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Hydrological Impact of Lagdo Dam Construction on Upper Benue River Basin (North Cameroon)

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Abstract

The construction of a water retention structure across a river in a catchment inevitably leads to changes in its natural functioning downstream. This study investigates the hydrological changes observed on the Benue at the town of Garoua before and after the construction of the Lagdo dam in the Upper Benue catchment using statistical and frequency analysis of flows upstream and downstream the dam. The results indicate that the shape of the hydrograph has changed, with a reversal of the hydrological regime characterised by a drop in flood flows and an increase in low-water flows. For the pre-dam period, the flood hydrograph shows a maximum in September and a minimum in March, which may be zero in years with dry water hydraulicity. The impoundment of the Lagdo dam in 1983 led to a reduction in peak flows of around 40% and a 90% increase in low flows on the Benue at Garoua. The maximum flows observed at Lagdo are retained in the dam for the production of hydroelectric power and part is released downstream towards Garoua with a reduction of about 34% and 35% of 100-year and 50-year floods respectively. These changes can have a significant impact by reducing the amplitude of floods in the Benue valley and consequently, the flooding phenomenon. The entire hydrological dynamic of the Benue valley has thus been modified, moving from a natural tropical rainfall regime to an altered regime characterised by the release of water to support low-water flows.

Keywords

Hydrological Regime, Lagdo Dam, Altered Regime, Benue River, Flow, North Cameroon

1. Introduction

The search for water has historically represented one of humanity's most fundamental needs within its environment [1] [2]. This vital requirement has led to the gradual occupation and transformation of river basins through hydraulic engineering aimed at harnessing water resources. According to [3]-[6] hydraulic infrastructures like dams play a fundamental role in socio-economic activities and water security worldwide and particulary in soudano-sahelian regions with seasonal river flow by providing key functions such as energy production, irrigation, navigation, drinking and flood control. In addition to development concerns, dams were perceived as symbols of modernity, power, or as a means of managing and forecasting risks and/or hydrological hazards [7].

However, numerous studies have highlighted the disruptive impacts of hydraulic infrastructures—particularly dams—on river flow regimes across the world [5] [6] [8]-[11]. Dams significantly alter natural flow patterns by reducing peak discharges, modifying low-flow conditions, and affecting interannual flow variability [12] [13]. They can also influence the frequency and magnitude of both floods and droughts, ultimately disturbing the natural dynamics of river systems [14]. According to [1], the construction of reservoirs and dams across a river has a strong influence by converting a river segment of the natural watercourse into stagnant water which intercepts not only a large part of the flow but also sediments transport. These hydraulic developments also generate numerous environmental constraints such as sedimentation in reservoirs, changes in the morphology of riverbeds, eutrophication and the proliferation of new aquatic species and water losses through evaporation.

In addition to the changes to river flow caused by the construction of dams, climate change has also been reported to be a cause of modification to river flow. Changes in climatic parameters, such as temperature and rainfall, significantly impact the hydrological regime of the Upper Benue River [15] [16]. By analyzing the potential effects of climate change on flow patterns in the Upper Benue river, [15] indicated that climate change has significantly impacted the basin's water resources between 1950 and 2014, with a downward trend. The combined effects of altered hydrology and climate change can have serious environmental and socio-economic consequences for populations located downstream. Understanding the impact of dam construction in the context of climate change and climate variability is critical for mitigating flood risks, and this understanding must be combined with an awareness of how these risks are changing over time. It is therefore important to take account of the combined action of climatic and anthropogenic factors on hydrological changes, which are often difficult to dissociate.

In Cameroon, several dams have been constructed during the 1970s in order to harness water for socio-economic development, including Lagdo dam in the Upper Benue river [17]. The Upper Benue river is considered as one of the most important catchments in the northern part of Cameroon. Many socio-economic activities depend on this catchment area. A dam was constructed across the river in Lagdo district in 1983 for a variety of purposes [3]. The main objective of the construction of this structure was to ensure the production of electrical energy as well as agricultural irrigation, river navigation and flood management through the partial regulation of the River Benue [18]-[21]. The volume required to achieve these objectives during the low-water period is estimated at around 4,600 hm^3. The resulting production of electrical energy has improved socio-economic conditions and development in the northern regions of Cameroon [22]. However, despite the advantages offered by the construction of this hydraulic structure, very few studies have been devoted to analyzing the impacts of this structure on the hydrological regime of the Benue downstream the dam [18] [20] [23]. In this context, it is important to understand the patterns of high and low water levels over time, as well as the impact of operations at the Lagdo dam on the flow of water downstream.

In order to assess the impact of dam construction on hydrological regimes, many studies have compared the hydrographic characteristics estimated before and after dam construction on flows at downstream gauging stations [12] [14]. The alteration of the hydrological regime can also be assessed through geomorphological studies of the downstream channels [17]. Other studies have investigated the impact of dam construction on the flow regime using indicators of hydrological alteration (IHAs), which are a set of hydrological parameters used to assess the degree of hydrological alteration caused by human activities [4]-[6] [11]. Globally, IHA provides a framework for analyzing hydrologic changes and quantifying the impacts of human activities on river systems. In addition, IHA analysis requires at least 20 years of pre- and post-data. Due to the lack of daily data during the pre-dam period and the availability of only monthly data and maximum daily flows, the IHA could not be used in this study. Therefore, the aim of this study is to analyze the impact of the impoundment of the Lagdo dam on the hydrological regime of the Benue by comparing the hydrological regime before the pre-dam period and after the post-dam period on the one hand and the regime upstream and downstream of the dam on the other. We quantified changes in mean annual flows, monthly flows, and magnitude and timing of maximum daily flows. The paper is structured as follows: the description of the study area, the Upper Benue river, the description of the data source and the methods including statistical and frequency analysis in section 2. The results of the hydrological functioning of Upper Benue river before Lagdo dam construction were described and discussed in section 3. The conclusion was outlined in section 4.

2. Data and Methods

2.1. Study Area

The Upper Benue catchment is located in the northern part of Cameroon. It lies between longitudes 11˚47' and 15˚48' East and latitudes 6˚49' and 10˚51' North (Figure 1) and is administratively located in the Adamaoua, North and Far North regions.

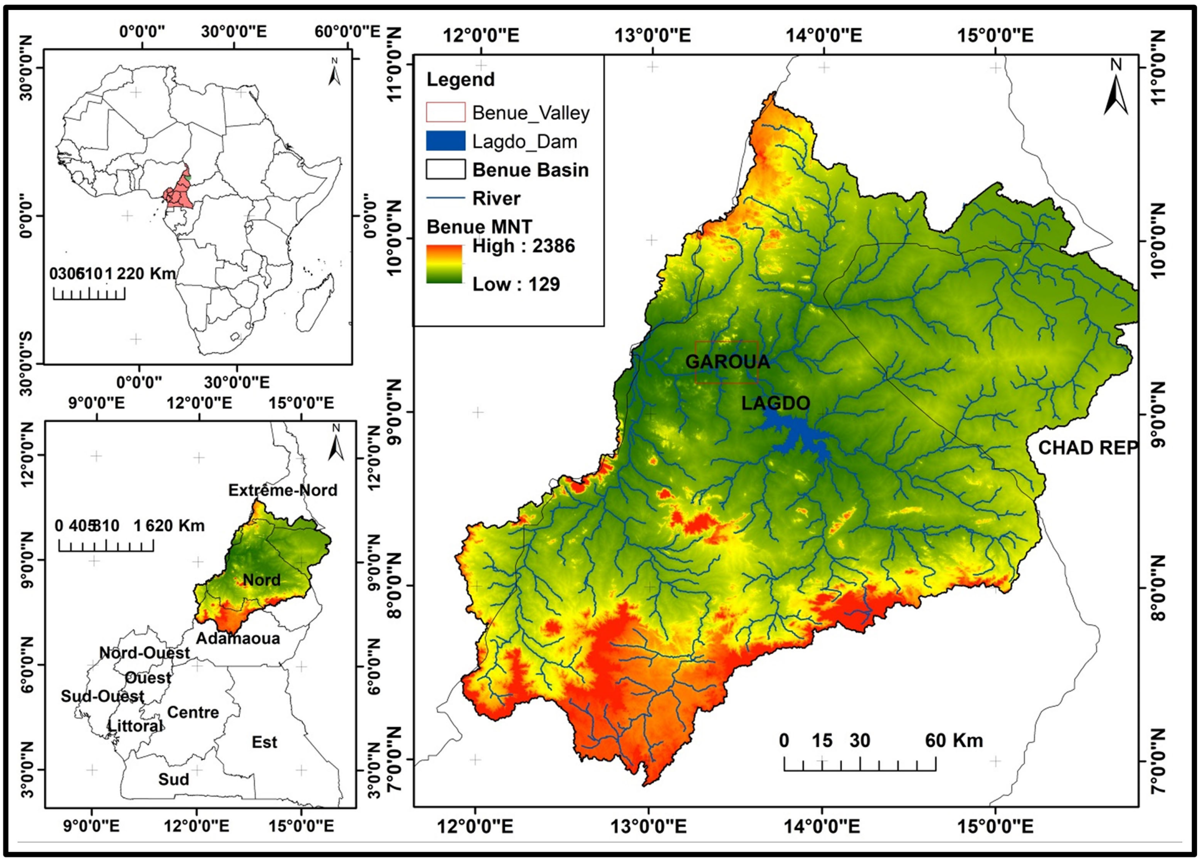

Figure 1. Location of Upper Benue basin.

The Upper Benue basin is a sub-basin of the Niger catchment. With a surface area of 95.626 km^2 and a perimeter of 2.473 km, the basin has its source in Adamaoua and on the Laka plateau in Chad. Its surface area in Chad is estimated at 19.186 km^2 with a perimeter of 760.4 km. The Benue station at Garoua controls a basin of around 60.500 km^2 and the Lagdo station covers an area of 31.600 km^2.

The basin presents a diversity of landscapes and climatic domains which contrast with the Sahelian zone in the north and more humid, heavily-watered plateau areas in the south. The climate is characterized by two alternating seasons: a dry season from November to May (7 to 8 months) and a rainy season from June to October (4 to 5 months). Rainfall at the Upper Benue catchment is dictated by the seasonal migration of the Inter-Tropical Convergence Zone (ITCZ). From November to March-April, continental high pressure and the Harmattan dominate with sparsely cloudy skies. As the Inter-Tropical Front (ITF) moves northwards from April onwards leads to the appearance of light rainfall, appears in May and June [24] [25]. According to [3] the annual rainfall varies between 800 mm and 1550 mm and increases from the north-east to the south of the catchment. Four major rainy months (June to October) concentrated about 65% of annual precipitation. In addition monthly temperature average range from 21˚C in January to 33.2˚C in April [26].

Several geological formations outcrop on a crystalline bedrock consisting of Precambrian intrusive and metamorphic formations overlain by Tertiary volcanic formations, Cretaceous arenaceous sediments and recent Quaternary alluvium. These formations support several types of soil such as lithosols, crude mineral soils, soils that are not very advanced belonging to the fersialitic soil family: tropical ferruginous soils and hydromorphic soils whose development is dominated by permanent waterlogging [3].

The river system network of the Upper Benue is dense and divided in four major sub-basins namely: high sub-basin, Mayo Kebi sub-basin, Faro sub-basin and Mayo Tiel sub-basin. These four sub-basins control the hydrological dynamic of the Upper Benue. According to [24] the Higher Benue takes its rise from the northern edge of the Adamaoua plateau at an altitude of about 1300 m and only a few kilometres from the bends of the "cliff". Its crosses the National Benue Park on a rocky bed where the most important tributary on the right bank is the Mayo Oldiri. On leaving this Park, it enters the Benue Valley where it receives the Mayo Rey and the Mayo Godi on the right bank, and the Mayo Mbay on the left bank [24]. After collecting the main tributaries on Benue valley, the river enters to the Lagdo dam [3]. The Lagdo dam is a hydroelectric structure located about 40 km from the town of Garoua and covers an area of 697 km^2 [18]. The construction of the dam began in 1978 and it was impounded in 1983. The hydroelectric plant comprises four generating units with a total installed capacity of 72 megawatts (MW). During peak flows periods, it is possible to regulate a volume of 1678 million m^3 between elevations 216 m and 218.18 m with a maximum discharge of 4.072 m^3/s [19].

2.2. Data Source

Hydrological data from the periods of 1952-1980 were obtained from the IRD (formerly ORSTOM) database for the hydrometric stations on the Benue at Riao (Lagdo) and the Benue at Garoua for the period 1952 to 1980, and from the Hydrological Research Center (CRH) for the periods 1995 to 1999 and 2009 to 2015. These data are available at daily and monthly scale and contain many gaps. Data on daily, monthly and annual inflows into the Lagdo dam as well as the volumes of water released from the dam, come from the AES SONEL (ENEO) database for the period 1983-2015. Monthly rainfall data from the Garoua station were used for the period from 1952 to 2020. These data come from the regional meteorological services of the North.

2.3. Methods

Analysis of hydro-climatic series requires reliable data of good quality. The methodological approach adopted in this study combines statistical approach technique with frequency analysis. The missing hydrological and climatics data were reconstructed using analogous proportionality criterion and extended to 2020 using the statistical methods established between two neighboring stations.

2.3.1. Reconstitution of Missing Data and Linear Correlation

The hydrometric data from the Garoua station present many gaps compared with the Lagdo station which is more complete. The method used to reconstruct the missing data is the analogous proportionality criterion. This method is generally used for stations located on the same watercourse [25]. The missing flow is estimated according to the Equation (1):

$$\frac{Q_1}{S_1} = \frac{Q_2}{S_2} \tag{1}$$

With Q_1 and Q_2 the flows corresponding to stations 1 and 2;

S_1 and S_2 the surface areas of the basins corresponding to stations 1 and 2.

The following relationship was obtained by taking into account the areas of Benue river in Garoua and Lagdo.

$$Q_{Garoua} = 1,91 Q_{Lagdo}$$

Linear regression was used to establish correlations between Lagdo flow and Garoua flow and to extend the flow series to 2020. This method has been used by several authors on hydropluviometric series with significant results [27] [28]. Linear regression consists of replacing the missing value calculated using simple or multiple regressions between the explained series and the explanatory series. In addition, some research estimated that a physically based characterization of discharge correlation between two stations could also contribute to improve the reliability of the estimate of long-term streamflow statistics in sites where only short-term records are available [29] [30]. The linear correlation between Lagdo flow and Garoua flow was established in order to reconstruct the missing data from the incomplete series of the Garoua station on one hand and on the other hand to update the flow data by extending the series from 2015 to 2020. The reliability of the reconstructed flow series with linear regression and proportionality criterion was quantify by comparing observed data versus infilled values using r and Root-Mean-Square Error (RMSE). Linear regression offers the best method of reconstructed flow according to the value of Root Mean Square Error and r (**Table 1**).

Table 1. Comparison between observed and infilled values using linear regression and proportionality criterion.

Observed/infilled values	Linear regression	Proportionality criterion
r	0.9	0.81
RMSE	0.288	0.329

2.3.2. Estimation of Hydrological Changes

Due to the major limitations related to data scarcity the hydrological changes (HC) were calculated by splitting discharge data into pre-and post-dam periods considering the year of operation of Lagdo dam. The estimation of the changes between pre-dam discharge and post-dam discharge was computed according to the degree of hydrological alteration estimated by [16] as below (Equation (2)):

$$HC = \left(\frac{Q_{\text{pre-dam}} - Q_{\text{post-dam}}}{Q_{\text{pre-dam}}} \right) \times 100 \quad (2)$$

Qpre-dam is the discharge observed before Ladgo dam construction et Qpost-dam discharge observed after Lagdo dam construction. HC can be daily, monthly or yearly.

2.3.3. Method of Estimating the Impact of Dam on Recurring Flows Upstream and Downstream the Dam

The effect of dam construction has been estimated on extreme discharge by applying frequency analysis to the maximum daily. According to [31] frequency analysis provides a suitable means for predicting hydrological and some meteorological parameters in both space and time, and this involves the estimation of the probability of occurrence of a specified event. The most frequency model frequently used to describe the statistical behavior of extreme values is the Gumbel distribution which is a probability distribution commonly used for modeling river flows. The Gumbel distribution is a statistical method used to estimate the discharge values associated with different return periods for extreme events like floods. This method is ascertained as a better distribution for flood prediction and is particularly useful for modeling the distribution of maximum annual river flows [31] [32]. It has successfully modelled the flood frequency over the Niger Delta in Nigeria, in Pra river catchment in Ghana and in Robigumoro River in Ethiopia [31]-[33].

The magnitude of floods with different return periods have been estimated before and after the dam construction and the changes has been assessed by comparing the two values. The magnitude of expected flood to occur is predicted the Gumbel distribution. The distribution function of the Gumbel distribution F(x) is expressed according to [34] [35] as follows:

$$F_x(x) = -\exp\left[-\exp\left(-\frac{x-a}{b}\right)\right] \quad (3)$$

with u = x − ab the reduced variable of the distribution function and a and b the parameters of the Gumbel model; u is expressed as u = −ln (−ln (Fx)).

For this analysis the return period (T) used is 10 years, 20 years, 50 years, and 100 years.

3. Results

3.1. Hydrological Functioning of the Benue before the Lagdo Dam Construction: Natural Flow Regime

The Lagdo dam was built across the Benue River for multiple purposes. Before the dam was constructed in 1983, hydrological dynamics of the Benue River at Garoua depended on rainfall [3]. The monthly flow hydrographs at the Lagdo-Riao and Garoua stations showed the same pattern, with alternating periods of high and low water (**Figure 2**). The evolution of monthly flows shows that flows gradually increase from April to September and then significantly decrease from October to March. The peak flows occur between mid-July and October, while the low flows occur between November and June according to the concentration of the main portion of the annual precipitation. According to [15] most of the annual rainfall occurs during the four rainy season. The hydrological regime was then conditioned by rainfall which is the primary driver of surface water in the region and thus belongs to the tropical domain. In addition, the alluvial groundwater at the Kébi-Benue confluence could sometimes enhance the level flows of the Benue at Garoua during the dry period according to observations by [24].

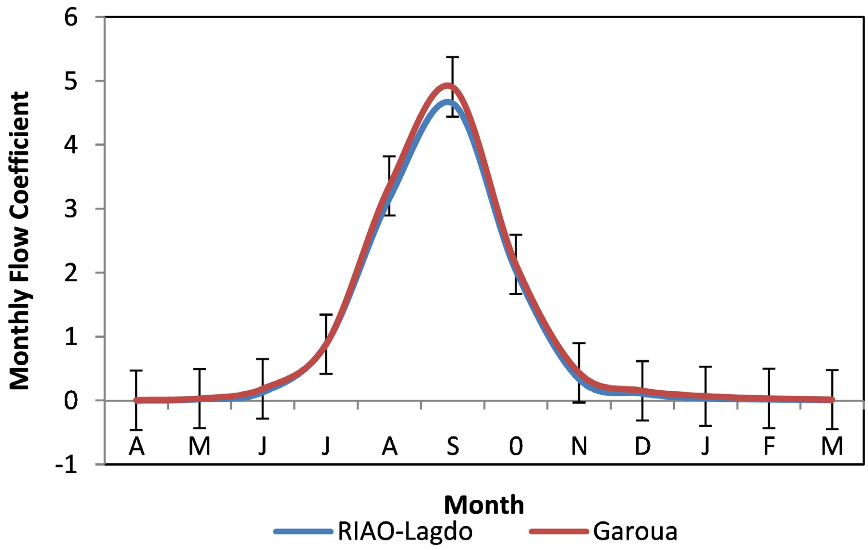

Figure 2. Monthly hydrograph of flows at Lagdo and Garoua before the construction of the dam between 1952 and 1980.

The Garoua hydrograph (**Figure 2**) is unimodal and shows seasonal variations in water levels, with peak flows occurring during the rainy season (July to September) and low flow occurring during dry season (October to June). The flood curve begins to rise in June, reaching its peak in September. The period of deflooding marks the gradual reduction in flows until the river dries up in November. This dry period can last for 3 to 4 months or even longer. As a result, there will be little or no flow in dry years. The water will therefore dry up completely.

The same observation has been done by [36] in Jebba station in Nigeria. Thus, about 96% of the flow of the Benue river transits throws Garoua station between June and November (6 months). The wettest months (August and September) concentrated about 2/3 of the annual inflow, with September accounting for about 41%. However, the peak flow of the Benue at Garoua is higher than that of the Riao at Lagdo. This difference can be explained by the fact that the Benue at Garoua receives the Mayo Kebi from Chad on its right bank, which contributes around 27% of the annual inflow.

The interannual variability of flow upstream and downstream the Lagdo dam is shown in Figure 3(b). It should be noted that, flow vary one year from another year depending on climatics conditions of the Upper Benue catchment. The annual average flow of the Benue at Garoua was higher, with flows exceeding 600 m³/s and an interannual average of around 380 m³/s (Figure 3(a)). At Lagdo, on the other hand the average was around 230 m³/s. Despite the difference about the value of the annual flow, the both stations had the same hydrological pattern before the Lagdo dam was built. In an extreme wet year (1960-1961) for example, floods were observed simultaneously at both stations. The primary factor affecting hydrological dynamics is rainfall this implies that a change in rainfall will have an impact on surface runoff at both stations. In the case of drought events for example, the drop in runoff will be felt simultaneously at both stations. This observation was confirmed by the value of the correlation between the observed flow in Lagdo and Garoua station (Figure 3(b)). The r value (0.9) indicate a positive correlation between the two stations. This highly correlated flows might indicate that they are both influenced by the same rainfall patterns. This means that the dynamic river of the two stations are related and tend to increase or decrease together according to the rainfall patterns. This information will be helpful in the terms of planning and managing water resources, including predicting potential flood risks or drought conditions.

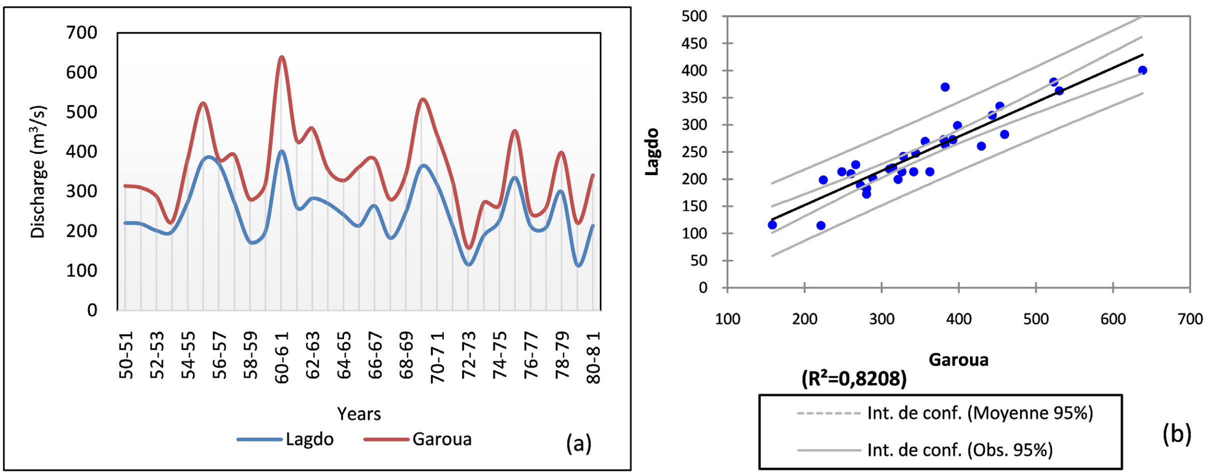

Figure 3. Interannual variability of annual flow at Lagdo and Garoua (a) correlation between annual discharge at Garoua-Lagdo from 1950 to 1982 (b).

The analysis of the annual discharge in the Benue River at the Garoua (Figure 4(a)) and Lagdo station (Figure 4(b)) shows a downward trend from the 1970s until the Lagdo dam was impounded. The mean interannual flow for this period is estimated to 290 m³/s at downstream the dam. This observation shows that the dam was impounded during a dry period. Annual flow decreases by around 24% on the Benue at Garoua and by 26% on the Benue at Lagdo. The drop in flows observed from the 1970s onwards is attributable to the dry period that affected the entire Sahelian area [36] [37]. This analysis highlights the effect of climate variability or climate change on flows upstream and downstream of the dam.

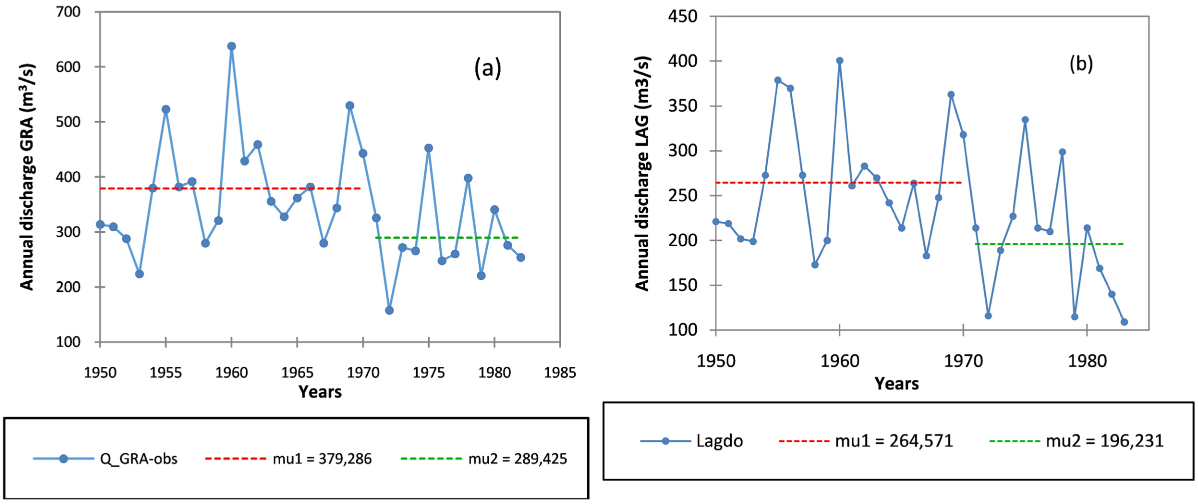

Figure 4. Interannual changes in annual flow rates during the pre-dam period in Lagdo (a) uptream; in Garoua downtream (b).

3.2. Hydrological Functioning of the Benue at Garoua after the Construction of the Lagdo Dam: Altered or Artificial Flow Regime

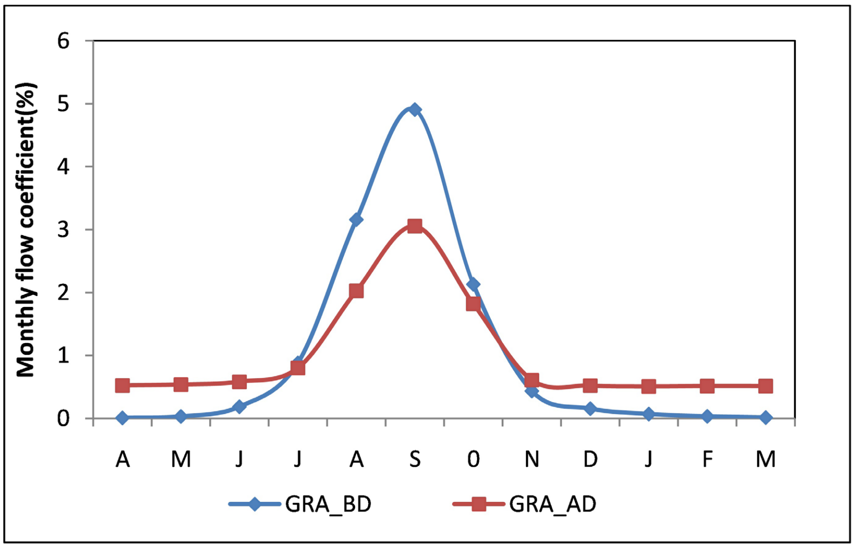

Figure 5. Average monthly variation in the flow of the Benue at Garoua before (BD) and after (AD) the construction of the Lagdo dam between 1999 and 2020.

The construction of the Lagdo dam and its impoundment in 1983 led to a change in the hydrological regime of the Benue River at Garoua, with a permanent flow and a relative reduction in flood flows (Figure 5). The flood hydrograph shows that the maximum flow is also observed in September in Garoua. However, the shape of the hydrograph has changed with a reversal of the hydrological regime characterized by a drop in flood flows and an increase in low-water flows. The shape of the hydrograph is more open than in the pre-dam period. The low-water curve is steeper with a considerable increase in flow during the low-water period. However, as soon as the precipitation stops, the low-water phase appears and lasts until the end of the dry season with flows that are not zero. As a result, flows have become permanent and are spread throughout the year, despite the absence of rain from November to March.

The new data available for the post-dam period enables us to estimate the interannual runoff of the Benue at 335 m^3/s, *i.e.*, a specific flow of 5.53 $l/s.km^2$. It also shows that more than 88% of the flow of the Benue transits Garoua between the months of June and November. This figure stood at 96% prior to the construction of the Lagdo dam. The month of September contributes about 28% of annual inflows, compared with 41% value observed before the dam was built. In addition, August and September contribute around 1/2 (50%) to the annual flow. This implies a reduction of 1/3 in flows. Low-water flows also increased by around 98%. The maximum flow observed in September decreases to 40%, while the low-water flow increases by 90%. Moreover, the pre-dam period receded more quickly than the post-dam period. This undoubtedly reflects a drop in the drying coefficient and consequently a slight rise in the average level of the water tables.

However, the construction of the dam modifies the hydrograph of the river downstream by enhancing the lower flows. A consistent rise in water levels during the dry season, is now governed by the release of water from the Lagdo dam and part of the groundwater. This finding is in line with the observations of many authors [12] [14] [17] [29]. Author [17] confirmed that the flow on the Benue at Garoua was enhanced during periods of low water and that morphogenic processes and erosive dynamics were accelerated. According to the author, this has reconfigured the hydrology of the Upper Benue. This increase in low-water flows has also been observed downstream at all the hydrometric stations in the Niger basin, more specifically in Nigeria and Niger [33] [36] [38]. For example, [10] showed that the low-flow rate increased significantly on the Benue at Jimeta (Yola) from 1983, the date of construction of the Lagdo dam. The author also confirmed the exacerbation of flooding in the Niger Delta in Nigeria when Lagdo dam is released in Cameroon.

3.2.1. Analysis of Flows Upstream and Downstream of the Dam

Comparing the flow between the Lagdo and Garoua stations during the post-dam period, the two hydrographs show a different evolution from the pre-dam period (**Figure 6(a)**). The Upper Benue river behaved differently upstream and downstream the Lagdo dam. This is confirmed by the correlation coefficient between flows at Garoua and Lagdo which falls from 0.9 to 0.7 (**Figure 6(b)**) when using linear or polynomial equation. The maximum flow is observed in September at both Lagdo and Garoua. Upstream and downstream of the dam, the low-flow period is observed from November to May.

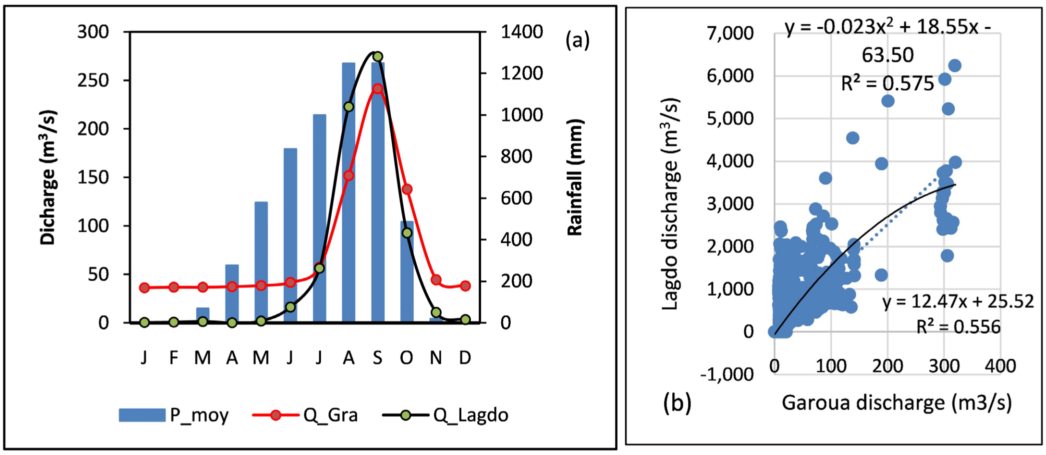

Figure 6. Monthly flow compared at Garoua and Lagdo between 2009 and 2020 (a) linear and polynomial correlation between flows observed at Garoua and Lagdo.

However, the peak of the hydrograph of the Benue upstream of the Lagdo dam is higher than that of the Benue at Garoua, whereas it was higher than that of the Benue at Lagdo during the pre-dam period. In addition, low flows had a similar trend during the pre-dam period, but low flows in the Benue at Garoua increased while those in the Benue at Lagdo were almost zero during the dry season. This increase in low flow is explained by a growing increase in the volume of water released from the Lagdo dam.

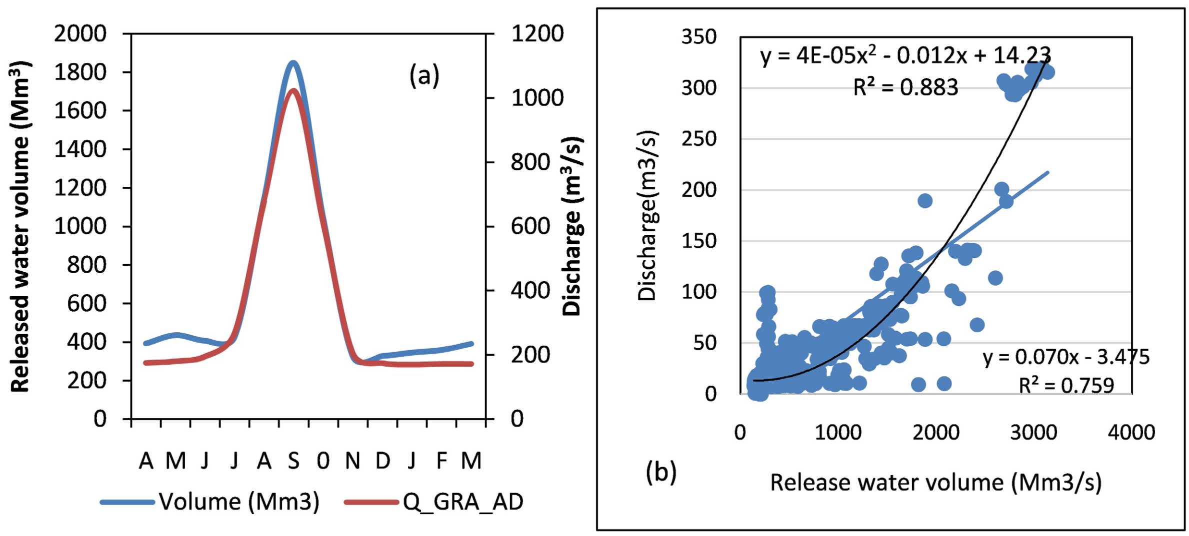

Figure 7. Variation in the volume of water released from the dam and the flow of the Benue at Garoua from 2009 to 2020 (a). Correlation between the volume of water released and the daily flow at the Garoua station (b).

The comparison made between the monthly flows at Garoua and the volumes of water released from the dam after hydropower production shows a similarity with flows proportional to water releases (Figure 7(a)). The maximum volume of water released coincides with the peak of the hydrograph of the Benue at Garoua and consequently with the flood period. During the low-water period, the volumes of water stored during the rainy season are used to generate electricity and are released downstream to maintain the flow. On the other hand, during the rainy season water is released to prevent damage to the dam. The correlation obtained between the two variables with an r value of 0.87 for the linear equation and 0,94 for the polynomial equation (**Figure 7(b)**), shows that low flows at Garoua are increased by water releases from the Lagdo dam.

This result implies that the operation of water released from Lagdo dam, contributes to downstream flooding, during peak flow events. However, for [22], the water released from the dam during periods of high flooding is sensitive to erosive effects, eroding banks and uprooting trees downstream. The authors also attribute the invasion of floating species in the riverbed following sediment deposition to changes in the hydrological regime.

3.2.2. Analysis of Maximum Daily Flows

The analysis of the maximum daily flows is used to assess the hydrological risks in a catchment or at a given hydrometric station. Maximum daily flows are generally responsible for heavy flooding in a catchment area. These floods have low return periods and are more destructive. The variability of the maximum daily flow during pre-dam and post-dam periods is indicated in **Figure 8**. It is observed that maximum flow varied significantly across the study period. This observation indicates that Upper Benue river downstream observed a decline in maxima floods between 1950 to 2014 with the increase in 2012 probably attributable to heavy rainfall observed during this year.

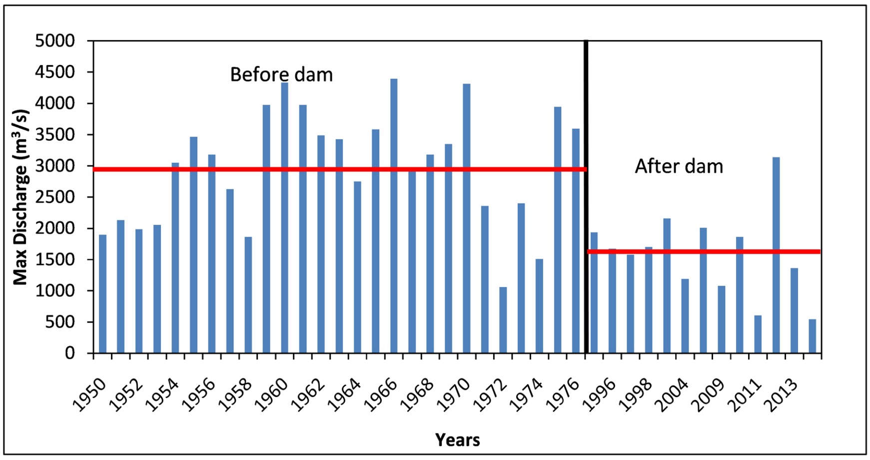

Figure 8. Maximum flows of the BENUE AT Garoua before and after the construction of the dam from 1950 to 2014.

The comparison of pre-dam maximum daily flow with post-dam data indicates a higher variability of maximum daily flows before dam construction and a less fluctuation after dam construction. The valley of Benue at Garoua experienced very high flooding in 1960, 1966 and 1970 before Lagdo dam construction and in 2022 after dam construction. The trend indicates a reduction of 46.4% in maximum daily flows between the pre-dam and post-dam periods on the Benue at Garoua. The decrease in maximum flows reflects a reduction in flooding which is characterized by a reduction in peak flows and consequently in the amplitude of high floods. However, this value cannot be attributed solely to the action of the dam during this long time period. The effect of climate change must also be taken into consideration, as we showed in a previous article that the upper Benue basin is suffering the effects of climate change [15]. Therefore, according to [36], the Lagdo and Jebba dam in Nigeria designed primarily for hydropower and irrigation, have significantly altered the seasonal flow regime and exacerbated downstream flooding in the Niger Delta, particularly during heavy rainfall events.

Furthermore, the reduction in maximum daily flows contributed to reduce the amplitude of floods around 47% and consequently flooding phenomena in the Benue valley downstream the dam. However, this alteration of flows cannot be attributed only to the effect of dam construction, it can be also attribueted to the combined effect of the dam and climate change. Authors [15] by analyzing the potential impact on climate change on the hydrological regime of Upper Benue-indicates that climate change has significantly affected the basin's water resources of Upper Benue between 1950 and 2014, with a downward trend. This result is also confirmed by the study of [39] after analyzing sections downstream of very large dams (capacity of more than 1.2 × 109 m^3) in the United States and showed that the latter have a marked impact on maximum daily and annual flows (average reduction of 67%). In addition, [13] found that the construction of dams on small catchments most often leads to a reduction in maximum annual flows an increase in low-water flows and a reduction in flow variability. Similarly, [7] analyzed maximum daily flows and showed that the amplitude and duration of floods decreased following the construction of the Nangbeto dam. In a similar vein, [40] [41] believes that the dam has reduced the effects of droughts in the lower valley by supporting low water levels and hydraulic fluctuation levels in the aquifer.

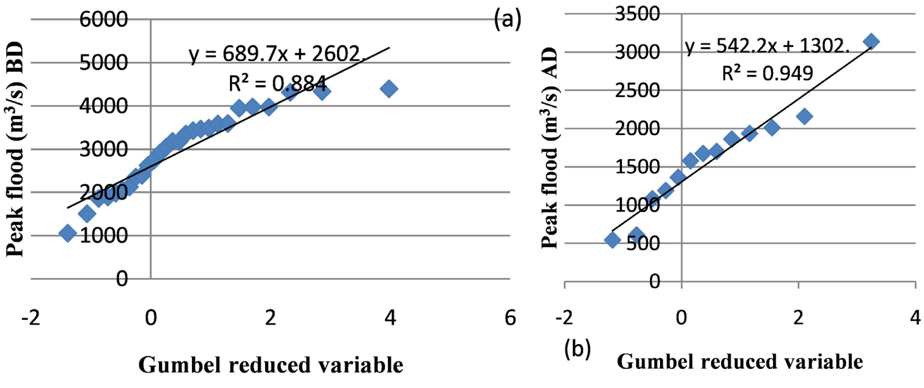

Figure 9. Graphical adjustment of maximum flows at Garoua (a) pre-dam period; (b) post-dam period.

To assess the extent of this cushioning on maximum flows downstream of the dam, peak flows corresponding to a certain return time, were estimated using Gumbel's distribution. **Figure 9** shows that the maximum daily flows for the pre-dam and post-dam periods are adjusted according to Gumbel's probability law following a linear function with a good correlation between the maximum annual flows and the reduced Gumbel variable.

Floods were estimated for different return periods namely 100-years, 50-years, 20-years, 10 years and 5 years. The results are shown in **Table 2** below.

Table 2. Comparison of flows estimated by Gumbel's law between the pre-dam and post-dam periods at Lagdo and Garoua.

Recurrence	Flow rate from Benue to GAROUA(m^3/s)		Flow rate from Benue to LAGDO(m^3/s)	
	Pre-dam	Post-dam	Pre-dam	Post-dam
100 years	5776	3797	4296	6023
50 years	5294	3419	3938	5354
20 years	4651	2913	3461	4461
10 years	4154	2523	3092	3771
5 years	3637	2116	2708	3051

This table shows that the construction of the Lagdo dam has greatly affected the recurrence flows downstream of the dam with percentages varying between 34 and 42%. The 100-year and 50-year floods show an approximate clipping of 34 and 35% while the flows recurring greater or equal to 5 years are the most clipped. At Lagdo, on the other hand the reduction is not very significant. The 100-year and 50-year floods show an approximate clipping of 29% and 26% while flows recurring every 5 years or more are clipped by only 11%.

A comparison of flood flows upstream and downstream of the dam during the post-dam period (**Table 3**) shows a reduction in the amplitude of rare floods with return periods of 100 and 50 years of approximately 37%. Referring to the work carried out by [8] on the Matawi River in Quebec, the construction of the dams resulted in a reduction in the maximum monthly discharge and a change in the period of flood occurrence. It can therefore be said that the Lagdo dam acts as a flood damper by capping or reducing the maximum flow of the Benue at Garoua, particularly for floods with return periods of 50 and 100 years. This value of capped water would correspond to the volume of water stored in the Lagdo dam during periods of high flooding for energy production throughout the year.

Table 3. Comparison of flows estimated by Gumbel's law between upstream and downstream during the post-dam period.

Recurrence	Upstream of the dam	Downstream of the dam
100 years	6023	3797
50 years	5354	3419
20 years	4461	2913
10 years	3771	2523
5 years	3051	2116

This assessment of the Lagdo dam's impact on flooding shows that the dam has moderately reduced the devastating impact of the 100-years and 50-years floods that are most often responsible for flooding phenomena. It can therefore be said that the Lagdo dam has provided protection and reduced the extent of the 30-years floods to the 100-years floods observed in the Benue valley downstream of the dam particulary in the Niger Delta in Nigeria. However, this flood control action is limited when predefined thresholds are exceeded following heavy rainfall. When the water level reaches the 210 m threshold in the Lagdo dam, the excess water is automatically released to prevent the risk of the dam bursting, thereby ensuring the dam's safety in the event of a 50-years or 100-years flood. For example, in 2012 the Lagdo reservoir has been released simultaneously with heavy rainfall downstream and exacerbated flooding in the Niger Delta. The maximum flow observed in this year due enabled the dam to be emptied as a precautionary measure resulting in the total submersion of the Benue valley and the consequent flooding phenomena. These floods caused considerable damage with many people losing their lives.

Table 4. Compared analysis of flood during pre and post dam period at Garoua station.

	Period pre-dam 1952-1980	Period post-dam 1999-2020	Rate of change
Low water flow	17.6	173,1	+90%
Annual peak flow	1695	1012	40%
Annuel mean flow	290	335	13.4%
Maximum mean flow	2994	1604	46.4%
Peak flow (june-november)	96%	%	−8%
100-years flood	5776	3797	−34%
50-years flood	5294	3419	−35%

This table (**Table 4**) shows a reduction in flood flows, average flows and maximum flows between the pre- and post-dam periods. However, low-water flows seem to have increased significantly. We can therefore say that the construction of the dam led to a reduction in the amplitude of floods and an increase in low-water flows thanks to the release of water from the dam. The entire hydrological dynamic of the Benue valley has thus been modified moving from a natural tropical rainfall regime to an artificial or socialized regime characterized by water releases that support low-water flows.

4. Conclusion

To understand the impact of the Lagdo dam on Upper Benue river regime, discharge data of the pre-dam period (1950-1982) and post-dam period (1983-2020) have been analyzed. Despite major limitations related to data scarcity, it appears from the above that the construction of the Lagdo dam has affected the hydrological dynamics of the Benue at Garoua. The results highlight a change in the shape of the hydrograph with a reduction of about 40% of peak flows and an increase of 90% of low flows. In addition, the reduction in maximum daily flows by around 47% in 100-year and 50-year floods, illustrates a regularization and reduction in the amplitude of floods. This has reconfigured the hydrological dynamics of the Upper Benue basin. The Lagdo dam therefore acts as a flood damper by reducing maximum flows. This has made it possible to reduce the amplitude of floods in the Benue valley and consequently, the flooding phenomenon. The dam is therefore a tool for regulating the Benue River and controlling flooding in the Benue valley. Nonetheless, it is important to take into consideration the effect of climate change on the anthropogenic factors, which have been recognized in the previous study. While the Lagdo dam can be effective in mitigating flood risks in Benue valley, its operation requires careful planning, coordination, and consideration of potential negative impacts on the environment and local communities located downstream. Overall, these results would be useful for effective and efficient management of water resources downstream of the dam in the current and future context of global change.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Walling, D.E. (2006) Human Impact on Land-Ocean Sediment Transfer by the World's Rivers. *Geomorphology*, **79**, 192-216. https://doi.org/10.1016/j.geomorph.2006.06.019

[2] Moritz, M., Laborde, S., Phang, S., Ahmadou, M., Durand, M., Fernandez, A., *et al.* (2016) Studying the Logone Floodplain, Cameroon, as a Coupled Human and Natural System. *African Journal of Aquatic Science*, **41**, 99-108. https://doi.org/10.2989/16085914.2016.1143799

[3] Fita, D.E. (2019) Impacts de la variabilité climatique sur le régime hydrologique de la Bénoué Supérieur (Nord-Cameroun). Thèse de Doctorat en Science de l'Ingénieur, Université de Maroua, Cameroun, 332 p.

[4] Mezger, G., González del Tánago, M. and De Stefano, L. (2021) Environmental Flows and the Mitigation of Hydrological Alteration Downstream from Dams: The Spanish Case. *Journal of Hydrology*, **598**, Article 125732. https://doi.org/10.1016/j.jhydrol.2020.125732

[5] Bello, C., Suarez, W., Drenkhan, F. and Vega-Jácome, F. (2023) Hydrological Impacts of Dam Regulation for Hydropower Production: The Case of Lake Sibinacocha, Southern Peru. *Journal of Hydrology*: *Regional Studies*, **46**, Article 101319.

https://doi.org/10.1016/j.ejrh.2023.101319

[6] Fang, G., Yan, M., Dai, L., Huang, X., Zhang, X. and Lu, Y. (2023) Improved Indicators of Hydrological Alteration for Quantifying the Dam-Induced Impacts on Flow Regimes in Small and Medium-Sized Rivers. *Science of The Total Environment*, **867**, Article 161499. https://doi.org/10.1016/j.scitotenv.2023.161499

[7] Amoussou, E., Camberlin, P. and Mahé, G. (2012) Impact de la variabilité climatique et du barrage nangbéto sur l'hydrologie du système Mono-couffo (Afrique de l'ouest). *Hydrological Sciences Journal*, **57**, 805-817. https://doi.org/10.1080/02626667.2011.643799

[8] Assani, A.A., Buffin-Bélanger, T. and Roy, A.G. (2005) Analyse d'impacts d'un barrage sur le régime hydrologique de la rivière matawin (Québec, Canada). *Revue des sciences de l'eau*, **15**, 557-574. https://doi.org/10.7202/705469ar

[9] Amoussou, E. (2010) Variabilité pluviométrique et dynamique hydrosédimentaire du bassin versant du complexe fluvio-lagunaire mono-ahémé-couffo (Afrique de l'ouest). Thèse de Doctorat unique, Université de Bourgogne, 315 p.

[10] Ankidawa, B.A. (2014) Sustainability of Water Abstraction by Hand Drilling in the Floodplain of River Benue of Yola, NE Nigeria. Published PhD, University of Brunel, 375 p.

[11] Ekka, A., Keshav, S., Pande, S., van der Zaag, P. and Jiang, Y. (2022) Dam-Induced Hydrological Alterations in the Upper Cauvery River Basin, India. *Journal of Hydrology*: *Regional Studies*, **44**, Article 101231. https://doi.org/10.1016/j.ejrh.2022.101231

[12] Mailhot, A., Talbot, G., Ricard, S., Turcotte, R. and Guinard, K. (2018) Assessing the Potential Impacts of Dam Operation on Daily Flow at Ungauged River Reaches. *Journal of Hydrology*: *Regional Studies*, **18**, 156-167. https://doi.org/10.1016/j.ejrh.2018.06.006

[13] Deng, Y., Jiang, W., Tang, Z., Li, J., Lv, J., Chen, Z., *et al*. (2017) Spatio-Temporal Change of Lake Water Extent in Wuhan Urban Agglomeration Based on Landsat Images from 1987 to 2015. *Remote Sensing*, **9**, Article 270. https://doi.org/10.3390/rs9030270

[14] Magilligan, F.J. and Nislow, K.H. (2005) Changes in Hydrologic Regime by Dams. *Geomorphology*, **71**, 61-78. https://doi.org/10.1016/j.geomorph.2004.08.017

[15] Fita, E.D., Ombolo, A., Fotso-Nguemo, T.C., Saïdou, D.B., Daïka, A., Chouto, S., *et al*. (2024) Analysing the Potential Impact of Climate Change on the Hydrological Regime of the Upper Benue River Basin (North Cameroon). *Journal of Water Resource and Protection*, **16**, 569-583. https://doi.org/10.4236/jwarp.2024.168032

[16] Patro, E.R., Ghadimi, S., Shahrood, A.J., Fazel, N., Makarieva, O. and Haghighi, A.T. (2024) Flow Regime Alteration in Arctic Rivers Due to Dam Operations and Climate Change. *Global and Planetary Change*, **237**, Article 104442. https://doi.org/10.1016/j.gloplacha.2024.104442

[17] Mbele Abbo, F. (2021) Erosion fluviale et mutations morphométriques du drainage dans le secteur aval du barrage de lagdo (Bassin de la Bénoué, Nord-Cameroun). *Proceedings of the International Association of Hydrological Sciences*, **384**, 113-119. https://doi.org/10.5194/piahs-384-113-2021

[18] Toro, S.M. (1997) Post-Construction Effects of the Cameroonian Lagdo Dam on the River Benue. *Water and Environment Journal*, **11**, 109-113. https://doi.org/10.1111/j.1747-6593.1997.tb00100.x

[19] AES-SONEL (2013) Aménagement hydroélectrique de Lagdo. Rapport des activités. Slide Presentation, 13 p.

[20] Ngounou, N.B., Njitchoua, R. and Naah, E. (2004) Le barrage de lagdo (Nord-Cameroun), Impact sur les plaines d'inondationde la Bénoué. *Gestion intégrée des Zones inondables Tropicales*, 455-474. https://horizon.documentation.ird.fr/exl-doc/pleins_textes/divers09-03/010030382.pdf

[21] Mbélé, A.F. (2018) Analyse morphohydrologique du lit majeur de la Bénoué, de la confluence avec le Mayo-Kebi à la frontière Cameroun-Nigéria. Thèse de Doctorat PhD, Université de Ngaoundéré, 387 p.

[22] Tchotsoua, M., Fotsing, J.M. and Moussa, A. (2007) Évaluation des risques d'inondation dans la vallée de la Bénoué en aval du barrage de Lagdo (Cameroun). Actes de Colloque, JSIRAUF, Hanoi, 6-9 Novembre 2007, 1-9.

[23] Tanoï, N.F. (2014) Prévisions numérique et stochastique des crues du Bassin de la Bénoué. Mémoire de Master de Statistique Appliquée, École Nationale Supérieure Polytechnique de Yaoundé, 113 p.

[24] Olivry, J.C. (1986) Fleuves et rivières du cameroun, coll. Monographies Hydrologiques ORSTOM n°9, Edition MESRES-ORSTOM, 781 p.

[25] Djoufack, V. (2011) Etude multi-échelles des précipitations et du couvert végétal au Cameroun: Analyses spatiales, tendances temporelles, facteurs climatiques et anthropiques de variabilité du NDVI. Thèse de Doctorat, Université de Bourgogne, 322 p.

[26] Fita, D.E., Ombolo, A., Ewodo, M.G., Chouto, S., Bineli, A.E., Abate Essi, J.M. (2015) Caractérisation de la variabilité spatio-temporelle des précipitations dans la zone soudano-sahélienne du Cameroun au cours des cinq dernières décennies. *Afrique Science*, **11**, 331-348.

[27] Marie-Rosine, F.N., Drissa, S.T., Gbombélé, S., Rodrigue, O.K. and Lanciné, G.D. (2020) Modélisation de la relation pluie-débit dans un contexte de gestion en eau: Cas du sous bassin versant du n'zi en Côte d'Ivoire. *European Scientific Journal*, *ESJ*, **16**, 68-88.

[28] Dao, A., Kamagate, B., Mariko, A., Goula, B.T.A., Seguis, L., Maiga, H.B. and Savane, I. (2010) Variabilité climatique et réponse hydrologique du bassin versant transfrontalier de kolondièba au sud du mali. *European Scientific Journal*, **43**, 435-444. https://www.researchgate.net/publication/229096385

[29] Ardoin-Bardin, S. (2004) Variabilité hydroclimatique et impacts sur les ressources en eau de grands bassins hydrographiques en zone Soudano-sahélienne. Thèse de Doctorat, Université de Montpellier II, 440 p.

[30] Laborde, J.P. (2000) Eléments d'Hydrologie de surface. U.M.R. 5651 "Espace" du C.N.R.S., 204 p. http://cours.st.free.fr/semestre%207/M1%20cours/hydro/cours/Cours%2520Hy-drologieJPL.pdf

[31] Osei, M.A, Amekudzi, L.K., Omari-Sasu, A.Y., Yamba, E.I., Quansah, E., Aryee, J. N.A. and Preko, K. (2021) Estimation of the Return Periods of Maxima Rainfall and Floods at the PRA River Catchment, Ghana, West Africa Using the Gumbel Extreme Value Theory. *Heliyon*, **7**, 1-13.

[32] Temtime, G.S. (2024) Flood Frequency Analysis Using Gumbel Distribution Method: A Case of Robigumero River, Abay Basin, Ethiopia. *Hydrology*, **12**, 1-7. https://doi.org/10.11648/j.hyd.20241201.11

[33] Okeke, O. and Ehiorobo, J. (2016) Frequency Analysis of Rainfall for Flood Control in Patani, Delta State of Nigeria. *Nigerian Journal of Technology*, **36**, 282-289. https://doi.org/10.4314/njt.v36i1.34

[34] Gumbel, E.J. (1960) Statistics of Extremes. 2nd Edition, Columbia University Press.

[35] Bodian, A. (2012) Approche par modélisation pluie-débit de la connaissance régionale de la ressource en eau: Application au haut bassin du fleuve Sénégal. Thèse de Doctorat, Université Cheikh Anta Diop de Dakar, 288 p.

[36] Eteh, D.R., Egobueze, F.E., Paaru, M., Otutu, A. and Osondu, I. (2024) The Impact of Dam Management and Rainfall Patterns on Flooding in the Niger Delta: Using Sentinel-1 SAR Data. *Discover Water*, **4**, Article No. 123. https://doi.org/10.1007/s43832-024-00185-8 https://link.springer.com/article/10.1007/s43832-024-00185-8

[37] Mahé, G., Lienou, G., Bamba, F., Paturel, J.E., Adeaga, O., Descroix, L., Mariko, A., Olivry, J.C., Sangare, S., Ogilvie, A. and Clanet, J.C. (2011) Le fleuve Niger et le changement climatique au cours des 100 dernières années. *Hydro-Climatology*, 34, 131-137. https://iahs.info/uploads/dms/16774.25-131-137-344-08-Mahe-corr.pdf

[38] Sighomnou, D., Descroix, L., Genthon, P., Mahé, G., Bouzou Moussa, I., Gautier, E., *et al.* (2013) La crue de 2012 à Niamey: Un paroxysme du paradoxe du Sahel? *Sècheresse*, **24**, 3-13. https://doi.org/10.1684/sec.2013.0370

[39] Graf, W.L. (2006) Downstream Hydrologic and Geomorphic Effects of Large Dams on American Rivers. *Geomorphology*, **79**, 336-360. https://doi.org/10.1016/j.geomorph.2006.06.022

[40] Chouto, S. (2016) Variabilité hydrologique et vulnérabilité des populations dans la Plaine d'inondation du fleuve Logone (Région de l'Extrême Nord-Cameroun). Mémoire de Master 2 en Sciences Environnementales, Université de Maroua, 157 p.

[41] Mujere, N. (2011) Flood Frequency Analysis Using the Gumbel Distribution. *International Journal of Computer Applications in Engineering Sciences*, **3**, 2774-2778.