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Contribution to the control of the drying up of Lake Chad in a context of climate change

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ABSTRACT
In a poorly gauged to ungauged environment, the exploitation of Digital Terrain Models of the Chari and Logone sub-basins has made it possible to highlight their water potential. The extraction of the physical characteristics of the related sub-watersheds led to the determination of their respective flows by the use of Model of the NRCS (National Resources Conservation Service). The aggregation of flows and the processing of the consecutive water flow directions will contribute to controlling the drying up of Lake Chad and the ecosystems will be relieved of climate stress.

KEYWORDS
Paleohydrology, Ecosystem, Climate adaptation, Drying, Digital Terrain Model, Discharge, Direction of water flow, flow rates.

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I. INTRODUCTION

Since the end of the (BP) era, Lake Chad has experienced a very negative reduction in its surface area ranging from 25,000 km2 to 4,000 km2. This severe reduction exposes it to the risk of drying out. The effects of climate change seriously affect the ecosystems of the Sahelregion, the Congo Basin and that of Lake Chad as well as its tributaries, the Chari and Logone. From the chronological series of the fluctuation of Lake Chad , it is presented antagonistic trends of the progression of aridity as well as its regression and this in different time steps in Pouyaud, B. et al. (1989). Uncertainties in the future of Lake Chad are marked in Magrin, G. and Lemoalle, J. (2019) leaving the only option of transferring river water from the Congo Basin for its refilling.

However, the project to transfer rainwater from the Congo Basin to Lake Chad had initially planned a flow of 100km3/year of water in Bonifica (1982). The object of the project is drastically revised downwards twenty years later to a flow of 3.8 km3 / year in Géraud M. (2022). The riparian populations of the Lake Chad Basin are constantly suffering. Notwithstanding the non-contribution of aquifers and the crown of granite basement surrounding Lake Chad in Yombombe, M. T., and Tamo, T. T. (2023), anthropogenic actions continue to increase the global temperature, considerably impacting that of the entire Congo Basin. Forecasts of climate trends in the Congo Basin, the source of rainwater transfer from the BONIFICA Project in Bonifica (1982), Géraud M. (2022), marked longer and more frequent dry seasons in the northern regions of the Congo Basin in Tazebe B. et al. (2013).

Among so many authors, some have specified methods for designing an empirical hydrological modelon the basis of the rainfall-flow relationships according to Numerical Terrain Models in Murugesu, S. et al. (2003),K. Sawicz, T. et al. **(**2011**)** and others have proposed scientific approaches for the estimation of water levels in floodplains by statistics by Degré, A. et al. (2008) and flows in watersheds on the exploitation of satellite images by Hostache, R. et al. (2006).

Our hypothesis is to test the Digital Terrain Models (DTMs) in order to determine the flows that can be mobilized to contribute to the control of the drying up of Lake Chad in a context of climate change by a series of sustainable and balanced refilling of Lake Chad without affecting the ecosystems of the Congo Basin in Yombombe, M. T., and Tamo, T. T. (2023).

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II. MATERIAL AND METHODS

2.1. Research scope

The orographic basin of Lake Chad contained several rivers the main tributaries of which are the Chari and theLogone. The silting up of their riverbeds does not promote a regular and significant transfer of rainwater during flood periods. A permanent spilling is observed when their respective riverbeds are overfilled during wet periods (rainy season). Figure 1 below indicate the extent of the orographic basin of Lake Chad

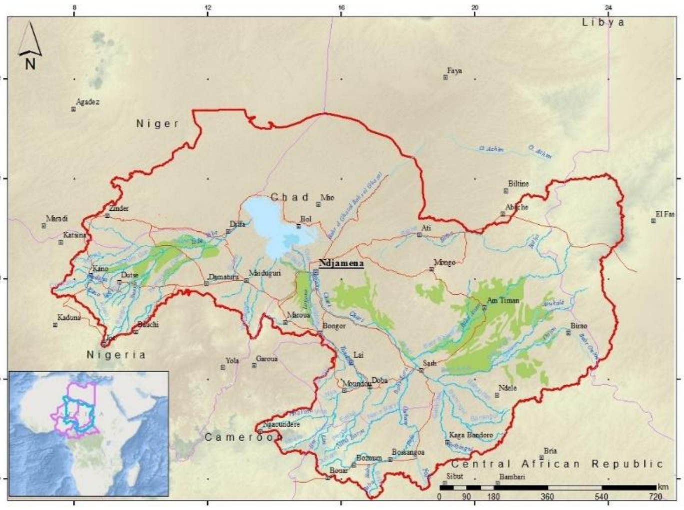

Figure 1. Map of the Orographic Basin of Lake Chad, RAS - Lake Chad, 2019

From the orographic basin, we will extract three model sub-basins with favorable characteristics in flood production zones for our study.

The study sub-basins had the same geoclimatic and environmental similarity. There were two seasons, including a rainy season from May to October and a dry season from November to April with variations in climate change. Figure 2 presented the study sub-basins.

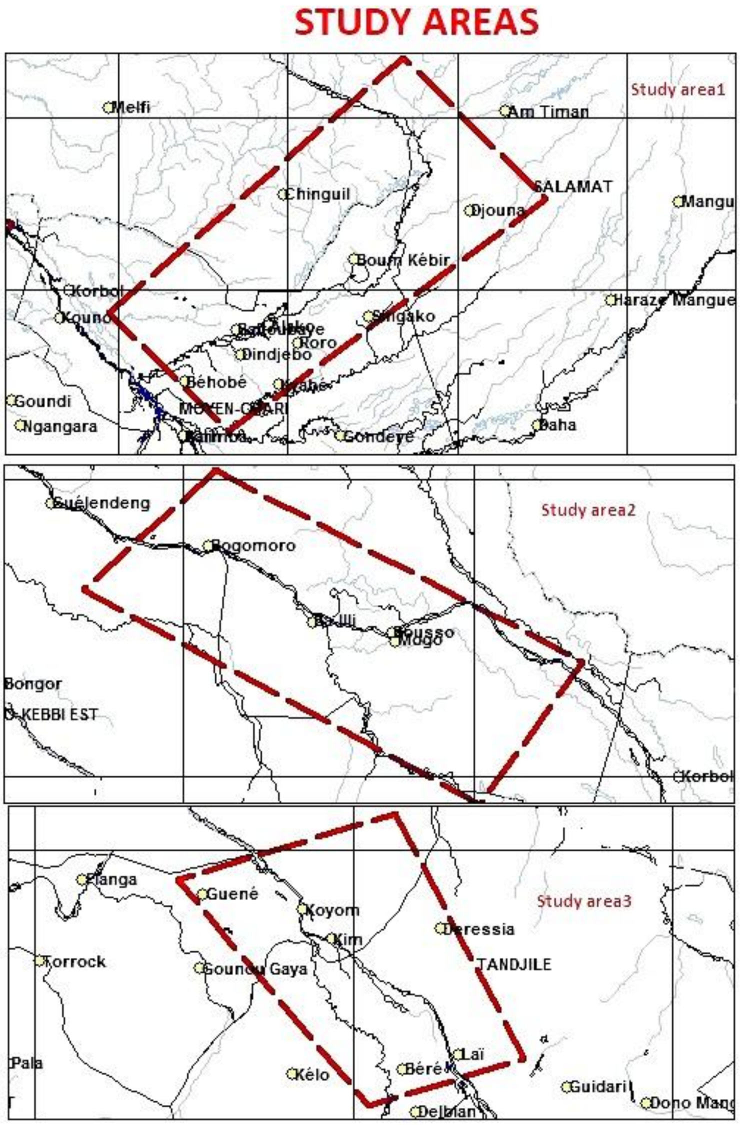

Figure 2. Sub-basin of studies

The three sub-basins are grouped into two study blocks:

- DOBO (area1) and ABSORTO (area2):

In this grouping of sub-basins, the hydrographic network consists of rivers in Olivry, J.-C. et al. (1996) including the Bahr Keita, the Salamat, the Aouk, the Lake Iro and the Mares (Haraze). Their runoff directions were North-East to South-West. Rainwater flowed into the Chari River through the channels consisting of Barh Salamat and Barh Aouk. From the Chari River, spills during flood periods were particularly observed on parallel branch of a river along the Migna-Kouin-Korbol-Banker-Absorto-Laïri flood axis of Massenya. The area is typical of a wooded savannah with a clear tendency with herbaceous characteristic of the floodplains. The average rainfall was 891 mm/year.

- BOUMO (area3):

This sub-basin covered the floodplains of Tandjilé and Mayo Kébbi East. The Logone River was the main river system. The spilling followed the Laï-Kim-Djoumane-Bongor axis, part of whose rainwater flowed into the Yaérés. Although it was little wooded, the presence of herbaceous plants specific to flooded areas was marked.
The flows of the Chari and Logone rivers according to the characteristics of the related watersheds were of significant importance in Yombombe, M. T., and Tamo, T. T. (2023).

2.2. Methodology

In the light of the present research work, we have reconstructed the paleohydrological profile of Lake Chad according to the geological time scales by combining the absolute age resulting from the quantified data of the ages of the strata in number of years from the origins then the relative age resulting from the current and evolving situation of Lake Chad .The paleohydrological profile takes into account the time dimensions according to the (BP) age and the historical time scale from the birth of Jesus Christ, the depth and the relative area occupied by the waters in the orographic basin of Lake Chad. The profile dual integrates BP ages and historical time series twice.ad. Then, we proceeded to the identification of the study sub-basins and the modeling of the relative Digital Terrain Models by the extraction of satellite data according to the technique of interferometryin Yombombe, M. T., and Tamo, T. T. (2023),Guezoui, Z. (2014).

Through this process, we acquired physical characteristics of watersheds (altitudes, slopes, areas, etc.) and hydraulic processes. The knowledge of the physical parameters allowed the materialization of the grids of the directions of flow and accumulation of the rainwater. It has led to knowledge of the fields of production, transfer, and storage of rainwater. The directions of water flow were done by coding and varied according to the approaches of the theoretical conventions in Delaigue, O. et al (2020). This allowed the identification of the directions of water flow according to the lowest altitude by Bouvier, C. (1994). In our study sub-basins, low altimetry was found to generate a risk of flow discontinuity followed by water stagnation in low depressions. For the control of the continuity of flows in the sub-basins towards Lake Chad, it is recommended the inversion of the hydrographic path in places with either the digging of the collar of the depression, or the filling of the depressions. We ended up, by this means in the definition of the rainwater transfer function of our study model. Figure 3 showed the different directions of rainwater flow.

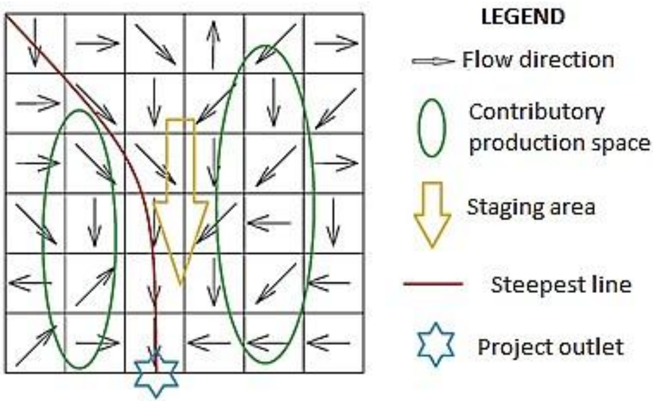

Figure 3. Flow direction models

We have adopted the National Resources Conservation Service (NRCS) Model for its reliability in applicability in thinly-gauge environments by Pietrusiewicz, I. et al (2014),Merz, R. (2006). This enabled us to acquire over two consecutive decades the average flows for each pilot sub-basin. . In addition to the interpolation of missing rainfall data, their consolidation contributed to the evaluation of flows and inputs by pilot sub-basin covering the Chari and Logone rivers. Our flow aggregation function consisted in mobilizing all the micro-flows of the sub-basins along the line of greatest slope. It led us to establish the hydrological balance of our study with iterative parameters which depended on local anthropological requirements. Then, our activation function, served as a triggering factor for the drainage of relative flows towards Lake Chad.

III. RESULTS

From the paleohydrological profile that made it possible to identify the different trends in the drying and rainwater supply of the intrinsic basin of Lake Chad, we presented the importance of the exploitation of NTMs, the treatment of missing rainfall data given the poorly gauged environment, the different flows as well as their losses and the hydrological balance of our study in the quest to control the drying of Lake Chad.

3.1. The paleohydrological profile of Lake Chad

The paleohydrological profile of Lake Chad results from the following major findings:

- Before 50,000 BC, the entire orographic basin was flooded with the exception of the mountain ranges of Hoggar (Algeria), Ennedi-Tibesti-Ouaddaï (Chad) and Adamaoua (Cameroon)." The climatic phenomenon continued during the "Wet African Period in Favreau, L. G. et al. (2006), Ghienne, J-F. et al. **(**2006**)**. At this time, it is observed a spilling of the waters of Lake Chad into the Atlantic Ocean by the wakes of the Mayo Kébbi hydrographic networks and then the Benue basin when the waters reached the +324 m coast.
- A resumption of rainfall activities, a sign of the reappearance of aqueous malarial and lake environments between 18,000- and 12,000-years BP in Lézine, A.-M. et al. (2011).
- In the present time of Lake Chad, there is a resumption of stormy activities in ambivalence with the rise in temperature and a trend of flooding.

In addition, Lake Chad is marked by three (03) periods of complete drying including:

- A complete disappearance of the lake between the years 30,000 to 20,000 years before Jesus Christ in Servant, M. andServant, S. (1983).
- A much accentuated aridity of age ranging from 4200 years to 4000 years BP in Rognon, P. (1983).
- A complete drying up of Lake Chad for 20 to 30 years in the middle of the fifteenth century with a return of waters followed by drowning of the villages located in its riverbed by Lemoalle, J. and Magrin, G. (2014).

The paleohydrological profile obtained by our methodological approach represents the evolutionary footprint of Lake Chad. It is influenced by climate change as shown in Fig.4.

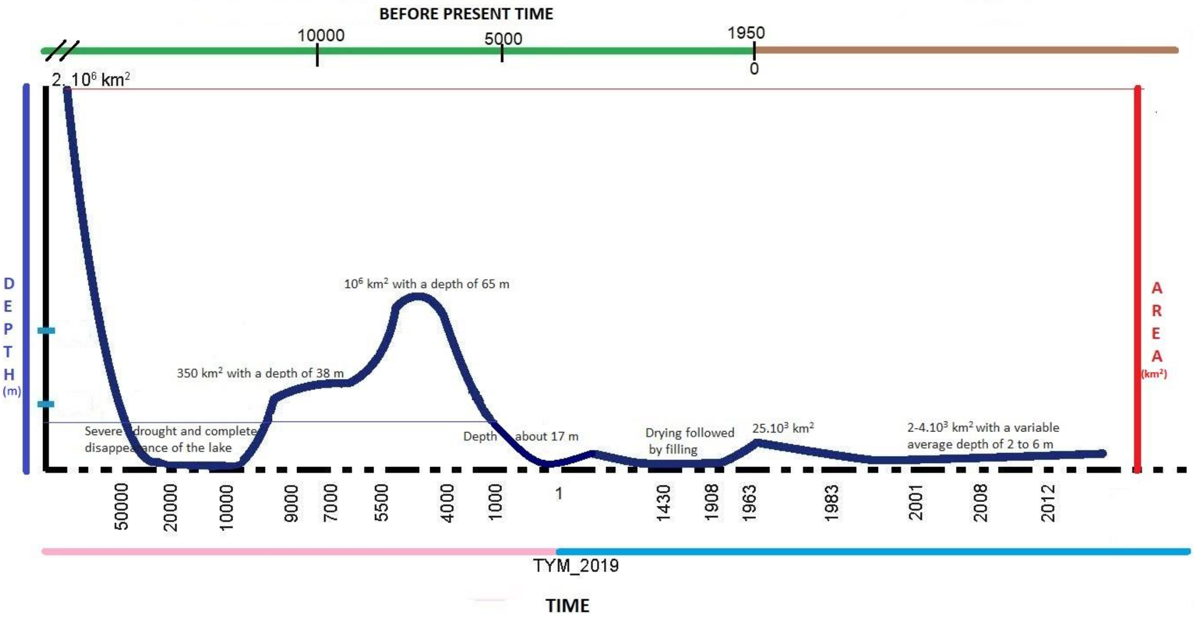

Figure 4. Reconstruction of the paleohydrological profile of Lake Chad

3.2. The quality of Digital Terrain Models

The Digital Terrain Models of the study sub-basins obtained in 3D format, with an accuracy of 30 m, are presented as below by grouped Fig. 5.

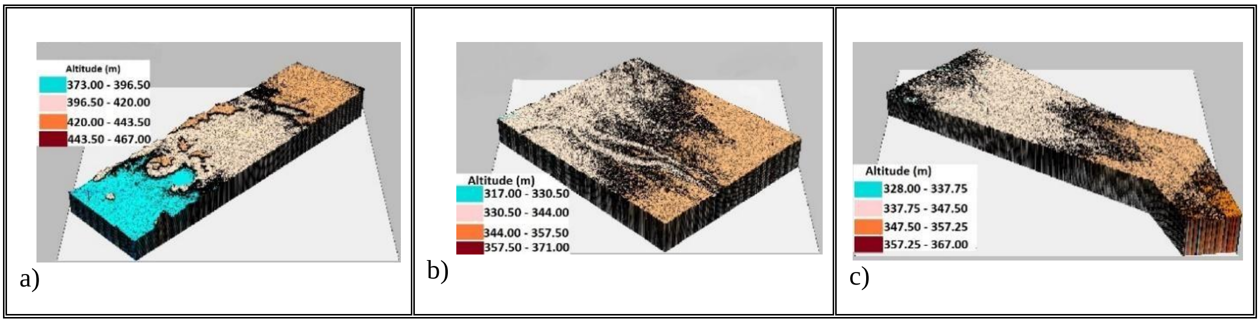

Figure 5. a) Dobo area (Bahr Azoum floodplains) – b) Absorto area (floodplains overflowing on Massenya) – c) Boumo area (Lai floodplains to Kim).

From these NTMs, we extracted precise data on their characteristics including their surfaces, dimensions, slopes and fairly precise delimitation of flood zones and dry areas. They clearly showed the areas of spilling, return of runoff and irregularities of the riverbeds of the Chari and Logonein Yombombe, M. T., and Tamo, T. T. (2023).

3.3. Flow rates

For its reliability applied to watersheds that are poorly gauged and do not require multiple parameters, we adopted the National Resources Conservation Service (NRCS) method for determining the ten-year average flows for each study sub-basin, over two consecutive decades. The flow rates were shown in Tables 1 and 2.

Table 1.Ten-year average flow estimate – year 1995 to 2004

No.	AREA	CN	S [mm]	P [mm]	A [km^2]	Q [m^3s^{-1}]
1	ABSORTO	86	41	798	4732	750
2	BOUMO	77	76	949	1977	864
3	DOBO	86	41	1023	11700	977
	TOTAL			2770		2591

Explanations: A - area; CN - parameter; P - precipitation; Q - flow; S - basin's retention volume

Table 2.Ten-year average flow estimate – year 2005 to 2014

No.	AREA	CN	S [mm]	P [mm]	A [km^2]	Q [m^3s^{-1}]
1	ABSSORTO	86	41	798	4732	361
2	BOUMO	86	41	949	1977	1043
3	DOBO	86	41	1023	11700	992
	TOTAL			2770		2396

Explanations: A - area; CN - parameter; P - precipitation; Q - flow; S - basin's retention volume

4.4. Losses

From the decennial flows obtained, we also checked the flows from the Chari to Sarh – Chad, on the borders of the Oubangui-Chari, and from their transit point of Mailao, upstream of N'Djamena point of embouchure with the Logone River. The losses are presented in Fig. 6.

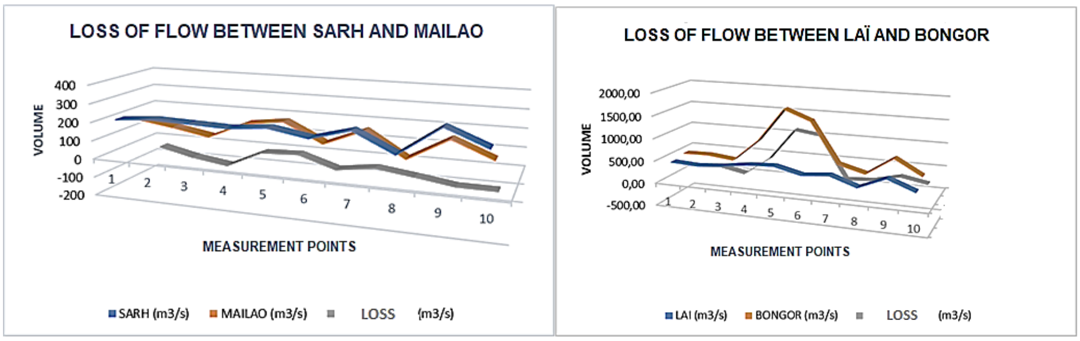

Figure 6. a)Loss of flow between Sarh and Mailao; b) Loss of flow between Laï and Bongor

The median rate of loss of flows of the Chari River was of the order of 30%, this without taking into account the high production of uncontrollable rainwater from the Dobo (Bahr Azoum floodplains) and Absorto (floodplains overflowing Massenya) sub-study basins.

Despite losses close to 31% due to the high spilling, we observed a good refilling of the Logone Riverbed from the floodplains after the Djoumane site (Chad).

Indeed, we stated the hydrological balance of our study. It integrates the global and sustainable balance between hydrodynamic, environmental and anthropogenic parameters.

It is summarized in the following equation (mathematical translation of the model):

$$Q_j + \Omega Q_j + P_j + \frac{\zeta Hlj}{Slj} \geq E_{li} + ETP_{li} + I_{li} + \frac{\psi Hli}{Sli} \quad (1)$$

With the notations below:

- Q_j: initial contributions from tributaries (Km^3yr^{-1}).
- ΩQ_j: cumulative contributions from production areas (Km^3yr^{-1}).

- P_j:local rainfall over Lake Chad (Km^3yr^{-1}).
- $\frac{\zeta Hlj}{Slj}$: Relative stock of stability relative to time (Km^3yr^{-1}).
- E_{li}: direct evaporation on Lake Chad (Km^3yr^{-1}).
- ETP_{li}: evapotranspiration taking into account the ecosystems of Lake Chad (Km^3yr^{-1}).
- I_{li}: direct infiltration from Lake Chad (Km^3yr^{-1}).
- $\frac{\psi Hli}{Sli}$: relative volume sought over time (Km^3yr^{-1}).
- S_{li}: surface of Lake Chad before the project (Km^2).
- S_{lj}: surface of Lake Chad of the project (Km^2).
- ψH_{li}: water level prior to the project ($m.yr^{-1}$).
- ζH_{lj}: stable water level of the project ($m.yr^{-1}$).

IV. DISCUSSIONS

We set our hypothesis to verify through Digital Terrain Models the mobilizable water potential of the study sub-basins to contribute to the control of the drying up of Lake Chad in a context of climate change. The water potential of the Chari and Logone basins were conclusive in view of the results obtained. We took our reference mark opportunely on the entry point of the waters of the various water transfer projects of the Congo Basin in Bonifica (1982), Géraud M. (2022) in order to lead the discussions on the basis of our two sub-basins of study of Dobo and Absorto, within the scope of the Chari River.

Being in a poorly gauged environment, we proceeded by interpolation to obtain missing rainfall data in the study sub-basins while considering the uniformity of rainfall in the Chari watersheds and surface runoff with a supposedly saturated soil. Regional transfer functions were variable in an ungauged settingby Poncelet, C. (2016). The average flow was around 900 m3.s-1 over two (02) consecutive decades over an area of 11700 km2 in the Dobo sub-basin, without neglecting all losses due to infiltration and evapotranspiration phenomena. From the Digital Terrain Models, we observed the riverbed of parallel rivers that bordered the Chari as well as irregularities. They captured runoff water and drained it towards the flood-prone areas of Massenya with significant losses observed after the analysis of the loss of flow from the Chari River according to the consolidated results obtained on the Mailao site. The results obtained, through our work, were similar to those from the following ridge workby Billon, B. et al (1974),in which the maximum observable flood over twelve years in the Bahr Azoum (Am-timan) watershed is 324 $m^3.s^{-1}$ while the average median flood is around 250 m3.s-1. Also in the Barh Keita (Kyabé) over a catchment area of 14,000 km2, the maximum flow was 547 $m3.s^{-1}$ over ten (10) consecutive observations. The maximum annual flow of median frequency is of the order of 260 $m3.s^{-1}$.

For our study, the two-decadeaverage flow taking losses into account was aroundQ_{tx1} (Dobo) ≈ 650 $m3.s^{-1}$. However, for the water transfer project from the Congo Basin to Lake Chad at the entrance to the Chari River, the objectives were set as follows:

- $108\ m^3.s^{-1} \leq Q_{bclt} \leq 300\ m^3.s^{-1}$.
- $3\ 000\ km^2 \leq S_{bclt} \leq 5\ 500\ km^2$
- $0{,}50\ m \leq H_{bclt} \leq 1\ m$

Of which :

- $Q_{tx1(Dobo)}$: mobilizable flow of the Dobo study sub-basin.
- Q_{bclt} : flow rate to be achieved set by the project to transfer water from the Congo Basin to Lake Chad.
- S_{bclt} : area of Lake Chad to be reached set by the transfer project from the waters of the
- Congo Basin to Lake Chad.
- H_{bclt} : depth of Lake Chad to be reached set by the draft transfer of water from theCongo Basin to Lake Chad.

It is proven that the Chari River represented the largest provider of rainwater inflow to Lake Chad in Olivry, J.-C. et al. (1996) without the mobilized flows of our study, however we considered not to fix important parameters such as the height of the water from the outset.

Water and the area to be reached in order to avoid the shock of sudden return of water to Lake Chad according to our study model. In addition to the balance between the input and output elements of our water balance, we have stated two activation functions {ψHi, ζHj }. They are dynamic, iterative and progressively adjusted. The climatic adaptation of the populations to the sustainable replenishment of Lake Chad and in relation to its Si and Sj areas and anthropogenic needs were the keys to the activation of our hydrological balance. Our results could contribute to avoid stressing the ecosystems of the Congo Basin.

V. CONCLUSION

Obsessions are developed on the risk of drying up of Lake Chad. Climate change supported this approach. Our work has elucidated the process allowing to highlight the advantage of the exploitation of Digital Terrain Models in a weakly gauged to ungauged environment for the processing of data reduced to the rainfall-runoff couple. Our research model revealed the waterpower available in Chadian territory and the mobilizable refilling stock capacity of surface water in the Chari and Logone basins.

In perspective, we would like the dissemination of instruments for measuring hydrological and bioclimatic parameters in the orographic basin of Lake Chad in order to contribute to reducing the uncertainties and errors associated with the control of water withdrawal controls in Cameroon and Nigeria. Associated with the control of spills and floods, Lake Chad would be sustainably refloated without the contribution of water from the Congo Basin.

DECLARATION OF COMPETING INTERESTS

The authors declare that they have no known competing financial conflict of interest or personal relationships that could have appeared to influence the work reported in this paper.

AUTHOR CONTRIBUTIONS

- Yombombe Madjitoloum Theophile (Ph.D. Student) developed the theory and idea, on top of that, wrote the manuscript.
- Nimpa Giscard Desting (Senior Lecturer)revised the manuscript.
- Tamo Tatietse Thomas (Full Professor) research direction,critical review of the manuscript.

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