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Article

Hydro-Climatic Variability and Water Balance of Lake Fitri, Sahel (Chad)

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Abstract

This study investigates the hydroclimatic functioning of the Lake Fitri basin in eastern Chad, combining rainfall records, hydrological observations, water balance analysis, and hydrological modelling. Results show a strong Sahelian climatic control, with rainfall concentrated in a short wet season (July–September) and potential evapotranspiration largely exceeding precipitation. Batha River flows are highly seasonal, generating short flood pulses that drive lake level fluctuations and aquifer recharge. Water balance estimates indicate that recharge is limited and episodic (≈ 70 – 120 mm in 2020), representing only 14–24% of annual rainfall, and occurring almost exclusively during extreme rainfall events. GR2M modelling captures the seasonal dynamics of the Batha but underestimates peak floods and recession due to transmission losses and floodplain storage. Compared with Lake Chad, Lake Fitri is more directly sensitive to local rainfall variability, reflecting its dependence on a single tributary. Overall, the findings underline the fragility of this hydrosystem and the need for reinforced monitoring and integrated management to ensure sustainable water resources under increasing climatic variability.

Keywords: Lake Fitri; Batha River; Sahel; hydroclimatic variability; groundwater recharge; GR2M modelling

1. Introduction

Sub-Saharan Africa is particularly vulnerable to climate variability due to the fragility of its ecosystems and the strong dependence of its populations on natural resources (IPCC, 2007; Nicholson, 2013). This variability strongly influences water availability and hydrological dynamics throughout the Sahel, with significant repercussions on wetlands that support both essential socio-economic activities and ecological functions (Lemoalle & Magrin, 2014). According to Kouassi et al. (2010), hydro-climatic variability can be understood as the deviation of climatic and hydrological parameters from their long-term mean values, reflecting both natural fluctuations and external forcing. Although inherent to all environments, it is especially critical in wetlands, which serve both as biodiversity hotspots and as vital water reservoirs supporting dense human populations (Acreman & Holden, 2013). The lakes of Chad, like many endorheic lakes worldwide, are particularly exposed to these changes (Coe & Foley, 2001; Lemoalle, 2004). Lake Fitri, located about 300 km northeast of N'Djamena in central Chad at an altitude of 285 m, lies at the heart of the Sahel. The Batha River feeds it from time to time, and its size is mostly determined by the river's occasional floods (Yalikun et al., 2019). Lake Fitri is often perceived as a scaled-down version of Lake Chad (Lemoalle and Morgan, 1987; Schuster et al., 2019). The lake and the wetlands around it are important for water flow and also support farming, fishing, and pastoralism in the area (Moupeng, 2006; Raimond & Zakinet, 2019).

Lake Fitri is one of the least studied lakes in Chad, even though it is very important for strategy. Its functioning is still not well understood (Raimond et al., 2019). Although included in several

development and research projects, the available studies remain fragmented and insufficient (Poulin, 2018 ; Poulin et al., 2019; Schuster et al., 2019). This knowledge gap is problematic since surface water systems in the Sahel are both the most accessible and the most vulnerable resources, around which populations are rapidly concentrating (Favreau et al., 2009; Leduc et al., 2001). In this context, several important issues come to mind: how has Lake Fitri reacted to changes in the weather and a growing population? What hydro-climatic changes are observable, and what are their consequences for the basin's hydrological equilibrium? Answering these concerns is important for making water resource management and resilience methods better in the Sahel (Taylor et al., 2013; MacDonald et al., 2012).

The aim of this study is to enhance the comprehension of hydro-climatic variability in the Lake Fitri basin, emphasizing the synergistic impacts of climate change and accelerated population expansion.

2. Study area

2.1. Geographic and Socio-Economic Setting

Lake Fitri is located in the Batha watershed (Figure 1), the entirety of which lies in the Sahelian zone (Raimond et al., 2019). The upper Batha basin is located in the east of the country, in the Ouaddaï massif, with a boundary located approximately on the Guéréda-Adré line. It has an area of about 96,000 km² (Figure 1). Its downstream point is Lake Fitri. Crossing the Batha region from north to south, one finds the sandy cordon of the Mega Lake Chad, which marks the morphological boundary between the Batha, Guéra and Fitri regions. The region has a very flat topography, with the exception of the cordon itself, which overhangs the plain by about ten meters, the few rocks that can be observed at Yao or Guéra, and the multiple dune formations of various shapes (transverse, linear or barchanoid) to the southwest of the lake. This lake area has a very high agricultural (with berbere as the main driving force), fishing and pastoral potential and is considered a cereal granary and a refuge area for farmers, fishermen, transhumant herders and wildlife, mainly during the dry period. However, it very often experiences grain deficits (Raimond et al., 2019). Apart from a few fishermen and rare market gardens on the shores, Lake Fitri remains entirely natural, in a dry savanna zone.

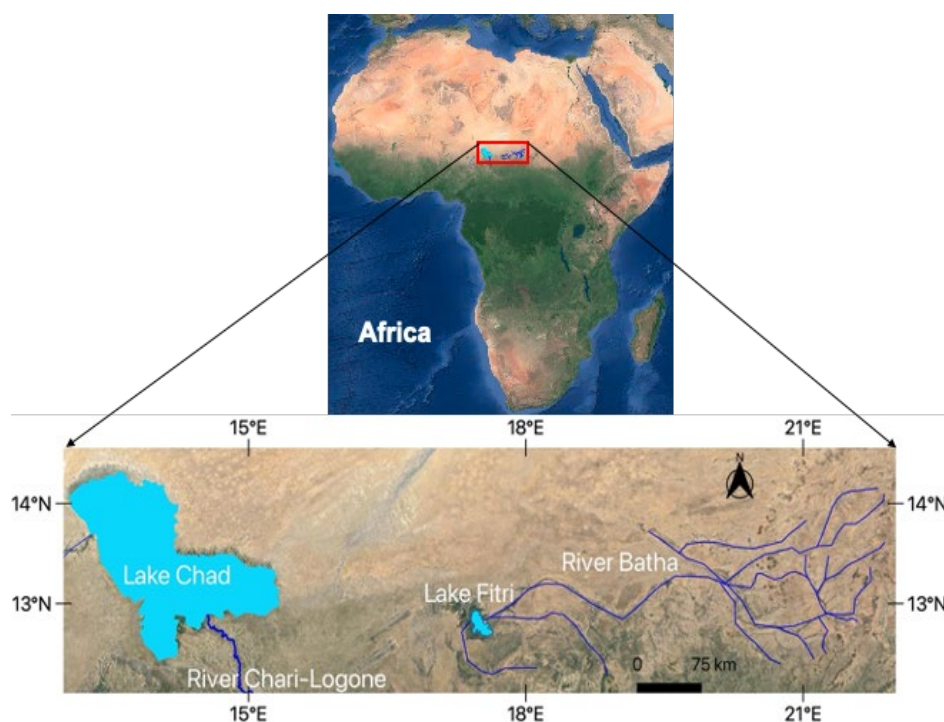


Figure 1. Location of the studied site (a) in central Sahel. (b) the Lake Fitri and its catchment area drained mainly by the Batha river.

2.2. Geological and Hydrogeological Context

The study area is covered by Quaternary formations that extend to the Ouaddaï foothills in the east and the Guera in the south. Around the lake, the Precambrian bedrock is visible through the Quaternary cover, in the form of granitic inselbergs (Figure 2). Lake Fitri is hydrologically distinct from Lake Chad, the two basins being divided by a structural sill formed from ancient massifs. It has the same sedimentation properties as the Chadian basin (Lemoalle, 1987). At its biggest, it was also part of the Mega Lake Chad (Schuster et al., 2019). Aquifer resources can be found in many places. There is a generalized water table over the entirety of the sedimentary formations, although these are different depending on the sector or type of formation (Schneider and Wolf, 1992). The Quaternary water table, and the Pliocene and Continental Terminal aquifers are observed (Figure 2).

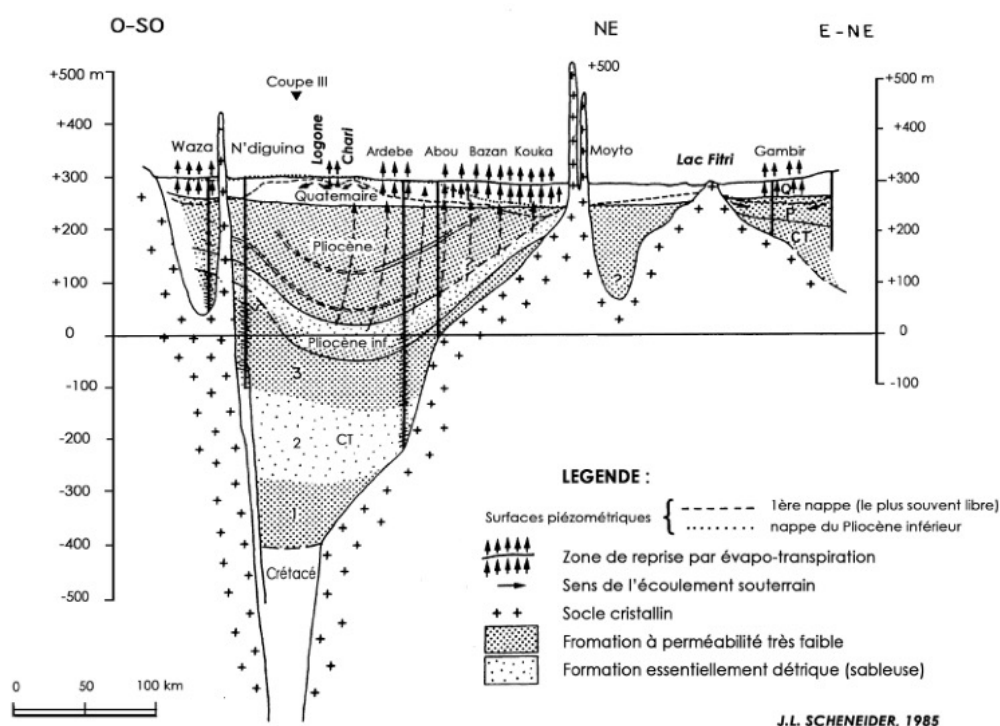


Figure 2. Hydrogeological map from Waza to Gambir (after Schneider and Wolf, 1992).

2.3. Hydro-Climatic Context

The climate is marked by the alternation of a four-to-five-month rainy season, centered on August, and a six-to-seven-month dry season (Raimond et al., 2019). Lake Fitri, with its strongly Sahelian character, is a terminal lake that is a sensitive and privileged recorder of monsoon variability and its impact on past landscapes and ecosystems. The study of the climate variability of the Lake Fitri basin has been little addressed in previous works. The hydrographic network is made up of several intermittent rivers, the most important of which is the Batha River with its tributaries the Melmélé, Zilla, Zerzer and Abourda rivers (BIEP, 1989). Lake Fitri is only fed for two or three months of the year by temporary streams because its watershed is located entirely in the Sahelian climate zone (Moupeng, 2006). It also receives significant inflows of ouadis from the Aboutelfan. Its surface area is highly variable depending on the water inflow in its watershed. The lake can dry up almost completely in 1973 for example, but also in 1901 (Moupeng, 2006). At its maximum extension, it could reach 1300 km²; this was the case in 1870. On average, its surface area is 800 km² (Lemoalle and Magrin, 1987).

3. Methodology

In order to appreciate the hydro-climatic variability of Lake Fitri, we collected all the climatic and hydrological data available on the study area. These data were collected from the National Agency of Meteorology (ANAM) and the Direction of Water Resources (DRE) in Chad. These data were completed by measurements that were carried out thanks to the instrumentation of the Fitri lake and its watershed in the framework of the LMI VIABELEAUX project since 2019.

3.1. Collection of Meteorological Data

The meteorological dataset used in this study includes precipitation, air temperature, relative humidity, wind speed, and evaporation. Data were collected from three monitoring stations located at (i) Yao, on the shore of Lake Fitri, (ii) Ati, approximately 90 km upstream on the Batha River, and (iii) N’Djamena, the Chadian capital (Figure 3). At Yao, monthly precipitation records are available from 1980 to 2018. These were complemented by a weather station installed in November 2019 on the lake shore, providing continuous hourly measurements of rainfall, air temperature, relative humidity, wind speed, and evapotranspiration. At Ati, monthly rainfall records cover the period 1985–2015. In April 2021, a new automatic station was installed, enabling hourly monitoring of precipitation, temperature, humidity, and wind speed. At N’Djamena, monthly precipitation data are available for the period 1980–2018, providing a complementary long-term climatic record for the region. All of the automatic stations include Campbell Scientific dataloggers: the CR200 at Yao and the ClimatVue at Ati. This makes sure that the measurements are high-resolution and continuous. The three stations were chosen because they could measure both local and regional changes in the Lake Fitri basin’s hydro-climate. The Yao station, which is right on the coast of the lake, gives us data that show how local weather affects the lake and how the weather and the lake interact directly. The Ati station, which is on the Batha River, the major river that feeds Lake Fitri, gives important information about rainfall and hydro-climatic inputs that affect the lake’s seasonal changes. Lastly, the N’Djamena station gives us a long-term picture of the region’s climate, which is a good example of how the Sahelian climate changes over time. Together, these complementary datasets allow for a robust analysis of both spatial and temporal variability in hydro-climatic parameters, from local to regional scales, and ensure a better understanding of the drivers controlling water balance in the Lake Fitri basin.



Figure 3. Ati and Yao weather stations (credit @M. Taher, February 2022).

3.2. Collection of Hydrological and Altimetric Data

The hydrological dataset includes water level measurements from Lake Fitri and its main tributary, the Batha River, at its outlet into the lake. Since November 2019, in situ measurements have been carried out twice a month by a trained observer at Yao using a graduated limnimetric scale. These data are complemented by additional records provided by the Direction of Water Resources (DRE), which manages several observation stations in the basin. The periods of observation used in this study depend on the availability of records from the meteorological and hydrological services and were integrated to analyze hydro-climatic variability in time and space. Limnimetric scales are installed both on the Batha River (Ati and Yao) and on Lake Fitri. These instruments are regularly levelled and georeferenced to ensure consistency of measurements. In the framework of the LMI VIABELEAUX project, an additional limnimetric scale was installed on the Batha River at its mouth into Lake Fitri, thereby strengthening the monitoring network and improving the spatial representativeness of water level data.

In addition to ground observations, satellite altimetry data were used to complement and extend the temporal coverage of hydrological records. Altimetric data for Lake Fitri covering the period April 2013 to August 2023 were downloaded from the Hydroweb database (<https://www.theia-land.fr/hydroweb-lalimetric-des-lacs-et-riviere-en-ligne/>). Hydroweb is a hydrometric monitoring service of rivers and lakes developed by Theia, with the support of CNES and LEGOS (UMR CNES–CNRS–IRD–UPS), in the framework of the SWOT downstream program. This dataset, which is based on satellite radar altimetry, gives a constant and impartial source of information about water levels. This is especially useful in areas where in situ records are few and far between. Using both in situ limnimetric data and satellite altimetry is a strong way to get both short-term and long-term hydro-climatic trends and local changes in the Lake Fitri basin.

3.3. Rainfall Variability Assessment Using the Standardized Precipitation Index (SPI)

We used the rainfall index method to see how the amount of rain in the Lake Fitri basin changed over time. This method is commonly used to show periods of too much and too little rainfall in a series (Kouassi et al., 2010). The Standardized Precipitation Index (SPI) was selected as the principal tool for analyzing rainfall variability. The SPI was first used to find and keep track of dry spells. It only uses rainfall data and can be figured out for different lengths of time, such as months or years. This flexibility makes it a strong and versatile tool for finding both short-term problems and long-term patterns (McKee et al., 1993; Daif, 2017). The SPI is important because it shows when there are droughts and when conditions are wetter than normal. This is very important in semi-arid areas because years with too much or too little water can change how water flows in those areas. The Palmer Drought Severity Index (PDSI) and the Rainfall Anomaly Index (RAI) are two more indicators that have been used in Sahelian settings. The RAI, on the other hand, only shows how much rainfall has changed in relation to other places, which makes it hard to compare them (Van Rooy, 1965). The PDSI is a common tool in temperate areas, but it doesn't work as well in dry and semi-arid areas where soil and vegetation parameters aren't well-defined (Guttman, 1998). By contrast, the SPI requires only precipitation data, which is the most reliable and widely available hydro-climatic variable in the Sahel. For this study, the SPI was therefore chosen as the most appropriate method to characterize rainfall variability in the Lake Fitri basin. It is computed from centered and normalized seasonal rainfall totals for each station and for a given period. When the SPI is greater than 0, it means that the weather is wetter than usual (surplus). When the SPI is less than 0, it means that the weather is dryer than usual (deficit) (Kaboré et al., 2017). The SPI can be written out in math as:

$$IPS = \frac{(X_i - X_m)}{\sigma}$$

X_i is the total amount of rain that fell in year i , and X_m and σ are the mean and standard deviation of the yearly rainfall that was observed for a specific series.

4. Results

4.1. Meteorological Characterization

The analysis of meteorological data from the Lake Fitri basin, based on observations at Yao (2020–2022) and Ati (2021), highlights the marked seasonal fluctuations typical of the Sahel, as well as notable interannual and spatial differences between the two sites.

4.1.1. Seasonal and Interannual Variability at Yao Station (2020–2022)

Between June and September, Yao gets a lot of rain. The months of July and August alone account for nearly 75% of total annual rainfall (Figure 4, Table 1). In 2020, precipitation was unusually abundant, with a peak of 274 mm in a single month and an average of 43.3 mm/month. By contrast, 2021 was considerably drier, recording a maximum of only 55 mm and a monthly mean of 9.3 mm. These contrasts are confirmed by the high standard deviation in 2020 (80.5 mm vs 16.1 mm in 2021), reflecting the irregularity of rainfall events. Temperature exhibits a bimodal cycle, with maxima in March–April and October–November and minima in July–August. The mean values stay the same (29.7 °C in 2020 vs. 30.2 °C in 2021), while the humidity changes more from year to year, going from above 80% in 2020 to a low of 10.4% in 2021. Evapotranspiration is quite similar to the thermal regime, with averages of about 140 mm/month and peaks in the hot, dry months. The wind speed is moderate and stays about the same, but it is a little higher during the dry season. Overall, the comparison shows that 2020 was wetter and more humid, whereas 2021 was hotter and dryer.

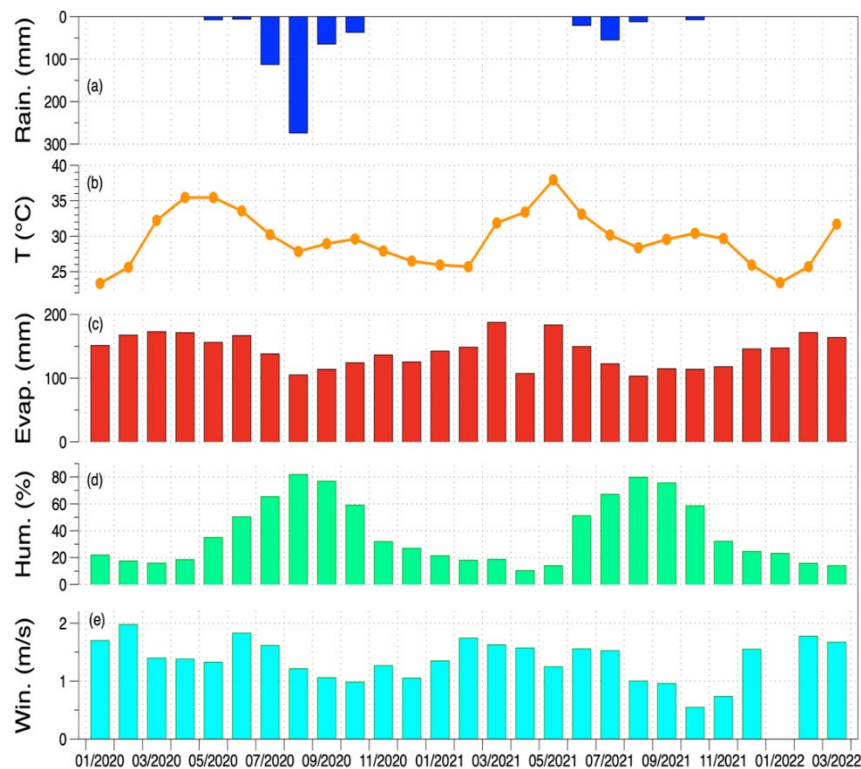


Figure 4. Monthly evolution of meteorological parameters (precipitation, temperature, evapotranspiration, humidity and wind speed) at Yao station from 2020-2022.

Table 1. Monthly weather variables for the years 2020-2021 at Yao station.

	Rainfall (mm)		Temperature (°C)		Humidity (%)		ETP (mm)		Wind speed (m/s)	
	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021
Max	274	55,2	35,5	37,9	81,8	79,8	173	187,7	2	1,8
Min	0	0	23,3	25,7	15,9	10,4	105,2	103,3	1	0,5

Mean	43,3	9,3	29,7	30,2	41,8	39,3	144,2	136,5	1,4	1,3
St.dev	80,5	16,1	3,8	3,6	24	25,6	23,6	28,2	0,3	0,4

Table 1 summarizes the main descriptive statistics of rainfall, temperature, relative humidity, evapotranspiration (ETP), and wind speed for the years 2020 and 2021.

4.1.2. Seasonal Dynamics at Ati Station (2021)

Records from Ati (Figure 5, Table 2) confirm the same seasonal rhythm but with lower annual rainfall. In 2021, monthly rainfall ranged from 0 to 129 mm, with a sharp peak in August (>150 mm) and an annual mean of 35.7 mm. This heavy rain in a short amount of time is similar to what happened at the Yao station, which strengthens the monsoonal control. The temperature of the air was 29.2 °C on average, with a range of 21.2 to 34 °C. August had the most rain, but it also had the coolest air. During the wet season, the humidity was 80%, but it dropped to 12% in April, which shows that the long dry season is very dry. Evapotranspiration averaged 138 mm/month, exceeding 200 mm in April–May and falling to 60 mm in August. Wind speed was stable, with a mean of 0.9 m/s, slightly higher in the rainy months.

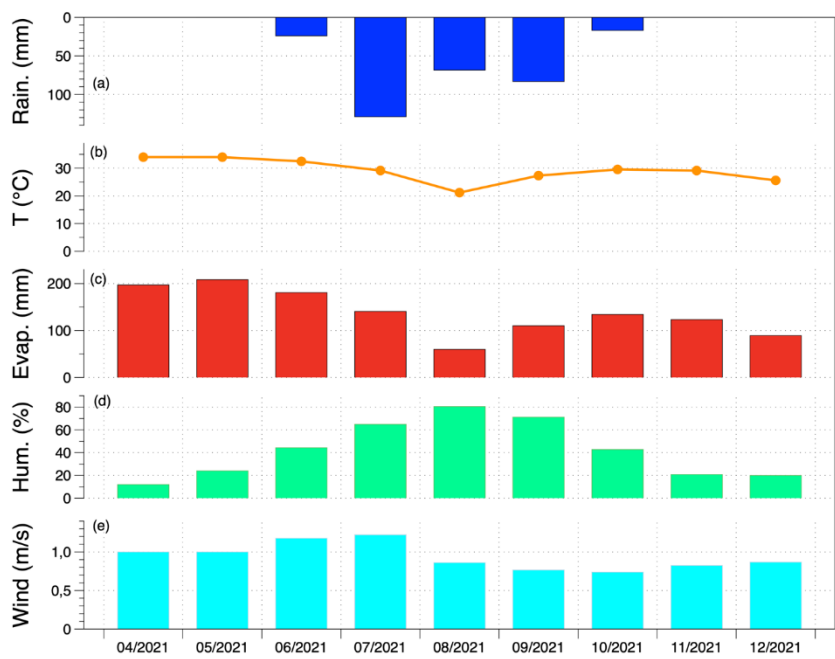


Figure 5. Rainfall, temperature and evaporation trends for Ati for the year 2021.

Table 2. Monthly weather variables for the year 2021 at the Ati station.

	Rainfall (mm)	Temperature (°C)	Humidity (%)	ETP (mm)	Wind speed (m/s)
Max	129	34	80,5	208,5	1,2
Min	0	21,2	12	60	0,7
Mean	35,7	29,2	42,3	138,2	0,9
St.dev	46,9	4,1	25,1	49,7	0,2

4.1.3. Rainfall–Temperature Interaction: Ombrothermal Diagram

The ombrothermal diagram (Figure 6) highlights the strong seasonal contrast between rainfall and temperature in the Lake Fitri basin. Rainfall is almost entirely confined to July–September, with a sharp maximum in August (>270 mm), while the rest of the year remains nearly dry. On the other hand, temperature follows a bimodal pattern, with highs in March–April (before the rains) and

October–November (after the rains), and lows in July–August when it rains the most. This inverse relationship shows how the West African monsoon affects the weather. It delivers humid air and cooler weather in the summer, while the Harmattan, which blows from the northeast, makes the weather drier and hotter. During the rainy months, more clouds and damp soil cause a brief cooling impact. In the dry season, intense insolation causes the most evapotranspiration requirement. Overall, the diagram gives a synthetic confirmation of what Yao and Ati found: the Lake Fitri basin’s water supply is closely tied to the brief monsoon season, which shows how sensitive the area is to changes in the weather.

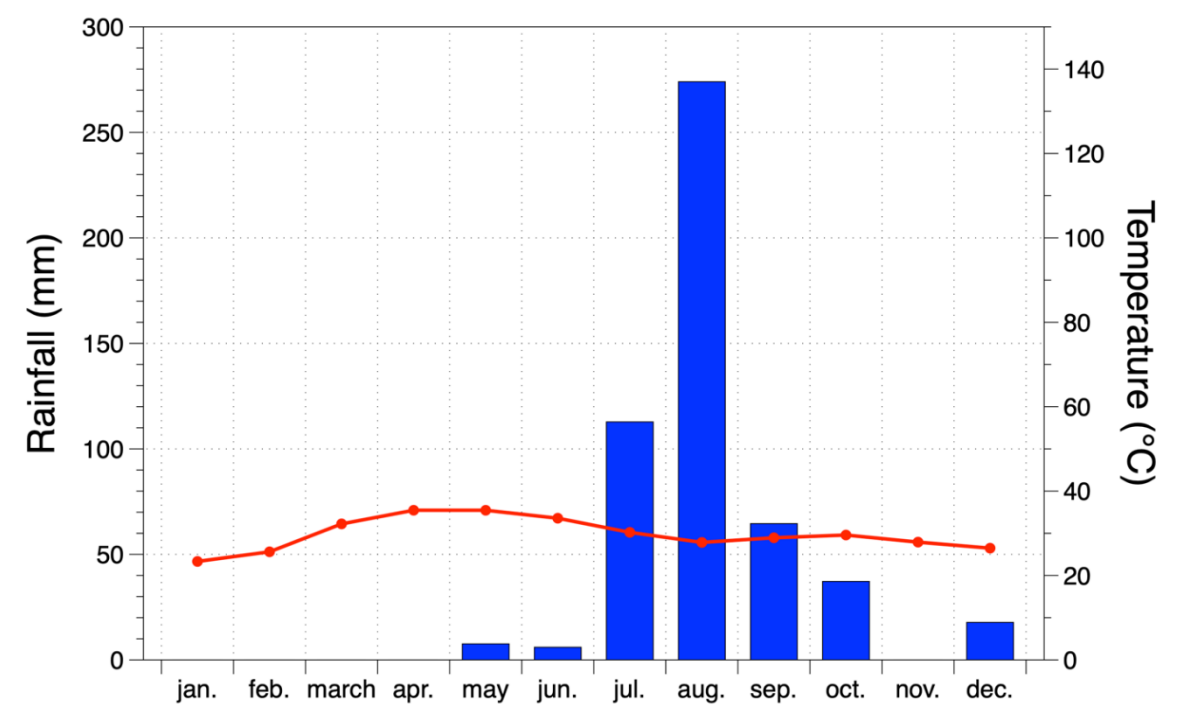


Figure 6. Umbrothermal diagram. Data of the Sstation Yao.

4.2. Hydrological Dynamics

4.2.1. Batha River at Ati

The water level of the Batha River at Ati between late July and October 2021 shows a pronounced seasonal flood pulse typical of Sahelian rivers (Figure 7). When monitoring started in late July, the river stage was about 320 cm. During August, the river stage rose rapidly and continuously, attaining nearly 500 cm in early September, which corresponds to the main flood peak generated by intense rainfall in the upstream catchment. Following this maximum, water levels dropped sharply, falling to around 380 cm by mid-September. There were big short-term changes in the level because to rain and changing inflows from tributaries. A secondary rise occurred in mid- to late September (≈440 cm), before a gradual and sustained recession set in from early October onwards. By late October, the river had returned to lower levels, close to 260–280 cm. This hydrograph shows how closely linked the seasons of rainfall and river flow are in the Sahel. The Batha flood only lasts for a few months (2–3 months), and the water level rises and falls quickly because of heavy rain upstream and the basin’s low storage capacity. These kinds of changes show how important the Batha is as a temporary but important part of the water balance of Lake Fitri and its floodplains.

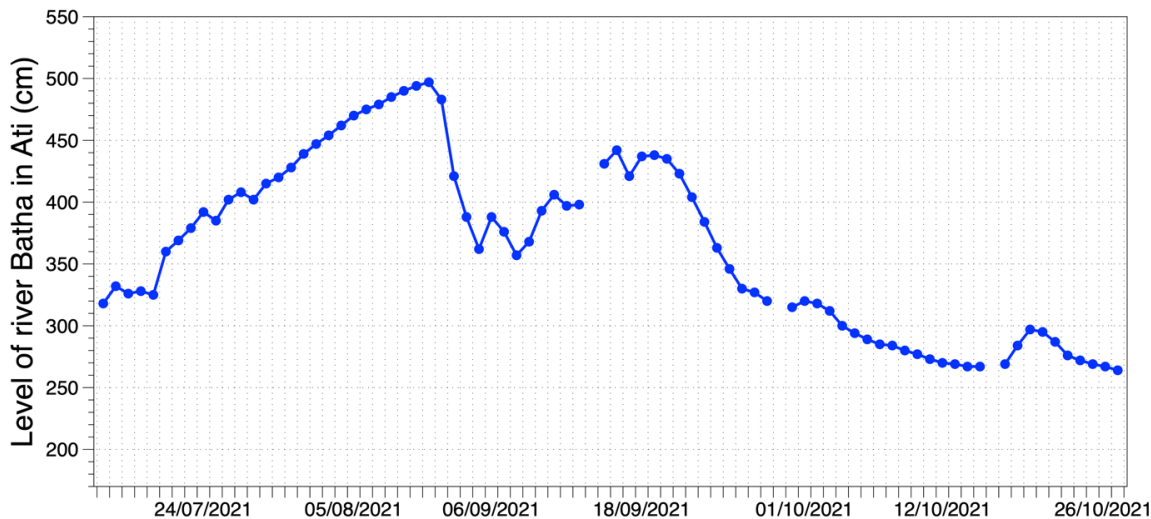


Figure 7. Variation of the Batha River level in Ati from July to November 2021.

4.2.2. Batha River at Yao (lake inlet)

At Yao, where the Batha River flows into Lake Fitri, the river has a clear seasonal hydrological regime that is directly affected by changes in rainfall in the Sahel. Three different flood cycles were reported between July 2019 and April 2022 (Figure 8). These were the rainy seasons of 2019, 2020, and 2021. In 2019, the water level rose gradually from ≈ 2.1 m in July to a peak of 3.8–3.9 m at the end of August before steadily declining from October onwards. A comparable pattern was observed in 2020, with a peak again close to 3.9 m in early September. The highest level in 2021 was a little lower (about 3.6–3.7 m), but the patterns stayed the same. There was a quick rise in July and August, followed by a slow drop to the dry-season baseflow of about 2.0–2.1 m. The river stays at 2.0–2.2 m between November and June, which means it is only there for a short time and depends on monsoon rains in the watershed above. The steep slopes of the hydrograph and the height of the seasonal flood (about 1.5–2.0 m) show that the basin doesn’t have much room to store water and reacts quickly. These numbers show that the Batha only adds to the water balance of Lake Fitri for short periods of time. Its floods provide a critical, yet highly variable, input that governs recharge processes in the floodplain and connected shallow aquifers. Consequently, the sustainability of Lake Fitri’s hydrological regime is tightly coupled to the intensity and duration of the monsoonal rainy season.

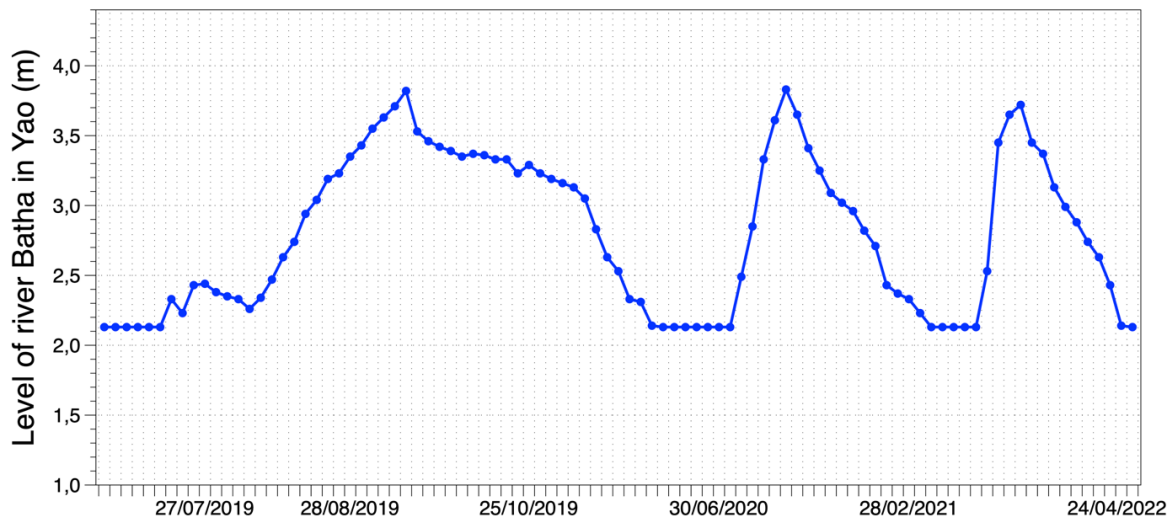


Figure 8. Variation curve of the Batha level at Yao from April 2019 to April 2022.

4.2.3. Lake Fitri Level Variability

The hydrograph of Lake Fitri from 2013 to 2023 shows that it has a very seasonal regime that is strongly related to rainfall and water coming in from the Batha River (Figure 9). The level of Lake Fitri generally fluctuates between 287.0 and 289.5 m, with an annual range of approximately 2.0 to 2.5 m. Flooding of the Batha River causes a rapid rise in water levels during the rainy season (July–September), followed by a steady decline throughout the dry season (October–May). This seasonal cycle highlights the lake's heavy dependence on direct rainfall and inflows from its upstream tributary. There is also significant interannual variability. In wetter years, such as 2014, 2015, 2018 and the period 2020–2022, the lake reached higher water levels, while drier years, notably 2016–2017 and 2019, were characterised by reduced maxima and prolonged recession phases. These contrasts can be explained largely by the basin's limited storage capacity, combined with the high climatic variability of the Sahel. Overall, analyses indicate that Lake Fitri functions as a highly dynamic system in which episodic but intense rainfall, irregular inflows from the Batha River and significant evaporation losses interact to control the hydrological balance. This sensitivity makes the lake particularly vulnerable to extreme climatic events, highlighting the crucial role of flooding from the Batha River in maintaining water levels, ecological processes, and the livelihoods of surrounding communities.

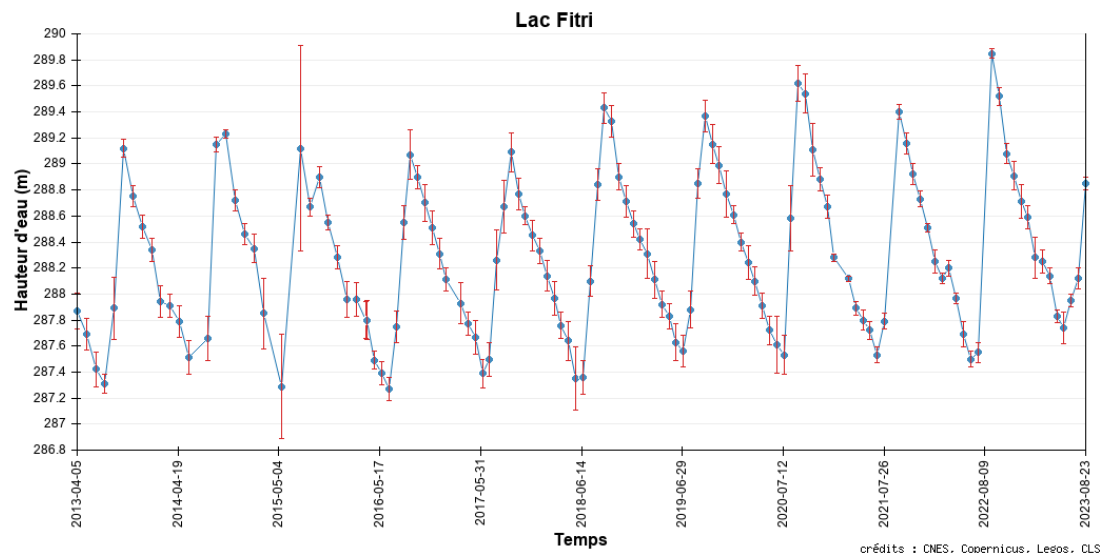


Figure 9. Variation in lake Fitri height. (Hydroweb database. <https://www.theia-land.fr/hydroweb-lalimetre-des-lacs-et-riviere-en-ligne/>).

4.3. Rainfall–Runoff Modeling (GR2M)

The Hydrology Response of the Batha Basin was assessed using the GR2M monthly precipitation-runoff model, which uses precipitation and potential evapotranspiration (PET) as input data. This parsimonious two-parameter model is structured around a production reservoir (X1) and a routing reservoir (X2). We used data from weather stations and satellites to find out how much rain fell in an area, and we used known formulas to find PET. Missing data were reconstructed using climatological ratios, and a one-year warm-up period was applied to stabilize the model. The performance of the model was evaluated using the Kling-Gupta Efficiency Index (KGE), supplemented by NSE, PBIAS and RMSE measures. Calibration was performed for the period 1981–2000, while the validity of the model was assessed for the period 2001–2020. Figure 10 shows a simulated hydrograph illustrating the seasonal variations in the flow of the Batha River. From July to September, there are short, strong flood pulses, and during the long dry season, there is almost no flow. The model reproduces well the timing of flood peaks associated with monsoon rainfall but tends to underestimate both the magnitude of extreme events and the length of the recession phase.

These variations are likely due to processes that are not explicitly represented in GR2M, such as transmission losses in sandy channels, retention in floodplains, and groundwater exchanges. Nevertheless, performance indicators show that the model effectively reproduces the main seasonal dynamics of the Batha River and its interannual variability. The simulated hydrographs also reflect the strong influence of Sahelian rainfall fluctuations on river discharge. For example, wetter years like the early 1990s and 2012 cause much higher flood peaks than dryer years like the mid-1980s and 2017. This shows that the Batha flows depend on monsoon rain upstream and that this temporary catchment responds quickly to changes in water levels. The GR2M simulations show that the Batha is a very important but very variable part of the Lake Fitri water balance. They also show that we need better methods that include high-resolution rainfall products, different PET estimates, and clear interactions between the floodplain and groundwater to make the simulation of extremes and recession phases better.

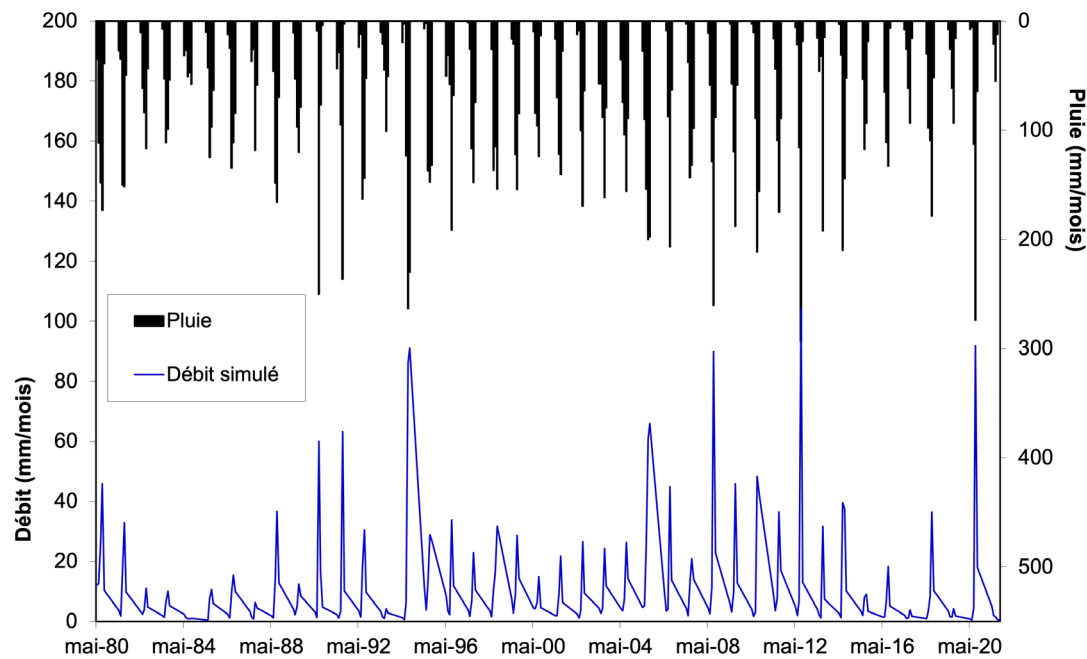


Figure 10. Rain flow model.

5. Discussion

5.1. Rainfall Variability and Climatic Forcing in the Sahel

The analysis of rainfall indices (SPI) for N’Djamena and Yao over 1980–2020 reveals the typical alternation of wet and dry phases that characterizes Sahelian climates (Figure 11). A prolonged deficit period was observed between 1982 and 1993, corresponding to the severe droughts that affected the whole Sahel and caused major hydrological and ecological disruptions (Nicholson, 2013; Lebel & Ali, 2009). The weather got a lot better after 1994. There were some wet years (1994, 2005, 2008–2012, and since 2018) and some dry years (2013–2017) in between. This pattern of changes shows how much the West African monsoon changes from year to year. This has already been discussed in a more general way (Panthou et al., 2018). This kind of change has a direct effect on the hydrological processes in the Lake Fitri basin, which changes the flow of the Batha River, the level of the lake, and the aquifer’s recharge.

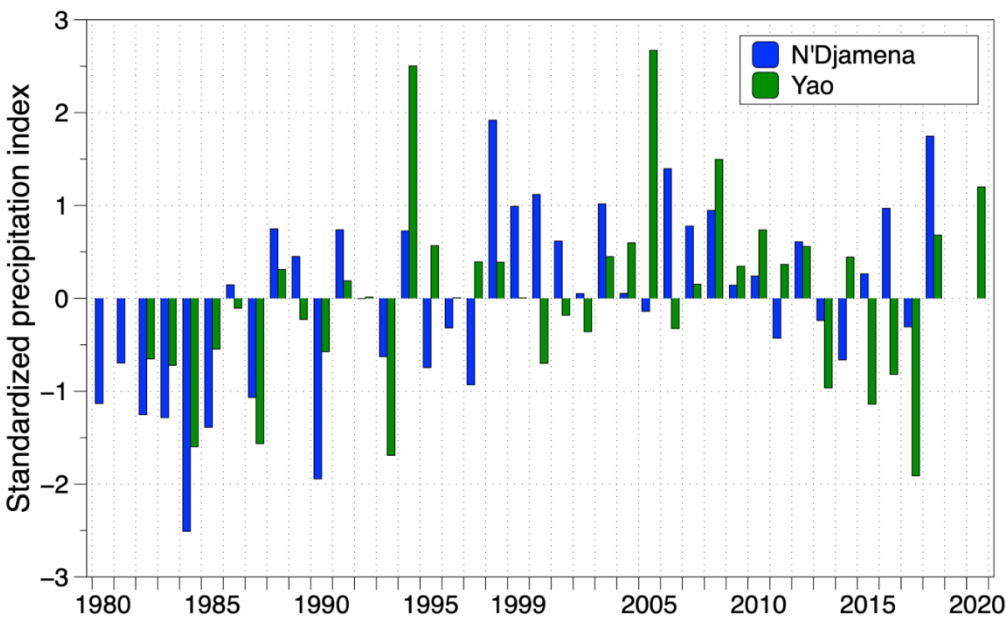


Figure 11. Evolution of rainfall indices of Yao and Ndjamenana from 1980-2020.

5.2. Temporal Evolution of Rainfall at Yao and N'Djamena

The comparison of rainfall data from Yao and N'Djamena (1980–2020) confirms both the strong interannual variability and the spatial coherence of rainfall across the Lake Fitri basin (Figure 12). In Yao, the annual rainfall has varied between a minimum of 205 mm in 2017 and a maximum of 669 mm in 2005, with a long-term average of 402 mm. In N'Djamena, totals are generally higher (~573 mm on average), but interannual variability is very similar to that recorded in Yao. It should be noted that both stations recorded exceptionally wet years in 1994, 2008 and 2018. This consistency indicates that precipitation variability is mainly controlled by regional atmospheric forcing rather than local effects. The alternation between dry phases (1982–1987; 2015–2017) and wetter periods (1994; 2003–2014; 2018–2020) reflects fluctuations in the Sahelian monsoon observed throughout the region (Ali & Lebel, 2009; Nicholson, 2013). Overall, these results confirm that rainfall variability is the main determinant of hydroclimatic dynamics in the Fitri system, directly influencing both surface water flows and groundwater recharge.

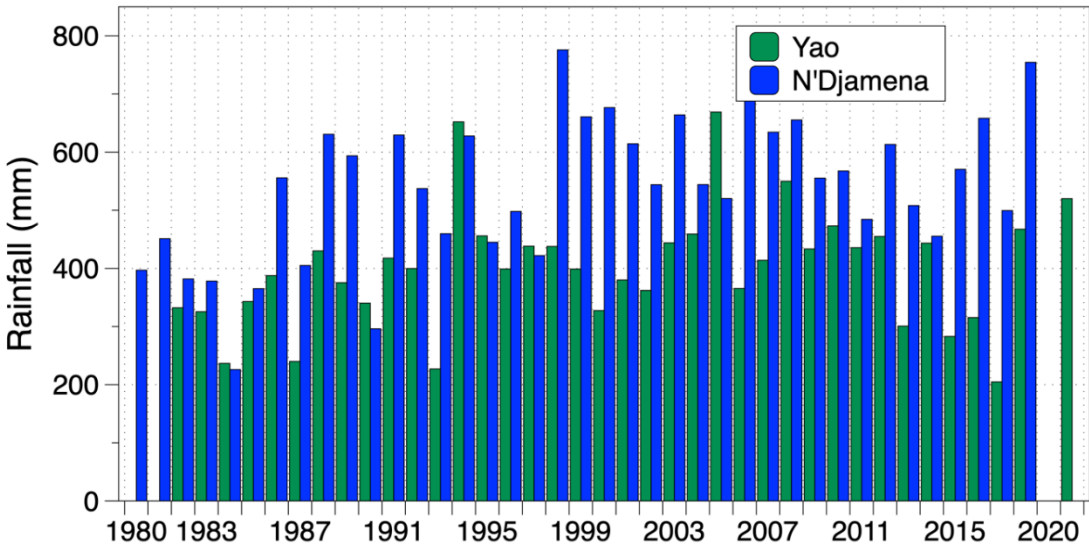


Figure 12. Annual change in rainfall in Yao and Ndjamenana from 1980-2020.

5.3. Hydroclimatic Seasonality and Climatic Constraints

Figures 4 and 5 provide meteorological data from the Yao and Ati stations, which show how sharply the seasons change in the Sahel. There is a short rainy season from July to September, during which time rainfall is concentrated. However, potential evapotranspiration (PET) remains quite high throughout the year (approximately 3,800 to 4,000 mm), which is much higher than the amount of rainfall each year (approximately 400 to 600 mm). This persistent imbalance leads to a chronic water deficit, meaning that aquifers are only recharged during occasional episodes of heavy rainfall (Ali Gamane et al., 2021). The contrast is amplified by elevated temperatures from March to June (reaching 37–38 °C) and by cooler conditions in July–August, linked to increased cloud cover and higher soil moisture. Relative humidity is highest (approximately 80 to 90%) when rainfall is heaviest. When rainfall is lowest (less than 15%), the long dry season makes water evaporation even more difficult. Due to low rainfall, high PTE and large seasonal differences, the water balance in the Fitri basin is very fragile. This is true in Sahelian climates as well (Courel et al., 1997; Descroix et al., 2018).

5.4. Comparative Hydroclimatic Responses of Lake Fitri and Lake Chad

Satellite imagery confirms that Lake Fitri’s surface area is highly sensitive to rainfall variability. Years with a lot of rain (1994, 2014, 2020) show big increases in both open water and swampy regions, while years with a lot of drought (1972, 1986–1987) show big decreases in open water areas (Yalikun et al., 2019). The lake has been somewhat stable since the early 2000s, but it still changes a lot from year to year based on how much rain falls. This path is like Lake Chad’s, which got a lot smaller during the droughts of the 1970s and 1980s but then got a little bigger again in wetter decades (Bader et al., 2011; Lemoalle et al., 2012). But there are big differences in how they work and how big they are. Lake Chad gets water from a lot of big rivers, like the Chari-Logone and the Komadougou-Yobé. Lake Chad reflects general regional rainfall patterns, while Lake Fitri depends mainly on inflows from the Batha River and direct rainfall, making it highly sensitive to local monsoon variability. Both lakes act as indicators of Sahelian hydroclimatic change, but Lake Fitri responds more rapidly to rainfall fluctuations and is therefore more vulnerable to their impacts.

5.5. Groundwater Recharge and Water Balance

The residual water balance established for Yao in 2020 (Tables 3 and 4) provides valuable information on groundwater recharge processes in Sahelian conditions. Of the 502 mm of annual rainfall, most is consumed by evapotranspiration (ET = 384-434 mm), due to potential evapotranspiration of up to 1,730 mm. Recharge occurs mainly in August, when rainfall (274 mm) exceeds the soil’s storage capacity, allowing percolation beyond the root zone. The estimated recharge is between 69 mm and 119 mm, which is only 14–24% of the total annual rainfall. This depends on how well the soil can hold water (50 mm vs. 100 mm). The findings indicate that recharge is largely episodic and concentrated within a single wet month, in agreement with observations reported for other Sahelian settings (Leduc et al., 2001; Favreau et al., 2009). This limited and irregular recharge highlights the vulnerability of groundwater resources during dry periods, as illustrated by 2017, when annual rainfall fell to just 205 mm. The results indicate that the Lake Fitri aquifer is fragile and highly sensitive to interannual rainfall variability and episodes of intense rainfall.

Table 3. Hydrological balance of Yao for a useful reserve=50mm.

Parameter	jan.	feb	march	apr.	may	jun.	jul.	aug.	sep.	oct.	nov.	dec.	total
Rainfall (mm)	0	0	0	0	8	6	113	274	65	37	0	0	502
ETP (mm)	151	168	173	171	156	167	138	105	114	124	137	126	1730
ETR (mm)	0	0	0	0	8	6	113	105	114	38	0	0	384
RU (max 50 mm)	0	0	0	0	0	0	0	50	1	0	0	0	0
Recharge (mm)	0	0	0	0	0	0	0	119	0	0	0	0	119

Table 4. Hydrological balance of Yao for a useful reserve=100mm.

Parameter	jan.	feb	march	apr.	may	jun.	jul.	aug.	sep.	oct.	nov.	dec.	total
Rainfall (mm)	0	0	0	0	8	6	113	274	65	37	0	0	502
ETP (mm)	151	168	173	171	156	167	138	105	114	124	137	126	1730
ETR (mm)	0	0	0	0	8	6	113	105	114	88	0	0	434
RU (max 100 mm)	0	0	0	0	0	0	0	100	51	0	0	0	0
Recharge (mm)	0	0	0	0	0	0	0	69	0	0	0	0	69

5.6. Hydrological Modelling of the Batha with GR2M

The GR2M simulations reproduce well the annual flood pulse of the Batha, with pronounced rises between July and September and near-zero flows during the extended dry season (Figure 10). Although the model reproduces the flood schedule fairly accurately, it tends to underestimate both the magnitude of peak flows and the duration of drawdown periods. These shortcomings are probably related to processes that are not explicitly represented, such as transmission losses in sandy beds, storage in floodplains, and exchanges with groundwater. Comparable limitations have been documented in other Sahelian basins. For example, GR2M underestimated base flows in the Niger basin (Mahé et al., 2005; Descroix et al., 2009) and was sensitive to the quality of rainfall data when applied to the Senegal basin (Ardoin-Bardin, 2004). Similar difficulties have also been reported in the Logone-Chari system, where transmission losses and storage in floodplains play a major role (Massuel et al., 2011). Nevertheless, the GR2M remains a useful tool for analysing the seasonal and interannual dynamics of ephemeral streams in semi-arid environments. The results for the Batha show that it is a very important yet very variable part of Lake Fitri’s water balance. However, future improvements should include integration of high-resolution rainfall products (e.g., CHIRPS, GPM), testing of alternative PET formulations, and coupling with models that explicitly account for floodplain–groundwater interactions.

6. Conclusions

This study demonstrates the strong influence of climate on hydrological processes in the Lake Fitri basin. The flow of the Batha River and the fluctuations of Lake Fitri are mainly caused by variations in rainfall, which follow a cycle of wet and dry years. Hydrological observations confirm the short-lived and pulsed nature of the Batha’s contribution, while water balance estimates indicate that groundwater recharge is highly episodic and limited—occurring mainly in August and representing only 14–24% of annual precipitation. Compared to Lake Chad, Lake Fitri is more directly sensitive to local monsoon variability, as it depends almost exclusively on a single tributary. GR2M simulations captured the seasonal pattern of Batha flows but underestimated extreme peaks and recession phases, largely due to transmission losses and floodplain storage processes. The Lake Fitri system is a vulnerable and very responsive hydrosystem overall. This shows that we need to improve monitoring and integrated management to make sure that water resources stay sustainable as the climate changes more and more.

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