

Leveraging Remote Sensing and GIS in 3D Modeling of a River Section for Sandbar Assessment: The Case of the Mbam River in Cameroon

by Frédéric Laurent Esse Esse,
Blaise Ngwem Bayiha,
Philippe Mbevo Fendoung,
Yota Manfouo Kerena,
Moussa Sali, Emmanuel Yamb Bell

The aim of this article is to utilize remote sensing in the bathymetric study of a river section, by integrating GIS into 3D modeling of the seabed in order to measure, map, and assess sediment accumulation for potential exploitation of sandbanks.

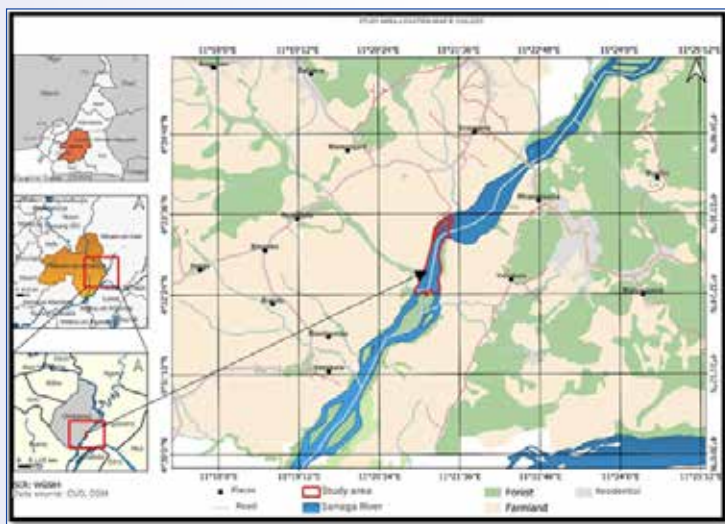


Fig. 1 - Location of the study area.

The seabed is an essential component of the Earth system and contains a diversity of sedimentary resources of significant economic interest, particularly in the construction and public works sector. These resources include sandbanks and marine aggregates, which are used as construction materials in the production of concrete and mortar, as components of embankments, and as granular fillers for infrastructure projects. During flood periods, sediment movement in rivers can be affected [1], thus increasing the volume of deposits, and this variation in sediment flow could be amplified, as the frequency and intensity of floods are expected to increase with climate change [2-3]. Globally, the demand for granular materials is increasing, driving more efficient and sustainable exploration of seabed sedimentary resources. A large amount of accurate data on river cross-sections is essential for predicting river levels [4]. However, data measured on river cross-sections are generally scarce. A major technical challenge in seabed exploitation is the accurate detection of sediment accumulation zones, as well as their detailed mapping at a spatio-temporal scale compatible with industrial planning. The literature indicates that several methods

are used to define the dimensional characteristics of rivers and their banks. LiDAR techniques have been widely used to describe dry riverbank areas, excluding regions covered by water [5,6]. Airborne techniques LiDAR also presents limitations for underwater terrain measurements [7]. Traditional bathymetric surveys or SONAR techniques are alternative solutions for obtaining measured data on river cross-sections [8]. An effective method involves performing bathymetric surveys using the multibeam method. echo sounder (MBES) », these surveys provide topographic data of the underwater relief, but their interpretation requires advanced geospatial processing to extract sedimentary features [9].

For several years, sand mining in Cameroon has been carried out on a small scale, often chaotic and without proper technical oversight. On the banks of rivers like the Mbam, extractions are generally done by hand or with rudimentary equipment, without prior site surveys or environmental monitoring. The sale of marine sand is an economic activity that, while barely meeting the needs of local populations, does not generate optimal yields due to the artisanal or village-based nature of the operation. This method, although widespread,

has numerous consequences: riverbank erosion, destruction of riparian vegetation, conflicts over resource use, and low profitability for operators. Faced with the increasing demand for construction materials and the growing pressure on natural resources, it is becoming urgent to introduce modern tools to plan, regulate, and optimize this activity. Indeed, river sand is increasingly sought after, and its underwater detection remains complex. Many operators have no knowledge of the seabed topography or sand deposition zones. The rudimentary method commonly used is probing with a metal rod. This does not provide a realistic model of the river's cross-section, let alone its actual depths. Operators suffer enormous losses due to the installation of their river sand pumping equipment in areas where the bathymetry and sand deposition environments are not fully understood. They lack a three-dimensional overview of their marine environment and sometimes navigate by trial and error. Furthermore, sand-pumping vessels are sometimes blocked by rocks or deployed in areas devoid of sand. All of this leads to an underestimation and underexploitation of the river's actual marine sand resources.

The literature informs us that several methods are used to define the dimensional characteristics of rivers and their banks. LiDAR techniques have been widely used to describe dry areas of the banks, excluding water-covered regions [5,6]. Airborne techniques LiDAR also presents limitations for underwater terrain measurements [7]. Traditional bathymetric surveys or SONAR techniques are alternative solutions for obtaining measured data on river cross-sections [8]. An effective method involves performing bathymetric surveys using the multibeam method. echo “Sounder (MBES)” surveys provide topographic data of the submarine relief, but their interpretation requires advanced geospatial processing to extract sedimentary features [9]. 1D, 2D, and 3D models are available, but it has been shown that 1D models cannot accurately represent the actual physical and hydrodynamic conditions, which are essential for understanding different fluvial processes [10]. To improve our understanding of hydrodynamics and fluvial processes, the use of 1D hydraulic models in many applications is now being complemented or replaced by 2D and 3D hydrodynamic models [6, 11-19]. Geographic Information Systems (GIS) combined with three-dimensional (3D) modeling tools have transformed the way geoscientists represent and analyze the seabed. The use of GIS allows for the synthesis of heterogeneous datasets (bathymetry, backscat-

ter, sedimentary samples) into integrated 3D models, thus facilitating the visualization of sedimentary volumes and the spatial characterization of exploited deposits [20]. The application of a 3D model generates more reliable results in terms of sediment transport [21]. Furthermore, advanced statistical approaches, such as non-stationary spatial processes, allow for the inference of the geotechnical properties of sediments from sparse or irregularly distributed measurements [22]. 3D modeling is not limited to visual representation: it has also become a tool for simulating the dynamics of marine and estuarine sediments, understanding transport and accumulation mechanisms, and anticipating the potential environmental impacts of extraction operations [23]. Recent research in coastal and estuarine settings demonstrates how 3D models can highlight the relationships between seafloor morphology, hydrodynamic processes, and sediment distribution [3]. Studies related to sediment accumulation in rivers, using various methods such as modeling, observations, and remote sensing, have long been conducted at a relatively local scale, focusing on a specific river basin or coastline [24–28]. For sediment extraction to be both efficient and sustainable, it is essential to integrate robust geomatics approaches, advanced GIS, and geostatistical or numerical models capable of informing industrial and environmental decisions. This integration paves the way for more rational extraction strategies based on explanatory 3D seafloor models that consider not only resource distribution but also ecological, regulatory, and economic considerations. Investors want a three-dimensional view of their exploitation area to make informed decisions. These situations make sandbank exploitation difficult, but not impossible; the challenge lies in characterizing the underwater topography of the Mbam River in 3D to select a suitable site for industrial sandbank exploitation.

The aim of this article is to utilize remote sensing in the bathymetric study of a section of the Mbam River by integrating GIS for 3D seabed modeling, in order to measure, map, and assess the exploitable sediment accumulation. The main challenge is to highlight the potential for establishing various quarries to exploit the sandbanks along this river. The remainder of this article is organized as follows. Section 2 presents the study area, specifically the location of the river section on which the study will focus. Section 3 details the equipment used in the experimental phase and the methodology employed. In Section 4, we present the results and discuss their implications for the planning and

as all collected data is processed within the same digital interface. Figure 5 presents the primary data required for the purposes of this study.

► Satellite images of the site

one of the innovations of GIS is the creation of extensions (features) capable of providing direct access to satellite imagery. In ArcGIS software, the “ basemap “ extension allows users to obtain georeferenced images of the site.

► Acquisition of Normalized Difference Water Index (NDWI), Normalized Difference Moisture (NDMI), Index and Infrared (IR)

the Normalized Difference Water Index (NDWI) is used to monitor changes in water content in bodies of water. Because water bodies strongly absorb light in the visible to infrared electromagnetic spectrum, NDWI uses green and near-infrared bands to highlight water bodies.

The NDWI is calculated according to the following relationship:

$$NDWI = \frac{Green - NIR}{Green + NIR} \quad (1)$$

Where:

NIR (Near Infrared) is a portion of the electromagnetic spectrum located just after visible red (approximately between 0.7 and 1.3 micrometers) Green is the green band of the visible spectrum (wavelengths of approximately 0.52 to 0.60 micrometers)

Index values above 0.5 generally correspond to bodies of water. Vegetation typically corresponds to much smaller values, and built-up areas to values between zero and 0.2 [29] . Image acquisition was performed via the Copernicus remote sensing image server.

The Normalized Difference Moisture (NDMI) is a spectral index designed to estimate vegetation moisture and, by cautious extension, the water status of covered soils [30] .

The NDMI is calculated according to the relationship:

$$NDMI = \frac{Green - NIR}{Green + NIR} \quad (2)$$

Where:

SWIR (Short- Wave) Infrared) is a portion of the electromagnetic spectrum located just after the NIR (approximately between 1.3 and 2.5 micrometers).

A NDMI value between 0.2 and 0.8 indicates wet and active vegetation. In the study, deposition in-

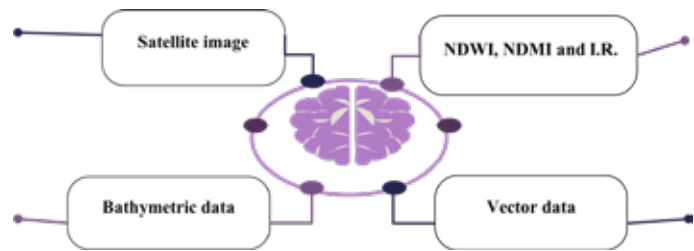


Fig. 5 - Primary data required.

stances will be separated as NDMI and NDWI .

► Vector data

The vector data required for the study area are: the cross-section of the watercourse and the length of access roads. This data is generated via the OpenStreetMap server installed in the QGIS GIS software ; the collected map data is reusable under the ODbL open license .

► Bathymetric data

Bathymetry here consists of defining the seabed topography by determining the georeferenced water depth using submerged acoustic sensors (single-beam or multi-beam echosounders, sonars, probes, etc.), a surface GNSS receiver , and by analyzing the acquired data. The steps involved in conducting a bathymetric survey vary depending on the type of vessel and the environment being surveyed; Figure 6 illustrates the steps of a bathymetric survey.

Interpolation of bathymetric data

Bathymetric data interpolation is a crucial step in transforming measured points into a continuous surface or a digital underwater terrain model (bathymetric DEM). Bathymetric measurements using echo sounders produce irregularly spaced points, making interpolation necessary to create a smooth DEM. Because the points are irregular, data interpolation is performed using the “

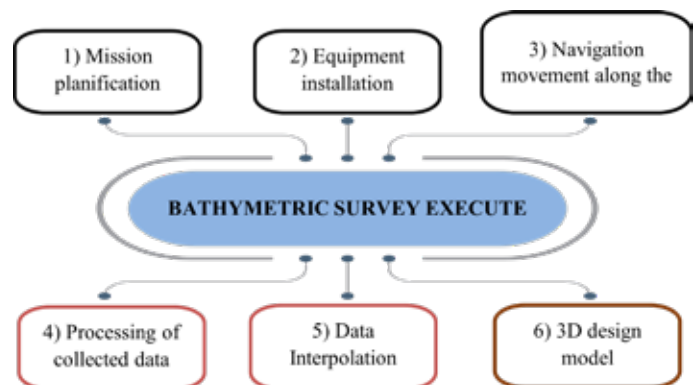


Fig. 6 - Bathymetric survey execute stage.

Kriging “ method, a geostatistical interpolation that utilizes the spatial structure of the data (semi-variogram). The interpolation method is summarized in Figure 7.

2D and 3D design of a bathymetric model of the river section

The design software used is ArcGIS . This is a software suite with extensions that allow for the creation of 2D and 3D models in different interfaces. ArcMap is used for designing a 2D bathymetric model using spatial interpolation. For designing the 3D model, ArcScene and ArcGlobe are well-suited. Layers can play various roles in the 3D view. They can float independently on other layers, drape over a separate 3D surface, or provide surface heights for draping other layers.

ArcScene cannot directly use DEM datasets as an elevation data source. Therefore, the area of interest was exported to a raster. Figure 8 shows the configuration of the bathymetry raster model.

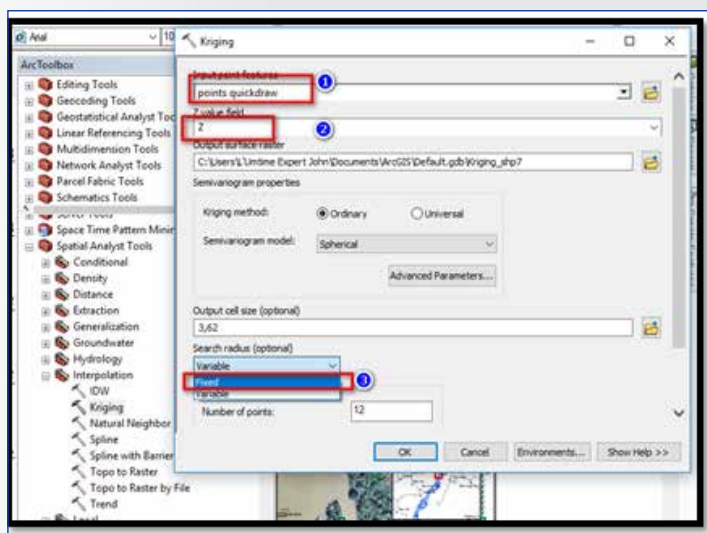


Fig. 7 - Configuration of depth value interpolation parameters.

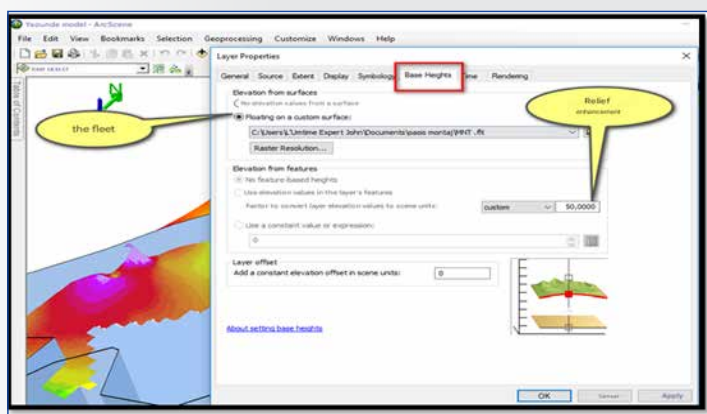


Fig. 8 - Bathymetry raster modeling configuration.

Design of the river sandbank exploitation plan

The design of a river sandbar exploitation plan takes several elements into account. The first concerns field analysis and determination of the direction of water flow. Water flow in rivers is dictated by the surface and subsurface topography. At the surface, the focus is on the geomorphology of the watercourse. This involves observing the types of channels that shape the river landscape and describing their form (braided , meandering , anastomosing, straight, etc.). Several studies have been compiled based on the analysis of channel types [31-35]. The second element involves analyzing the drainage and deposition system of the sandbars. The deposition system of sandbars depends on the type of channel traversed as well as bathymetric parameters. Indeed, in meandering channels, coarse deposits are found in the convex part of the meander. In a straight section, one essentially finds fine deposits. In anastomosing and braided channels, deposits form both upstream and downstream of the channels. The constraints on the drainage of sandbars in the river are shown in Figure 9.

The third element is the digitization of the deposition zone and the design of the extraction plan. This plan depends on the type of meander and the bathymetric model of the section being studied. Observations made using the echo sounder with its “CLEAR VU” technology are also incorporated. This technology allows for the observation of structures at depth. A sandbank can easily be distinguished from a rock or a tree trunk. Thanks to this technology, the sand deposit cover in the favorable zone is efficiently numbered. In this case, we are dealing with significant deposits. Extraction will be primarily concentrated in the area of significant sand deposits. Therefore, the industrial extraction mechanism for underwater sand is dredging. Figure 10 shows the components of the river sandbank extraction system for the adopted extraction method.

The fourth element is determining the route for the vehicles transporting the sand. The major concern in mining operations is choosing the access

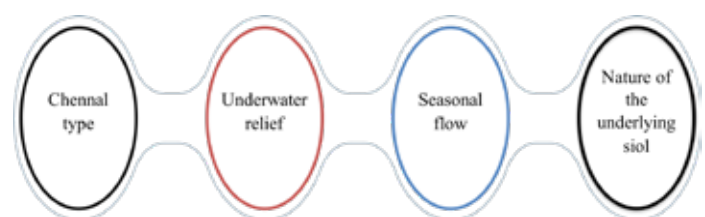


Fig. 9 - Constraints on drainage and deposition of sandbanks.

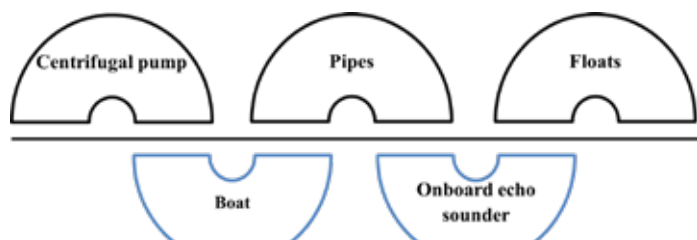


Fig. 10 - Composition of the river sandbank extraction device.

route. The technique for determining the shortest route to reach the site is network analysis. We used the network analysis algorithm of the QGIS software; Figure 11 illustrates the process of determining the shortest path.

Results and discussion - Mapping of rocky areas constituting obstacles to sand deposition

Images generated from the ESRI image server provide crucial top-down information, clearly showing the rocks that form natural barriers, reducing water flow and simultaneously hindering the free movement of sandbars in the river. Satellite imagery is just one tool; when combined with other parameters, it offers a more precise understanding of the depositional environment. Figure 12 shows the rock barrier in the studied section of the river. The observed rock formation is dense and extensive. Its impact on sandbar drainage is evident in the satellite image. The river landscape is virtually reshaped by these vegetation-covered blocks. The channel, which generally has a meandering shape, is now overhung by very compact rock formations. This creates a new anastomosing channel, making sandbar drainage difficult during the dry season.

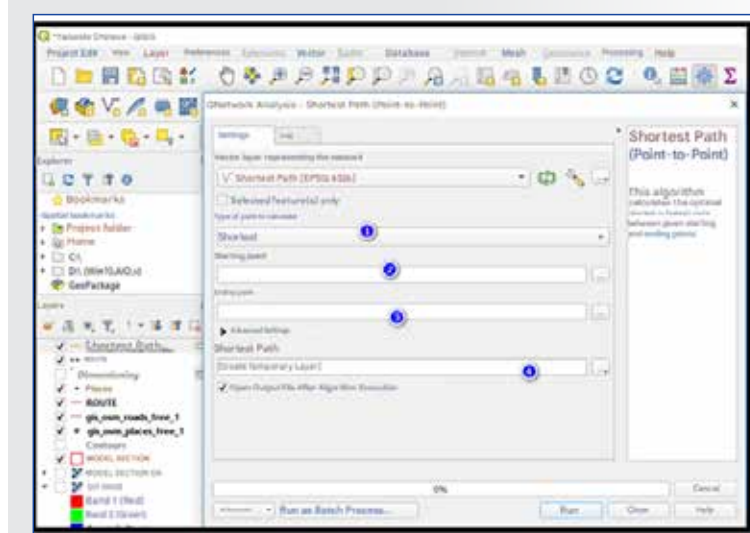


Fig. 11 - Determining the shortest path: (1) choice of path; (2) starting point; (3) arrival point; (4) exit from the shortest path.

Mapping of NDWIs

NDWIs are used to identify potential depositional zones. Areas of sand concentration at shallow depths are less saturated with water and visible in the NDWI image spectrum. Figure 13 shows the variation in NDWIs for the studied river section. DIDA: Fig. 13 - Variation in NDWI of the studied river section.

This NDWI image illustrates the spatial distribution of wetlands and aquatic areas in the studied section of the Mbam River. Blue clearly represents water surfaces, highlighting the main channel of the river as well as submerged sandbars and surrounding islets. The NDWI index is particularly useful here for effectively differentiating water from other land surfaces, including vegeta-



Fig. 12 - Identification of the rock barrier.

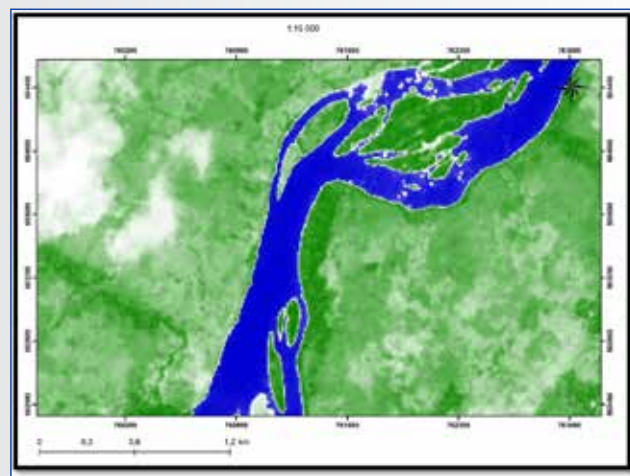


Fig. 13 - Variation in NDWI of the studied river section.

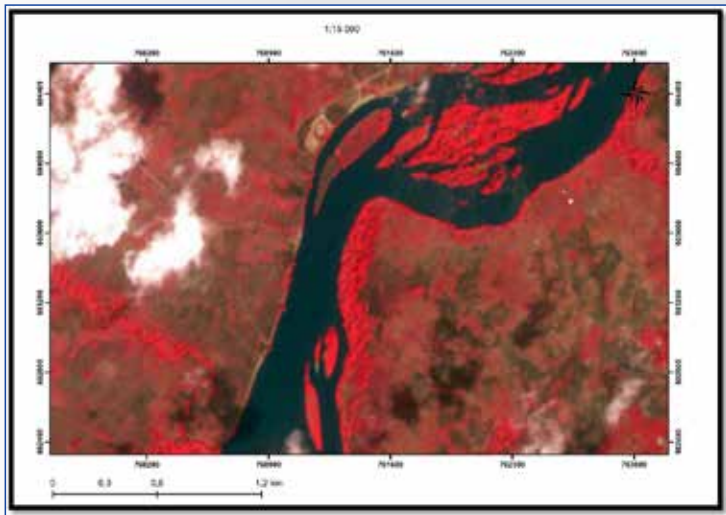


Fig. 14 - Image false color

tion (in green) and bare soil (lighter or blurred areas). This provides a clear map of areas suitable for industrial sandbar exploitation, distinguishing between open water and emerged areas. This spatial representation allows for the precise targeting of exploitable areas, while also facilitating the assessment of potential impacts on the riparian ecosystem, including the surrounding aquatic and terrestrial vegetation.

Mapping of IR

Infrared imaging allows us to distinguish between bare rock, sandbanks, and water of varying depths. It is widely used in the detection of shallow soils and geological formations. This type of image provides information on water flow direction through the visible trail of sediments carried by the water. Figure 14 shows the false-color image.

Mbam River section allows for better differentiation of the various surface and vegetation types. The vegetation appears bright red, characteristic of near-infrared images, as leaves strongly reflect this wavelength. This coloration highlights the density and health of the riparian vegetation, which plays a vital role in bank stability and the river ecosystem. The river water is represented in black or very dark blue, facilitating the precise delineation of the waterway and the sandbars within it. This

clear distinction between water and vegetation is essential for identifying potential sandbar development areas. Finally, darker or gray areas may correspond to bare land or areas with less dense vegetation. This infrared image is therefore a valuable tool for understanding the distribution of different natural environments around the river, thus facilitating the planning of environmentally sound industrial development.

Mapping of the 3D bathymetric model

The information provided in this study enabled the creation of a 3D bathymetric model of the river section; Figure 15 presents the 3D model of the Mbam river section studied.

The model derived from bathymetric data already shows us depressions at depths of 3 m, 5 m, and 6 m. We also observe areas very close to the river surface (red to purplish-pink in color). The boundaries of these depressions already constitute barriers that could impede drainage in both the dry and rainy seasons. These three depressions represent the deepest points where pumping devices could be installed. The shape of the depressions leads us to suspect that there may have been some mining activity at this site. Additional evidence, such as older images, could answer this question. However, such a basin could provide a favorable environment for sandbar deposits, as these are traps for drainage.

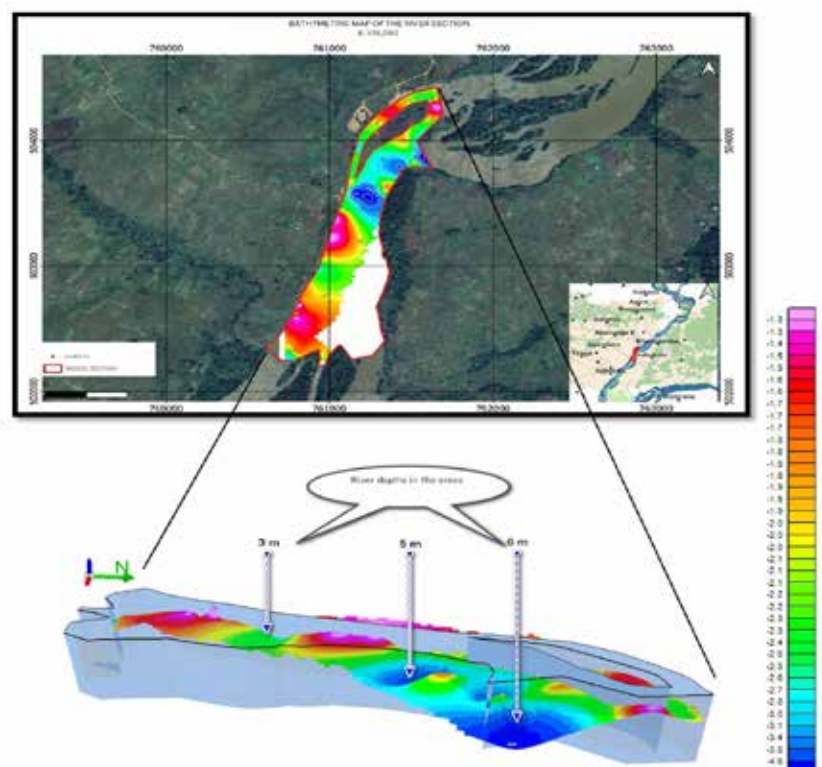


Fig. 15 - 3D model of the studied section of the Mbam River.

Site accessibility, dimensional characteristics of the sand deposition environment and estimation of the deposition volume

Site analysis is highly recommended as an approach in the decision-making process regarding the exploitation of river sandbanks. All the elements necessary for understanding the navigation and extraction environment are illustrated. This helps avoid significant financial losses. Knowing the dimensions of the waterways complements the information on depths. Indeed, a waterway can be wide but shallow, preventing the deployment of the suction dredger (navigation and pumping equipment for the sandbanks). The section of the river under study contains an island that divides the watercourse into two branches of different sizes, as shown in Figure 16.

We observed a channel approximately 80 m wide and a wider channel approximately 232 m wide. Considering field observations and echo sounder readings, we found that the water depths are very shallow in the 80 m wide channel. The 232 m wide channel, however, has significant depths. This observation led us to focus on the wider channel and identify suitable locations for dredging. Figure 17 shows the potential dredging locations.

By combining this information with the meander deposition system and the echo sounder results, the deposition environment on the cover was di-

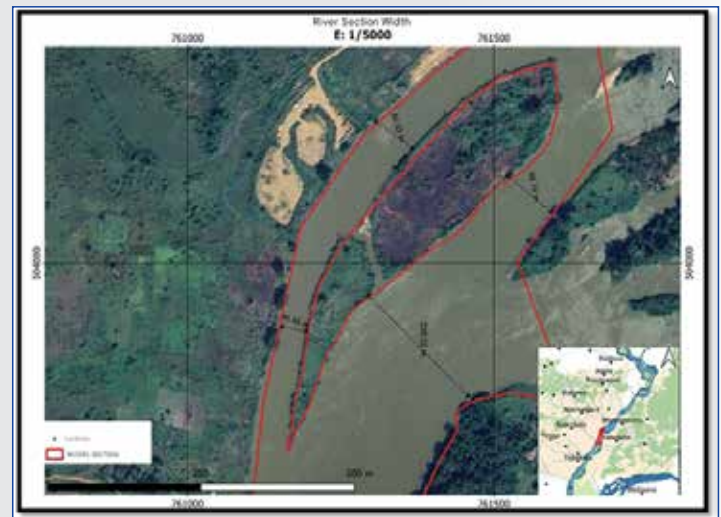


Fig. 16 - Width of the different branches of the watercourse.

gitized; Figure 18 illustrates the deposition environment of the sandbanks on the river section. An estimate of the marine sand deposits has been made, the volume of sand in deposits is estimated at more than 874866.52 m³ which makes this site a profitable location and suitable for industrial exploitation of marine sand.

Sandbank exploitation plan for the deposition area

The results of section 4.5 enabled the development of a sandbank extraction plan. Traditional operators had previously created a navigation channel by cutting through the intermediate islet between the two arms and clearing a path. This same channel will be used for modern operations, as the presence of sandbanks of significant depth has been confirmed. The former traditional storage area will be rehabilitated and adapted for the large-scale storage of sand deposits. Figure 19 presents the planned industrial sand extraction plan.

The proposed storage location optimizes the dredger's travel distance. While accessible by road, road improvements are necessary. This study has a limitation: it is incomplete. For civil engineering projects, it is essential to verify the certified quality of the material before use. Therefore, every industrial quarry must have a certified datasheet describing the geotech-

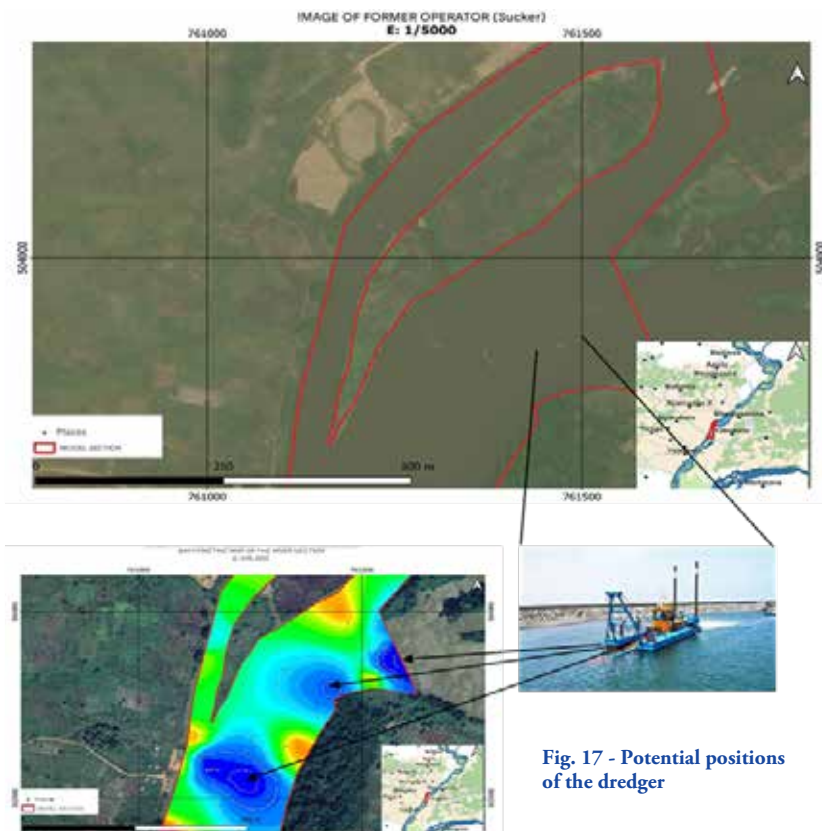


Fig. 17 - Potential positions of the dredger

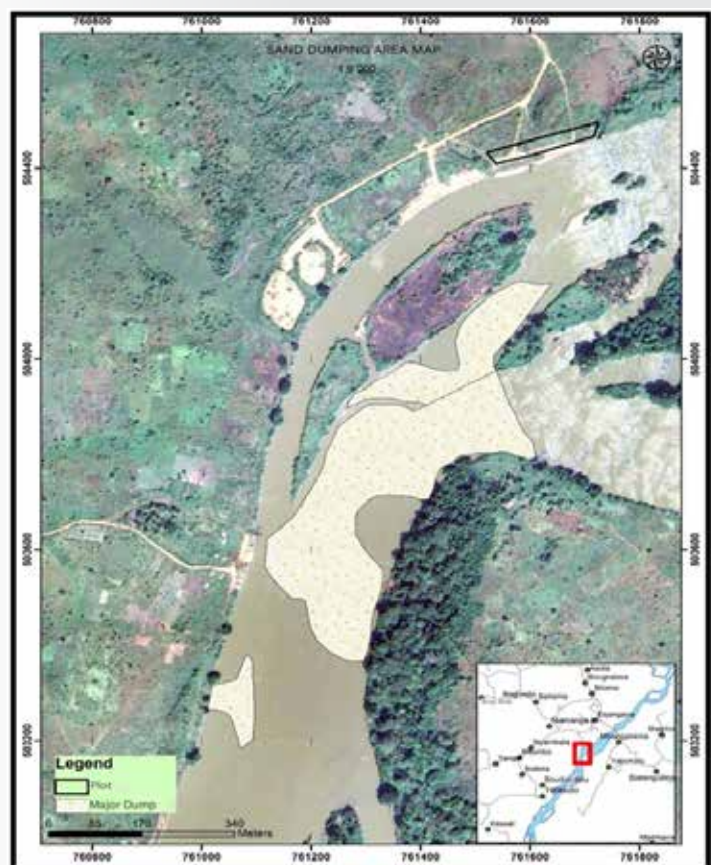


Fig. 18. Depositional environment of sandbanks on the river section.

nical parameters of its material. This confirms its suitability and effectiveness for the intended applications. Geotechnical tests are used to characterize this sand; Figure 20 illustrates the geotechnical tests required to validate the sand's use.

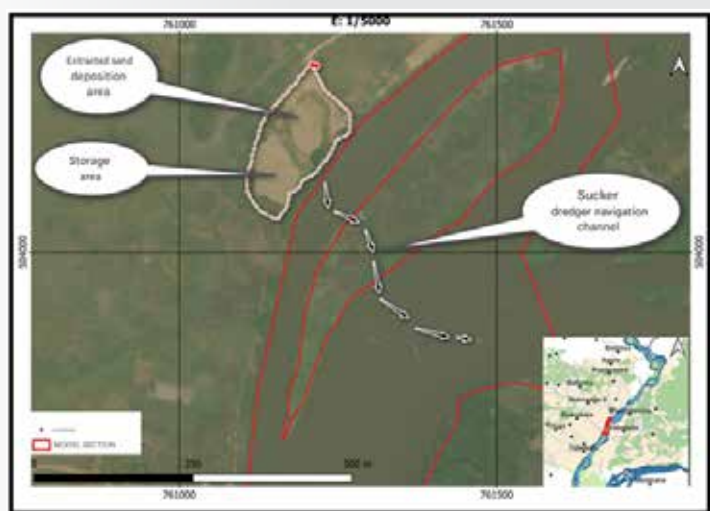


Fig. 19 - Sandbank extraction and storage plan.

Conclusion

The objective of this work was to create a three-dimensional model of a section of the Mbam River from bathymetric data in order to propose a rational management plan for the sandbanks. Several methodological steps were rigorously followed. The process began with the collection of data in the field using an echo sounder equipped with a GT52 transducer, which provided the underwater topography of the river section. This data was then integrated into a Geographic Information System (GIS), where spatial interpolation generated a Digital Terrain Model (DTM) of the riverbed. This DTM served as the basis for constructing a precise 3D model, facilitating the analysis of the distribution of sand deposits. In addition to the 3D model derived from bathymetric data, satellite imagery such as NDWI and infrared images were used to complement the analysis. The results obtained clearly identified areas suitable for sand extraction. These results show that this artisanal mining site is well-suited for industrial-scale extraction of its marine sand; the area studied could allow for the dredging of a significant quantity of sand, primarily for use in civil engineering projects, particularly in building and public works.

As a recommendation, we believe this 3D model can be used as a decision-making tool, useful for framing and planning the sustainable exploitation of this resource. Geotechnical studies must be conducted at the extraction site to ensure the safe use of this marine sand. It is essential to combine the results of this study with an awareness campaign, appropriate regulations, and the implementation of a regular monitoring system.

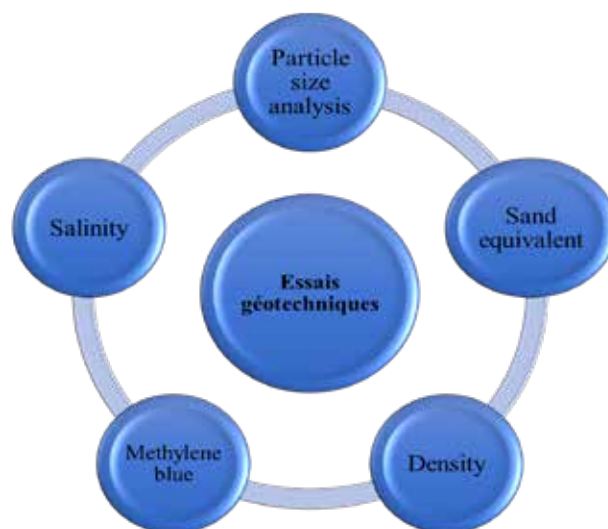
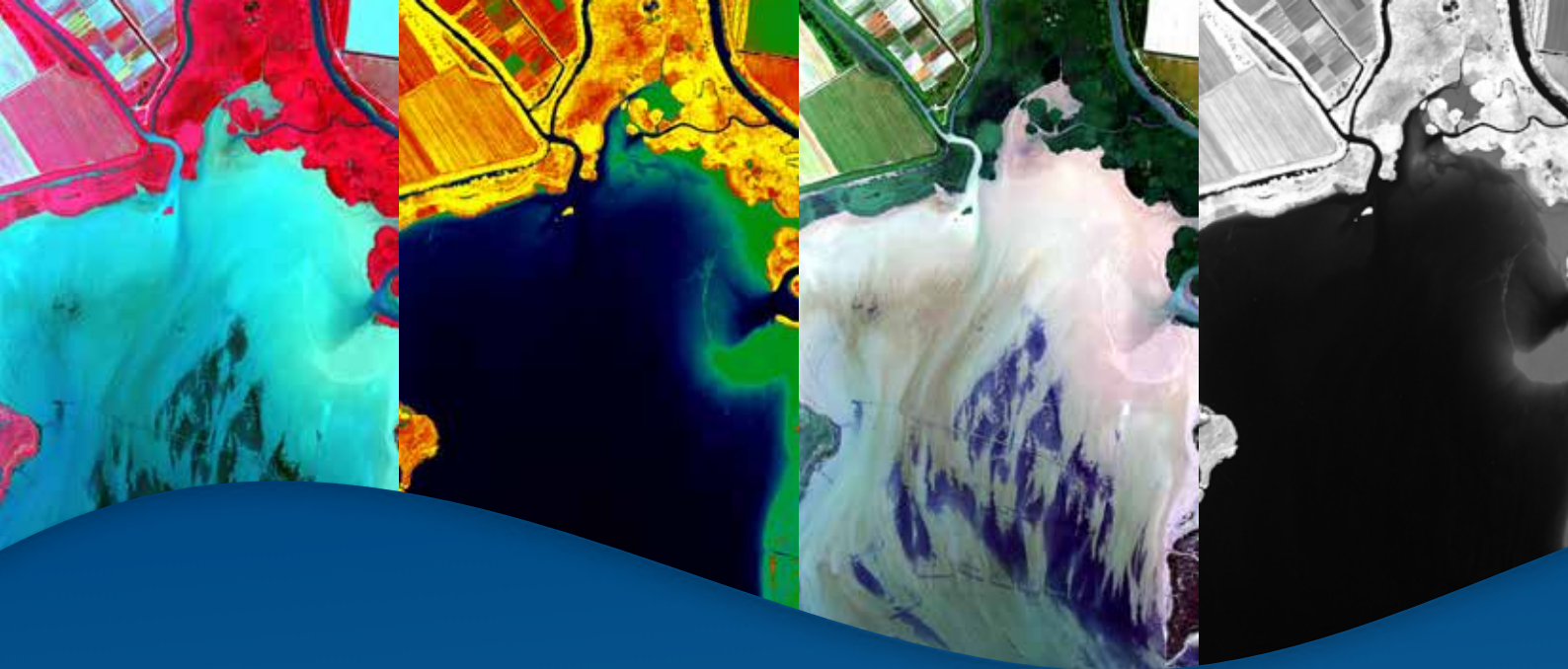


Fig. 20 - Geotechnical tests for characterizing the sand to be extracted.



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ABSTRACT

The aim of this article is to utilize remote sensing in the bathymetric study of a river section, by integrating GIS into 3D modeling of the seabed in order to measure, map, and assess sediment accumulation for potential exploitation of sandbanks.

This work is part of a broader effort to modernize the exploitation of this resource, which until now has been carried out without planning and control tools. A methodological approach combining passive and active methods was adopted. The passive approach relied on the analysis of satellite imagery, particularly NDWI (Normalized Data Wave Index) data. Difference Water Index) and infrared (IR) imaging were used to identify wetlands, depositional environments, and river dynamics. In addition, an active approach employed a GT52 echo sounder to collect precise bathymetric data on the riverbed depth. This data was then processed in a GIS environment to generate a Digital Terrain Model (DTM), a depth interpolation, and a 3D model of the river cross-section. The results enabled the identification of the main depositional areas of exploitable sandbanks and their volume, the assessment of their accessibility, and the proposal of an optimized extraction plan. This work thus provides a reliable technical basis for guiding industrial sand extraction with a focus on ecological sustainability and also serves as a decision-making tool for this economic sector.

KEYWORDS

REMOTE SENSING; GIS ; 3D MODELING ;
BATHYMETRY ; SANDBANKS ; RIVER

AUTHOR

FRÉDÉRIC LAURENT ESSE ESSE I *, BLAISE NGWEM BAYIHA I , PHILIPPES MBEVO FENDOUNG 2, YOTA MANFOUO KERENA, I MOUSSA SALI 3 , EMMANUEL YAMB BELL I

1 DEPARTMENT OF CIVIL ENGINEERING, ADVANCED TEACHERS TRAINING COLLEGE OF THE TECHNICAL EDUCATION , UNIVERSITY OF DOUALA, DOUALA 1872, CAMEROON

2 DEPARTMENT OF LAND SURVEYING , NATIONAL ADVANCED SCHOOL OF PUBLIC WORKS, PO BOX 510, YAOUNDE , CAMEROON

3 LABORATORY OF MATERIALS, MECHANICS AND CIVIL ENGINEERING, NATIONAL HIGHER POLYTECHNIC SCHOOL OF MAROUA, MAROUA 46, CAMEROON

* CORRESPONDING AUTHOR . TEL: +237 651036834. EMAIL ADDRESS :

ESSEFREDOO6@GMAIL.COM

HTTPS://ORCID.ORG/0009-0006-5113-5206

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