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Research Article

Contribution of Remote Sensing to the Evolution of Ivorian Coastal Lacustrine Environments: The Case of Lake Hebe (Southeastern Côte D'Ivoire)

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Abstract

The Ivorian coastal zone hosts a wide variety of hydrosystems such as lagoons, estuar ies, rivers, and lakes, which play essential ecological, hydrological, and socio-economic roles. Lakes, in particular, serve as vital freshwater reserves for surrounding populations and are also used for fishing, irrigation, tourism, and recreation. However, these fragile ecosystems are increasingly subjected to both natural and human-induced pressures, including uncontrolled urbanization, intensive agriculture, sand extraction, and the proliferation of aquatic vegetation. These factors contribute to increased sedimentation, a reduction in water depth, and the progressive degradation of water quality. This study focuses on Lake Hebe, located in southeastern Côte d'Ivoire, covering an area of approximately 274.53 hectares. Using remote sensing data and bathymetric analyses, it examines the spatio-temporal dynamics of the lake over a thirty-year period (1988–2018). Satellite imagery was used to monitor variations in surface area and changes in land use around the lake, while bathymetric surveys highlighted its morphology and sedimentation processes. The results reveal significant hydromorphological changes caused by both natural and anthropogenic pressures. Finally, decision-support tools and sustainable management strategies are proposed to preserve the ecological integrity of Lake Hebe and other lacustrine environments in Côte d'Ivoire.

Keywords

Lake Hebe, Côte d'Ivoire, Lacustrine Environment, Remote Sensing, Spatio-temporal Dynamics, Sustainable Management

1. Introduction

1.1. Background of the Study

The Ivorian coastline abounds with a variety of hydrosystems such as lagoons, estuaries, rivers, and lacustrine environments. These systems appear as large natural bodies of freshwater-or, more rarely, saltwater-found inland [1].

Lacustrine environments are well known for their capacity to serve as water reserves [2] that supply drinking water to

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local populations. They also provide fish resources for artisanal fishing. Both the watershed and the lake itself can be developed for tourism, recreation, and water-based activities such as motorboat rides and water skiing. Whether artificial or natural, a lake is perceived as a water reservoir. Accordingly, it is often used for hydroelectric power generation, as illustrated by the Soubre dam [3] in the Nawa region, with an installed capacity of 275 megawatts.

1.2. Statement of the Problem

In light of the above, lacustrine environments are subjected to numerous anthropogenic and natural pressures that tend to degrade them and impact their water storage and surface capacities. The phenomena of silting and sedimentation contribute significantly to this degradation, often accompanied by the proliferation of aquatic vegetation on lake surfaces [4]. These processes substantially reduce lake depth and water capacity through the accumulation of sediment at the bottom. The use of pesticides and fertilizers within the watershed also affects the stability of lacustrine ecosystems.

1.3. Objective of the Study

1.3.1. General Objective

To address the challenges facing these environments, this study aims to use remote sensing techniques to analyze the spatio-temporal evolution of Lake Hebe over three decades (1988-2018).

1.3.2. Specific Objective

Specifically, the objectives are:

1). To characterize the morphology of Lake Hebe through a bathymetric study;

2). To evaluate lake modifications using satellite imagery;

3). To propose decision-support tools for the sustainable management of lakes.

2. Data and Methodological Approach

2.1. Description of Study Area

Lake Hebe, located in the southeastern part of Côte d'Ivoire, covers an area of 274.53 hectares. It is bordered to the north by the Kodjoboue Lagoon and the town of Bonoua, to the west by the town of Grand-Bassam and the Comoe River, to the east by the town of Assinie, and to the south by the Atlantic Ocean (Figure 1). Administratively, Lake Hebe belongs to the municipality of Bonoua and is situated between latitude 5°12'13" N and longitude 3°33'2" W.

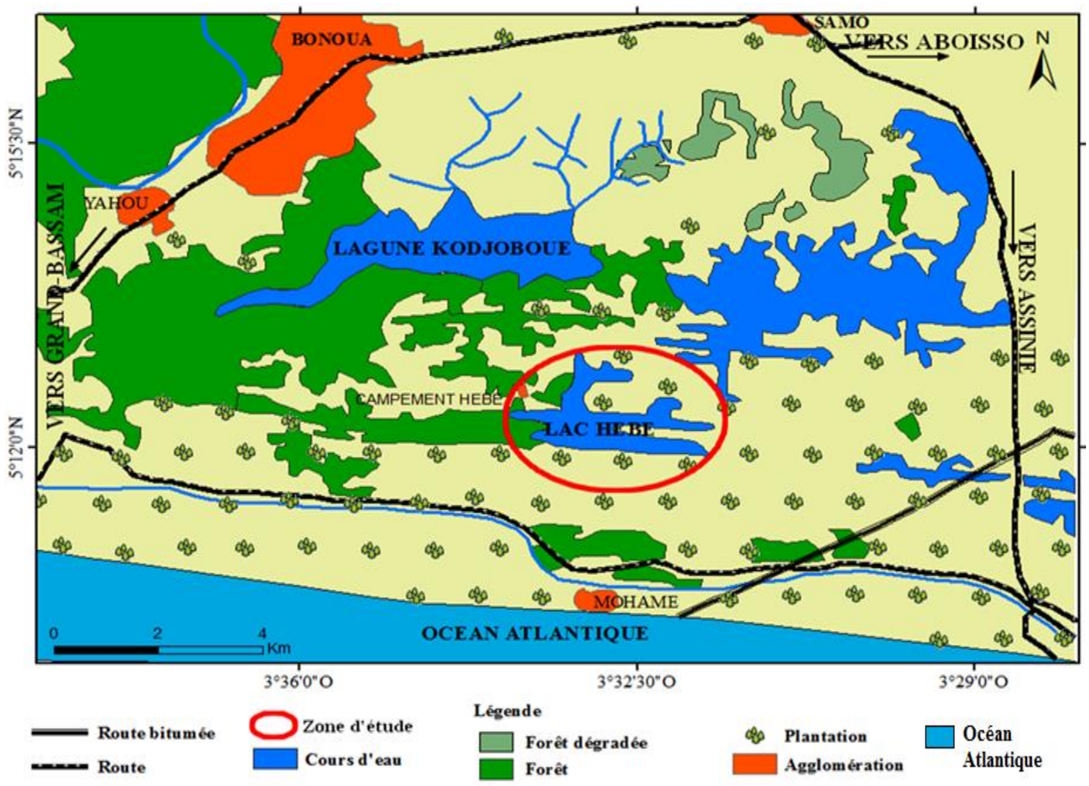

Figure 1. *Location of Lake Hebe.*

2.2. Methodological Approach

Two (02) main approaches were used in this study to achieve the stated objectives.

2.2.1. Bathymetry

Bathymetry is the study of the depth and relief of underwater surfaces, such as the seabed or the bottom of water bodies. It allows for the mapping of the underwater topography of seas, lakes, or rivers, in much the same way that topography maps land surfaces. The method involves identifying anomalies on the lakebed through echo sounding.

The equipment used consists of a central unit and a transducer, both mounted on the hull of the boat. The principle of bathymetry is based on emitting a sound pulse through a beam directed vertically beneath the vessel and measuring the time it takes for the signal to travel the round trip from the vessel to the bottom and back. The moment of detection is marked by a strong echo reflected from the lakebed. Any object located along the path of the acoustic signal will also reflect an echo toward the transducer, which, in receiving mode, converts the acoustic pulse into an electrical signal. This signal is then transmitted to the receiver, where it is processed and amplified. A time base converts the delay in echo reception into a distance. Knowing the time taken for the echo to return, the transmitter generates another pulse, and the process repeats [5].

According to the Bathymetric Survey Standardization Guide [6], which defines the positioning of soundings based on the distance between transects and the sampling interval while considering the surveyed area, the bathymetric survey conducted on Lake Hebe produced 7,425 sounding points. Regarding the transects, which help to characterize the morpho-sedimentary dynamics of the lakebed, sixteen (16) transects oriented in E–W and N–S directions were carried out.

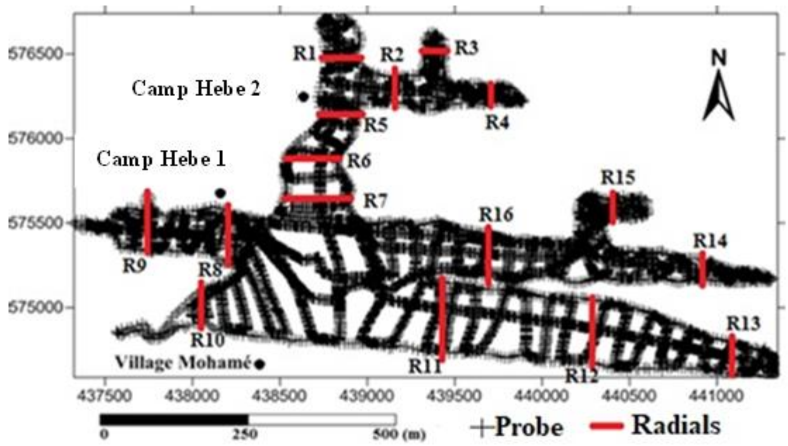

Figure 2. Positioning of Soundings and Transects on Lake Hebe.

2.2.2. Processing of Bathymetric Data

The bathymetric data were processed using Surfer 11 software. This software includes several modules that facilitate the processing and visualization of bathymetric data. The first step involves correcting the soundings by adding the immersion depth of the transducer. After this correction stage, the second step consists of georeferencing the data. A digital model is then generated, which enables the production of a bathymetric map.

Satellite Imagery

The satellite images used in this study were obtained from the USGS Earth Explorer website (http://earthexplorer.gov). Only dry-season images, which are less affected by cloud cover, were selected due to the high cloudiness typical of the subequatorial environment.

Three (03) types of Landsat images covering the period from 1988 to 2018 were used:

1). Landsat 4 image for the year 1988, captured by the TM (Thematic Mapper) sensor;
2). Landsat 7 image for the year 2000, captured by the ETM+ (Enhanced Thematic Mapper Plus) sensor;
3). Landsat 8 image for the year 2018, captured by the OLI (Operational Land Imager) sensor.

Table 1 presents the main characteristics of the satellite images used in this study.

Table 1. Characteristics of Landsat Satellite Images.

Lake	Images	Scenes (Path/row)	Acquisition date
Hebe	Landsat 4 TM	196-056	21 – 03 – 1988
	Landsat 7 ETM+	196-056	20 – 01 – 2000
	Landsat 8 OLI	196-056	02 – 03 – 2018

2.2.3. Processing of Satellite Imagery

The preliminary processing of satellite images aims to correct certain variations in data distribution caused by temporal differences in image acquisition. These variations are largely explained by factors such as the sun elevation angle, Earth–Sun distance, atmospheric conditions, sensor calibration, and viewing geometry, all of which can affect the digital values of the pixels [7, 8]. The Landsat images acquired were provided with geometric correction (WGS 84, Zone 30N) and correction level 1T. Only radiometric correction, atmospheric correction, and extraction of the study area were performed. Radiometric enhancement aims to correct the effects of various artifacts that interfere with radiometric measurements, particularly sensor defects and atmospheric haze. This process converts digital numbers into radiance values and is applied when luminance has been properly measured. Atmospheric correction is performed to harmonize ground luminance values and make images acquired under different climatic conditions and time periods comparable. As solar radiation passes through the atmosphere, it undergoes attenuation due to absorption and scattering processes. Atmospheric correction removes these atmospheric effects and converts radiance values into reflectance values.

1. Color Composition

Color composition involves the use of three spectral bands. According to SARR [9], it allows for better discrimination between geographic features. For this study, the selected color composite uses bands 5-7-4, which provide an enhanced visualization of land cover types.

2. Field Mission and Remote Sensing Data Collection

A two-day field mission was carried out to validate the different land cover classes within the study area. Detailed observations were made of the various types of land use and land cover present. Overall, this mission enabled both the identification and description of sites for image classification and the validation of classification results.

3. Supervised Classification Using the Maximum Likelihood Method

Classification is a crucial step, as it allows the generation of a thematic map of the classes of interest based on the spectral band data. The maximum likelihood classification method requires the user to define both the number of classes and the reference sites on which the software relies for grouping.

In this method, training sites (Regions of Interest -ROI) are selected-these are areas where the land cover type is known. The software uses these reference zones to classify the entire image by generalizing the spectral information obtained from the ROIs.

4. Classification Evaluation and Validation

The evaluation involves creating a confusion matrix to assess the statistical quality of the training samples (ROIs). The validation is based on three key indicators: overall accuracy, the Kappa coefficient, and the confusion matrix. According to SKUPINSK et al.; [10], the Kappa index represents the ratio between correctly classified pixels and the total number of sampled pixels, providing a measure of classification accuracy.

3. Results

3.1. Morphology of Lake Hebe

3.1.1. Seasonal Morphology of Lake Hebe

A detailed examination of the 2D bathymetric map of Lake Hebe during the dry and rainy seasons reveals depths ranging from 0 to 4.5 meters (Figures 3 and 4). The greater depths (4–5 m) are located along the main channel of the lake, which is oriented north–south (N–S). The slopes are more closely spaced near the shorelines and more widely spaced in the central part of the channel, reflecting the direction and dynamics of water flow within the lake.

During the rainy season, the higher depth values range between 4 and 5 meters, moderate depths between 2 and 3 meters, and shallow depths between 0 and 1 meter. In contrast, during the dry season, a slight decrease in depth is observed within the lake's main channel.

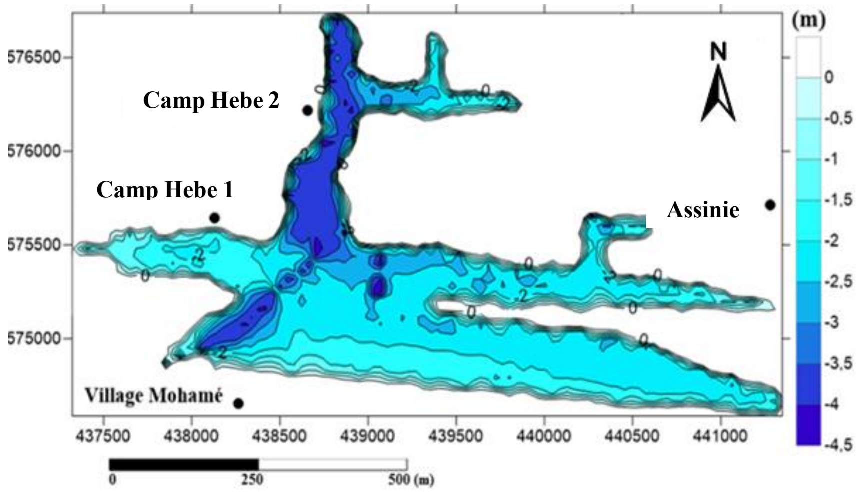

Figure 3. 2D Bathymetric Map of Lake Hebe (Rainy Season).

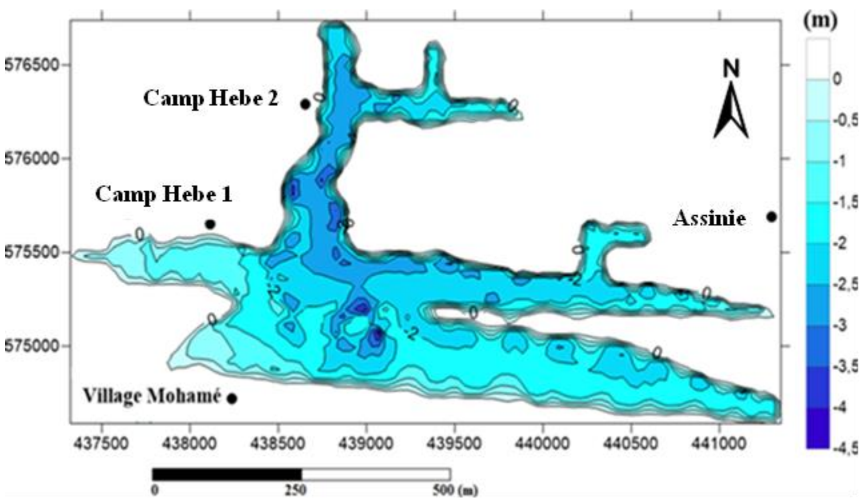

Figure 4. *2D Bathymetric Map of Lake Hebe (Dry Season).*

3.1.2. Digital Depth Model of Lake Hébé

The Digital Depth Model (DDM) provides a synoptic view of Lake Hebe (Figure 5). The map shows a generally gentle relief and highlights the presence of two morpho-structures in the lake: depressions and shoals.

1. Depressions: These appear as cavities within the lake and result from intense erosion caused by the acceleration of water currents. They indicate areas of highly turbulent hydrodynamic conditions. In Lake Hébé, the depressions are primarily located in the northern and central parts, where they reach depths of 4.5 meters.
2. Shoals: These are elevated areas on the lakebed, appearing as domes. The submerged shoals are mainly found in the central part of Lake Hebe. They are formed by the continuous accumulation of sediments. The height of these shoals relative to the water surface is approximately 4 meters. This type of submerged shoal is still in the process of development and is considered a young shoal, in contrast to a mature shoal (islet).

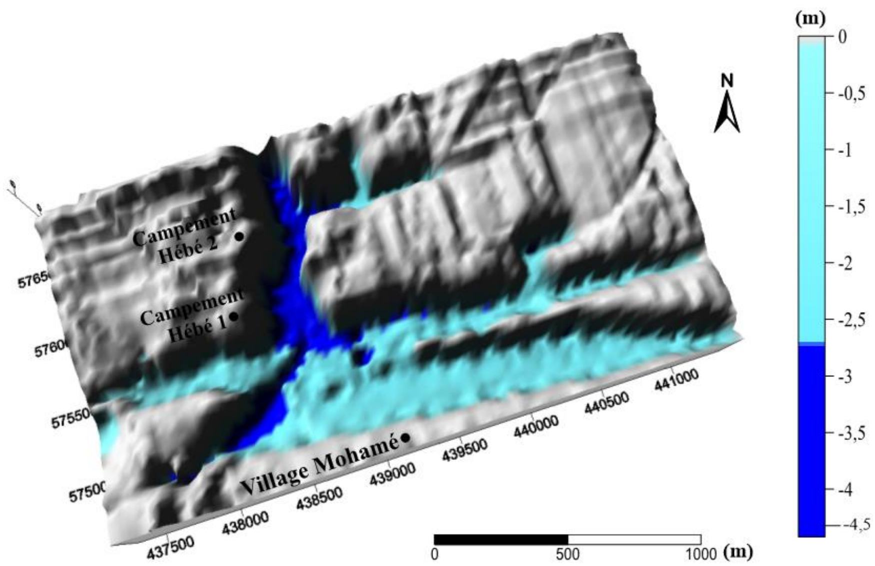

Figure 5. *Digital Elevation Model (DEM) of the Lake Hebe Area.*

3.1.3. Morpho-sedimentary Dynamics of Lake Hebe

The analysis of the morpho-sedimentary dynamics of Lake Hebe highlights the morphological evolution of the lakebed. The transects (radials) used in this study are oriented north–south (R4, R8, R9, R10, R11, R12, R13, R14, R15, R16) and east–west (R1, R3, R5, R6, R7). Analysis of these radials reveals two main types of morphology: the “Intermediate” form, which is the most common (81.25%), and the “U-shaped” form, which is less common (18.75%).

Intermediate-Type Bathymetric Profile

The bathymetric profiles obtained during the dry and rainy seasons show intermediate-type channels in Lake Hebe (Figure 6). These profiles are almost identical and cover nearly the entire lake. The overlay of these profiles indicates a slight sediment deposition, with an annual deposition area of 56,296.06 m^2 and a sediment volume of 5,629.6 m^3.

Most of these intermediate-type profiles originate from the radials R1, R2, R3, R4, R5, R9, R10, R11, R12, R13, R14, R15, and R16. These profiles reflect a balance between erosional forces and depositional processes within the lake.

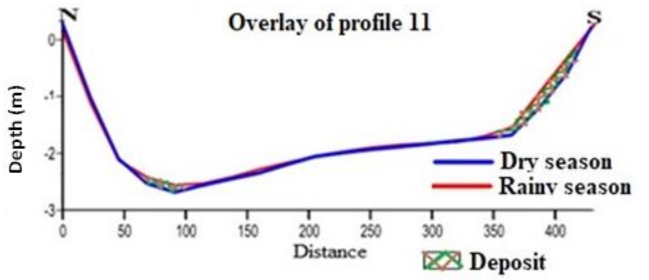

Figure 6. *Intermediate-Type Profile.*

"U" type bathymetric profile

The profile observed on Lake Hebe during the rainy season is of a 'U' shape. It features an almost flat bottom and nearly parallel sides. During the dry season, however, the profile is of an intermediate type, with a rise in the lakebed. Figure 7 shows the superimposition of these two bathymetric profiles. This overlay highlights the phenomenon of erosion. The annual eroded surface area is estimated at -566,112.95 m^2, and the sediment volume is evaluated at -849,169.42 m^3.

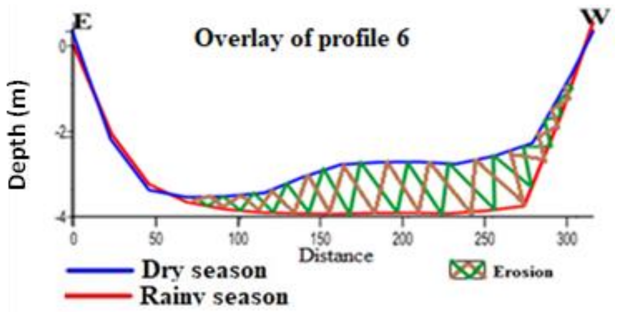

Figure 7. *"U" type profile.*

3.2. Surface Area Changes in Lake Hebe from 1988 to 2018

3.2.1. Land Use of Lake Hebe

Figures 8, 9, and 10 show the evolution of land use in the Hebe lake system over the last three decades (1988 to 2018). The overall accuracy is 98.30% with a Kappa coefficient of 0.97. In 1988, a large area of vegetation was recorded, estimated at 1,332.89 ha, while habitat and bare land occupied a small area of 22.38 ha. In 2000, vegetation declined (649.98 ha), while perennial crops occupied a large area (974.63 ha). The water body during that year was estimated at 279.95 ha. There was also an increase in habitat and bare soil, covering an area of 292.48 ha. As for the fallow/annual crop mosaic (MJCA), it occupied an area of 667.85 ha. In 2018, the surface area of the water body (274.53 ha) continued to decline, while that of habitat and bare soil increased (301.93 ha). Perennial crops occupy a significant area (940.96 ha) among the various land uses in the Hebe lake basin.

The decrease in water surface area between 1988 and 2018 could be due to heavy sediment deposition caused by vegetation clearing and, above all, bare soil.

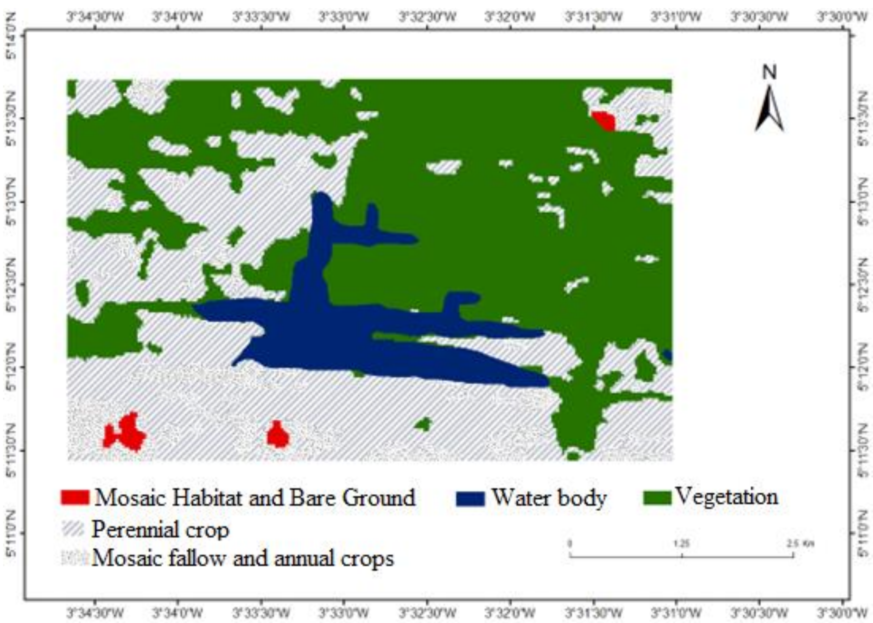

Figure 8. *Evolution of land use at Lake Hebe in 1988.*

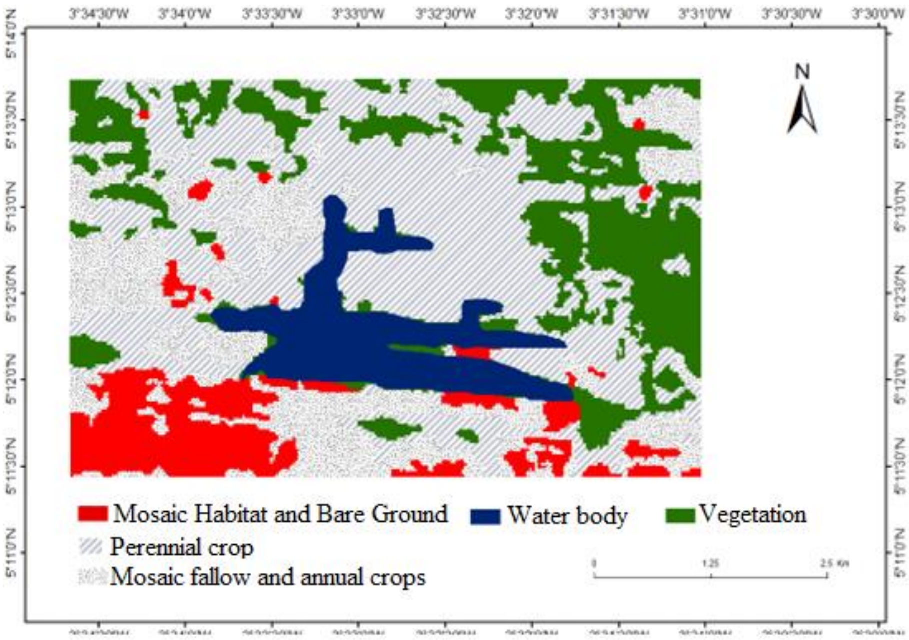

Figure 9. Evolution of land use at Lake Hebe in 2000.

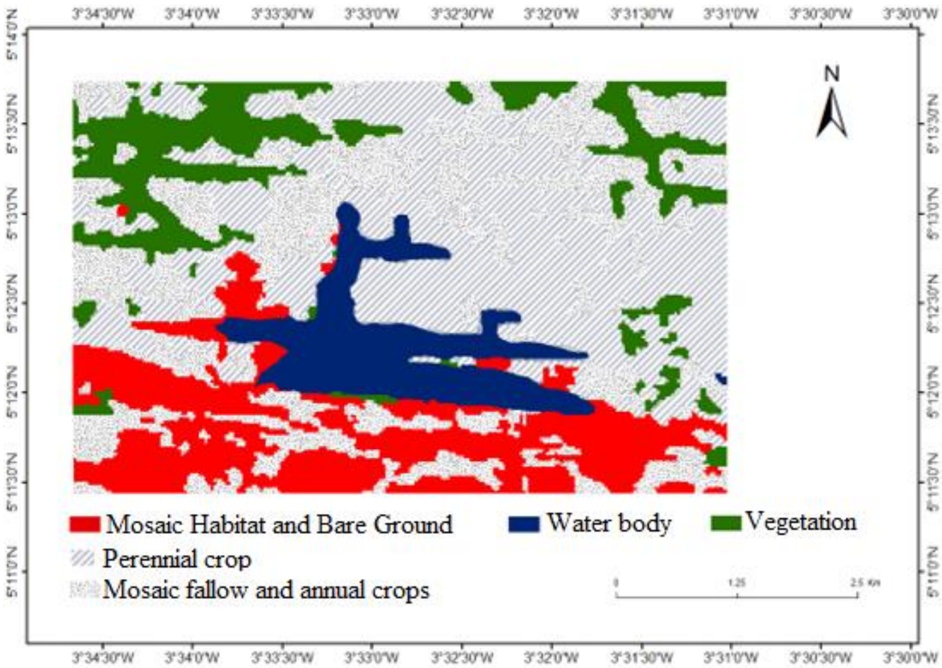

Figure 10. Evolution of land use at Lake Hebe in 2018.

3.2.2. Seasonal Trends in Lake Hébé in 1988, 2000, and 2018

Figure 11 shows seasonal changes in the lake's surface area. These changes are based on the four climatic seasons in 1988, 2000, and 2018. The surface area of the lake during these years varies very little (0.25 ha to 0.32 ha) from one season to another, and there is an overall decrease, with the equation of the line being negative. The lowest surface area was recorded during the long dry season of 2018, while the largest surface area was observed during the long rainy season of 1988. A multi-year study is needed to better track changes in the surface area of Lake Hebe.

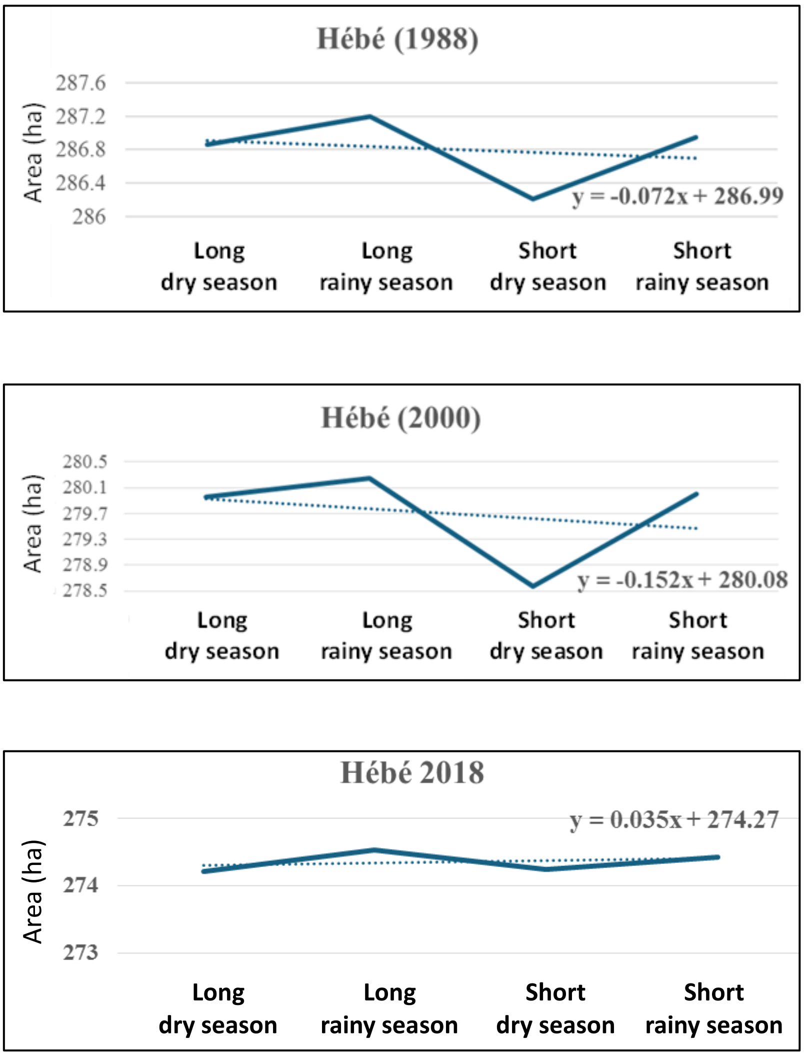

Figure 11. *Seasonal surface area evolution of Lake Hebe in 2018.*

3.2.3. Multi-year Surface Area Change (1988-2000 / 2000-2018)

1. 1988-2000

The surface area of the lake showed a slight variation between 1988 and 2000 (Figure 12). In 1988, Lake Hebe had a surface area of 286.86 ha. This surface area decreased in 2000 to 279.95 ha, representing a loss of 6.91 ha. This loss of surface area can be observed on the shores of Lake Hebe.

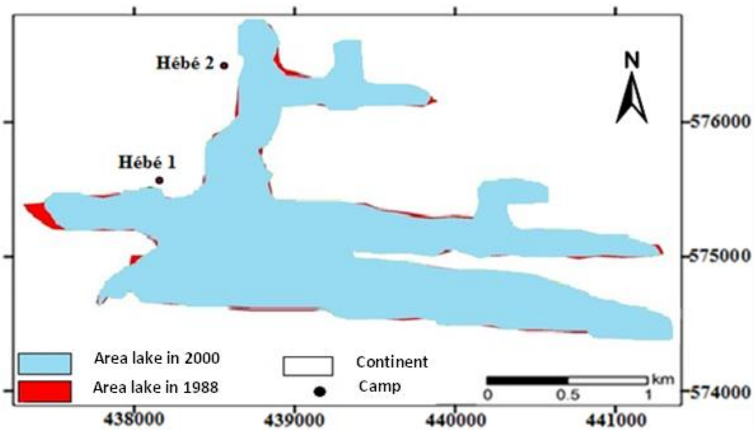

Figure 12. *Evolution of Lake Hebe from 1988 to 2000.*

2. 2000-2018

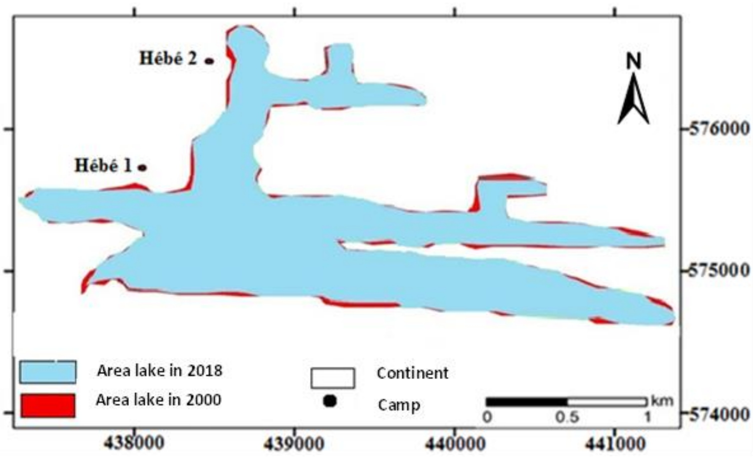

Figure 13. Evolution of Lake Hebe from 2000 to 2018.

Analysis of the change in surface area of Lake Hebe over the period from 2000 to 2018 shows a slight reduction in surface area across the entire lake (Figure 13). The lake's surface area, which was 279.95 ha in 2000, decreased to 274.53 ha in 2018. This loss of surface area at Lake Hebe over these eighteen (18) years is estimated at 5.42 ha.

3. Summary of changes in Lake Hebe between 1988, 2000, and 2018

Figures 14 and 15 summarize the multi-year evolution of the surface area of Lake Hebe from 1988 to 2000 and from 2000 to 2018. These figures show a continuous decline in surface area. During the period from 1988 to 2000, the lake's surface area decreased from 286.86 ha to 279.95 ha, a decline of 2.46%. Between 2000 and 2018, the surface area also decreased, varying from 279.95 ha in 2000 to 274.53 ha in 2018. This loss in surface area is estimated at 1.88%. In total, from 1988 to 2018, Lake Hebe lost an area of 12.33 ha, or 4.29%.

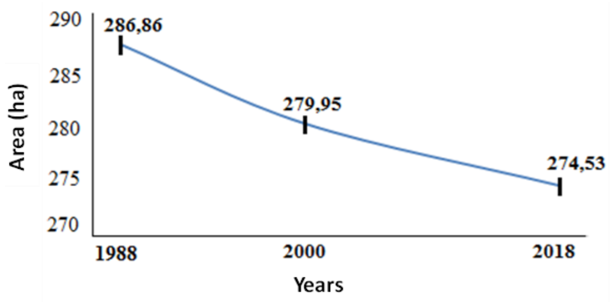

Figure 14. Overall evolution of Lake Hebe (1988-2000-2018).

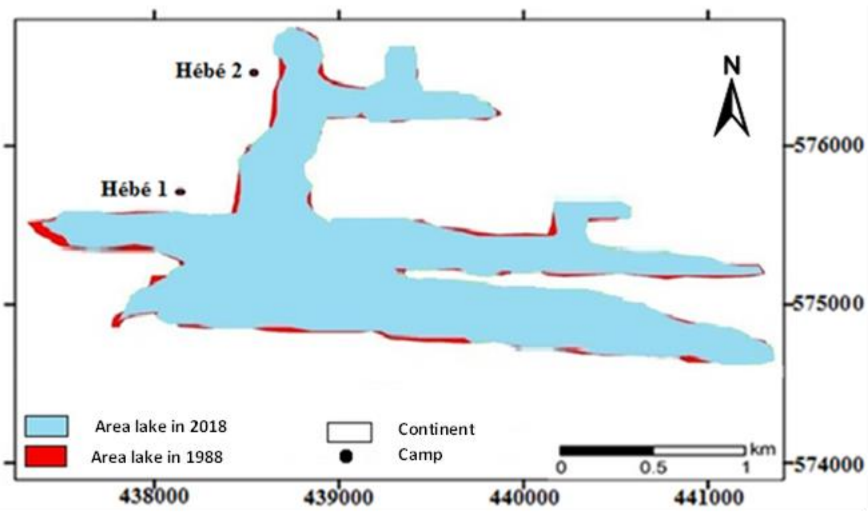

Figure 15. Overall evolution of Lake Hebe from 1988 to 2018.

4. Discussion

The morphological dynamics of the lake system's bottom highlight the typology of forms, which is reflected in an increase in depth from the banks towards the main channel. The bottom is virtually stable on Lake Hebe, as the depths observed vary from 4.5 m to 0 m during the two (02) seasons studied (the 2018 rainy and dry seasons). The depressions observed on the lake are mainly due to erosion. As for the shoals, they reflect fairly calm hydrodynamic conditions [11, 12]. These results corroborate those of [13, 14], and [4], who also highlighted these morphostructures on Lakes Bakre, Bacon, and Labion, respectively.

The sedimentary dynamics of the lake show “U” and ‘intermediate’ bathymetric profiles. According to ADOPO [11], a bathymetric profile with a “U” shape reflects a phase of sediment accumulation. The “U” type profile is generally observed in glaciers or in bodies of water that have undergone dredging. As Lake Hebe is a natural lake, i.e., it has not undergone dredging, the presence of these “U” channels would be of glacial origin. Indeed, [15] links the origin of lagoons and coastal lakes to the Würm glaciation. Thus, the presence of these U-shaped profiles in these lakes would be due to glaciation. Intermediate bathymetric profiles do not have a stable shape. They reflect a balance between the forces of accumulation and erosion.

Mapping the surface evolution of Lake Hebe Landsat TM, ETM+, and Oli images were used to track the surface evolution of the lake over the period from 1988 to 2018. This reveals morphological changes within the lake's hydrosystem. The lake's surface area decreased from 286.86 ha in 1988 to 279.95 ha in 2000 and 274.53 ha in 2018. Similar studies have highlighted changes in the surface area of bodies of water. LOUAYA et al.; [16] took the same approach in their geomorphological study of the Nador lagoon complex (Morocco). The same is true of the work of [17] on surface variations in the Burullus lagoon (Egypt) through the acquisition of Landsat images between 1973 and 2011.

Lake Hebe shrank by 12.33 ha between 1988 and 2018, a period of 30 years. This loss of lake surface area is due to developments in the watershed, reflecting the filling that took place during this period. These results corroborate those of [18] from 1955 to 2004 on Banco and Cocody bays and [14] from 1988 to 2015 on Bacon and Adaou lakes, which show surface area losses of 90 ha, 60 ha, 16.65 ha, and 4.23 ha, respectively, caused by the filling of the watershed. The lake is therefore undergoing regression or filling due to both natural and anthropogenic phenomena. These results confirm those obtained by [19] on coastal morphodynamics in the sub-prefecture of Grand-Popo and AGBANI [20] on fluvial-lacustrine dynamics in southwestern Benin.

5. Conclusion

The spatio-temporal analysis of Lake Hebe over a period of thirty years (1988-2018) highlights the morphological changes undergone by this coastal lake environment. Thanks to the complementarity between bathymetry and remote sensing, the study reveals a gradual regression in the surface area of the lake, morpho-sedimentary dynamics marked by the appearance of shoals and depressions, and an alteration in the “V” and “U” type bathymetric profiles linked respectively to erosion and sediment accumulation.

These changes are closely linked to anthropogenic pressures on the watershed, including land clearing, urbanization, and intensive use of agricultural inputs, but also to natural factors such as seasonal variations and internal hydrodynamic processes. The decrease in lake surface area, estimated at 12.33 ha over three decades, reflects the gradual filling of the lake, affecting its water capacity and ecological stability.

In response to these challenges, the study proposes decision-making tools based on spatial analysis and environmental mapping for the sustainable management of Lake Hebe. It highlights the need for an integrated approach, combining environmental monitoring, watershed management, and awareness-raising among local stakeholders, in order to preserve the ecological, economic, and social functions of this lake system.

Abbreviations

TM	Thematic Mapper
ETM	Enhanced Thematic Mapper
OLI	Operational Land Imager
ROI	Regions of Interest
DDM	Digital Depth Model
DEM	Digital Elevation Model

Conflicts of Interest

The authors declare no conflicts of interest.

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