PROCEEDINGS

THE 16TH WORLD LAKE CONFERENCE

"Lake Ecosystem Health and Its Resilience: Diversity and Risks of Extinction"

November 7-11th, 2016 Discovery Kartika Plaza Hotel, Bali - Indonesia

Organized by:

Indonesian Institute of Sciences
Ministry of Environment and Forestry
Ministry of Public Works and Housing
United Nations Educational, Scientific, and Cultural Organization - Asia Pacific Center for Ecohydrology
Bali Provincial Government
Udayana University
International Lake Environment Committee Foundation

ISBN: 978-979-8163-25-8

Lake Ecosystem Health and Its Resilience: Diversity and Risks of Extinction
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Published by:
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ASSESSMENT OF HYDROLOGIC ALTERATION WITHIN ECOSYSTEM IN A SAHALIAN SHALLOW LAKE: LAKE GUIERS, SENEGAL

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ABSTRACT

In this study, daily streamflow data of 35 years records and water quality data were investigated to determine Lake Guiers hydrologic alteration within its ecosystem. The Range of Variability Approach (RVA) was used to quantify the modification of the Indicators of Hydrologic Alteration (IHA) and the trophic State Indices (TSIs) was calculated to characterize the eutrophication level. Results show that the flow pattern at Lake Guiers is reversed from the pre-impact with high alteration on most of indicators. These changes on flow have greater impacts on the lake ecological functioning and on water quality. The trophic State Indices (TSIs) of Nitrogen (N) and Phosphorus (P) indicate respectively a eutrophic and hypereutrophic state. Lake Guiers hydrological alteration endanger its ecological integrity. Its restoration requires more than ever to reconcile economic needs and ecological requirements.

Keywords: Environmental flow, hydrologic alteration, indicator, Lake Guiers, Senegal, streamflow

INTRODUCTION

River flow regimes are considered to be the primary driving force of the river ecosystem (Poff et al., 1997). The integrity and stability of river ecosystems is largely dependent on the natural dynamic change characteristics of the streamflow (Poff et al., 1997). The development and management of water resources by humans has altered the natural flow of rivers around the world (Richter et al,.1997). Taking the example of Senegal River Basin (SRB), the downstream flow regime has been widely affected when the Senegal River Development Organization (OMVS), a regional cooperative management body of the Senegal River built along the river two dams (Diama 1985 and Manatali 1987) and structures (sluices, dikes, irrigation systems) in order to meet economic and social development needs for water resources.

In Lake Guiers, one component of the Senegalese River system, several studies have been carried out on first-order impacts in hydrology resulting from dam's operation. Water quality and environmental hazards in general are among the focus of research in the last twenty years. Bouvy et al., (2006) describes the phytoplankton/environment relationships and provides valuable information on algal strategies in a shallow tropical lake like Lake Guiers. Seasonal variations of zooplankton communities and their interactions with phytoplankton and environmental parameters has been investigated by Ka et al. , (2011). They find out the existence of seasonality in zooplankton communities and confirm the importance of using biological indicators such as phyto- and zooplankton to monitor Lake Guiers water quality. Sané, et al., (2013); Varis & Jussila, (2002) focused on Lake Guiers's eutrophication level and conclude that its management has to be revised because of changes in water quality and ecosystem and increasing pressure on its water resources. Berger et al., (2006) point out seasonal dynamics that will constitute an increasing challenge in Lake Guiers.

The impact of dams and the multipurpose use and water quality challenge in Lake Guiers has been investigated by Cogels et al., (1997; 2001). They describe the water quality effects on the management of the lake, with special emphasis on salinity and eutrophication. Recently by remote sensing tools (Diop et al., 2008; Merem & Twumasi, 2008) assess water quality. They compared the FUB-predicted image and study results with those from earlier studies and revealed good correlation.

As we can notice a large number of studies carried out have been focusing on water quality, hydro-biology, invasive aquatic plants, while limited research in view streamflow pattern (magnitude, duration, frequency, timing, and rate of change). Assessment of these streamflow characteristics is essential for understanding and predicting the biological impact of both natural and altered flow regimes on riverine biota (Zuo & Liang, 2015). In Lake Guiers this assessment is particularly important since 2013, the Lake Guiers authority has undertaken a wide project that aim to "restore the ecological and economic functions of the Lake". The main actions planned are: dredging channel, rehabilitating dyke, constructing water supply network and a crossing structure. How are the physical components expected to change after the re-planned development and what is the expected effect on ecological condition?

Accordingly, researchers have developed and applied methods to quantify indicators and to assess alteration in a flow regime through time. A great number of methods has been suggested for this purpose. The 33 Indicators of Hydrologic Alteration (IHA) (Richter et al., 1996) are intended to represent each of the major facets of the flow regime (Olden & Poff, 2003). As one set of proposed hydrologic indices assessment, the Streamflow Analysis and Assessment Software (SAAS) 4.0 (Metcalfe et al., 2013) was developed based on/focusing on hydrology-based environmental flow methods. It calculates hydrological indicators through time with respect to a reference condition, and relate hydrological alteration to changes in ecological condition (Metcalfe & Schmidt, 2014). The Range of Variability Approach (RVA) was established to evaluate the hydrologic alteration caused by hydraulic control structures (Richter et al., 1997, 1998). In this study, we focus on changes in the hydrologic regime and its potential impacts on ecosystem caused by dam's operation. To assess this particular impact, time series of daily mean discharge for Ngnith station (water treatment plant) were evaluated using the Indicators of Hydrologic Alterations (IHA) (Richter et al., 1996; 1998) and RVA associated SAAS (Metcalfe et al., 2013). Comparison of pre- and post-dams periods allows evaluation of their effects on hydrology and ecosystem. The ability to assess the condition of lake and river ecosystems, evaluate sensitivity to alteration, and identify potential changes to the ecosystem resulting from different development and redevelopment options is important to inform decision maker. In this perspective, this study focuses on variables of a flow regime strongly associated with ecological condition and, therefore, most suited to serve as indicators of hydrologic alteration. It aims to quantify and assess Lake Guiers hydrologic alteration arising from in-stream development. This assessment will inform a decision-making process and the implementation of a post-alteration monitoring program; and build knowledge that can inform future policy and management directions by allowing the analysis of information collected in a standard way across sites consistent with an adaptive management approach.

Study Area

Lake Guiers is an important fresh water reserve for Senegal. Its water is used for irrigating crops and drinking water resource for urban centres, including Dakar, the capital city, as well as for continental fishing and livestock breeding. It is located in the north of Senegal on the right bank of the Senegal River, between latitudes 16'23 N and 15'55 N, and longitudes 16'12 W and 16'04 W. It lies on the downstream of the Ferlo hydrological Basin **(Fig 1).**

Hydrology

The lake is 53.5 km long and up to 7 km wide, with a surface area of 274 square kilometers (measured and calculated with Google earth Pro and GIS). Its maximum depth is 4m and average depth is 2 m. Like most of the sahelian lakes, it is classified as a ''shallow lake''.

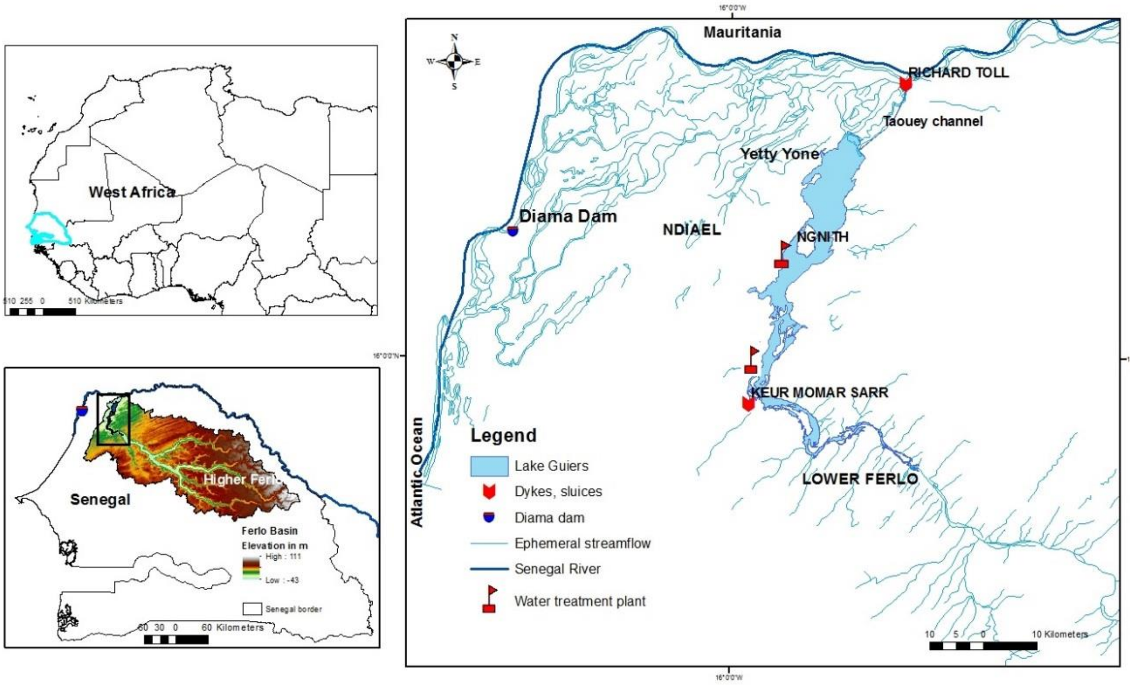


Figure 1. Study area: Lake Guiers within its hydrologic Basin and the main hydraulic infrastructures.

Lake Guiers hydrological system is composed of the following hydrological units (**Fig.1):**

- Taouey canal: It connects Lake Guiers to the Senegal River at Richard Toll city. Originally Taouey was a winding stream of 26 Kilometers, rectified by a canal long to 17 kilometers. It supplies 88% of the total water into Lake Guiers from Senegal River (Cogels, Fraboulet-Jussila, et al., 2001) .
- Yetty Yone: Situated on west of Lake Guiers, it is a 28 kilometers hydraulic axis which supplies the Ndiael depression.
- Ndiael: it is a depression designated as wetland area by the RAMSAR convention in 1977. The great expanse that is the core of the Ndiael covers 10,000 hectares. The site is listed on the Montreux record (endangered sites) since 1990.
- Lower Ferlo: Located in the southern part of the lake, it is complemented by the Ferlo valley. A dyke built in Keur Momar Sarr regulates the outflow from the lake into the lower Ferlo region.

Climate

The climate in the basin of Lake Guiers is similar to much of the Sahel and characterized by two main seasons: a dry season that lasts nine months from October to June, and a rainy season of three months (July–August-September). Total annual rainfall is generally low, but highly variable among years. In the basin, the average of total annual rainfall from 1982-2012 is estimated to 225 mm. The mean annual temperature oscillates around 27.6°C and fluctuates between a maximum average of 30.6°C in the month of June and a minimum of 23°C in the month of January **(Fig.2).**

Lake Guiers hydrological functioning before and after dam's construction

Before the construction of dams, Senegal River used to be a typical rainfall runoff river (Henny, 2012).The river's flow regime depends mostly, on rain that falls in the upper basin in Guinea (about 2,000 mm/year). In the river, this creates a high-water period or flood stage between July and October, and a low-water period between November and May to June (Cogels et al., 1997). Furthermore, sea water intrusion up to 250 kilometers inland occurs in Senegal River during four or five months per year due to low flow rates and a very slight slope (Cogels et al., 1997).

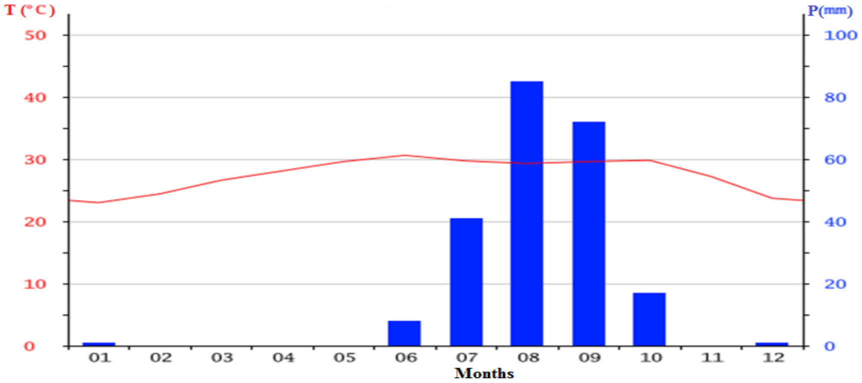


Figure 2. Climate graph (Precipitation and Temperature) 1982-2012, Lake Guiers Area, Senegal. Data source: (http://de.climate-data.org; average 1982-2012).

In Lake Guiers, the hydrology depended on these situations described above. During high water period the lake was filled once a year from the Senegal River and the damming up of the northern region and the closing of the southern and western outflows made it into the largest water reservoir which can be used extensively as a stable freshwater source throughout the dry season (Cogels et al., 1997). Under the combined effect of insufficient filling (during drought years in the whole basin), increased pumping for irrigation, and evaporation (2.2 meters per year), the level of the lake in certain years went below the threshold levels. Extreme conditions were reached during water year 1983- 1984 when the lake was almost completely dried up (Cogels et al., 1997).

In order to meet economic and social development needs for water resources, OMVS has undertaken the construction of Diama and Manantali Dams along the Senegal River. The Diama Dam is located 30 kilometers upstream of the city of Saint Louis. It was built in 1985 in order to stop the dry season intrusion of seawater along the river bed and to irrigate 375,000 hectares of former flood plain for production of two crops per year, especially for rice production (Cogels, Fraboulet-Jussila, et al., 2001).The second dam, the Manantali, was completed in 1987 and is located in Mali 1,200 kilometers upstream from the Senegal River outlet. Its storage capacity is 12.8 km^3. It was built on the river, which supplies approximately 60% of the annual flow of the Senegal River in a reservoir.

Since 1986, the operation of the Diama Dam has prevented any seawater intrusion upstream and fresh water is available all the year at the Taouey - Lake Junction (Cogels et al., 1997). Since 1992, the steady and continuous operation of the Manantali Dam and the regulation of the river have changed the hydrological conditions in the lower valley and the delta region. There is now a constant supply of fresh water, sufficient to fill the lake several times a year. From 1986 to 1991, as before 1986, the lake was filled only once a year during the annual flood. However, water levels became clearly higher than before 1986 with an average levels of 0.8 m, compared with 0.4 m prior to 1986 (Cogels et al., 1997). Since 1992, the partial regulation of water flow by the Manantali Dam has further altered the hydrological regime of the Lake Guiers, which may now be filled several times a year. The annual average level has reached 1.5 m and its annual range is not greater than 0.96 m. Since 2002, the annual average level has reached 1.9 and the range of water level in the Lake is between 1.9 and 2.5 m.

METHODS

The daily flow data were used to analyse the variation of the flow regime at Ngnith station (water treatment plant). We collected observed water level data from 1976 to 2011, a total of 35 years of hydrological data, provided by Lake Guiers Authority (OLAG). Discharge has been calculated from daily water level using Manning- Strickler equation:

$Q= K*RH * i$ **(1)**

Q: Discharge in m/s
K: Roughness coefficient
RH: Hydraulic flow radius
i: Flow slope in m/m

A literature review allowed us to determine the following variables in the flow calculation: hydraulic flow radius (RH) = 7 m; the flow slope in Ngnith station (i) m / m = 0.001; and the roughness coefficient (K) = 35.

The stream flow data from 1976 to 2011 was divided into pre-impact period (1976–1986) and post-impact period (1987–2011), representing the stream flow under natural conditions (before dams) and changeable conditions (after dams), respectively. To address hydrologic regime alteration, we investigated stream flow through Stream flow Analysis and Assessment Software (SAAS) 4.0 developed by Metcalfe et al., (2013).

SAAS is a tool based on/focusing on hydrology-based environmental flow methods. Comparison of pre- and post-dam's periods allows evaluation of the dam's effects on hydrology and ecosystem. **Table 1** shows input data and time periods used for the analysis.

To determine the flow regime target, the Range of Variability Approach (RVA) (Richter et al., 1997) was used to evaluate the hydrological alterations. The RVA was formulated to quantify the modification of the Indicator of Hydrologic Alteration (IHA) by comparing the frequencies within three fixed intervals. The RVA is a milestone in the hydrologic alteration assessment and has been widely used (e.g.: (Chen, 2012); (Irwin & Freeman, 2002); (Shiau & Wu, 2004); (Zuo & Liang, 2015)). Richter et al., (1998) used the degree of hydrologic alteration as a measure to quantify a deviation of the post impact flow regime from the pre-impact one. The degree of alteration D is defined as:

$D = [(Post-Pre) / (Pre)]*100\%.$ **(2)**

Where "Post" is the median flow of the post-impact period, "Pre" is the median flow of the pre-impact period. Richter et al., (1998) further suggested that the value of D ranging between 0 and 33% represents little or no alteration (i.e. low alteration); 33-67% represents moderate alteration, and 67-100% represents high alteration. In order to characterize water quality alteration, we use monthly water quality data from 2008 to 2010 provided by Direction de la Gestion et de la Planification des Ressources en Eau du Sénégal (DGPRE), a national management body of Senegalese water resources. These data were observed in 7 sites in Lake Guiers from nord to south (Richerd Toll, Mbane, Téméye, Syer, Gnith, Keur Momar Sarr, and Lower Ferlo). However, in this study the focus in water quality analysis is primarily on salinity and eutrophication.

To characterise the trophic state in Lake Guiers, we calculate the Trophic State Indices (TSIs) of Secchi Disque (SD), Nitrogen (N) and Phosphorus (P) by using Environmental Protection Agency (EPA)'s nutrient criteria technical guidance manual (Gibson et al., 2000).

The results were interpreted according to EPA's criteria. It suggested that the value of TSI <40 represents oligotrophic state. The value of TSI ranging between 50 and 60 represents a eutrophic state and the value of TSI>60 represents a hypertrophic state.

Table 1. Input data and time periods used for streamflow analysis

	Input data and time periods	
Months	Before impact (dams)	After impact (dams)
Flow time interval	Daily	Daily
Drainage Area	273 Km^2	273 Km^2
Annual analysis period	January 1 to December 31	January 1 to December 31
Total period of record (POR) (for Seasonal Analysis)	12 years	26 years
Number of data values loaded	4380	9490
Number of data values loaded	4380	9490
Season 1	180 days (Jan 1 to June 29)	180 days (Jan 1 to June 29)
Season 2	185 days (June 30 to Dec 31)	185 days (June 30 to Dec 31)

RESULTS AND DISCUSSIONS

Indicator of Hydrologic Alteration

Streamflow

The operation of Diama and Manatali Dams has significantly modified the flow regime of Lake Guiers over the past 30 years. The annual flow increased by more than 269% at Ngnith station. **Table 1** shows a summary record of stream flow statistics. The maximum flow during pre-impact (15.6 m^3/s) is far less than in post impact (30.7 m^3/s). It can be noticed that zero flow days, decreased drastically between the pre- and post-impact periods, from 1041 to 153 days and has been eliminated since 1991.

Table 2. Stream flow statistics in Lake Guiers before and after dams construction

Streamflow statistics	Before dams construction	After dams construction	Unit
Maximum	15.6 (27 Sept-1981)	30.7 (01-Nov-2007)	m^3/s
Minimum	0 (Multiple Date)	0 (Multiple Date)	m^3/s
Mean	4	15.1	m^3/s
Standard Deviation	4.1	6.2	m^3/s
Coefficient of variation (SD/Mean)	1	0.4	m^3/s
Median	3	17.1	m^3/s
Upper quartile	6.9	19.8	m^3/s
Lower quartile	0.1	11.2	m^3/s
Relative Dispersion (IQR/mean)	2.2	0.5	m^3/s
Number of zero flow days	1041	153	---

The flow pattern in Lake Guiers is reversed from the pre-dam. Significantly greater median flows occurred almost during all twelve months (increases of 14 m^3/s), which were the typical high flow that occurred in September - October during the pre-dam period **(Fig.3).**

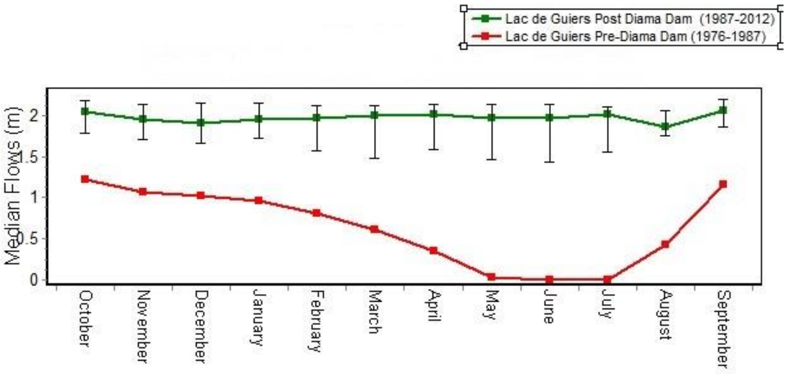
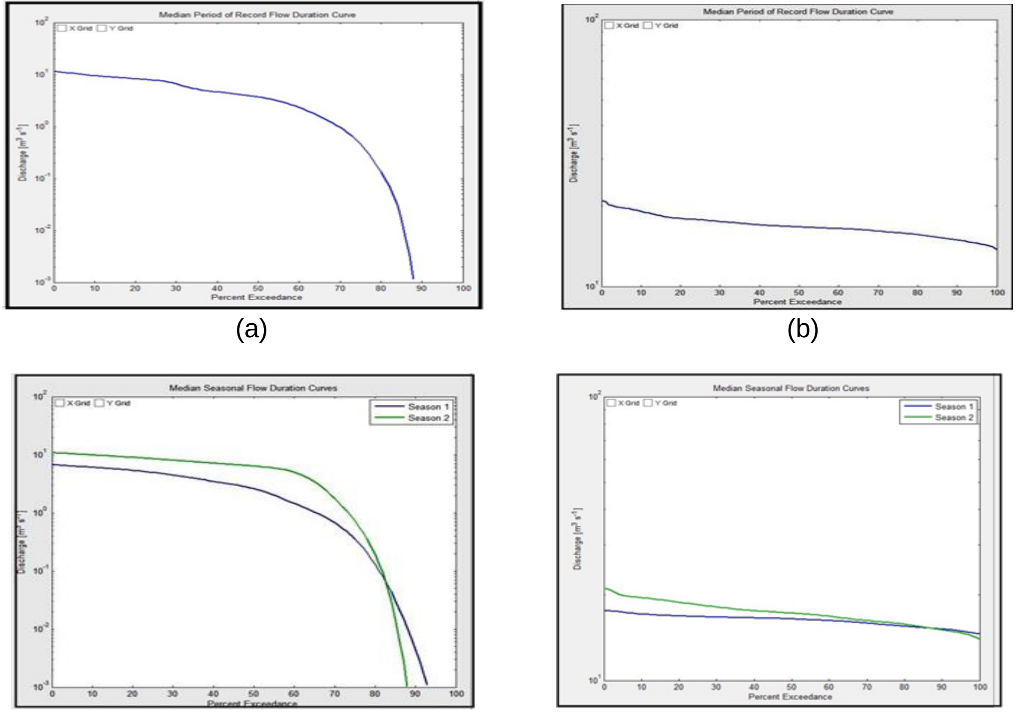


Figure 3. Monthly alteration with RVA in Lake Guiers 1976-2011

Flow duration

A flow-duration curve (FDC) represents the relationship between the magnitude and frequency of daily, weekly, monthly (or some other time interval) of stream flow for a particular river basin, providing an estimate of the percentage of time a given stream flow was equaled or exceeded over a historical period (Vogel & Fennessey, 1994). **Fig.4** compares annual and seasonal median of FDCs at Lake Guiers using two different periods of record (pre- and post impact). The FDC for these two periods are significantly different. For instance, i.e. in pre-impact period the highest Q = 11.4 m^3/s and the percentage of exceedance equal to 0.01%; and the lowest Q= 0.00m3/s and the percentage of exceedance equal to 99.9%. For Post impact, the highest Q = 21 m^3/s and the percentage of exceedance equal to 0.01%; the lowest Q = 13.7 m^3/s and the percent exceedance equal to 99.9%. Comparable changes are also observed on seasonal median FDCs.



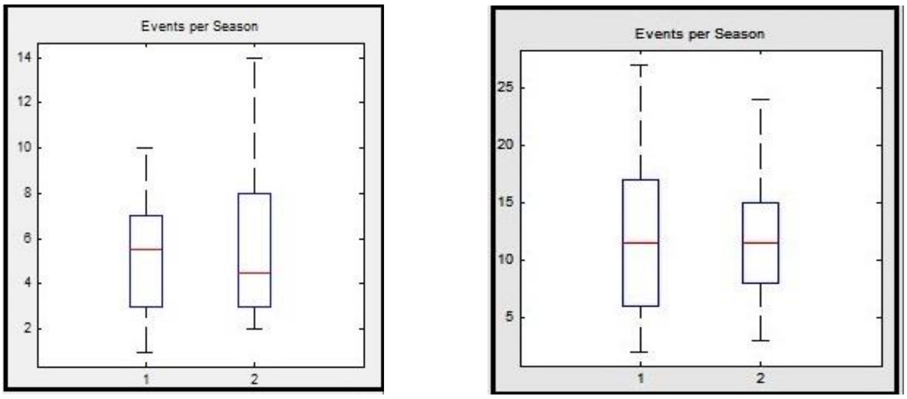
(a) (b)

(c) (d)

Figure 4. Annual (a) and (b) and seasonal median (c) and (d) FDCs at Lake Guiers before impact (a, c) and after impact (b, d)

Base flow index (BFI)

Base flow is defined as the stream flow portion generated by persistent slowly varying sources (i.e. groundwater, lakes, and wetlands) between precipitation events (Dingman, 1994). SAAS separates base flow from stream flow using a recursive digital filtering as described by Nathan & McMahon, (1990). The filter parameter recommended by Nathan and McMahon of 0.9 is used in the SAAS daily stream flow and base flow separation analysis with three filter passes. Base flow separation technique was used to estimate Base flow Index (BFI). Base flow index (BFI) is the ratio of the base flow to the total stream flow. The value ranges from 0 to 1. Therefore, a BFI of 0.5 indicates that 50% of total stream flow can be attributed to base flow for the respective time period (i.e. period of record, month or season). In Lake Guiers, before the dam's operation BFI for the entire period of record was 0.73 which is less than after dam operation (BFI= 0.92). This implies that 73.9 % of total stream flow can be attributed to base flow for the respective time period. In the post impact period it's 92.6% that can be attributed to base flow. Before and after impact periods, base flow constitutes the highest part on total stream flow. High and low flow.

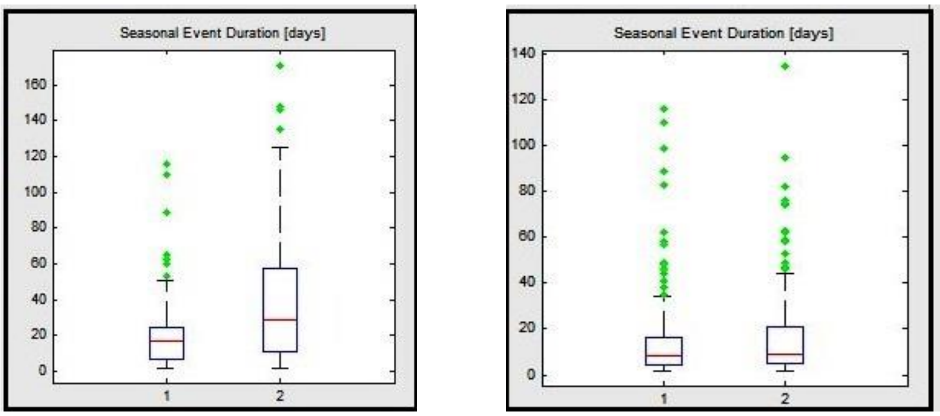


(a) (b)

Figure 5. Seasonal High Flow Frequency

This figure show the seasonal High flow frequency on pre-impact (a) and post impact (b). For pre-impact, the total events equal to 133 and the number of year = 12. During season 1, the 25 % ile = 3; Median = 5.5 and 75% ile= 7; during season 2, the 25 % ile = 3; Median = 4.5 and 75% ile= 8. For post-impact period, the total events equal to 655 and the number of year = 26. During the season 1, the 25 % ile = 6; Median = 11.5 and 75% ile= 17 and during season 2, the 25 % ile = 6; Median = 11.5 and 75% ile= 15.

Fig. 5 shows extreme hydrologic event (high and low flow). The extreme low flow during 1976- 1986 was more than twice the average number during 1987-2011 at Ngnith station. By using the high flow events, we explore the frequency and duration of those events on seasonal basis **Fig. 5 and 6**. The frequency refers to how often a flow above a given magnitude recurs over some specified time interval. The duration is the period of time associated with a specific flow condition. Duration can be defined relative to a particular flow event or a composite expressed over a specified time period (Richter et al., 1996).



(a) (b)

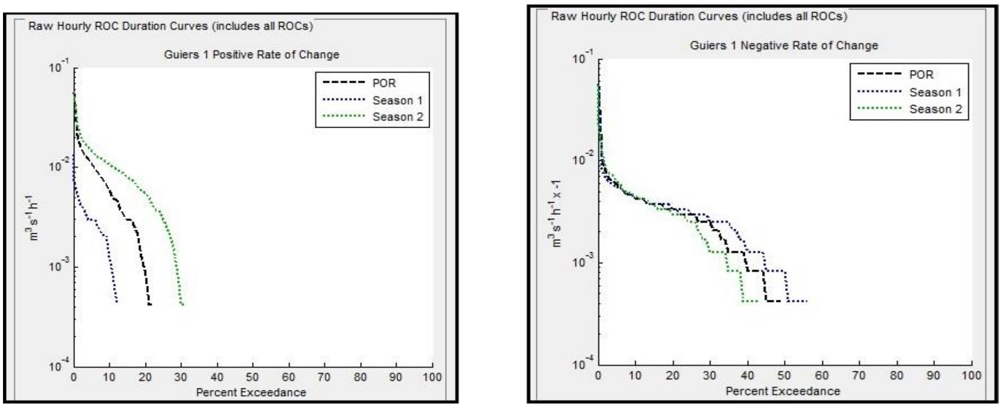
Figure 6. Seasonal High Flow duration

This figure show the seasonal High flow duration on pre-impact (a) and post impact (b). For pre-impact, the total events equal to 133 (S1 = 63; S2 =70). During season 1, the 25 % ile = 7; Median = 17 and 75% ile= 24.75 and during season 2, the 25 % ile = 11; Median = 29 and 75% ile= 57. For post-impact period, the total events equal to 655 (S1= 339; S2=316) and during the season 1, the 25 % ile = 4; Median = 8 and 75% ile= 16 and during season 2, the 25 % ile = 5; Median = 9 and 75% ile= 21.

While seasonal high flow frequency has increased by 109% during season 1 and 130% during season 2, high flow duration has decreased to (-53 %) during season 1 and, (- 69%) during season 2 in Lake Guiers **(Table 3)**.

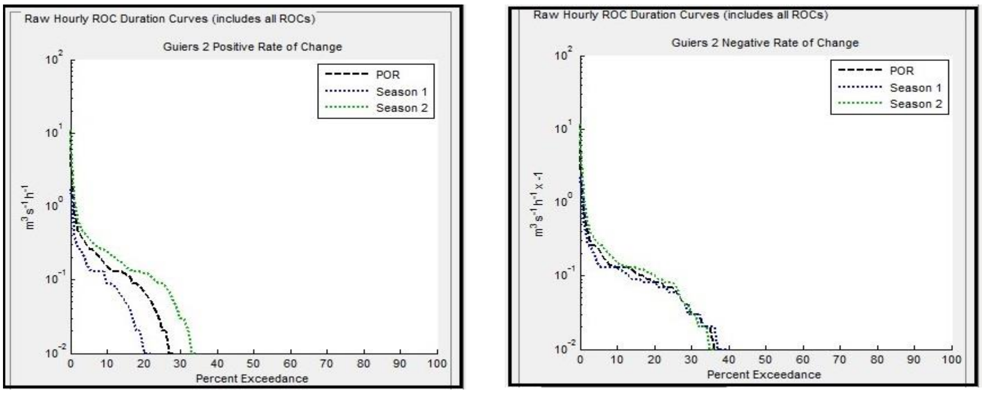
Rate of change (ROC)

Rate of change represents the change between stream flow data points. **Fig. 7 and 8** show POR and seasonal raw rate of change. Its duration curves was created using the unfiltered rates of change (i.e. all rates including low flows) (Metcalfe & Schmidt, 2014). For daily input data, these hourly rates are calculated by dividing the daily rates of change by 24, assuming a linear rate of change throughout each day. Raw ROC curves terminate at less than 100 percentage of exceedance because the percent exceedance is calculated using all rates (i.e. positive, negative and zero) (Metcalfe & Schmidt, 2014). In Lake Guiers, for pre-impact the POR ROC duration curves show that 21% of the time the rates are positive and 49% of the time they are negative, implying that 2% of POR rates are zero. Compared to post impact period ROC duration curves show that 27% of the time the rates are positive and 36% of the time they are negative, implying that 1% of POR rates are zero.



(a) (b)

Figure 7. POR and seasonal raw rate of change on pre-impact period. It shows the positive POR and seasonal raw rate of change (a) and negative POR and seasonal raw rate of change (b) on pre-impact period

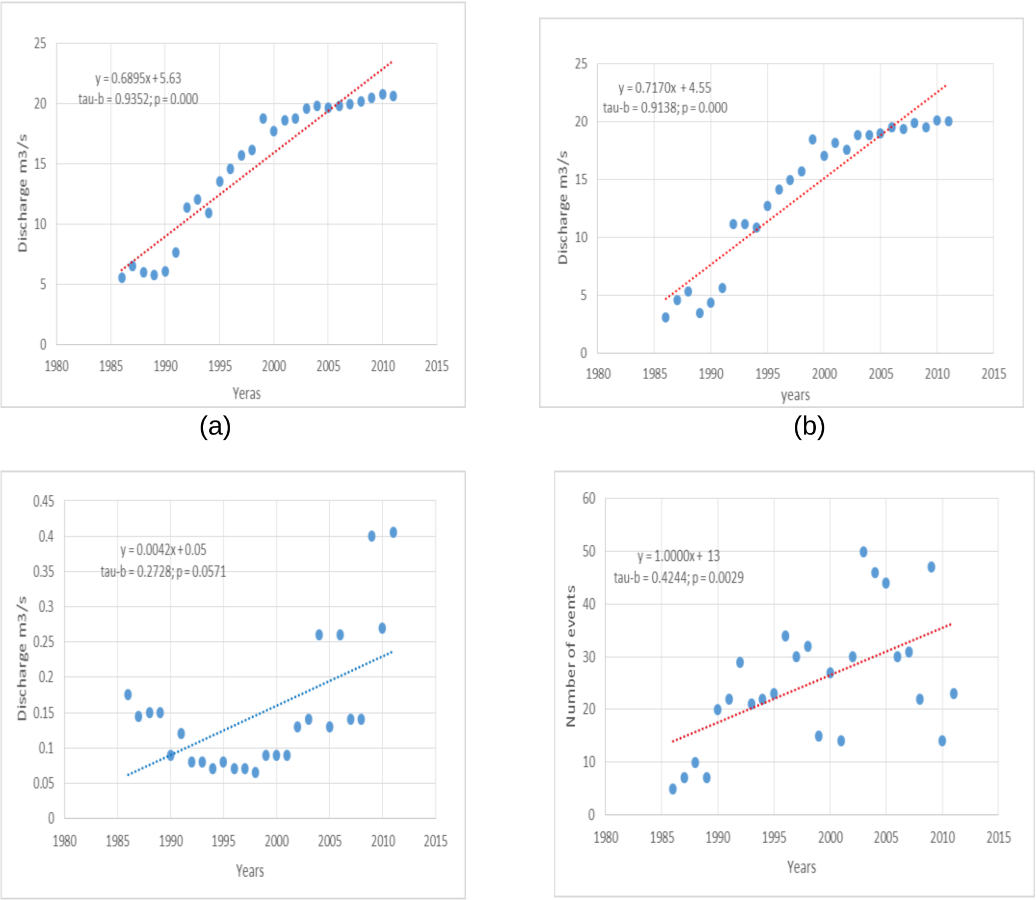


(a) (b)

Figure 8. POR and seasonal raw rate of change on pre-impact period. It shows the positive POR and seasonal raw rate of change (a) and negative POR and seasonal raw rate of change (b) during post-impact period.

Trends in hydrologic indicator

The Mann-Kendall non-parametric trend test is used to statistically assess whether there is an upward or downward monotonic trend in a variable. The temporal variability (summarized annually) of a variety of hydrologic metrics (annual median stream flow, annual median base flow, and annual number of high flow events) were tested **(Fig. 9).** The Mann-Kendall τb (tau-b) test statistic, similar to the correlation coefficient in regression analysis, and the associated p-value used to test the zero-slope hypothesis (at 95% confidence a p-value of 0.05 or less allows the zero-slope hypothesis to be rejected). During post impact period, the stream flow shows an increased trend of 93% with 95% confidence. In addition, base flow and number of high flow events show respectively trends 91% and 42%. They are statistically significant. However, temporal trend was not detected in the annual median rate of change.



(a) (b)

(c) (d)

Figure 9. Temporal variability of hydrologic metric. It shows trends in stream flow (a), base flow (b) rate of change (c) and number of high flow events (d) during post impact period in Lake Guiers. Trend lines are shown in red if the slope of the line is significantly different from a slope of zero (i.e. temporal trend detected) with 95% confidence.

Hydrologic alteration magnitude

The median flow was used to quantify a deviation of the post impact flow regime from the pre-impact ones for Lake Guiers. The results show that the reservoir was strongly affected by the construction and operation of Diama and Mananatli Dams **(Table 3).** The hydrologic regime of Lake Guiers has been altered over the past 30 years. Annual flow increased more than 100% at Ngnith station. Monthly flows for May in dry season and monthly flows for October in flood season were selected to analyse monthly water condition alterations, which indicated magnitude alteration in Lake Guiers reservoir. Median monthly flows for May, the driest month, at Lake Guiers increased up to 100 %, (**Table 3).** Median monthly flows for October, the month in which, the flood pick occurs, account for 33.3% of the total annual flows. The increasing trend of flow is obvious. During all months, flow increased and the largest monthly alterations occurred during the dry season.

Table 3 Hydrologic alteration at Ngnith station, Lake Guiers, *1976-2011.*

Indicator of Hydrologic Alteration	Pre-Impact	Post-Impact	RVA (target)		Deviation % (Magnitude)	Class
			Lower	Upper		
Stream flow						
Mean	04.0	15.1			269	H
Maximum	15.6	30.7			96.3	H
Zero Flow Days	1041	153			-85.3	H
POR BFI	0.7	0.9			25.5	L
Seasonal BFI						
Season 1	0.8	0.9			18.9	L
Season 2	0.7	0.9			27.5	L
Monthly High flow frequency (median)						
January	2	2	0.5	3	0	L
February	1	2	0	3	100	H
March	1	1.5	0	4	50	M
April	0	2	0	4	-	-
May	0.5	1	0	3	100	H
June	0	2	0	3	-	-
July	0	2	0	4	-	-
August	1	2	1	3	100	H
September	1	1.5	0	2	50	M
October	1.5	2	1	2	33.3	M
November	1	1	0	3	0	L
December	0.5	2	0	3	300	H
POR High Flow Frequency(median)	10.5	23	7.5	31	119	H
Seasonnal High Flow Frequency (median)						
Season 1	5.5	11.5	3	17	109	H
Season 2	5	11.5	3	15	130	H
POR High Flow Duration(median)	20	9	4	43	-55	M
Seasonnal High Flowduration(median)						
Season 1	17	8	4	24.7	-52.9	M
Season 2	29	9	5	56.7	-68.9	H

RVA lower and upper targets are 25th and 75th percentiles value of pre and post impact hydrologic parameters. L, M, H represent Low, Moderate and High alterations respectively.

Water quality alteration indicator

Secchi disque (water transparency)

Variation in Secchi disque (water transparency) are quite low between 54 cm to 86 cm (coefficient of variation= 24%) with an average of 66 cm **(Fig. 10). T**hroughout the study period, Secchi values remained less than 100 cm. However, they seem to draw a slight difference from year to year and show a seasonal trend. In addition, the fluctuations in water transparency seem to follow water volume variation in the lake. The increase in lake's water volume resulted in a decrease of transparency and vice versa.

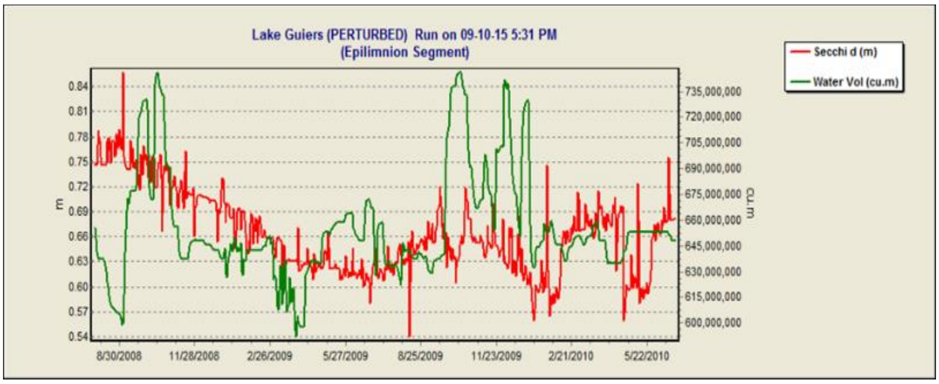


Figure 10. Water transparency with water volume in Lake Guiers,2008-2010

Salinity

The results of surveys between 2008 and 2010 indicates an average salinity in Lake Guiers of 199ppt (392 µS /cm) with a maximum of 257 ppt (506 µS /cm) and a minimum of 124 ppt (244 µS /cm). **Fig. 11** shows the evolution of the salinity during this period, superimposed with water volume in the lake. We can notice that the salinity increases when lake's water volume is low and decrease when lake's water volume is high.

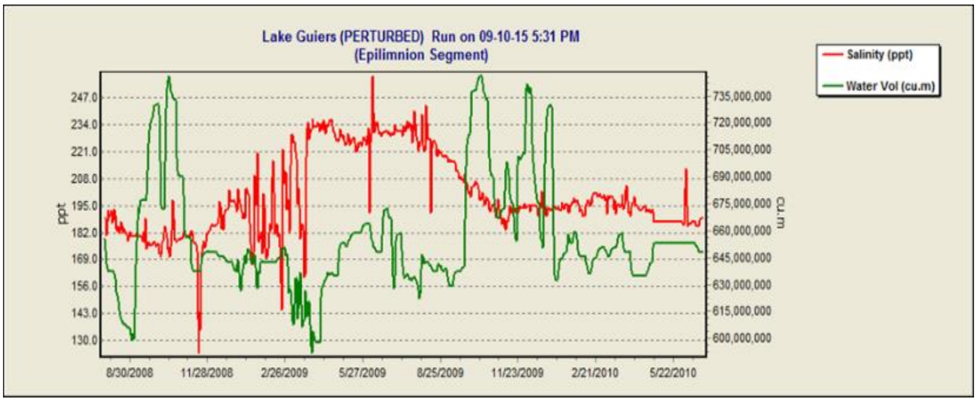


Figure 11. Evolution of salinity in Lake Guiers with water volume 2008-2010.

In addition, there is a spatial and temporal distribution of salinity into the lake. The results show a north - south gradient of salinity. The measurements observed from Richard Toll increase significantly as we move towards Keur Momar Sarr. They are even more (10 times higher) towards lower Ferlo

They also indicates a seasonal trends of salinity. Higher concentrations were noticed in August 2009 **(Figure 11).**

The main source of salt concentration into the Lake is an inappropriate discharge outlet in lower Ferlo and a high evaporation rate. The irrigated crop drainage water discharged into the northern part of the lake is the second main source of salts accumulation. It accounts for 56% of the salt influx (Cogels, 2001).

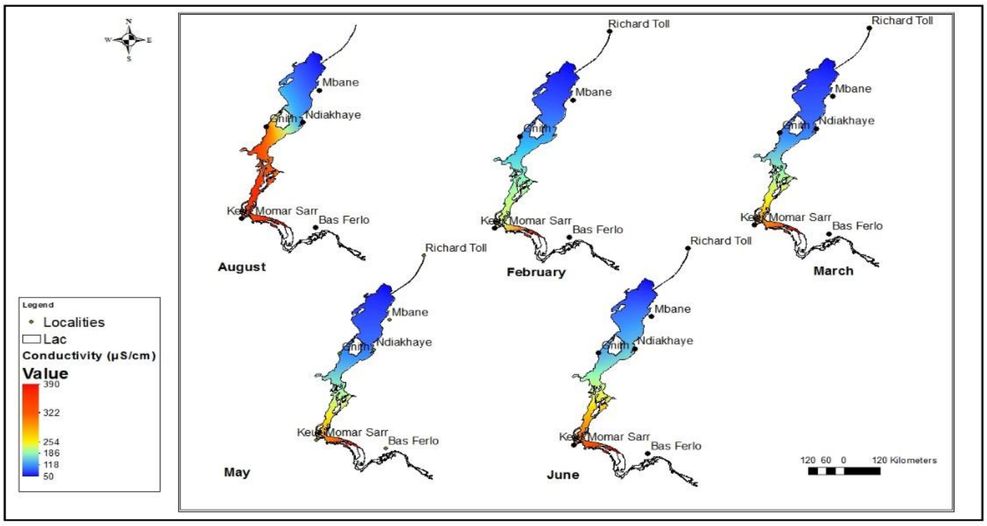


Figure 12. Spatial and temporal distribution of salinity in Lake Guiers 2008-2010

Nutrients concentration
Results of nutrient surveys between 2008 and 2010 show stabilized concentrations not exceeding 1 mg / L.

Total Nitrogen (N) during the study period ranged from 0.74 to 0.90 mg/L with an average of 0.75 mg / L. Total Phosphorus (P) ranged from 0.15 to 0.27 Mg/L with an average of 0.19 mg/L **(Fig. 13).**

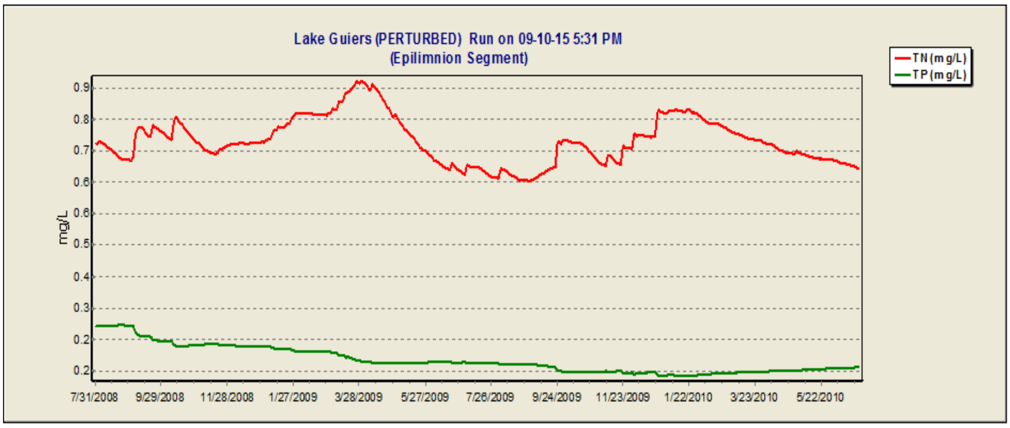


Figure 13. Evolution of Nitrogen (N) and Phosphorus (P) in Lake Guiers, 2008-2010.

In addition, **Fig. 14** show during the study period, Total Ammonia (NH3 & $NH4^+$ (mg/L)) varying between 0.1 mg/L and 0.09 mg/L with an average of 0.1 mg/L. Nitrates (NO3 (mg/L)) range from 0.7mg/L to 0.5 mg/L. Concerning pH, it varies between 8.5 and 6.3. However, no correlation was found between NH3 and pH.

These results did not reflect the spatial tendency of the nutrients which change from the Taouey canal, the northern part of the lake towards the south and Ferlo

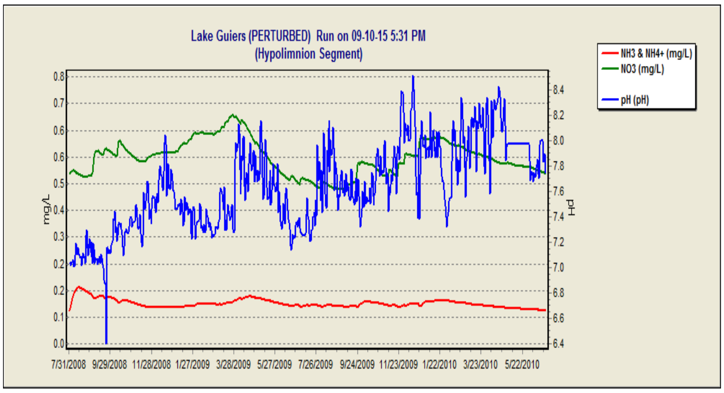


Figure 14. Evolution of ammonia with pH in Lake Guiers, 2008-2010.

Trophic State Indices (TSIs) in Lake Guiers

Throughout the study period, the low measured water transparencies reveal a TSI of Secchi disque of 65.91, which would indicate a hypertrophic state. Total N measured show a TSI of 50.22 indicating a eutrophic state. Finally, total P measured indicate a TSI of 79.57 which would indicate a hypertrophic state.

DISCUSSIONS

Lake Guiers hydrologic alteration

Key ecosystem components that have important functions in determining the integrity of river ecosystems include hydrologic regime, sediment regime, water quality, thermal regime, and biologic components. However, this study focuses on hydrologic regime and water quality factors that most strongly shape the ecological condition of river systems and that are often of greatest importance to the health of valued ecosystem components. Components of flow regimes considered important for maintaining the ecological condition of riverine ecosystems are described in Table 4, while important characteristics commonly used to define their pattern are (magnitude, duration, frequency, timing, and rate of change).

Table 4. Environmental flow components important for maintaining the integrity of aquatic ecosystems

Flow component	Description	Ecological function
Overbank flows	Infrequent, high flow events that exceed the normal channel.	These flows shape and redistribute physical habitats, purge invasive species, provide lateral connectivity between the channel and the active floodplain, provide life-cycle cues for various species, and facilitate exchange of nutrients, sediments and woody debris.
High flow pulses	Short-duration, in-channel, high flow events.	These flows maintain physical habitat by flushing silt and fines and preventing the encroachment of riparian vegetation into the channel, providing lateral connectivity to oxbows and providing life-cycle cues for various species.
Low flows	Normal flow conditions between high flow events sustained through the release of surface and groundwater storage.	These flows maintain water tables for riparian vegetation (lateral connectivity), provide longitudinal connectivity, and provide a range of suitable habitat conditions that maintain the diversity of the natural biological community.
Subsistence flows	Infrequent, naturally occurring low flow events of long duration (occurring over seasons).	These flows maintain sufficient water quality and provide sufficient habitat and connectivity to prevent direct mortality of aquatic species and ensure survival of organism populations capable of recolonising the river system once normal base flow returns.

In Lake Guiers, flow regimes pattern considered important for maintaining the ecological condition of riverine ecosystems have been investigated. Results show that hydrology in Lake Guiers depend in natural conditions on the filling and discharge phases following the rhythm of floods and low flows of the Senegal River. These hydrologic events played an important role in regulating the structure and function of the lake and flood plains. Low flows are necessary for many processes in riverine ecosystem functioning. If the low flow situation reaches extremely low levels, however, ecological communities are impaired. Low frequency but high intensity events, such as severe floods or droughts that used to occur in Lake Guiers had long lasting effects on the structure and function of lotic ecosystems. Extreme low flows may be necessary to dry out floodplain areas and enable certain species of plants to regenerate. On the other hand, water chemistry and dissolved oxygen availability can become highly stressful to many organisms during extreme low flow (Chícharo et al., 2009).

Since 1986, in-stream developments along Senegal River and Lake Guiers has changed the distribution of flow magnitude, duration, frequency, seasonality, and rates of flow increase and recession. The steady and continuous operation of dams and its regulation have changed the hydrological conditions. These new conditions have favored a few years after the proliferation of invasive aquatic plants.

Faye et al., (2016) show that aquatic plants has settled on a surface area of 7,458ha in Lake Guiers from 1988-2010. This has led to a decrease of 2,339 ha on open water and 4,021 ha on flood plains area.

Lake Guiers's water salinity

During the study period, results indicates an average salinity in Lake Guiers of 199ppt (392 µS/cm) with north / south gradient. This result is supported by studies carried out in September 2004 by DHI water and environment and TROPIS under the Long-Term Water Project (Projet Eau Long Terme). They showed a salinity gradient of about 30 µS/cm in Taouey channel entry until about 550 µS/cm to Keur Momar Sarr dyke and a strong rise about 992 µS/cm in lower Ferlo.

Studies carried out before Diama dams showed large variations in salinity in Lake Guiers. Indeed, the salts concentration from the Senegal River was relatively low with a salinity of 20-50 µS/cm (Carl Bro International c / o in Sané et al., (2013). However, it gradually increased in the Taouey before becoming constant in northern part of the lake. Then it increased again in lower Ferlo due to high evaporation rate and increase of dissolved salts in water.

The large variations in salinity (from 1972 until 1985) were therefore due to the intrusion of seawater. After Diama dam, the oscillations were due to the opening and closing of the valves at Richard Toll. The Lake was still subject to relatively large salinity oscillations until 1992.

These continuous variations were probably due to salt discharges stored in Lake Guiers's sediments. Since 1992 with Lake Guiers water level regulation (between 1.90 m and 2.50 m), annual variations in salinity are limited to minor seasonal variations

However, Sané et al.,(2013).noted that the water salinity in Lake Guiers did not show a significant difference between 2002 and 2003 with respectively average value of 180.5 and 178.4 µS / cm. However, a significant increase occurred in 2004 and 2005 with respectively an average of salinity of 220.6 and 207.0 µS / cm. This is probably due to water level elevation and a low water renewal.

Eutrophication level in Lake Guiers

Nutrient surveys during the study period show stabilized concentrations not exceeding 1 mg /. These results do not reflect those obtained previously. According to (Cogels et ,al., 2001) eutrophication is already a serious problem in Lake Guiers. Total N and nitrates are quite higher into the lake. They are even higher in the Taouey canal. However, they tend to decrease and stabilize in the central and southern parts of Lake Guiers. Mean concentrations of nitrogen (N) range from 1 to 2.5 mg/L in the lake and Ferlo, whereas in the Taouey they are estimated to be 6.5 mg/L (Cogels, et al., 2001). The Taouey channel provides significant amount of phosphorus (24%) and nitrogen (25%) into the lake, especially during the rainy season (Cogels, et al., 2001). This could probably be attributed to agricultural activities around the lake. (Faye et al., 2016) indicates that irrigated agriculture is currently the most common activities in the area. The irrigated areas comprise a large-scale irrigation field and peri-urban irrigated horticulture. About 20,063 hectares of land are now cultivated around Lake Guiers.

In this study, the TSIs of N (50.22) and P (79.57) would indicate a eutrophic and hypertrophic state, respectively. These results are likely due to over-use of nutrients by algae and plants. (Sané et al., 2013-3) also describe a eutrophic state from 2002 to 2004 and hypertrophic since 2005, based on chlorophyll estimation. According to them, their production has tripled in 2005.

CONCLUSIONS

Daily streamflow data of 35 years records and water quality data were investigated to determine Lake Guiers hydrologic alteration within its ecosystem. Comparison of pre- and post-dam's periods allows evaluation of their effects on hydrology and ecosystem. The results show that dams and sluices profoundly affect the hydrologic conditions in the Lake Guiers. They reduced high monthly variability of discharges, increased the range of daily discharges, altered the timing of high and low flows, and changed the timing of the yearly maximum and minimum flows.

Hydrologic features demonstrated obvious changes during the post-impact period. The flow magnitude was smaller and the frequency of low flow events decreased during all the year; and the maximum flows and minimum flows increased. The number of high flow events presented increasing trend. Annual median rate of change appeared as a decreasing trend. Base flow remains low both in pre- and post impact. The trophic State Indices (TSIs) of Nitrogen (N) and Phosphorus (P) indicated respectively a eutrophic and hypereutrophic state. These new features in hydrology regime resulting to in stream development lead to changes to the ecosystem. The flood plain ecosystems have been mostly affected. After 1986, Diama dam blocked seawater intrusion. The water into the Lake is now fresh year-round, creating ecological conditions favoring the proliferation of freshwater plants (Typhas australis, Pistia startioles, Salvinia molesta and various alga species). Recent studies show that invasive plants currently occupy 7,458 hectares in Lake Guiers. These are very invasive and eutrophication has begun at some places in the Lake. Downstream of the Diama dam, perturbations in the functioning of ecosystems takes the form of an increase in salinity and/or a drying-up during part of the year (Ndiael wetlands) due to the reduction of flooding or the destruction of water inflow channels during construction of hydrologic infrastructures (dikes, irrigated areas).

With the permanent standing freshwater, aquatic plants developed to excess and now prevent access to the water at some places. The Typha australis constitutes a refuge and a spawning area for fish. However, the abundance of vegetation also constitutes an obstacle for fishing. In addition, infrastructure installations represent obstacles for fish migration to spawning areas.

Lake Guiers's hydrological alteration endanger its ecological integrity. Each aquatic ecosystem requires a certain amount of water to maintain its ecological integrity. These environmental water requirements can be defined as the quantity and quality of water required to protect the structure, function, and species composition of that ecosystem. Therefore, to ensure ecologically sustainable development, we propose the following recommendation: After an alteration in the flow regime, a hydrometric monitoring program should be implemented to provide a thorough assessment of the degree of alteration. This would include measurement of continuous discharge using a data recording frequency that adequately captures the pattern of flow in the altered flow regime.

Continuous discharge measurements of inflows to the structure should also be estimated using back-calculations or measured directly. This will be particularly important where there are no upstream alterations, providing an indication of the natural variability in streamflow during the assessment period of interest. We also encourage the implementation of best management practices on water resources and landscapes to reduce non-point sources of phosphorus transport in the Lake. Also, we recommend that water resources manager work with municipalities to protect the lake shorelines and floodplains in order to better accommodate their natural processes as well as to improve resilience to flooding and to improve water quality. Finally, water resources managers should increase public education and provide resources for local residents regarding impacts of fertilizer use on water quality and the benefits of vegetated buffers.

ACKNOWLEDGEMENT

The authors thank the West African Service Center on Climate Change and Adapted Land Use (WASCAL) for funding this work, and the University of Abomey Calavi-Benin which hosts the Graduate Research Program on Climate Change and Water Resources. We are further thankful to Lake Guiers Authority (Senegal) where this work was mainly conducted and for their various supports.

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