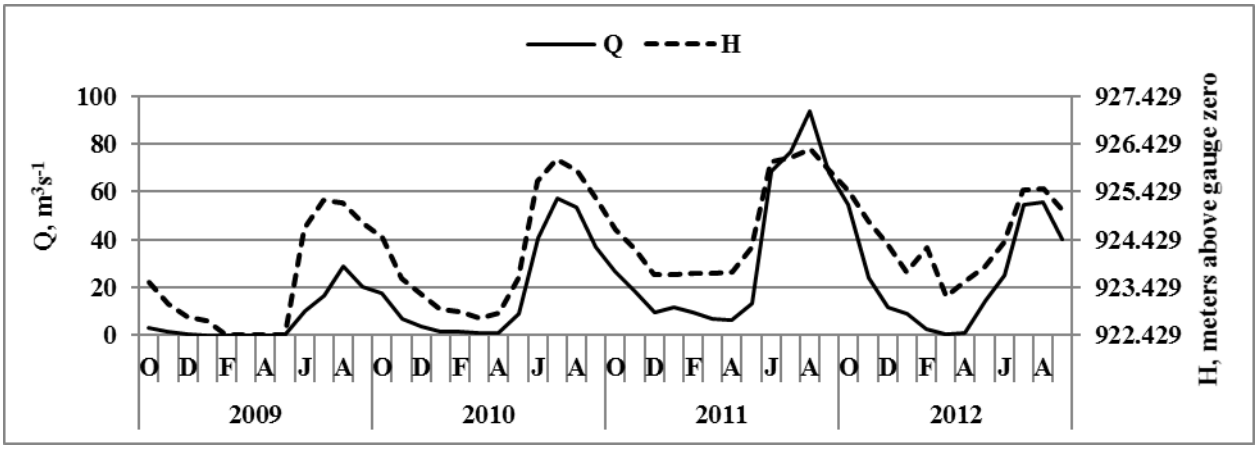

Figure 7: Monthly average water flow discharges (Q) and water levels (H) at Mogapelwa on Lake River between 2009 and 2016. Mogapelwa is 922.429 m above the mean sea level. Each year represents one hydrological year.

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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