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Sedimentary Inputs and Morphology Characterization of the Bottom Agropastoral Lake of Nafoun (North Ivory Coast)

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Abstract

A bathymetric and sedimentological analysis carried out respectively in July 2017 and April 2018 made it possible to characterize the sediments and the morphology of Lake Nafoun. The sediments of the lake consist of vases, fine to very coarse sands with average particle sizes ranging from 475.67 and 2111 µm. There is a predominance of very coarse elements (43.50%). The standard deviation of the lake sand is between 1.21 and 1.86 and is poorly classified. The skewness fluctuates between −0.06 and 0.41. The sediments were deposited at the bottom of the lake due to a progressive decline in the flow of water that carried them. Moreover, this study made it possible to realize the first bathymetric chart of Lake Nafoun, 42 years after its impoundment in 1975.

Keywords

Sediments, Morphology, Nafoun Lake, Bathymetry

1. Introduction

In the north of Ivory Coast, the development of agriculture has faced significant water deficits. These constraints led the State to envisage palliative measures to store surface water [1]. Thus, in the 1970s, 300 dam lakes were built in rural areas of northern Ivory Coast for drinking water supply, agriculture and lives-

tock [2]. A few decades later, there is a decrease in the number of these works.

In 2012, 275 hydro-agricultural and pastoral schemes were inventoried in northern Côte d'Ivoire [1]. These reservoirs, which represent major assets to support the country's development, are threatened by hydrological variations, pollution and siltation problems. Filling water reservoirs is due to agricultural activities, rapid and uncontrolled urbanization that intensify erosion and increase sediment production [3] [4]. Thus, eroded sediments accumulate in the lake reservoir and reduce their storage capacity [5] which leads to social problems such as conflicts between farmers and stockbreeders [6] [7].

In spite of the dangers inherent in filling reservoirs with the passage of time, no sedimentological and morphological studies have yet been undertaken on Lake Nafoun, the largest agropastoral dam in the Poro region put into water in 1975. [8] and [9] point out that the sedimentation of water reservoirs leading to the reduction of their life span is one of the most harmful consequences of water erosion. The management of lake ecosystems requires in-depth knowledge of hydrodynamic and sedimentary functioning in order to propose development scenarios adapted to the various constraints of the environment: maintenance of water quality, improvement of fish and aquatic organism habitat, protection of structures, development of recreational and ecotourism activities [10] [11] [12].

This article presents the first bathymetric map of Lake Nafoun, 42 years after being filled with water. It also presents the granulometric characteristics of the sands and their spatial distribution in the lake of Nafoun.

2. Materials and Methods

2.1. Study Area

The Nafoun water reservoir, which is the subject of this study, is located west of the Poro region in northern Côte d'Ivoire, between latitudes 9˚22'N and 9˚18'N and longitudes 6˚18'N and 6˚15'N (**Figure 1**) covers an area of 1500 ha. It is built on the Bou, tributary of the White Bandama River. The Nafoun lake basin belongs to the tropical Sudano-Sahelian regime whose rhythm of the seasons is regulated by the displacement of the Intertropical Front (FIT). The rainy season is unique and lasts 7 months. It is continuous and extends from April to October [13] [14]. The maximum rainfall is in August and September. The average annual rainfall of the region is estimated at about 1200 mm. The vegetation of the basin is essentially savannah. These are grassy, shrubby or treed savannas gallery forests and open forests are also encountered. These formations cover respectively 10%, 30%, 2% and 10% of the landscape, the rest of which is occupied by bare soils and crops [15]. The large fauna is still present, but in small quantities and is mainly found in classified forests. Geologically, the Lake Nafoun basin is part of the history of the West African craton [16] [17] [18]. There are two major sets on the lithological level: the Birrimian formations (volcanic, volcano-sedimentary and sedimentary, metamorphosed deposited in intracratonic furrows) and the Eburnian, granitoids formations (granite massifs within which

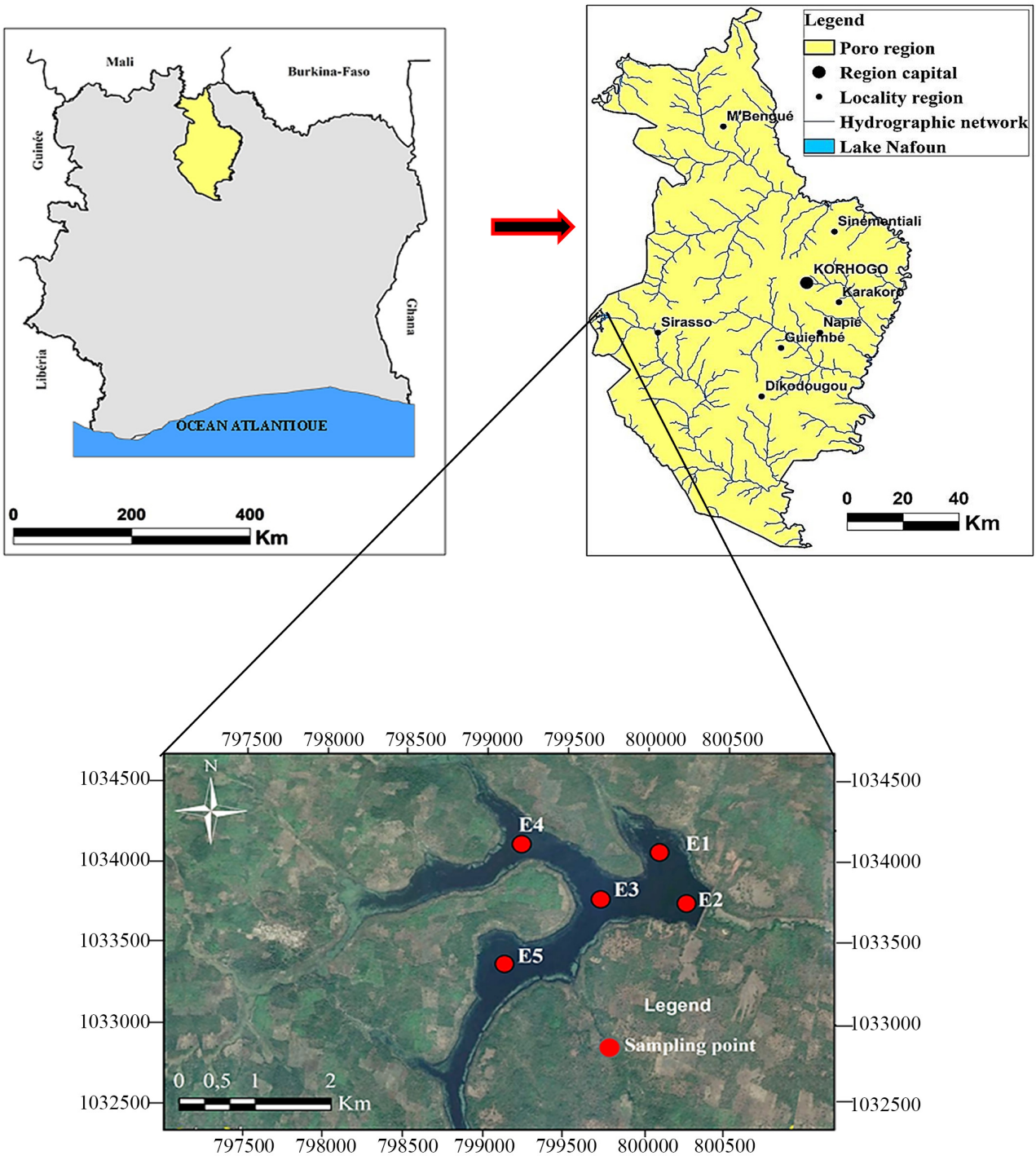

Figure 1. Location of the Nafoun reservoir.

several generations of granites and migmatites can be distinguished). Hydrogeologically, two types of aquifers are present: weathering reservoirs and crack reservoirs, which provide perennial water resources linked to the underground network of fractures very developed in these formations due to polyphase tectonics [13]. Overall, the relief of the Nafoun basin is flat and monotonous, but some peaks stand out, where the altitudes vary from 185 to 568 m.

2.2. Method of Study

To determine the granulometric characteristics of the sands of the Nafoun reservoir, 5 sediment samples were taken at depths between 4 and 1.5 m in the reservoir using a Van Veen grab and localized by a GPS-GARMIN. The Samples were taken during the wet season (April 2018). The sediments collected were subjected to a dry granulometric analysis according to the technique described by [19] (washing and separation of the fraction greater than 63 µm, drying in an oven at 105˚C, then sieving on a vibrating sifter surmounted by a column of 16 sieves of the AFNOR series of meshes between 5 mm and 63 µm). The sands of the Nafoun reservoir have been characterized according to three particle size distribution parameters, namely the mean particle size (Mz), the skewness (Sk) and the standard deviation or Sorting (So) determined using Folk methods (1957) [20]. The study of the morphology of the bottom of the Nafoun reservoir was carried out by means of bathymetric surveys (July, 2017), using a Lowrance type echo sounder model LMS-160. A total of 06 radials was drawn including one longitudinal and 05 transverse perpendicular to the flow directions. The bathymetric map of the Nafoun reservoir was made using the SURFER 11 software and the positioning maps were made using the Arc Gis 10.2.2 software.3.

3. Results

3.1. Lithological Description of Sediments

The macroscopic analysis of the superficial sediments of Lake Nafoun reveals three lithological facies. These are fine sands, medium sands and coarse sands. These facies result from alteration and disintegration of the parent rock and soils of the lake watersheds.

3.2. Granulometric Sediment Analysis

The semi-logarithmic cumulative curves of the lake sediments describe a logarithmic facies (**Figure 2**) which shows that the sediments were deposited by excess of charge after a progressive decrease of the energy of the water. The average values of the studied sand samples are between 475.67 µm and 2111 µm and indicate coarse to medium sands (**Table 1**). The size of the sand grains decreases going from the shallow depths (1 to 2 m) to the highest (3 to 5 m). The Skewness of superficial sediments ranged from −0.37 to 0.412. The grain size curves of lake sediments show a strong asymmetry ($Sk < 0$) towards coarse elements at shallow depths (1 - 2 m) and tend to become asymmetric ($Sk > 0$) towards fine elements from shallow depths towards the highest depths (3 to 5 m). This shows the existence of granulometric sorting, [21] already observed in the sediments of Lake Nafoun, going from shallow banks to the channels.

3.3. Classification of Lake Sediments

The granulometric study of the sediment fraction greater than 63 µm makes it possible to divide the sands of the lake. There are very coarse sands ($\phi \geq 1.25$

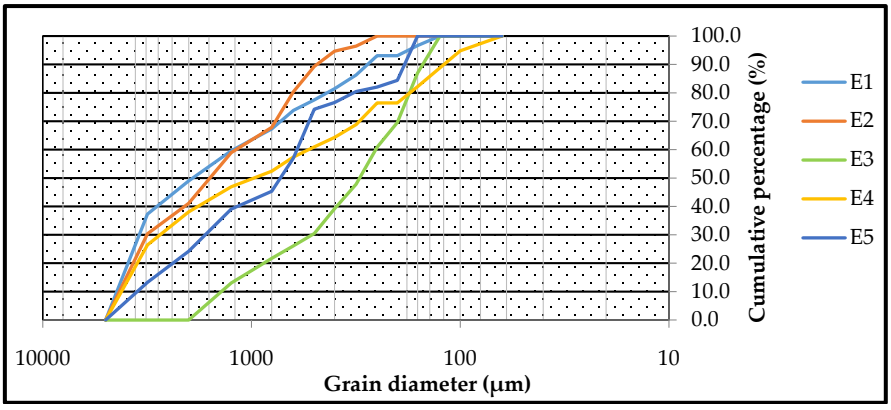

Figure 2. Particle size distribution curves of Nafoun lake sands.

Table 1. Granulometric characteristics of the sands of the Nafoun reservoir.

Samples	Φ5	Φ95	Φ16	Φ84	Φ50	Φ75	Φ25	Mz en µm	So	Sk	Median	Mode
e1	−2.174	2.165	−2.01	1.494	−0.94	−1.87	0.769	2111	1.535	0.412	−0.947	3.15
e2	−2.159	1.385	−1.96	0.793	−0.7	−1.77	0.508	2032.33	1.226	0.131	−0.7	0.25
e3	−0.755	2.943	0.025	2.644	1.816	0.571	2.419	475.66	1.215	−0.37	1.816	0.25
e4	−2.146	3.012	−1.91	2.404	0.006	−1.69	1.932	1652.33	1.861	0.138	0.006	3.15
e5	−2.047	2.531	−1.51	2.265	0.45	−0.97	1.098	1268	1.639	−0.06	0.45	3.15

Mz: Average; So: Standard; Sk: Skewness.

mm), coarse sands (0.63 mm ≤ ϕ < 1.25 mm), medium sands (0.315 mm ≤ ϕ < 0.63 mm), fine sands (0.125 mm ≤ ϕ < 0.315 mm), and very fine sands (0.063 mm ≤ ϕ < 0.125 mm). This classification is consistent with the AFNOR standard. Table 2 and Figure 3 show the different proportions of the lake's sands. Extensive analysis shows that very coarse sands 48.34% and fine sands 29.03% are the most abundant. Coarse sands have an average proportion of 12.02%. As for the medium and very fine sands, the proportions are low.

3.4. Bottom Morphology

Figure 4 shows the bathymetric map of Nafoun Restraint. It presents the general morphology of the lake. The main channel is elongated in an east-west direction. The reservoir has two arms in its western part. One oriented NE-SW and the other oriented NW-SE through which the waters from the Bou River tributary of Bandama arrive. The maximum depth of 5 m is observed near the dike and the isobaths are equidistant by 0.5 m. The isobaths are more tightened in the central part of the main channel. In general, depths increase from upstream to the dike. The bathymetry of Lake Nafoun shows values characteristic of shallow lakes. Sedimentary inputs related to the hydrodynamics of the lake are the main causes of lake filling. However, eutrophication also contributes to the filling of the lake. Both arms have maximum depths between 2 m and 3 m. The digital elevation model of the lake bottom shows 5 m depressions and shoals that are 1.5 m from

Table 2. Percentage of granulometric classes of sands in the Nafoun reservoir.

Echantillons	Long (m)	Lat (m)	VCS	CS	MS	FS	VFS
E1	800,249	1,034,296	59.57	14.25	12.48	13.7	0
E2	800,375	1,033,480	60.71	0.00	0.00	39.29	0.00
E3	799,474	1,033,338	26.09	17.39	0.00	56.52	0.00
E4	798,532	1,034,265	46.9	10.48	11.43	20	11.19
E5	798,222	1,032,468	48.44	17.97	17.97	15.63	0.00
%Total			48.34	12.02	8.38	29.03	2.24

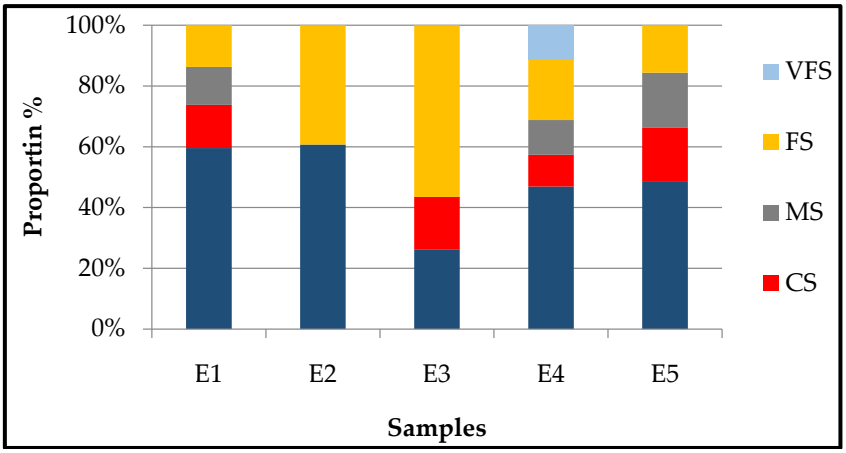

Figure 3. Percentage of the grain size fractions of the sands of the Nafoun dam (VCS: Very Coarse Sand; CS: Coarse Sand; MS: Medium Sand; FS: Fine Sand; VFS: Very Fine Sand).

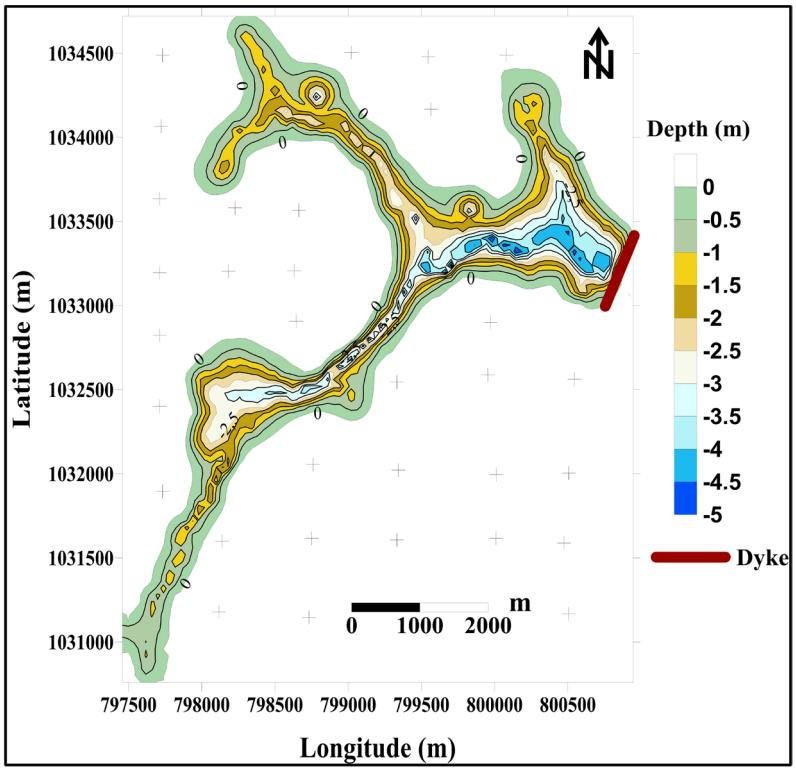

Figure 4. Bathymetric map of the Nafoun reservoir.

the river surface (Figure 5). Depressions are caused by the increase in the river current. The shoals reflect calm hydrodynamic conditions where formations would resist erosion or would be deposition areas.

3.5. Characteristic of the Nafoun Retainer Channel

The morphological study of the retaining channel was based on the tracing of six (06) radial (Figure 6) including one longitudinal and five transverse. The analysis of the different profiles shows three (3) morphological types of channels: the "U" type, the "V" type and the intermediate type. The morphological profile that emerges from the AB, CD and EF profiles is of the "V" type (Figure 7) more pronounced and asymmetrical with a high background. It translates a more intense erosive action. The slope is steep from the banks to the main channel. The IJ and GH profiles have a "U" shape. They are concave, flared and flattened at the base. The "U" profile is an action balance profile between accumulation agents and erosion agents. But a new erosive action can resume and start the digging work again. It is said that this action is cyclical. This is sometimes referred to as a cyclical form, which means "due to the action of erosion cycles. The KL longitudinal profile has an intermediate morphology between the "V" type and the "U" type. The morphology is sawtooth-shaped. This profile has not yet reached its form of balance which is the "U" morphology. The action of accumulation agents and erosion agents does not balance. These agents allow to

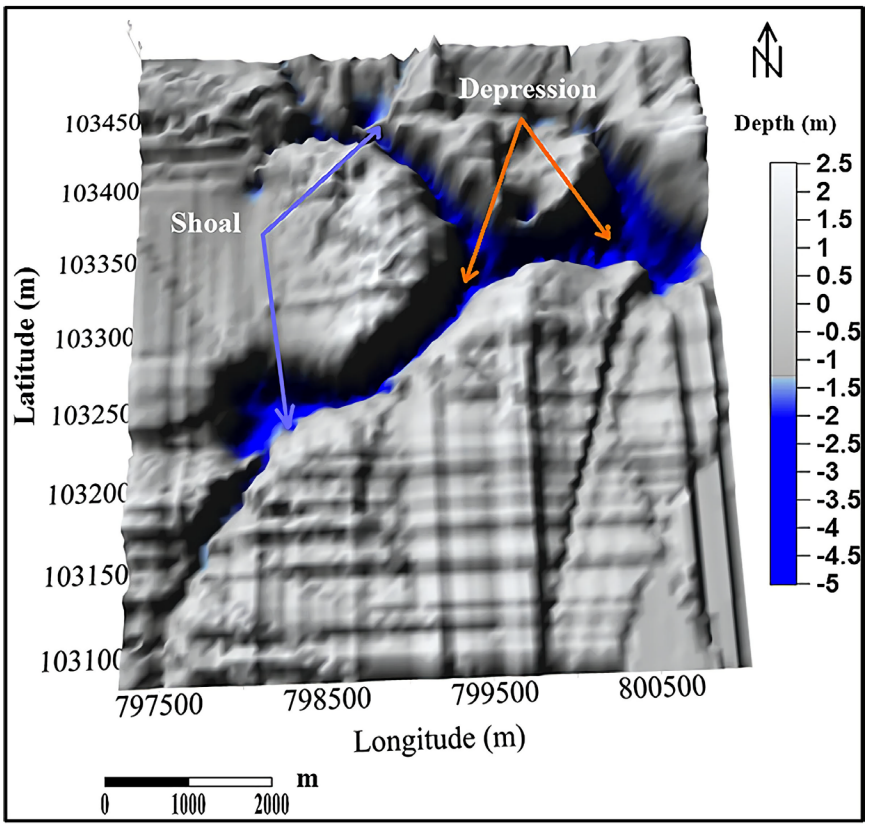

Figure 5. Digital elevation model of the lake bottom of lake Nafoun.

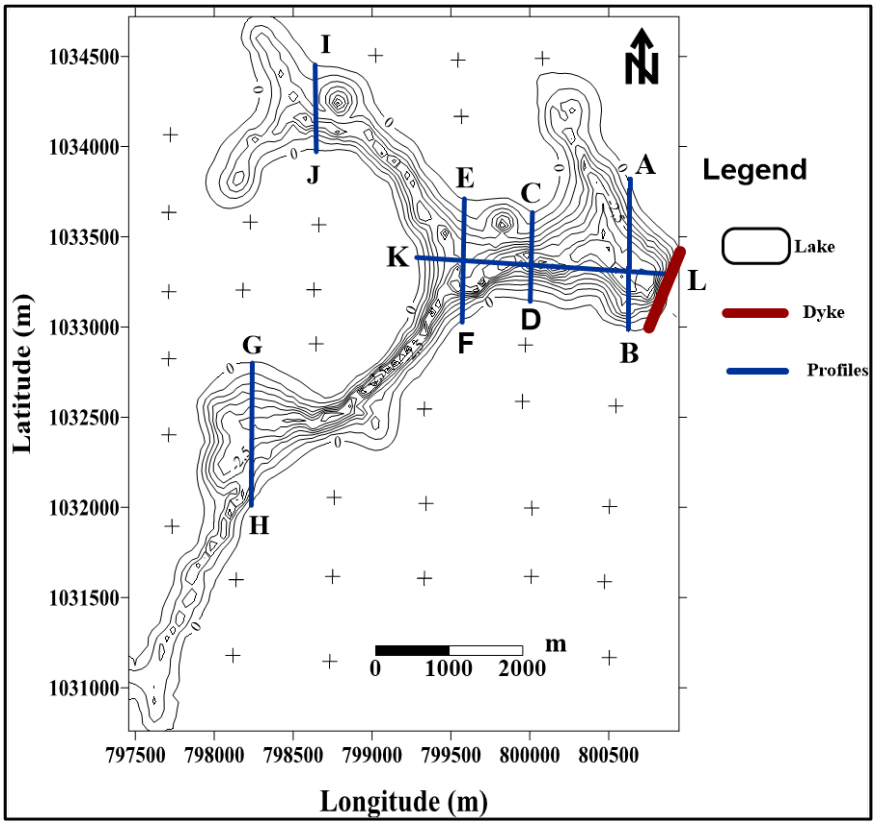

Figure 6. Bathymetric profiles at various points in Lake Nafoun.

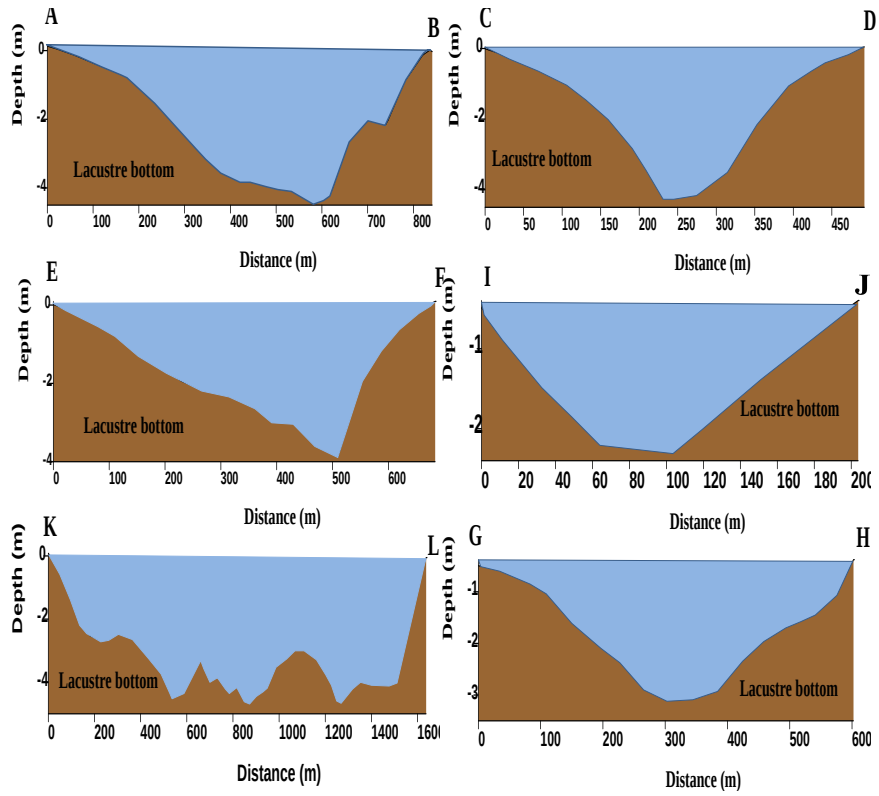

Figure 7. Bathymetric profiles of the Nafoun main channel.

track and understand the process of evolution of an erosion profile that is characterized by the transition from the "V" profile to the "U" profile.

4. Discussion

The granulometric analysis of sediments collected in Nafoun Lake consists of vases that contain organic matter, fine sands, medium sands and coarse sands. The granulometric average of these sands is between 475.67 m and 2111 m. These results are consistent with those found by [5] on Lake Taabo and by [22] on Lake Ayamé I. Our results differ from those obtained by [23] at the mouth of the Sassandra River. The standard difference in the lake sediments ranges from 1215 to 1861. This indicates that the sands of the lakes are poorly classified. According to [24] sands are poorly classified if they are made of different granulometry. The Skewness (asymmetry) of Lake V sediments has from 0.37 to 0.412. This means that in the sediments there are both fine sands and coarse sands better sorted. The sands most represented in the lake are the very coarse and fine sands. However, the presence of coarse and medium sands in the sediments is noteworthy. The predominance of very coarse sands could be explained by the distance covered by sediments in watery environments and also by the power of transport energy [24]. This assumes that the majority of coarse grains are transported over small distances. The study of the first bathymetric map of Lake Nafoun, 42 years after its impoundment, shows that it has considerable morphological irregularities. The depths of the lake vary between 0 and 5 m. Compared to other works, the average depth obtained in Lake Nafoun (1.58 m) is in the same value range as those obtained by [25] in Lake Nokoué in Benin (deep—1.5 m), and by [26] in Lake Digboue (deep—1 m) in Côte d'Ivoire. In general, the depths decrease from upstream (dike) to down-stream. The bathymetry of Lake Nafoun shows characteristic values of shallow lakes. Sedimentary inputs related to lake hydrodynamics are the main causes of lake filling [25]. However, eutrophication also contributes to the filling of the lakes. The numerical model of elevation of the lake bottom reveals two characteristic geo-morphological aspects. These are shoals and depressions. The shoals reflect calm hydrodynamic conditions where formations would withstand erosion or would be depot areas. Depressions are caused by the increase in the river current. Our results corroborate those obtained by [5] on Lake Taaboin central of Ivory Coast, and [22] on Lake Ayamé I in the south of the country, who made the same remarks. On the other hand, our results differ from that obtained by [27] on the berries of the Ebrié lagoon which showed that the depressions recorded in the lagoon are due to anthropogenic activities such as sand dredging.

5. Conclusion

The study carried out on Lake Nafoun during the rainy season (July 2017 and April 2018) showed that the lake bottom is very muddy. The sedimentary flows from the ravine of the banks and the anthropic activities such as the cultivation

of rice, tomato, eggplant, corn, sorghum, cotton, fonio at the approaches to the lake contribute to the filling of the lake bottom. Analysis of lithological facies and the granulometric of surface sediments identify vases, fine sands, middle sands and coarse sands, poorly classified. The most represented sands in the lake are the very coarse and fine sands. However, the presence of medium and coarse sands in the sediments is worth noting. The study of the first bathymetric map 42 years after its release shows that the depth oscillates between 0 and 5 m. These depths decrease from upstream (dike) to downstream. Nevertheless, the highest depths are observed in the areas of depression. Some formations (rocks) emerge in the form of shoals on the bottom of the lakes. The results of the bathymetric maps should be used to estimate, in the long term, the lifespan of the lakes studied. The bathymetric profiles of the lake show three types of channels: "U," "V" and intermediate. The "U" channels reflect a balance between the agents of accumulation and erosion. "V" channels resulting from erosion processes and intermediate-profile channels indicate an evolution of the "V" type in "U" or "U" in "V."

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Conflicts of Interest

The authors declare no conflict of interest.

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