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LAND USE DYNAMICS AND MORPHOLOGICAL EVOLUTION OF MAN-MADE LAKE SYSTEM OF YAMOUSSOUKRO, CÔTE D'IVOIRE

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Abstract

The municipality of Yamoussoukro encloses ten man-made lakes which have been designed for the embellishment of the city and the regulation of rainwater. However, despite their ecological, tourist and economic importance, human activities in the lake watersheds are causing a deterioration in water quality and siltation of the lakes' reservoirs. A study of land use was carried out through an analysis of satellite images from 1988 to 2018, coupled with a sedimentological study to assess the dynamics of land use and its impacts on the man-made lake system of Yamoussoukro. Land use and bathymetric maps show that the watershed suffered a significant degradation from 1988 to 2018. The resulting erosion, wastewater and household waste dumped into the lakes through a lack of adequate sanitation system accelerate the deterioration of the lake environment. The siltation and eutrophication of the Yamoussoukro lakes are very noticeable and pronounced. We are thus witnessing the gradual disappearance of these water bodies. The restoration of the integrity of the lakes and the implementation of a monitoring plan for the lake environments of Yamoussoukro city are necessary to embellish the city, improving the quality of the environment, developing tourism and preserving biodiversity.

Keywords*: Land use; Bathymetry; Siltation; Eutrophication; Yamoussoukro*

Introduction

Sediment transport is identified as cause of several disturbances: soil losses in urban or agricultural areas, deterioration in the quality of water, clogging of water treatment filters and siltation of navigation channels, reservoirs and ports [1]. Therefore, studies to predict and control sedimentation in rivers, reservoirs and estuaries are of great importance for their management [2-6].

Agricultural activities, rapid and uncontrolled urbanization increase the transport of suspended sediments and affect the morphology of water reservoirs [7-10].

The city of Yamoussoukro, the political and administrative capital of Côte d'Ivoire, is home ten man-made lakes since the 1970s for its embellishment. These lakes are also receiving environments for rainwater and water from wastewater treatment plants. Unfortunately, these lakes, which cover an area of about 140 ha, have lost their aesthetic charm and are almost completely colonized by aquatic plants [11].

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Indeed, siltation and eutrophication phenomena have intensified to such an extent that some lakes have almost lost their volume [12]. The rapid siltation of the lakes of Yamoussoukro is due to sediment transport, linked to erosion in the watershed due to human activities, including urbanization and agriculture. Furthermore, accelerated eutrophication is due to the discharge of untreated wastewater and solid waste into the lakes and the lack of a lake monitoring and maintenance plan [13].

The objective of this study is to evaluate the dynamics of land use and the evolution of the morphology of the man-made lake system of Yamoussoukro.

Site and Methods

Study site

The city of Yamoussoukro is in the central part of Côte d'Ivoire, between 6°40' and 7° North latitude and between 5°10' and 5°20' West longitude. The municipality of Yamoussoukro has ten (10) artificial lakes (Fig. 1).

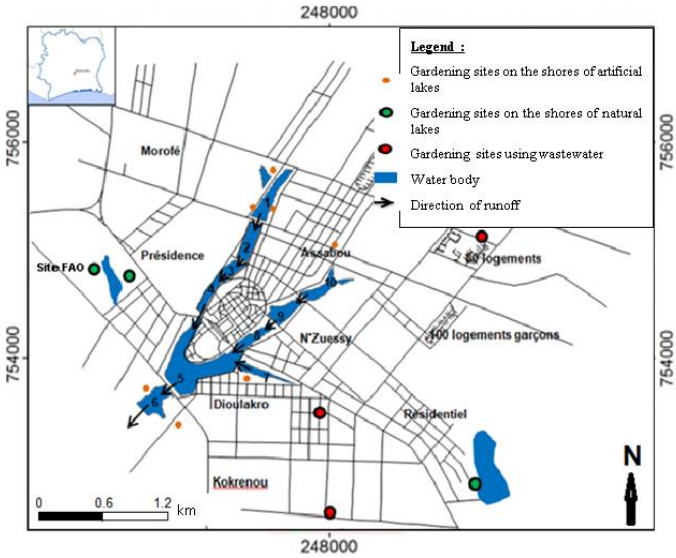


Fig.1. The ten (10) man-made lakes of Yamoussoukro [11]

The ten man-made lakes of Yamoussoukro represent a complex system that communicates with each other by gravity. At these communication structures, it is the overflow from the immediate upstream lake that flows into the adjacent downstream lake. The relief of the area is not very uneven, the average altitude is 200 meters. It is characterized by plateaus with clay, granitic and sandy soils in places [12].

The catchment area of this lake system covers 56.28km^2 and is part of the urban master plan of the city of Yamoussoukro.

These small lakes covered a total area of about 140ha [14]. However, the lakes of Yamoussoukro are threatened by eutrophication phenomena, with the result that their surfaces are colonized by aquatic plants.

With regards to climate, Yamoussoukro is located in the tropical regime, characterized by four seasons including two rainy and two dry seasons. Rainfall is highest from April to June (120-170mm) and from September to October (110-150mm). On the other hand, rainfall is lower from November to March (10-90mm) and from July to August (80-110mm). The average annual rainfall is about 1150mm with a standard deviation of 150mm and a coefficient of

variation of 0.13. *N'Guessan et al.*[15] highlight a trend towards shorter rainy seasons in the Yamoussoukro region.

Characterization of land use dynamics and evolution of the surface areas of the man-made lakes of Yamoussoukro

The methodology for characterizing the dynamics of land use and the evolution of the surface areas of the man-made lakes of Yamoussoukro is based on the use of satellite data and field observations. Three Landsat satellite images (LT05_L1TP_197055 of 23/12/1988; LE07_L1TP_197055 of 16/02/2000; LC08_L1TP_197055 of 09/02/2018) covering the area occupied by the ten lakes have been used. The unsupervised and supervised classification were applied in this study with the maximum likelihood algorithm.

The dynamics of land use are assessed by the spatial and temporal variations in the areas of land use classes between 1988 and 2018. The diachronic analysis of the images covering the study area made it possible to better appreciate the dynamics of the occupation of the basin. The transformation rates of the different land use classes are thus given by the following formula [16]:

$$T = 100 \times \left(1 - \left(\frac{S_i}{S_{i+1}} \right)^{\frac{1}{n}} \right),$$

where: T - Conversion rate; S_i - Area of the theme on the date 1; S_{i+1} - Area of the theme on the date 2; n - Number of years between the two dates.

Characterization of suspended solids and the nature of sediments

The data concerning the physico-chemical parameters, in particular suspended solids, were collected according to the hydrological seasons from June 2010 to June 2013. Sampling was carried out at 15 sampling points spread over all the ten artificial lakes (Fig. 2). For stations with depths exceeding 2 m, samples were taken at 0.5 and 2m depth. Water samples were taken using a hydrological bottle and then packaged in labelled vials.

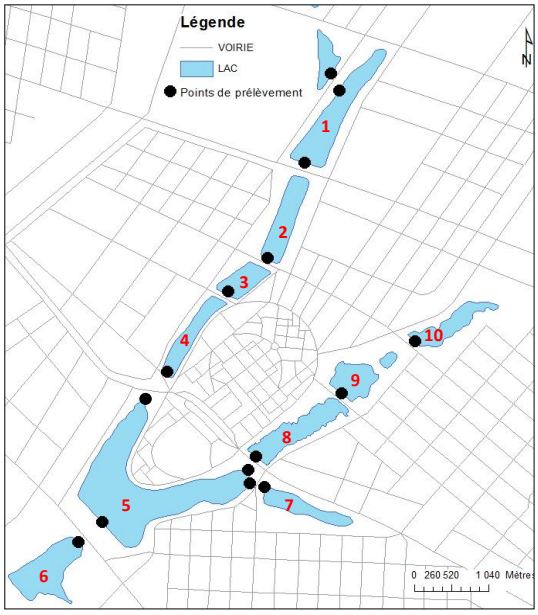


Fig. 2. Sampling stations in the man-made lakes of Yamoussoukro

Suspended sediment concentrations were determined by filtering the samples through 0.45 μm millipore filters and then determining the oven-dried weight of the filtered sediment [17].

The nature and grain size characteristics of sediments in the lakes were determined through 32 sediment samples collected from the lake bottoms and shorelines. Bottom sediment samples were collected using a Vann Veen bucket. The sediments were subjected to dry sieve analysis and the sieve parameters were determined using conventional methods [7, 18]. Mean grain size, grading index and skewness were determined using the methods of *Friedman* [19] and *Folk* [20].

Characterization of the morphology of the bottom of the man-made lakes of Yamoussoukro

The bottom morphology of the lakes was characterized using bathymetric surveys. These surveys were conducted using a Lowrance LMS-160 type sonar. The bathymetric surveys were conducted using a frequency of 160 kHz which does not allow transmitted signals to penetrate the mud [21].

Out of the ten man-made lakes, bathymetric surveys could only be conducted on three lakes: lakes 5, 9 and 10 (Fig. 2). Lakes 2, 3 and 4, known as crocodile lakes, because they contain many crocodiles and therefore present risks to navigation. In addition, lakes 1, 7 and 8 were almost covered by invasive aquatic plants on the shoreline and contain debris on their water bodies. It was therefore impossible to navigate on these lakes to conduct bathymetric surveys.

The radials were oriented in two main directions to cross the water body lengthwise and widthwise. In order to clearly define the shape of the lakes, the bathymetric surveys were supplemented by topographic surveys. The measurements were made using a TC 705 total station, Neika model. On each lake, fixed landmarks, whose recorded geographical coordinates, were chosen as the reference station for measurements.

Bathymetric maps were produced using ArcGis software based on a corrected satellite image. The interpolation method used is the IDW (Inverse Distance Weighting).

Results

Land use dynamics in the commune of Yamoussoukro

The 1988, 2000 and 2018 land use maps generally indicate four types of landscape units: forest, bare and built soils, water bodies, and crops and fallows (Fig. 3).

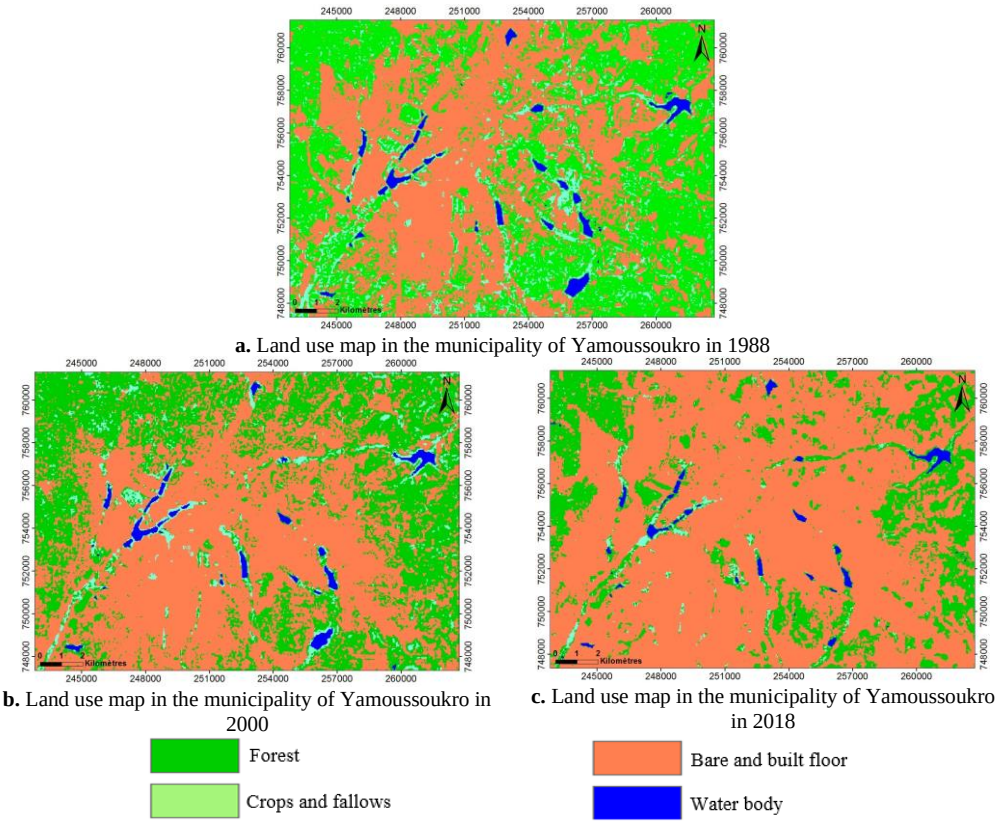
Land use maps show that from 1988 to 2018, the area of forest, crops and fallows and water bodies decreased significantly in favor of bare and built land areas. Indeed, the areas of forest, crops and fallows and water bodies have been reduced by 51.71%, 82.75% and 46.37% respectively (Table 1). On the other hand, the area of bare and built land increased by 76.92%.

Table 1. Evolution of landscape units in the municipality of Yamoussoukro from 1988 to 2018

	1988		2000		2018		Surface area evolution from 1989 to 2018	
	Sq km	%	Sq km	%	Sq km	%	Sq km	%
Forest	248.70	50.48	214.34	45.29	120.10	24.40	-128.60	51.71
Crops and fallows	32.53	6.60	4.95	1.05	5.61	1.14	-26.92	82.75
Bare and built	205.69	41.75	249.49	52.71	363.90	73.92	+158.21	76.92
Water body	5.78	1.17	4.51	0.95	3.10	0.63	-2.68	46.37

- lost area; + surface gained

The areas of the man-made lakes have been reduced over time. Their surfaces are sometimes occupied by aquatic plants (see Figure 3).



a. Land use map in the municipality of Yamoussoukro in 1988

b. Land use map in the municipality of Yamoussoukro in 2000

c. Land use map in the municipality of Yamoussoukro in 2018

Fig. 3. Land use maps in the district of Yamoussoukro from 1988 to 2018

Analysis of the images covering the study area shows that from 1988 to 2018 the lakes located in the heart of the city are more affected by siltation phenomena. This can be seen through the rate of reduction in the area of lakes 10, 9, 8, 7 and 5 (Table 2).

Table 2. Evolution of the surface areas of the man-made lakes of Yamoussoukro from 1988 to 2018

	Surface in 1988 (ha)	Surface in 2000 (ha)	Surface in 2018 (ha)	Surface area evolution from 1988 to 2018 (ha)	Change rate in surface area from 1988 to 2018 (%)
Lake 1	15.68	15.39	11.56	-4.12	26
Lake 2	12.80	12.63	12.33	-0.47	04
Lake 3	7.92	7.77	7.59	-0.32	04
Lake 4	10.02	9.72	9.69	-0.33	03
Lake 5	46.38	45.95	36.95	-9.43	20
Lake 6	11.81	10.77	9.55	-2.26	19
Lake 7	9.21	7.30	6.84	-2.37	26
Lake 8	11.08	11.23	7.96	-3.12	28
Lake 9	11.35	10.55	7.11	-4.24	37
Lake 10	12.60	11.23	4.18	-8.41	67

State of the environment of the man-made lakes of Yamoussoukro

Field observations showed that silting and eutrophication are quite noticeable on the lakes (Fig. 4). The silted parts of the lakes are used for food crops. Only lakes 2, 3 and 4 have a good conservation aspect.

a. Overview of silting and eutrophication phenomena on Lake 1

b. Development of food crops on the shoreline of Lake 6

c. Household waste dumps on the shoreline of Lake 5

d. Overview of Lake 2 relatively well preserved

Fig. 4. Overview of the environment of the lakes of Yamoussoukro

Disposal of aquatic plants by the municipality

The methods used to restore the surface of water bodies are manual mowing of aquatic plants (Fig. 5). The observation is that once removed, these plants are deposited on the banks and can therefore enrich the water body after their decomposition. Indeed, the plants stored on the banks are not completely removed.

a. Uprooting of aquatic plants

b. Plants stored on the shoreline

Fig. 5. Manual mowing and storage of aquatic plants in Yamoussoukro lakes

Concentrations of suspended solids in the lakes of Yamoussoukro

The solid loads of the lakes of Yamoussoukro vary according to the rainy seasons. Suspended solids concentrations are higher during the rainy seasons (Table 3). Lakes 7 and 10 have more suspended solids than the others.

Binocular observation of the particles collected on the filters showed the presence of organic and inorganic constituents. The solid charge corresponds to materials ranging from the size of colloids to that of clays and even sometimes of sands. Organic constituents contain

mainly plant debris and insects. The most abundant inorganic fraction is mainly composed of clay and detrital quartz.

Table 3. Average values of suspended solids concentration in the man-made lakes of Yamoussoukro

	Suspended solid concentration (mg/L)	
	Dry season	Rainy season
Lake 1	12.50	18.50
Lake 2	17.00	31.20
Lake 3	6.00	11.40
Lake 4	12.00	16.50
Lake 5	9.67	15.98
Lake 6	5.00	10.40
Lake 7	30.00	52.00
Lake 8	7.50	18.40
Lake 9	5.50	11.60
Lake 10	20.40	49.00

Sedimentary facies of the lakes of Yamoussoukro

The summary description of the surface sediments of the lakes highlights two lithological facies: sands and vases. The silt is predominant and represents about 60% of the sediments collected.

The average particle size of the sands encountered in the sediments of the lakes of Yamoussoukro is between 300 and 1850µm (Table 4). These are generally medium to coarse sands with an average grain size of 625µm. The sands on the main axis of the lakes are generally coarse to medium. They contain a small proportion of fine elements.

Table 4. Characteristics of the sediment of the lakes of Yamoussoukro

Lake	Station	Position		Description	
		X	Y	Average grain size	Facies
Lake 1	$S_{1\text{-}E}$	249466	756907	483	Medium sand
	$S_{1\text{-}M}$	249199	756696	< 63	Mud
Lake 5	$S_{5\text{-}1}$	247694	754174	375	Medium sand
	$S_{5\text{-}2}$	247789	754178	< 63	Mud
	$S_{5\text{-}3}$	247534	753879	303	Medium sand
	$S_{5\text{-}4}$	247652	753888	< 63	Mud
	$S_{5\text{-}5}$	247586	753618	338	Medium sand
	$S_{5\text{-}6}$	247492	753592	646	Coarse sand
	$S_{5\text{-}7}$	247726	753726	< 63	Mud
	$S_{5\text{-}8}$	247642	753557	405	Medium sand
	$S_{5\text{-}9}$	247624	753468	1006	Coarse sand
	$S_{5\text{-}10}$	247868	753689	< 63	Mud
Lake 6	$S_{6\text{-}E}$	247357	753321	< 63	Mud
	$S_{6\text{-}S}$	247002	752933	1850	Coarse sand
Lake 7	$S_{7\text{-}S}$	248658	753741	< 63	Mud
Lake 8	$S_{8\text{-}M}$	248867	754225	< 63	Mud
	$S_{8\text{-}S}$	248590	753952	800	Coarse sand
Lake 9	$S_{9\text{-}S}$	249243	754387	< 63	Mud
Lake 10	$S_{10\text{-}S}$	249724	754785	1836	Coarse sand

Morphology of the lake bottom

Bathymetry on the three lakes showed that the small lakes (9 and 10) are in a state of advanced eutrophication, so that the navigable surface area of each lake represents only about one-third of its initial surface area. Similarly, the depths are shallow (Figs. 6, 7 and 8).

Lake 5, the largest lake is subject to siltation and eutrophication in its northeastern part where it receives waters from the drainage system that mobilizes erosion products.

For lakes 9 and 10 it is also the northeastern part that we have a strong accumulation of erosion products. These deposits obey the direction of flow of the rainwater that mobilizes the eroded products and accumulates them on the banks of the lakes.

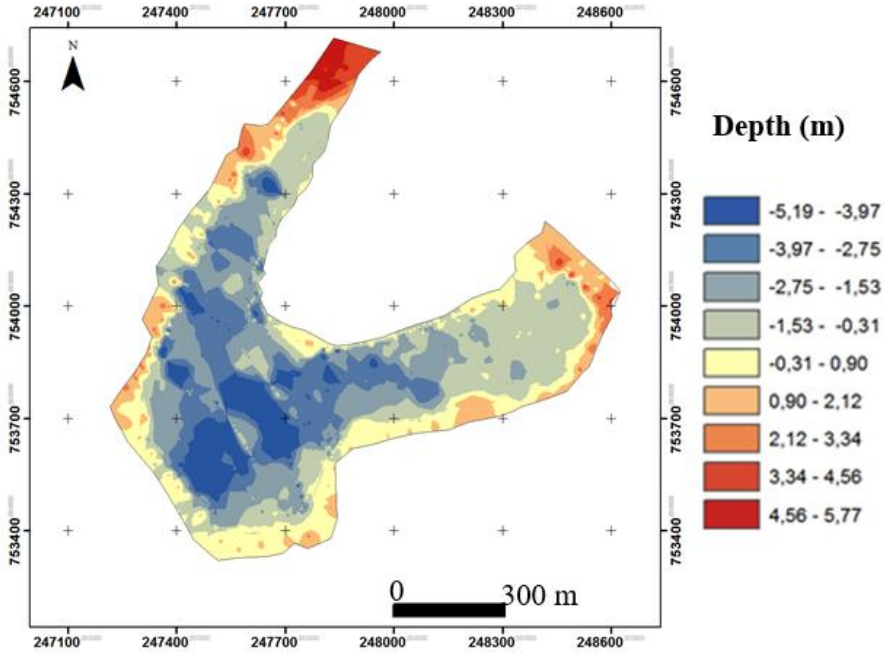


Fig. 6. Bathymetric map of Lake 5, June 2013

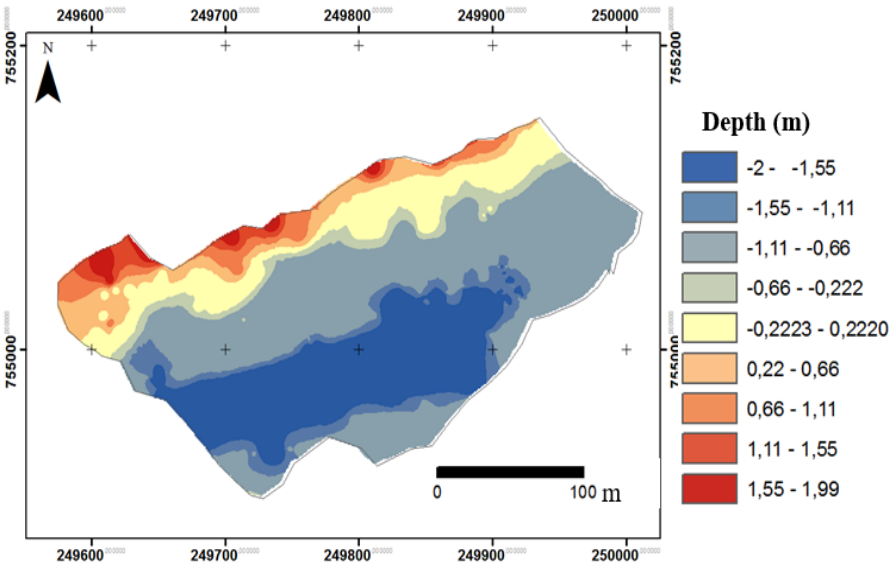


Fig. 7. Bathymetric map of Lake 9, June 2013

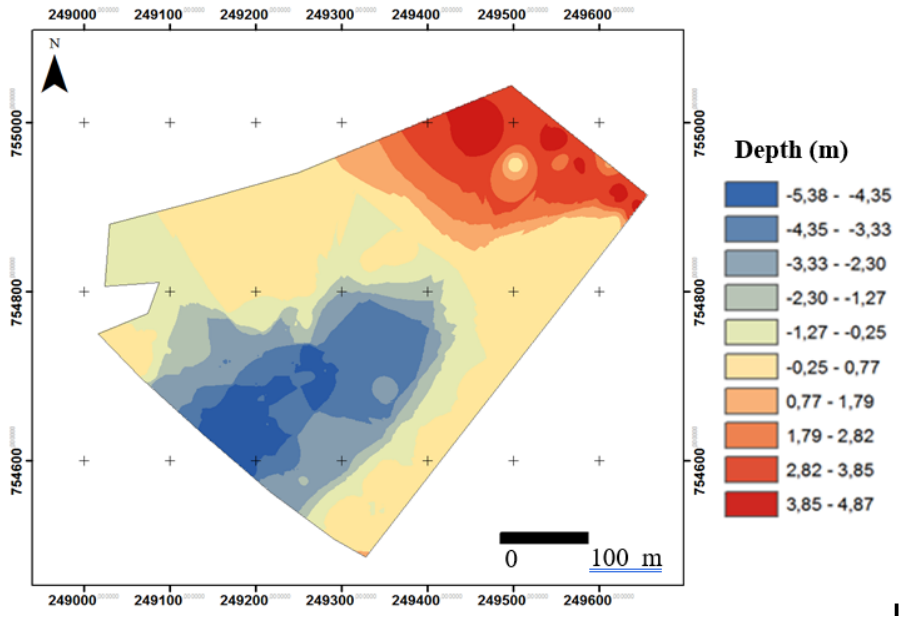


Fig. 8. Bathymetric map of Lake 10, June 2013

Discussions

The man-made lakes of Yamoussoukro were designed in the 1970s to embellish the city. They are also receiving environments for stormwater and effluent from wastewater treatment plants. However, wastewater treatment plants are mostly non-functional. As a result, the lakes receive untreated wastewater, which is a major source of pollution. In addition, erosion of the heavily urbanized watershed and the dumping of household waste on the shores of lakes contribute to filling the bottoms of these water bodies. Thus, these lakes are threatened by siltation and eutrophication phenomena [11-14]. The pollution of the lakes of Yamoussoukro is characterized by the presence of various types of suspended matter (detritic particles, household waste, plant and animal debris, etc.) and a massive presence of plants on the surface of these lakes. According to *Parinet et al.* [11] and *N'Guessan et al.* [14] the malfunctioning of wastewater treatment plants results in the discharge of untreated wastewater into the lakes, resulting in significant enrichment of these water bodies with nutrients and an increase in phytoplankton biomass.

Land use maps showed a significant reduction in vegetation cover in the district of Yamoussoukro, which can intensify erosion and sediment transport to the lakes. Sedimentation phenomena in lakes reduce their volume and lifespan [4, 8, 22, 23].

Bathymetric and topographic surveys conducted on the lakes showed that the man-made lakes of Yamoussoukro are shallow. Lake 5, the largest lake, has a maximum depth of 5 m towards its outlet. Of all the lakes, Lake 5 has the largest water reserve due to its size. The other lakes are quite confined and threatened by siltation and aquatic plants.

The significant reduction in their surface area by aquatic plants and the physico-chemical characteristics of the water reveal a tendency towards hyper-eutrophication [12]. The lack of data on the initial topography of these water bodies does not allow us to assess the rate of reduction in their capacity.

The restoration of integrity and the implementation of a monitoring plan for the lakes of Yamoussoukro city would contribute, as suggested *N'Guessan et al.* [11], to the embellishment of the city, improving the quality of the environment, developing tourism and preserving biodiversity.

Conclusion

The study of the dynamics of land use in Yamoussoukro City from 1988 to 2018 reveals a decline in vegetation cover in favor of bare soils and built areas. The solid transport resulting from the erosion of the basin causes solid loads in the lakes of Yamoussoukro.

This study also produced a bathymetric map of three accessible lakes. It showed that the lakes of Yamoussoukro have a shallow depth. The maximum depth of the largest lake (Lake 5) is about 5m. This first bathymetric survey is presented as reference data to monitor over time the siltation rate of the lakes of Yamoussoukro and the variation in lake capacity. Siltation and eutrophication are noticeable on the lakes.

The granulometric and mineralogical analyses carried out on the sediments collected during this study showed that the sediments that fill the bottom of the lakes are made up of mud, fine sand and medium sand. The sands present in the sediments are mainly medium to coarse, with an average particle size of 625µm.

The restoration of the integrity of the lakes and the implementation of a monitoring plan for the lake environments of the city of Yamoussoukro are necessary for the embellishment of the city, the improvement of the quality of the environment, the development of tourism and the preservation of biodiversity.

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