

# Assessment of the Recent Hydromorphological Features of Nokoue Lake and Its Channels (South-East Benin)

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## Abstract

Based on 2022 and 2023 hydrometric data and satellite images (Sentinel 2022, SPOT 2010), this study aims to present the Nokoué Lake and its channels' re-cent hydromorphological characteristics. Integrating flow, tributary morphology, and topography data determined specific power values along the axes studied. The values obtained range from 2.69 to 12.92 W/m<sup>2</sup> for Ouémé River and 2.46 to 10.99 W/m<sup>2</sup> for Sô River. The resulting water erosion on banks and bottoms is of linear, areolar, or gully and claw types. Lake bathymetry varies from -0.5 to -2.6 m (low flow period) and -1 to -4 m; in the Ouémé, Sô, and Totchè rivers, it varies from -5 m to -7 m, reaching -10 m at the Cotonou channel entrance (flood period). Bathymetric profiles reveal varied "U", "V" and "Intermediate" bottom morphologies, influenced by erosion/sedimentation processes and human activities. The flow facies identified are lentic in the northern tributaries and lotic in the Cotonou and Totchè canals. Spatial analysis identified nine (09) thematic classes. In 2022, the surface area of the water body has increased from 274 km<sup>2</sup> at low water to 280 km<sup>2</sup> at high water, whereas in 2010 (a recent year of exceptional flooding), the surface area was 270 km<sup>2</sup> at low water and 277 km<sup>2</sup> at high water. Significant changes in land use are observed between 2010 and 2022. The floodplain area

decreased slightly, from 421 km<sup>2</sup> in 2010 (year of exceptional flooding) to 419 km<sup>2</sup> in 2022. The evolution of land use shows a progressive expansion of the urban environment to the detriment of the natural environment. In the medium to long term, this trend could threaten the hydromorphological balance and even the existence of this important lagoon ecosystem.

## Keywords

Nokoué Lake, Ouémé River, Sô River, Cotonou Channel, Hydromorphology

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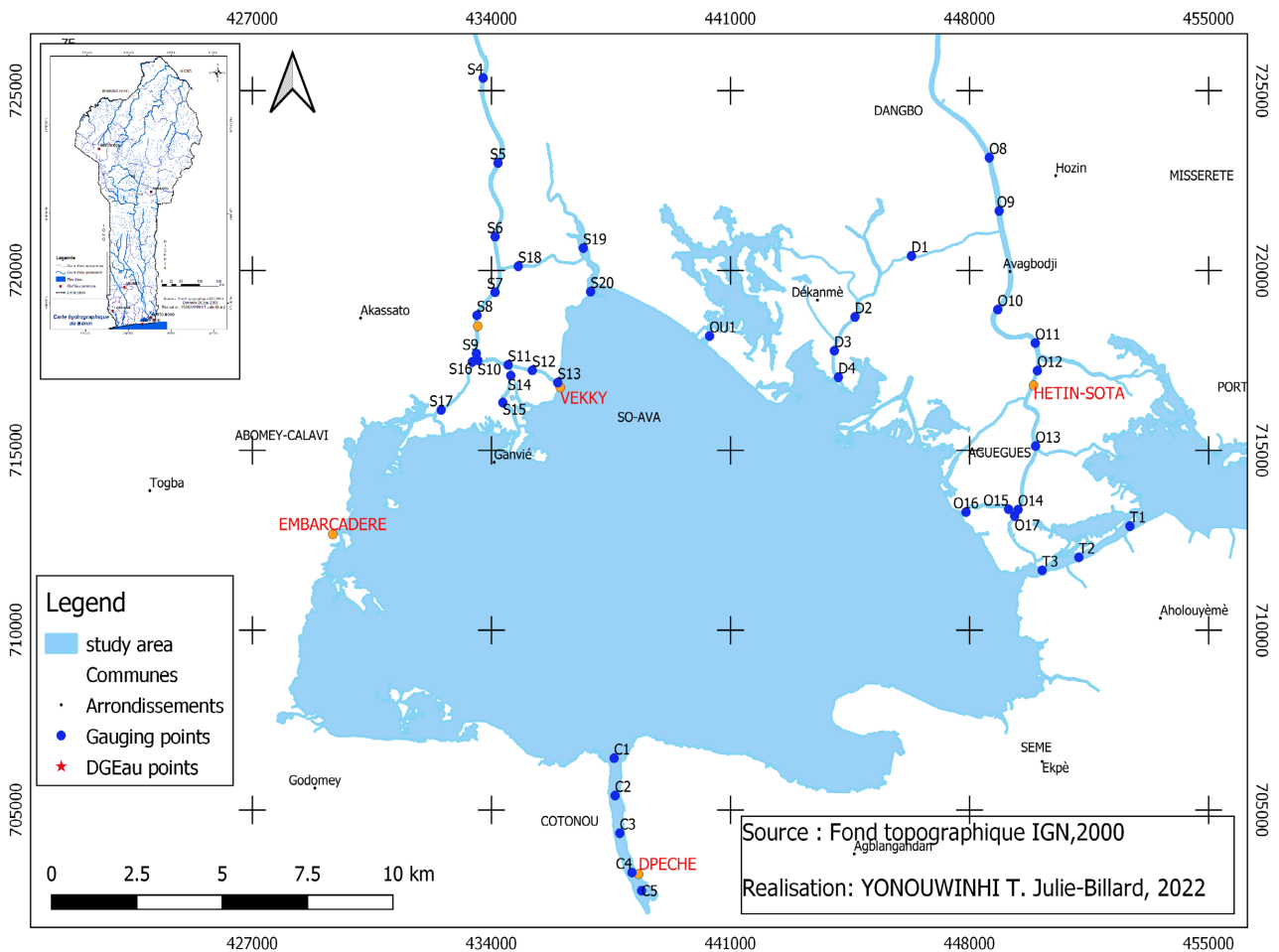
## 1. Introduction

Hydromorphological studies are of paramount importance for the sustainable management of watercourses and associated ecosystems. They offer the prospect for preserving aquatic ecosystems, flood risk prevention, sustainable river development planning, rehabilitation and balanced management of water resources [1] [2].

In Benin, Nokoué lake and its tributaries have been the subject of several research studies, which have shown that this complex has a seasonal hydrological regime, with a low-water period from December to April and a high-water period from September to November [3]-[15]. Exchanges between the lake and its tributaries are significant. Bathymetric analyses over the last ten years have revealed a considerable reduction in depth, mainly due to sedimentary input and anthropogenic activities. According to [16], a reduction in depth of around 0.6 m was observed after 20 years (from 1986 to 2006), *i.e.* around 0.03 m/year. This gradual filling of the lake could be linked to the enormous sediment inputs from the Ouémé River into the lake during high-water periods [17] and to the effect of fishing plant encumbrances [10]. This study integrates hydrological and satellite data from 2010, 2022 and 2023 to present the current hydromorphological status of Nokoué lake and its tributaries. The objective is to establish a robust foundation for comprehending the recent evolution of the hydromorphological system of Nokoué Lake and its channels, while identifying potential risk factors associated with the observed changes.

## 2. Presentation of Study Area

Situated between parallels 6°34' and 6°57' North and meridians 2°34' and 2°57', the study area comprises Nokoué lake and the termini of its main tributaries: Ouémé and Sô rivers, Totchè canal and Cotonou channel [4] [18] (**Figure 1**). With a surface area of around 150 km<sup>2</sup> at low water, Nokoué lake is separated from the Atlantic Ocean by a long, wide-barrier beach on which the city of Cotonou is built. It extends for around 20 km from east to west and 11 km from north to south [19] [20]. It is a peri-urban lake bordering three major conurbations, namely Cotonou, Abomey-Calavi and Sémè-Podji with a population of



**Figure 1.** Presentation of the study area with indication of gauging points.

over 1.5 million [21] [22]. The lake is linked to the Porto-Novo lagoon to the east by the Totchè canal of 5 km long and around 200 m to 300 m wide; to the south by the Cotonou channel of 4.5 km long and around 300 m wide; and to the north by the Sô and the Ouémé rivers [19] [23]. The Ouémé River, 523 km long and between 42 m and 125 m wide, rises in the Donga department in northern Benin and drains a watershed of 46,500 km<sup>2</sup> [19]. The Sô River, 70 km long and between 25 m and 80 m wide, drains a catchment area of 1000 km<sup>2</sup> and is connected to the Ouémé River during high-water periods. The riparian forest bordering the channels is made up of swampy forest and savannah, crops and fallow land, with or without palm trees. At Nokoué Lake, the vegetation consists of *Paspalum vaginatum*, *Cyperus articuleniensis*, *Phragmites australis*, *Eichornia crassipes*, *Crotalaria retusa*, *Penisetum palystachion* and *Pista stratiotes*. Soils are ferralitic, slightly denatured, impoverished and hydromorphic or low-humus to pseudo-gley at tributary level. Around the lake, clayey soils and littoral sands are present [18].

The **Table 1** summarizes the characteristics of the main tributaries and the linear lengths considered in this study.

### 3. Materials and Methods

The methodological approach adopted began by a selection of existing hydrological data (water levels; flows) present within the office of Benin General Directorate for Water (DGEau). This was followed by in situ several campaigns of measurement of flows and bathymetry, and finally by processing of the data collected and satellite images acquired.

#### 3.1. Materials

The equipment used for this study includes a Garmin GPS for georeferencing, a “Rio Grande” Acoustic Doppler Current Profilers (ADCP), equipped with four acoustic transducers emitting at a frequency of 1200 kHz, for flow measurements by gaging and a Garmin 521s dual-frequency Doppler echosounderbathymeter for bathymetric measurements (**Plate 1**).

#### 3.2. Methods

- **Selection of hydrological data**

Flow data for the years 2010 to 2022 from the Bonou station located on the Ouémé River and upstream of the study area were collected from the DGEau. Water level data were from Bonou station located at the North of the study area as well as from stations of Hétin-sota, Sô-Ava and Fisheries Directorate located in our study area.

**Table 1.** Lengths of the studied tributaries and linear features.

Nokoué Lake	Total Length	Study Line	Catchment Area
River Ouémé	523 km	15.011 km	46,500 km <sup>2</sup>
Sô River	70 km	12.30 km	1000 km <sup>2</sup>
Totchè Canal	5 km	4.019 km	-
Cotonou Channel	4.5 km	4.010 km	-



**Plate 1.** Views of the ADCP (a) et (b) and Garmin 521s echosounder (c) deployed on the Ouémé River and Nokoué lake (July 2022).

- **Field work**

The seasonal field campaigns took place in July, September, November 2022 and March 2023 for flow measurements and bathymetry.

- **Flow measurements and specific power estimation**

Stream flow can be calculated in a number of ways. According to [2], flow can be determined by:

$$Q = \sum(V \times A) \quad (1)$$

where:  $Q$ —flow (in cubic meters per second);  $V$ —current velocity measured at each cell by the ADCP (in meters per second);  $A$ —cross-sectional area of the flow corresponding to each cell (in square meters).

Flow data acquired during the 2022 and 2023 seasonal gaging campaigns, have been processed to obtain campaign and river averages values. Additional flow and water level data from stations close to the study area were used. Monthly and multi-year averages from 2010 to 2022 were calculated and some hydrographs were produced. This enabled a comparative analysis of flows in the various tributaries. In addition, flow data were used to determine total and specific power values along the studied watercourses [24].

A river power is used to measure a river's efficiency in sediment transport and bed modification. It can be determined by:

$$\Omega = \gamma QJ \quad (2)$$

where:  $\Omega$ —power in W/m;  $\gamma$ —water density in N/m<sup>3</sup> (9810 N/m<sup>3</sup>);  $J$ —slope of the energy line in m/m and  $Q$ —flow rate considered in m<sup>3</sup>/s.

The specific power  $\omega$  is defined as the quantity of energy transported by the water flow per unit width of the river. It thus characterizes the dynamic potential of erosive processes per river section (energy) for a given flood and cross-section [24].

$$\omega = \Omega/L \quad (3)$$

where:  $\omega$ —specific power in W/m<sup>2</sup>;  $\Omega$ —power in W/m;  $L$ —bed width for flow  $Q$ .

- **Bathymetric measurements**

Bathymetric measurements were carried out in October 2022 and March 2023.

These measurements concerned Nokoué lake, Sô and Ouémé Rivers, Cotonou channel and Totchè canal.

The bathymetric data collected were processed with various software programs to produce bathymetric maps and profiles [25] [26] [27].

- **Spatial analysis**

Satellite images (SPOT5 from 2010 and Sentinel 2A and 2B from 2022) were downloaded from the ESA website (<https://scihub.copernicus.eu/dhus/#/home>)

**Table 2.** Relationship between specific power and stream bank erodibility.

Specific Power	>100 W/m <sup>2</sup>	100 - 30 W/m <sup>2</sup>	30 - 10 W/m <sup>2</sup>	<10 W/m <sup>2</sup>
Bank Erodibility	Strong	Average	Low	None

and used to analyze land and water distributions around Nokoué lake, Ouémé and Sô Rivers from 2010 to 2022 (**Figure 2**). An object-oriented classification approach based on pseudo-spectral bands was adopted [28] [29] (**Table 2**).

The characteristics of the satellites are summarized in **Table 3** below.

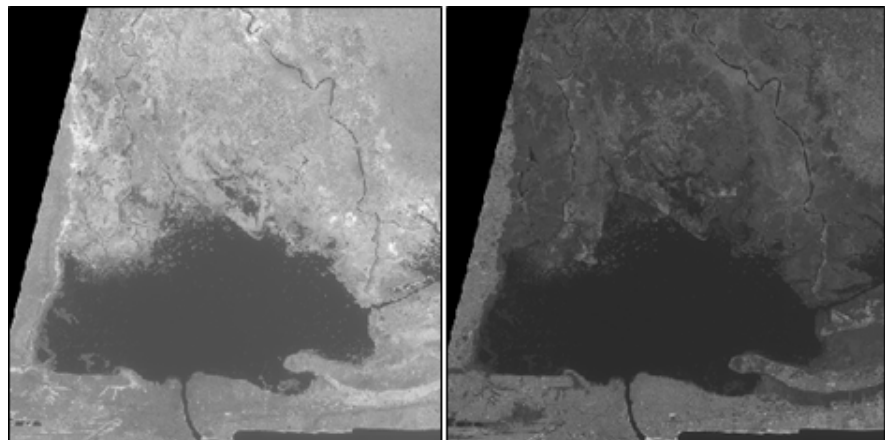
Object-oriented classification with the hierarchical classification algorithm is an effective method for classifying areas where land use is fragmented and complex [29]. The implementation steps led to change detection, using transition matrices to represent changes from one category to another [4] [19]. The methodological approach made it possible to present the spatio-temporal variations of the different classes in 2010 and in 2022-2023.

## 4. Results

### 4.1. Hydrological Regime

- **Water levels and flows**

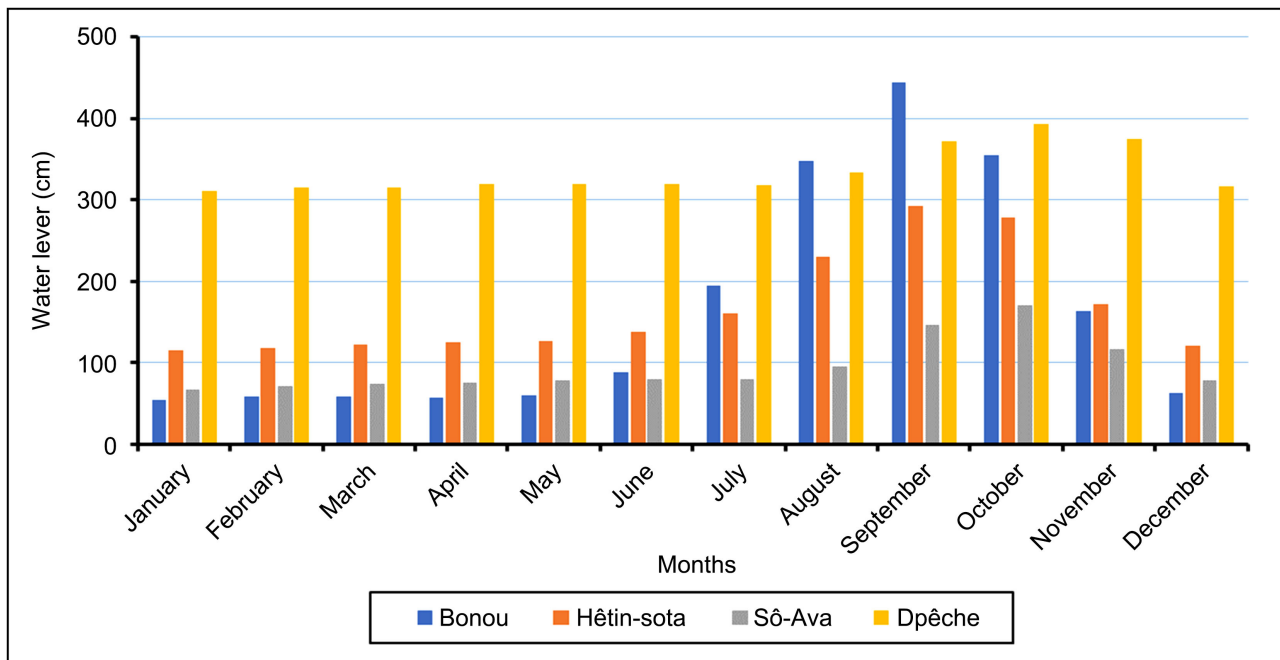
Water level measurements have shown that the hydrological regime of the various tributaries is linked to seasonal variations. The monthly average of water levels on the tributaries from 2010 to 2022 is shown on **Figure 3**. During the year, the peaks are reached in September but the highest water levels (over 300 cm), is noted in October at the Fisheries Directorate station which is located at the southern part of the study area. For the Bonou station located upstream of our zone, the peak recorded is 440 cm.



**Figure 2.** Sentinel 2 satellite images (low and high water).

**Table 3.** Characteristics of the multispectral satellite data used for the study.

Satellites	Agency	Year of Launch	Type Sensor	Broke	Spatial Resolution (m)	Bands Spectral	Frequency Acquisition
SPOT5	(CNES)	2002/2015	Optics	60 km wide	Multispectral: 10 meters	Visible and close infrared (4 bands)	1 to 3 days
SENTINEL 2A and 2B	ESA (European Space Agency)	2015/2017	Optics	290 km	Multi spectral: 10, 20, 60	Visible and close infrared (13 bands)	5 days



**Figure 3.** Graph of monthly average of water level on tributaries from 2010 to 2022 (Source: DG Water, 2022).

Comparative analysis of water level and flow data clearly shows a unimodal regime, with perfect correlation between these parameters (**Figure 4**). The Ouémé River, in accordance with his morphological and hydrological characteristics, exhibits higher flows and water levels than the Sô River, indicating greater water transport capacity.

Average of flows measured during the 2022-2023 campaigns vary from  $-185.19 \text{ m}^3/\text{s}$  in Totchè canal to  $1404.15 \text{ m}^3/\text{s}$  in Cotonou channel (**Figure 5**). The negative flow values on the Totchè canal indicate the inversion of the usual water flow direction, resulting from the daily influences of the tides. This observation underlines the importance of the tides in the hydrological dynamics of the region, and their effects on flows near coastal areas. The average of flood flow obtained on the studied Ouémé River is  $415.21 \text{ m}^3/\text{s}$ , (compared with  $773.35 \text{ m}^3/\text{s}$  recorded at Bonou during the exceptional flood of 2010), making it the most important tributary in terms of flow. This underlines the importance of the Ouémé River in hydro-sedimentary transfer processes toward Nokoué lake, particularly during flood periods.

- **Specific power and bank erosion**

Specific powers and bank erosion have been estimated for Ouémé and So tributaries. Bank erosion processes are a function of specific power (**Table 2**) and soil type. The coordinates of the measurement points and corresponding values are shown in (**Table 4**). The highest specific power values are noted upstream and decreasing downstream as the river approaches its mouth. On the Ouémé River, the highest specific power ( $12.92 \text{ W/m}^2$ ) comes from a segment with a section of  $92.39 \text{ m}$  wide. This value corresponds to a relatively high flow rate of  $608.57 \text{ m}^3/\text{s}$  and a bed topography, that favours increased conversion of potential

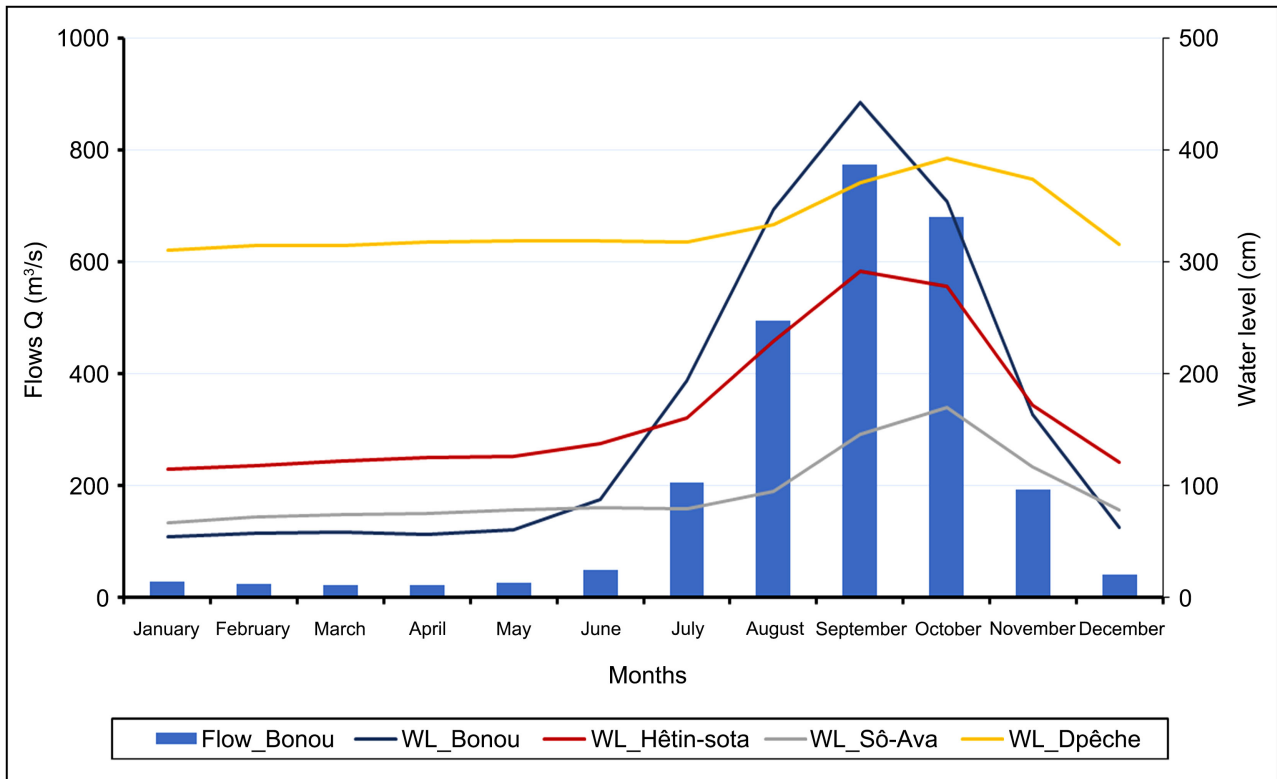


Figure 4. Monthly variations in flow and water level at selected stations on the tributaries of Nokoué lake (Source: DGEau, 2022).

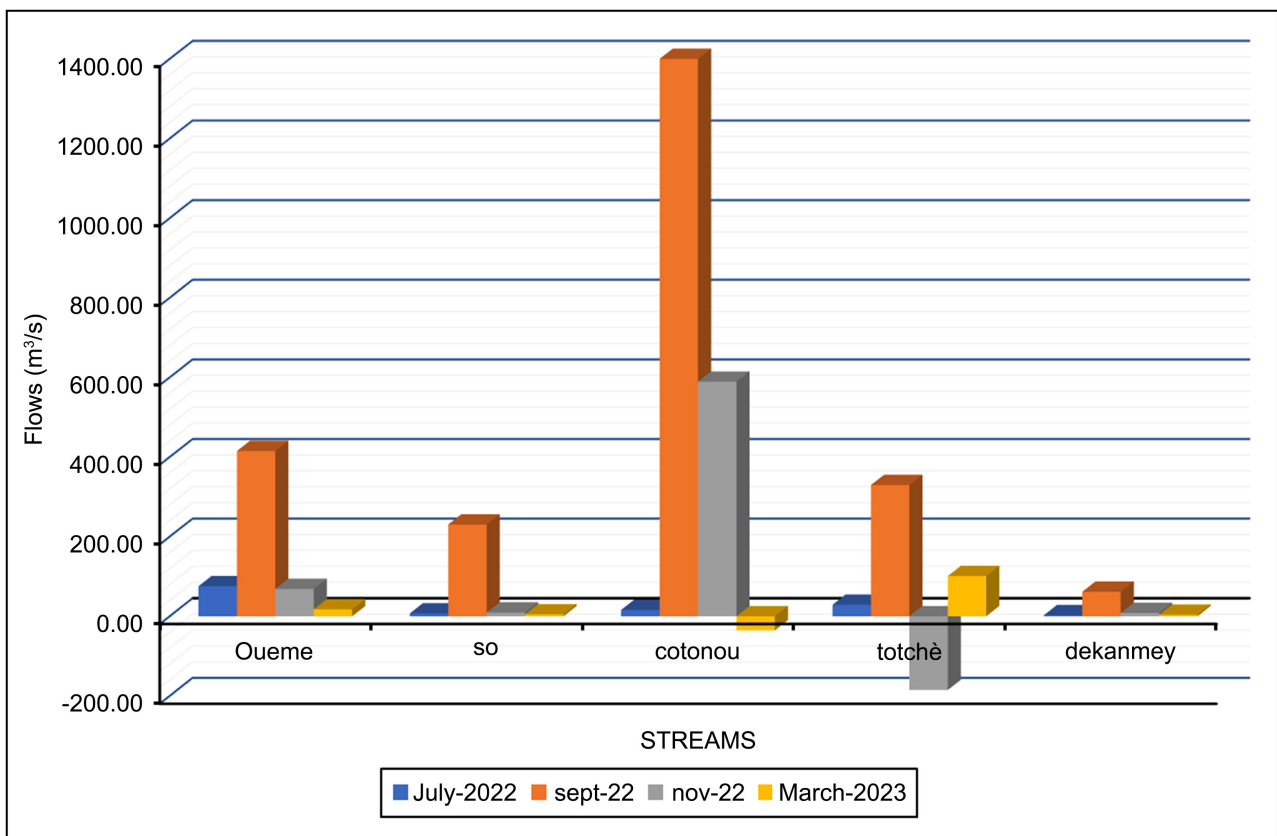


Figure 5. Average of seasonal flow of Nokoué lake's main tributaries.

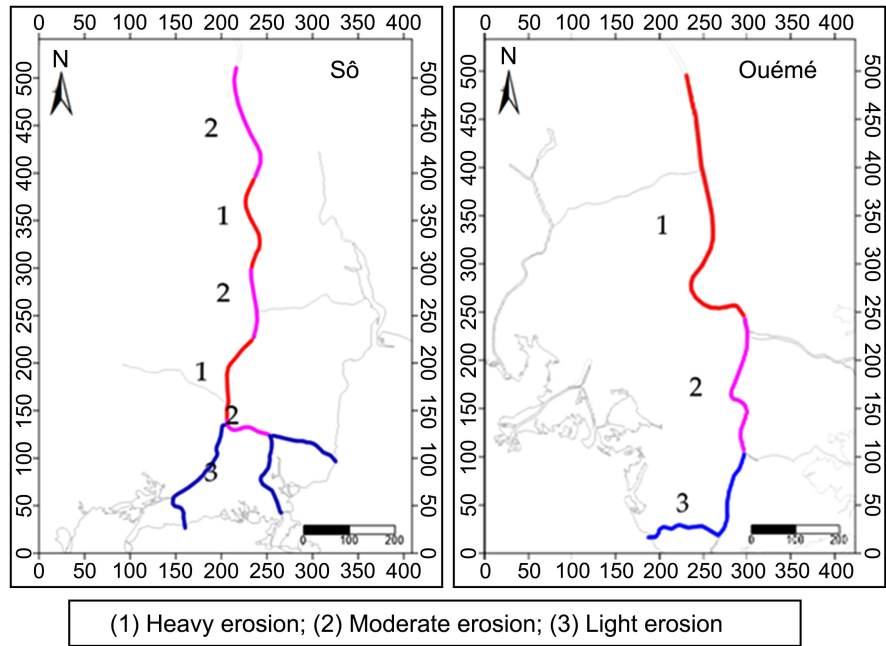
**Table 4.** Measurement points and their specific powers.

Ouémé River						Sô River					
Points	X_Long	Y_Lat	Flow (m <sup>3</sup> /s)	Power (W/m)	Specific Power (W/m <sup>2</sup> )	Points	X_Long	Y_Lat	Flow (m <sup>3</sup> /s)	Power (W/m)	Specific Power (W/m <sup>2</sup> )
O8	448,579	723,142	671.35	1317.19	12.54	S4	433,757	725,356	289.36	567.72	7.34
O9	448,868	721,661	653.97	1283.09	11.83	S5	434,193	722,994	342.37	671.73	8.53
O10	448,826	718,917	608.57	1194.02	12.92	S6	434,108	720,945	357.10	700.64	10.99
O11	449,925	717,986	588.26	1154.16	11.82	S7	434,105	719,398	288.63	566.29	6.61
O12	449,986	717,219	280.03	549.42	9.68	S8	433,578	718,757	332.46	652.28	8.96
O13	449,933	715,120	242.49	475.76	9.08	S9	433,558	717,694	300.28	589.16	8.49
O14	449,422	713,356	146.43	287.30	4.90	S10	433,600	717,508	227.40	446.16	5.60
O15	449,144	713,365	106.71	209.36	2.91	S11	434,489	717,377	247.48	485.56	6.39
O16	447,897	713,286	112.10	219.95	2.69	S14	434,567	717,081	151.99	298.21	4.55
						S15	434,334	716,332	137.03	268.86	4.13
						S18	434,786	720,121	43.35	85.05	2.46

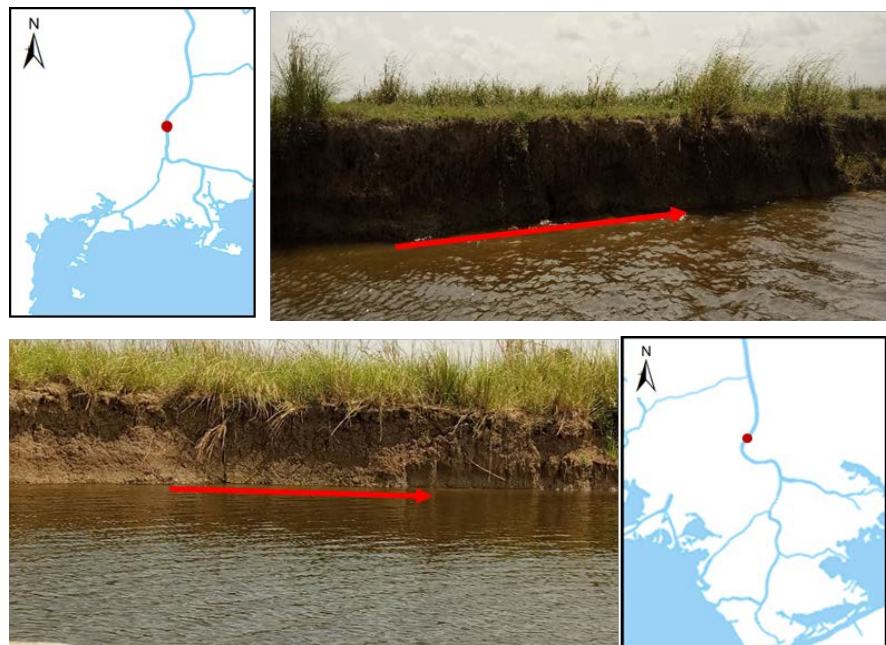
energy into kinetic energy, is capable to induce more significant erosion and geomorphological modification processes. The lowest specific power, 2.69 W/m<sup>2</sup>, comes from a segment with a section of 81.72 m wide, and reflects a lower level of energy per unit width. This value corresponds to a low flow rate (112.10 m<sup>3</sup>/s) and a bed topography that restricts the transformation of potential energy into kinetic energy. On the Sô River, the highest specific power is 10.99 W/m<sup>2</sup> for a segment with a section of 63.73 m wide, while the minimum specific power is 2.46 W/m<sup>2</sup> is related to a segment with a section of 34.54 m wide.

Segments colored in red along our studied sections of tributaries represent areas of high erosion, mainly due to high flows and soil characteristics. Segments colored in salmon-pink correspond to areas of moderate erosion, while segments colored in blue represent areas of low-bank erosion (**Figure 6**).

Different types of water erosion were observed in the study area. Areolar type of erosion (wash load) is observed in large sections, notably on the Cotonou channel and on certain tributary stretches (segment). Linear type of erosion is dominant and mainly observed in the northern part of the study area where removal of solid particles from the banks and the bottoms of watercourses and collapse of banks are noticeable (**Plate 2**). Near the lake, depending of the power of the flows, erosion is of gully or claw types. While runoff causes significant soil loss and watershed degradation, it also defines areas of deposition and erosion. Along the studied sectors, the sections with low specific powers are determined by a low erosion capacity, a zone of deposition and accumulation of fine sediments and a relatively flat bottom.



**Figure 6.** Type of bank erosion along the northern tributaries of Nokoué lake.



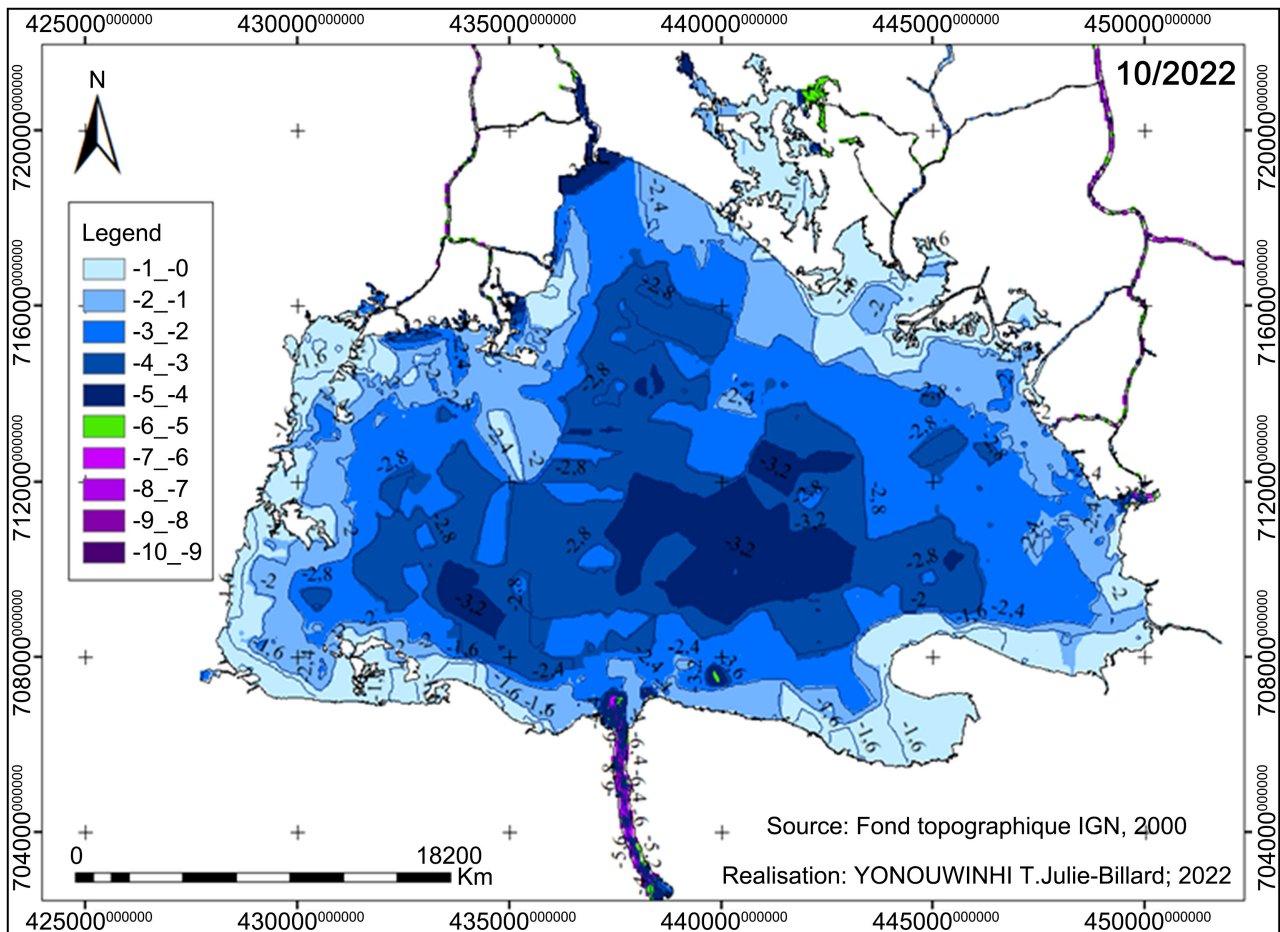
**Plate 2.** Views of eroded sections bank on the Sô and Ouémé rivers.

## 4.2. Morphology of the Study Area

### • Bathymetry

At flood stage (October 2022), the bathymetry of Nokoué lake and its channels shows significant depths of up to 10 m in some sectors (**Figure 7**). At lake level, the edges have shallow depths, generally between  $-1$  m and  $-2$  m, while the center of the lake has average depths between  $-2$  m and  $-4$  m.

During the low-water period (March 2023), the bathymetry of Nokoué lake



**Figure 7.** Bathymetric map of Nokoué lake and its channels during flood period.

and its channels shows depths of up to  $-6$  m and  $-7$  m on the Ouémé and Cotonou channels studied (Figure 8). At lake level, the edges have depths of between  $-0.5$  m and  $-1.2$  m, and the center of the lake has average depths of between  $-1.6$  m and  $-2.4$  m.

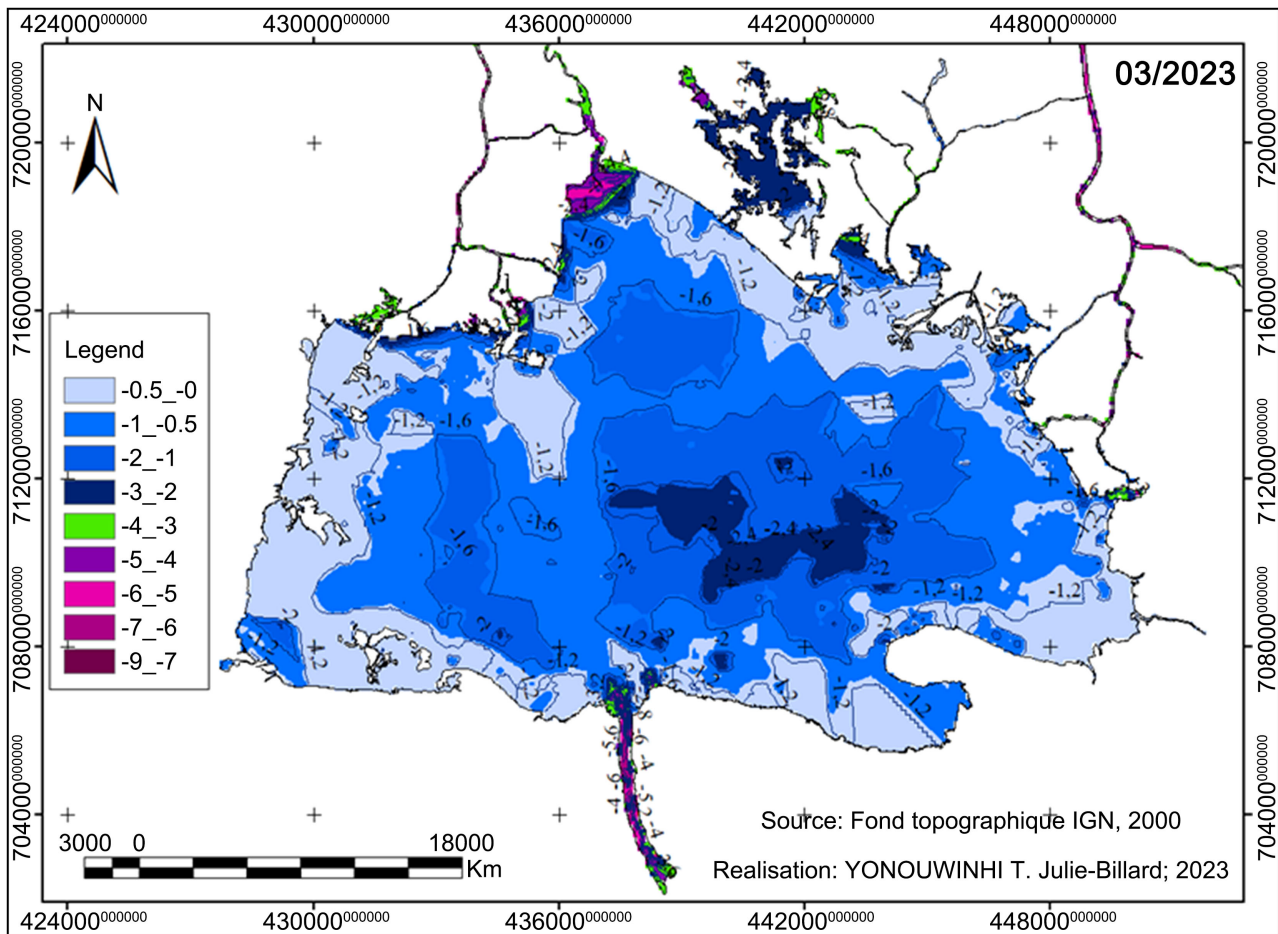
The bathymetric results for October 2022 and March 2023 highlight significant seasonal variations in depths in Nokoué lake and its channels. These variations reflect the influence of the hydrological regime, essentially controlled by rainfall, dredging activities and the clogging of the lake with plant debris.

- **Bottom morphology**

To present the bottom morphology of Nokoué lake, bathymetric data from seven (07) transects (four oriented North-South and three West-East) were acquired during low-water conditions. This made it possible to present the corresponding bathymetric profiles at non-standardized scales.

- **Lake bottom morphology**

For depths not exceeding 3 m in the lowest central zone, the profiles show, overall, three types of morphology at Nokoué lake level: “V”, “U” and “Intermediate” (Figure 9 and Figure 10). The north-south profiles (Figure 9) show a relatively gentle slope from north to center, and a steeper slope from the center



**Figure 8.** Bathymetric map of Nokoué lake and its channels during the low-water period.

of the lake to the south. The eastern sector (profiles AA' and BB') is less indented than the western sector (profiles CC' and DD'), which has a “V”-shaped bottom with clearer variations in depth due to significant hydro-sedimentary inputs from tributaries. The different bottom shapes correspond to flow zones.

The lake bottom in a west-east direction has an intermediate, almost flat morphology (Figure 10). In the eastern and western sectors, the erosive effect of the tributaries becomes less pronounced from north to south (profiles GG' and FF'), leading to a significant accumulation of sediment on either side of the central zone in the southern part (profile EE'). The central zone, which is less notched in the northern sector of the lake, is heavily notched in the transition zone with the Cotonou channel. Notched areas are associated with sectors close to tributary mouths and flow corridors. “U” shapes are associated with weaker currents, favouring sedimentation, while “V” shapes can be observed at mouths and along flow corridors.

○ **Longitudinal profiles of tributaries**

Cross transects on tributaries essentially yielded asymmetrical “U” and “V” profiles. Longitudinal profiles were produced to observe morphological variations along the studied river courses.

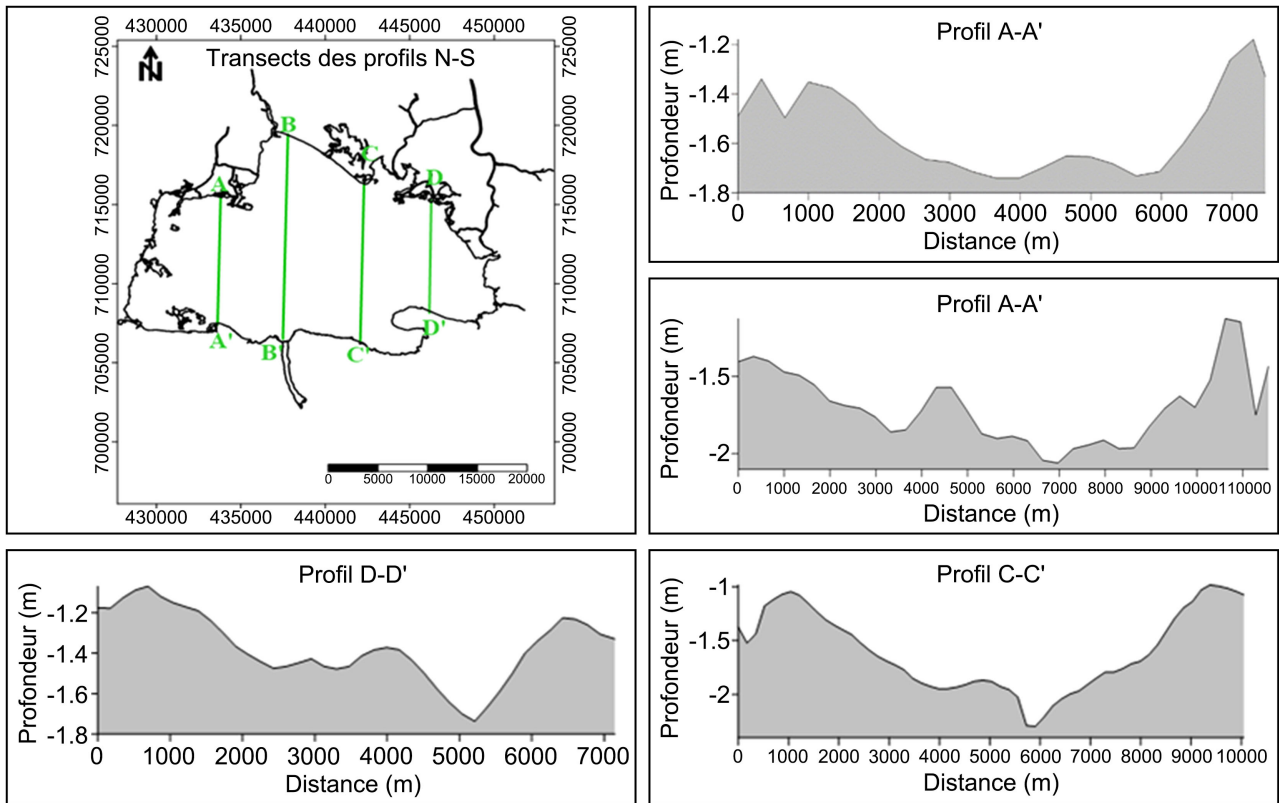


Figure 9. Bathymetric profiles of the lake from north to south (March 2023).

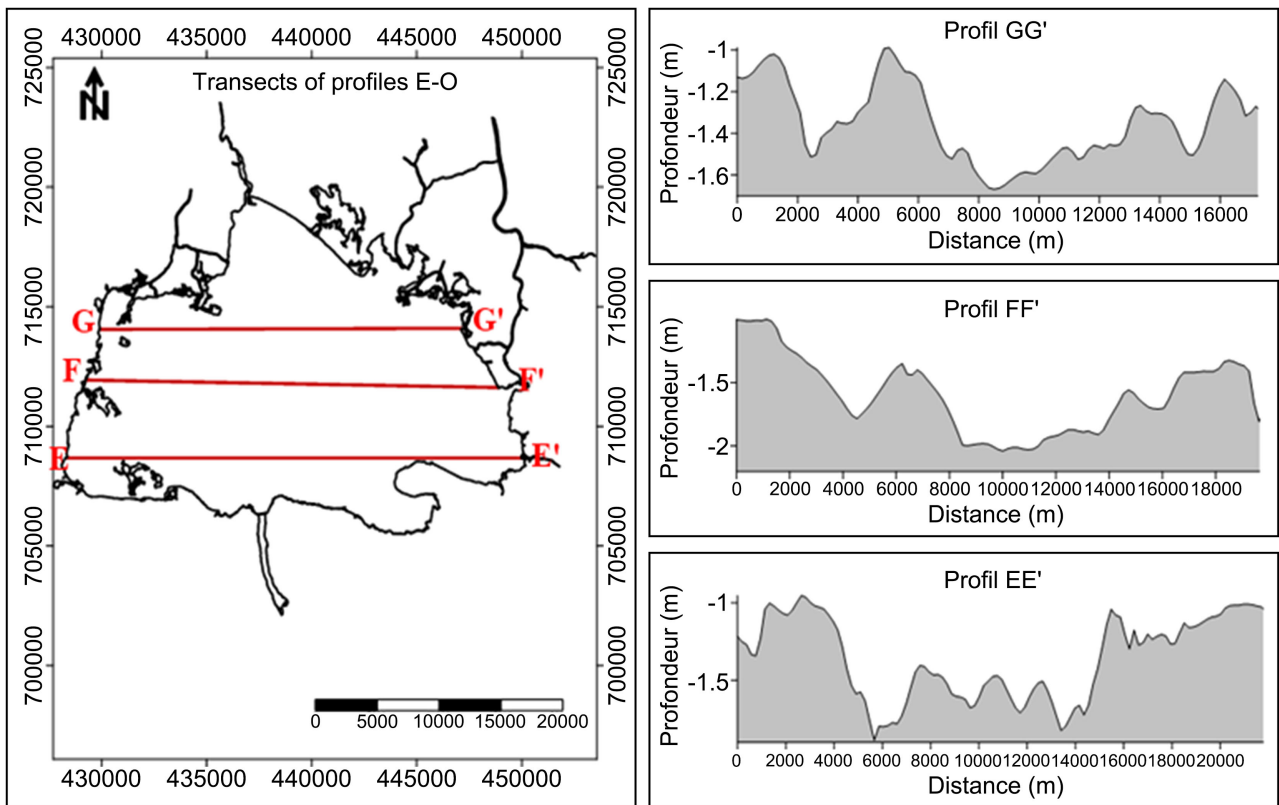


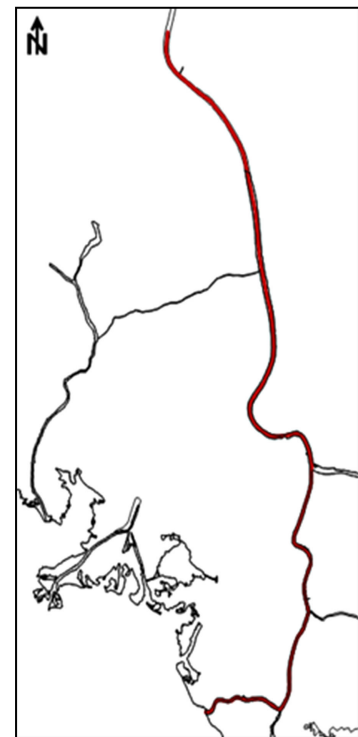
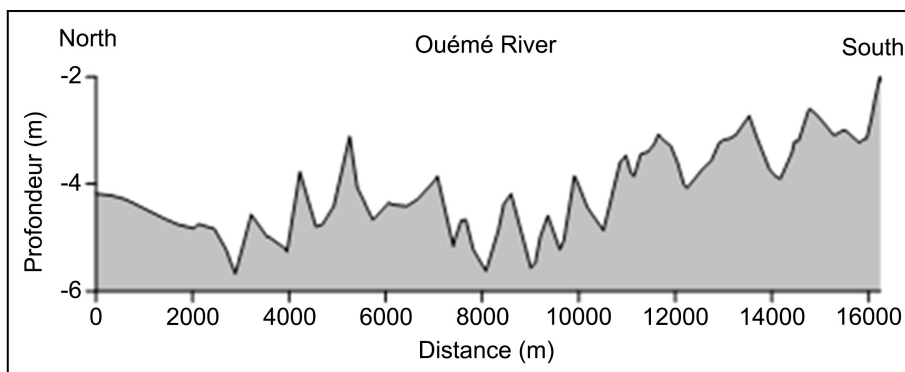
Figure 10. Bathymetric profiles of the lake from west to east (March 2023).

1) The longitudinal profile of the main tributary, the Ouémé River, shows a variation in depth from  $-6$  m to  $-4$  m upstream and from  $-4$  m to  $-2$  m downstream (**Figure 11**). There is a gradual decrease in depth towards the lake. The numerous gradients observed mainly reflect the connection zones with the multiple branches observed along the linear route. Also, flow corridors and dredging activities should not be overlooked.

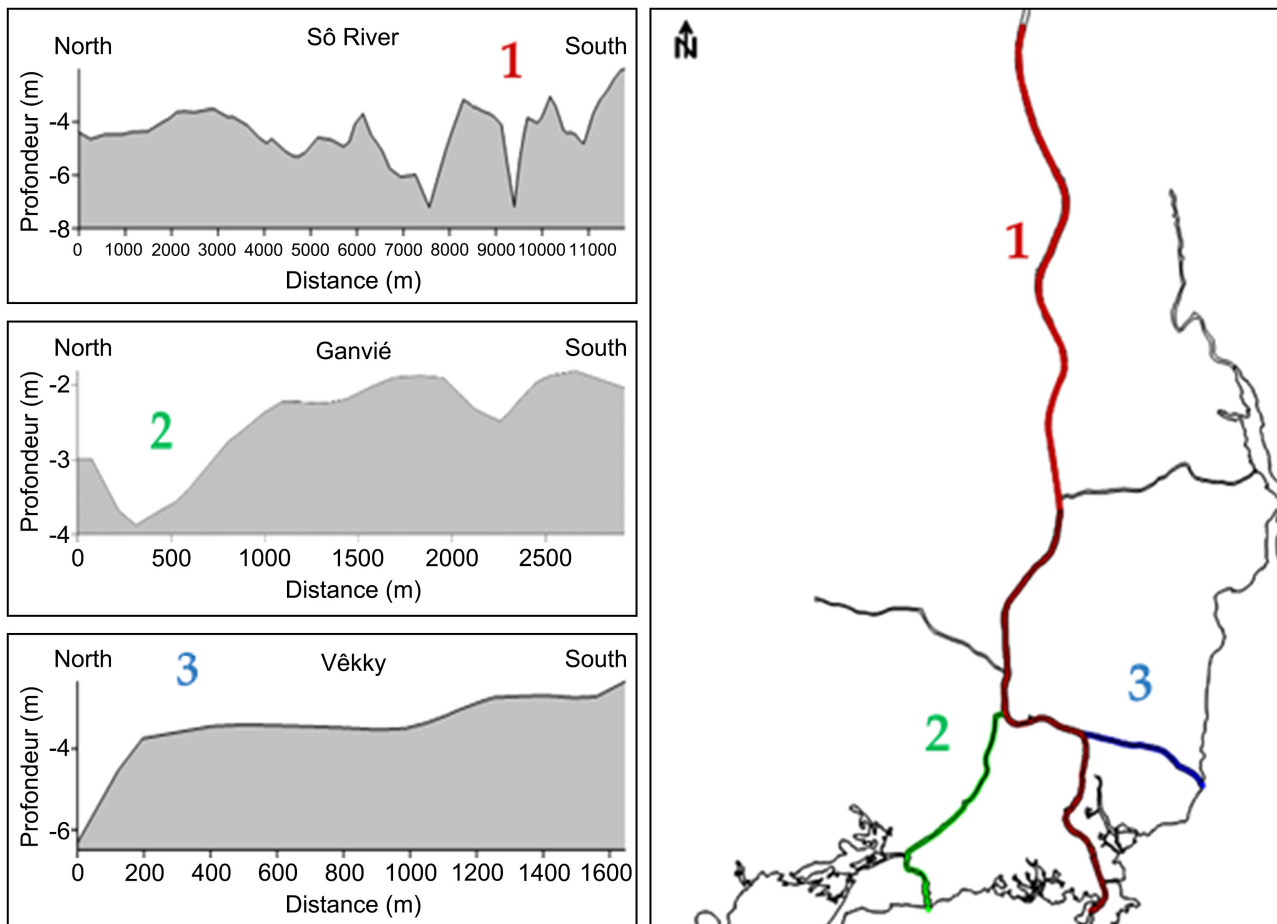
2) The longitudinal profile of the Sô River shows a relatively flat bottom of around  $-4$  m in depth over the more or less straight northern half, with almost no branches. Over the last six (6) kilometers of the river's length, there is a gradual decrease in depth, with two major drops of almost  $3$  m each marking the junction with the Ganvié and Vèkky branches (**Figure 11**).

The Ganvié and Vèkky arms, shown in green and blue respectively (**Figure 12**), have almost flat bottoms with depths of less than  $-4$  m. These depths gradually decrease towards the lake, reaching  $-2$  m. Only the connection zones with the Sô River are marked by deep notches ranging from  $-6$  to  $-4$  m.

3) The longitudinal profile of the Cotonou channel can be divided into two topographically homogeneous sectors with varying gradients (**Figure 12**). The upstream section has a relatively steep, non-rectilinear gradient over the first half of its length. The second half is characterized by a gradual rise of around  $1$  m over the remaining  $2$  km of the linear section. The bottom profile is highly variable, with gradients that punctuate the profile. This unevenness in the central zone may be the result of development work carried out to install structures (bridges) on the linear section.



**Figure 11.** Longitudinal topographic profile of the Ouémé River (March 2023).

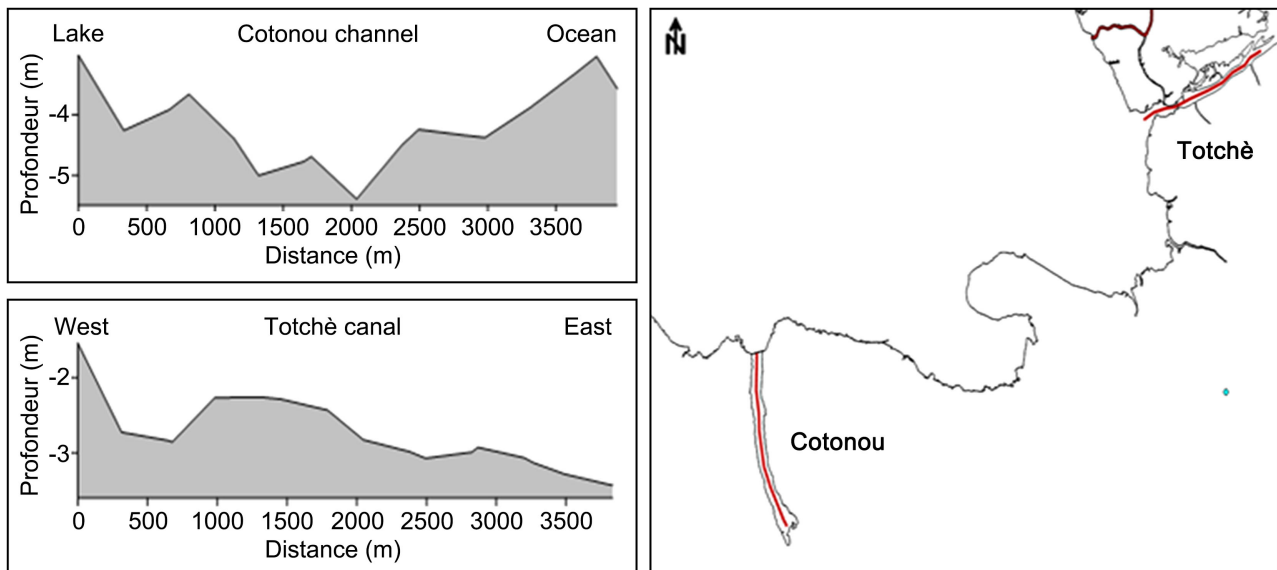


**Figure 12.** Longitudinal profiles of the river Sô and its branches (March 2023).

4) The longitudinal profile of the Totchè canal shows a gentle slope from west to east, resulting in an increase in the depth of the lake towards the Porto-Novo lagoon. Two notches at 500 m and 2500 m from the lake are probably linked to junction points between the canal and river branches of unequal size (**Figure 13**).

### 4.3. Flow Facies

Flow facies are generally linked to the hydrodynamic conditions and morphological characteristics of the watercourse. The simplified key to determining flow facies is based on four criteria: depth, flow velocity, cross-sectional profile and longitudinal profile of the stretches of the studied segment [30]. Based on these criteria, the Ouémé river, the Totchè canal and the Cotonou channel can be characterized by wetland-type facies which, depending on the section, can be subdivided into lentic channels, concave wetlands and lotic channels. The Sô River as a whole displays flow facies of the lotic channel type upstream and flat lentic to running downstream. These flow facies, generated by the geodynamic processes of erosion and solid transport, are one of the main tools for linking the hydromorphological and ecological functioning of rivers.



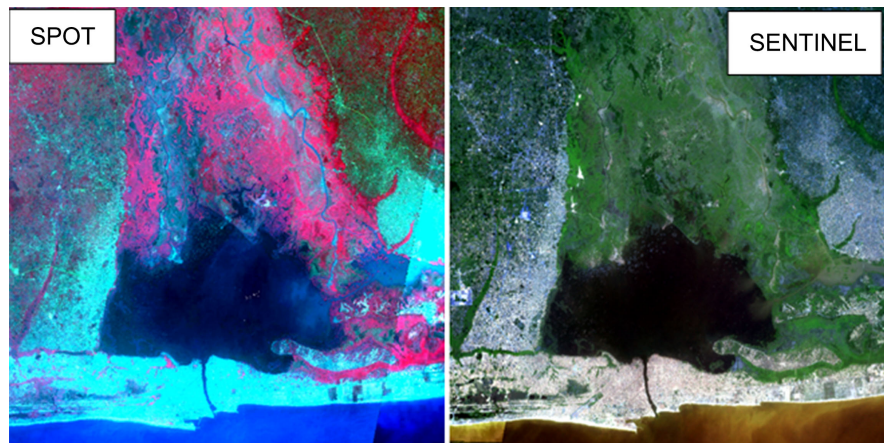
**Figure 13.** Topographic profiles of the Cotonou channel and Totchè canal in March 2023.

#### 4.4. Remote Sensing Contributions

For the spatial analysis of 2010 and 2022 satellite images of the study area, the visible spectral bands (blue, green, red) were used to visualize the presence of water, the near-infrared bands to map vegetation, and the mid-infrared bands to study soil composition (Figure 14). Classification was used to present the different classes of features or areas present in the images. The spatial analysis made it possible to identify nine (09) thematic classes. The results were then compared, class by class, in order to evaluate the changes. The information quality evaluation criteria calculated for each image gave values close to 1, validating the methodology used in image processing and indicating high information reliability. For the 2010 SPOT image, the kappa is 0.88 and the overall accuracy is 0.90. For the Sentinel 2B image from 2022, the kappa is 0.90 and the overall accuracy is 0.92. The classifications made it possible to obtain quantitative information on land occupation during these periods and on the temporal and spatial evolution of this occupation in the study area.

For the year 2010, variations in water distribution within the study area are highlighted by comparing low-water and flood periods. These variations are shown in blue. The surface area of all the water bodies is 270 km<sup>2</sup> at low water (Figure 15(a)), and 277 km<sup>2</sup> at high water, with a floodplain (wetland) of around 421 km<sup>2</sup> (Figure 15(b)).

For the year 2022, the surface area of the water bodies is 274 km<sup>2</sup> at low water and 280 km<sup>2</sup> at high water, with a floodplain (wetland) of 419 km<sup>2</sup>. The results of processing SPOT5 and Sentinel 2B satellite images show that morphological variation in the study area over a 12-year period is not very significant, with only minor changes to the shape of the lake (Figure 15(a) and Figure 16(a)). At the scale of the maps presented (Figure 15 and Figure 16), the channels show virtually no morphological variation.



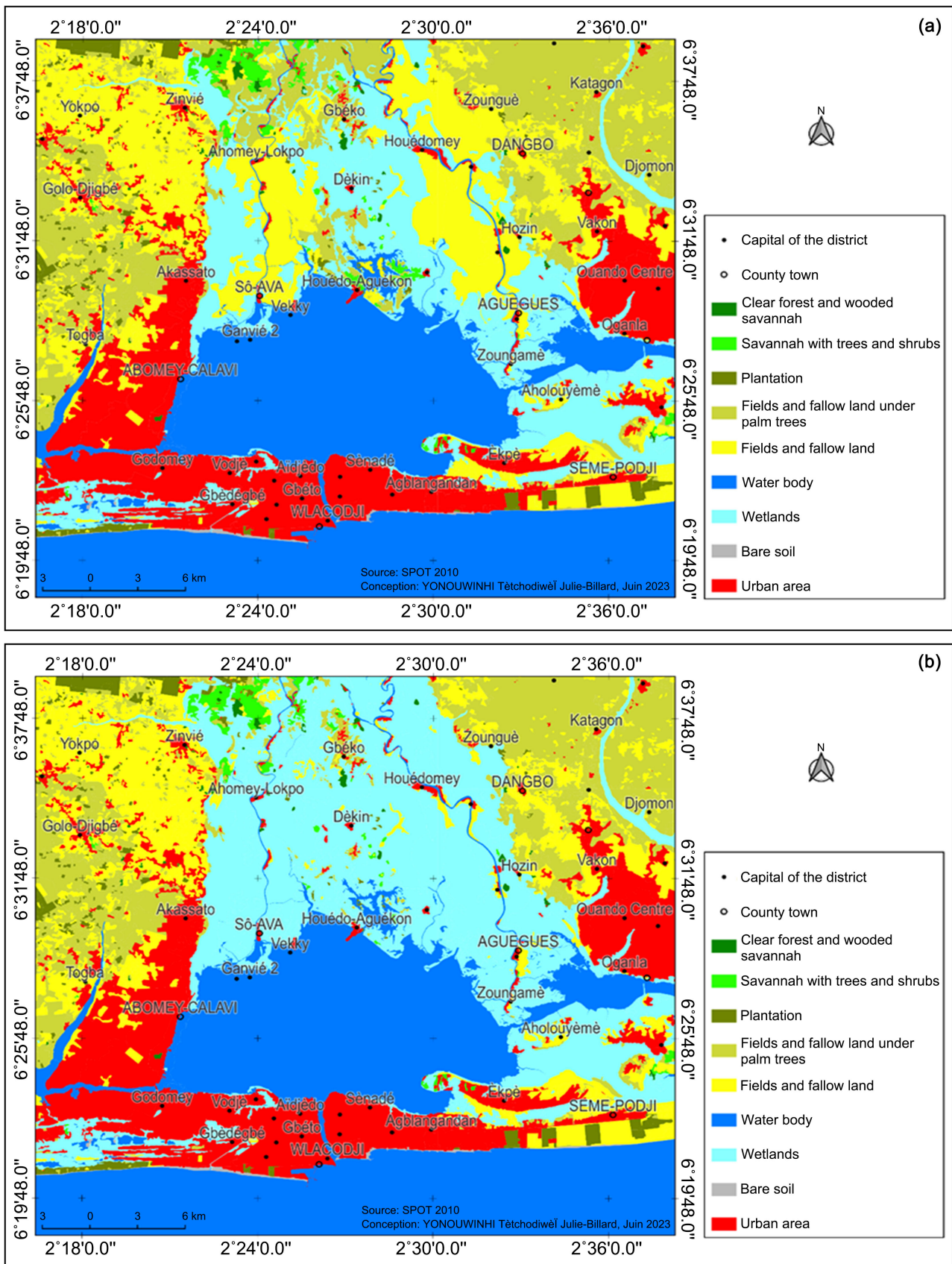
**Figure 14.** SPOT5 (2010) and Sentinel2 (2022) coloured satellite images.

Changes in land use over the period 2010-2022 were assessed. Among the factors influencing land cover change, human factors are more important than physical ones. Firstly, there is a significant and gradual expansion of the urban environment associated with a densification of existing areas then, a spatial expansion of this environment. The results show a trend towards an increase in anthropogenic formations at the expense of natural formations. Barren land and built-up areas have not undergone any conversion, but have increased at a rate of 3.6% and 69.15% respectively. Forest formations as a whole regressed by 4.29% and converted by 4.82%. Much of the vegetation has been destroyed for agricultural purposes, handicrafts (acadjas) or even domestic use (firewood).

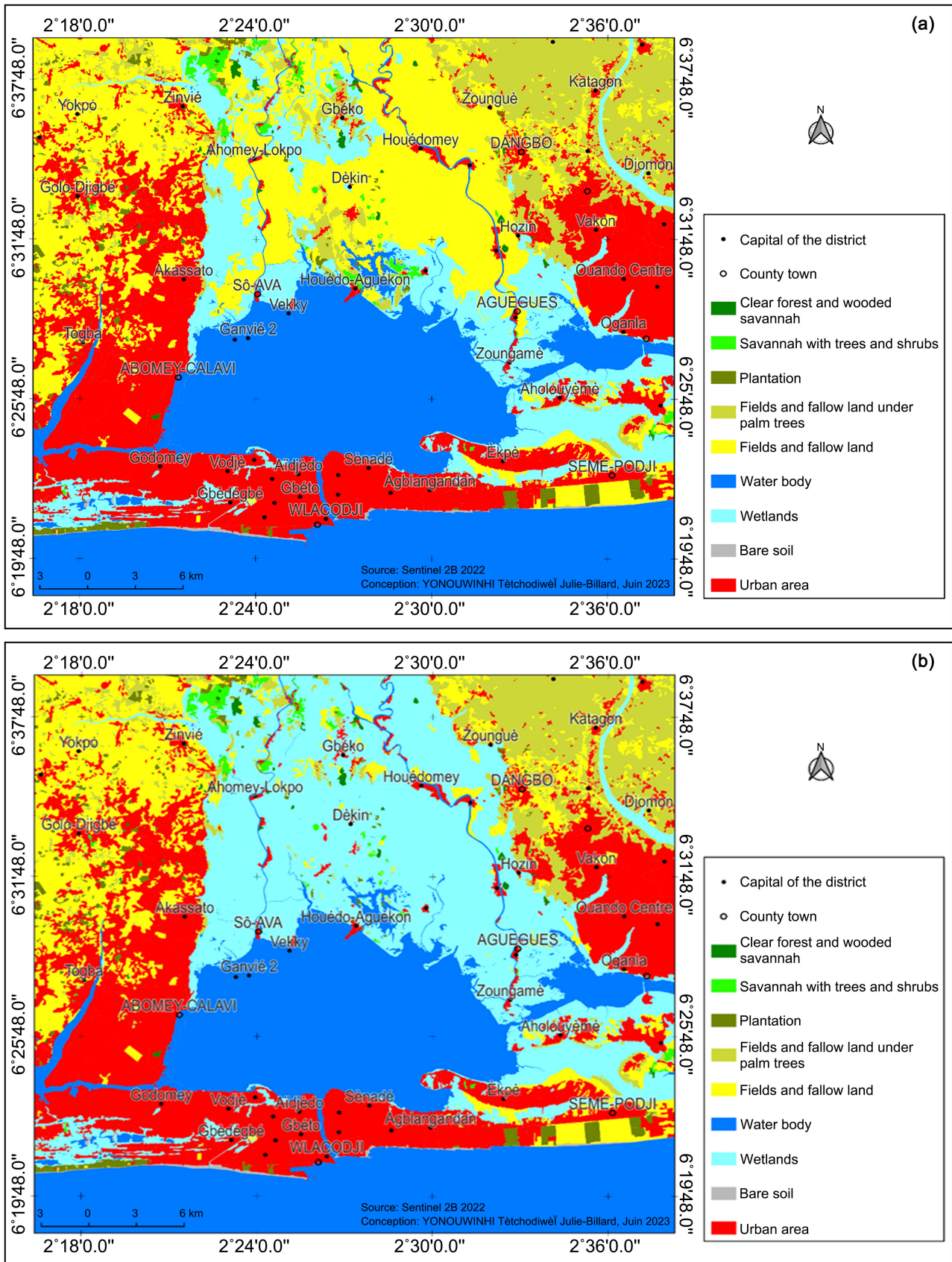
## 5. Discussion

The results obtained show that the hydrological regime of our study area is strongly influenced by rainfall variations. This hydrological pattern confirms the results of some previous work [3] [9] [15] [31] [32] [33]. Indeed, the seasonal regimes of the Ouémé and Sô rivers determine freshwater inflows to the lake, with flows of up to 671.35 m<sup>3</sup>/s on the Ouémé and 357.10 m<sup>3</sup>/s on the Sô. Variations in flow along the Ouémé and Sô rivers have enabled us to calculate the specific power of each section and determine the type of erosion that characterizes it.

Bathymetric results revealed that most of the lake has less than -2 m depths, and 20% of its surface area displays less than -1 m depths. In 1978, areas less than -1 m accounted for 18.5% of the total lake area, but by 2015 they had almost doubled to 31.7% [19] [20]. Currently, these shallow areas are growing steadily (40%). This spatio-temporal evolution of the lake's bathymetry is an important indicator of environmental changes and hydrological conditions in the region [34]. It is thought to be linked both to the significant sediment inputs from the tributaries, and to the increasing use of traditional fishing systems known as "acadjas", which continue to encumber the lake. Different current velocities, stream depths and section morphology have led to the identification of lentic and lotic flow facies.



**Figure 15.** Hydromorphological variation maps of Nokoué lake and its channels during low water (a) and high water (b) in 2010.



**Figure 16.** Hydromorphological variation maps of Nokoué lake and its channels during low water (a) and high water (b) in 2022.

The mapping of the evolution of land use showed the change in classes distribution over the period 2010 to 2022. The year 2010 was marked by an exceptional flood. The lake area increased from 270 km<sup>2</sup> in 2010 to 274 km<sup>2</sup> in 2022. Morphological change is difficult to perceive, due to the expansion of settlements around most of the lake. The floodplain area was 421 km<sup>2</sup> in 2010 and 419 km<sup>2</sup> in 2022. The various results validation indices show values close to 1, indicating the conformity of our results with the reality on the ground small objects, which have a similar spectral value or the same texture, have been well distinguished. For future studies, it should be noted that field campaigns are really necessary. The information obtained in the field would allow us to fully understand the land use types of the territory and to create an appropriate hierarchy of classes for object-oriented classification, while allowing better validation of the classifications. A land use mapping approach that would integrate classifications from high-resolution images should also be considered.

All the results presented can be used for predictions linked to the hydrological cycle and hydrological modeling of the study area.

## 6. Conclusion

This study is a major contribution assessment of the current hydromorphological features of Nokoué lake and its main tributaries. The hydrological and morphological data for Nokoué lake show that the high flows measured in September, reaching up to 653.79 m<sup>3</sup>/s on the Ouémé and 357.10 m<sup>3</sup>/s on the Sô, were identified as the main cause of this large flooded area. The specific powers obtained reveal different types of erosion. Bathymetric results showed that Nokoué lake has mainly shallow depths ranging from -0.5 to -2.4 m, while the channels present greater depths, resulting from erosional processes and artisanal dredging activities to meet local needs. Bathymetric profiles revealed various lake-bottom shapes. The lake has relatively flat bottom morphology, except at its various mouths. The flow facies identified are of wet type (concavity wetland, lotic channel and flat lentic facies). Spatial analysis revealed little variation in the lake's surface area over twelve-years. The surface increased from 270 km<sup>2</sup> in 2010 to 274 km<sup>2</sup> in 2022. However, during flood periods, water surface was of 421 km<sup>2</sup> in 2010 and 419 km<sup>2</sup> in 2022. The change in land use showed that there is a significant and gradual expansion of the urban environment associated with a densification of existing areas then, a spatial expansion of this environment. The analysis of variations in water and land use between low and high flows periods is an important step in integrated water resource management, environmental preservation and adaptation to climate change.

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## Data Availability Statement

The data presented in this study is available on request from the corresponding author. The data is not accessible to the public as it is the property of the ACE Partner project and the General Direction for Water of Benin.

## Conflicts of Interest

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

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