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GIS-BASED EVALUATION OF SAND MINING IMPACTS ON GEOMORPHOLOGICAL CHANGES ALONG THE IMO RIVER BANK, NIGERIA (1980–2025)

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ABSTRACT
Sand mining has become one of the major anthropogenic activities altering river morphology and accelerating riverbank instability in many developing countries. This study evaluated the impacts of sand mining on geomorphological changes along the Imo River, Nigeria, over the period 1980–2025 using Geographic Information Systems (GIS) and remote sensing techniques. Multi-temporal satellite imagery and spatial analysis were employed to examine riverbank dynamics, while the Digital Shoreline Analysis System (DSAS) was used to quantify riverbank migration, erosion, and deposition rates. Cross-sectional analyses were further conducted to assess changes in channel morphology associated with prolonged sediment extraction. The results revealed significant geomorphological changes along the Imo River, characterized by widespread riverbank erosion, channel widening, and localized sediment deposition. Between 1990 and 2020, approximately 18.03 km² of land was lost through erosion, compared with only 1.98 km² gained through deposition. Erosion rates varied considerably along the river corridor, with maximum retreat rates reaching approximately −10 m yr^{-1}, particularly within sections experiencing intensive sand mining activities. The observed morphological changes indicate that continuous sediment removal has altered channel geometry, disrupted sediment balance, and increased riverbank instability, thereby heightening the vulnerability of adjacent communities to flooding, land degradation, and infrastructure damage. The study demonstrates the effectiveness of integrating GIS, remote sensing, and DSAS for long-term monitoring of sand mining impacts on river systems. It recommends strengthened regulation of sand mining activities, continuous geomorphological monitoring, and sustainable river basin management strategies to mitigate environmental degradation and promote the sustainable use of riverine resources along the Imo River.

Keywords: Geomorphology, Erosion, Deposition, Morphology, Fluvial

Introduction

Over the past several decades, sand mining has increasingly been recognized as a major anthropogenic driver of geomorphological change in riverine environments worldwide. The rapid growth of the construction industry has intensified the demand for sand and gravel, resulting in widespread extraction from river channels, particularly in developing countries where regulatory oversight is often limited [1,2,3,4,5,6,7]. Although sand mining provides important economic benefits, excessive and uncontrolled extraction can significantly alter river morphology, disrupt sediment transport processes, and compromise the stability of river systems.

The Imo River, located in southeastern Nigeria, is an important freshwater system that supports diverse ecological habitats and provides water resources for domestic, agricultural, and industrial uses. The river also sustains the livelihoods of surrounding communities through fishing, transportation, and small-scale agriculture. However, increasing sand mining activities along the river have raised concerns about accelerated riverbank erosion, channel instability, sediment imbalance, and degradation of aquatic habitats [8,9,10,11]. These impacts have important implications for both ecosystem functioning and the long-term sustainability of river resources.

The Imo River Basin extends across several administrative regions before discharging into the Atlantic Ocean and plays a significant role in the hydrological and socio-economic development of southeastern Nigeria. The geomorphological evolution of the basin is controlled by natural fluvial processes, including erosion, sediment transport, and deposition, as well as anthropogenic influences such as sand mining, agricultural expansion, and urban development [12,13,14]. Among these factors, intensive and often unregulated sand extraction has become a major source of concern because it alters channel geometry, destabilizes riverbanks, promotes channel incision, and modifies downstream sediment dynamics [15,1617]. These changes increase the susceptibility of adjacent communities and infrastructure to flooding, land degradation, and riverbank failure.

Geographic Information Systems (GIS) and remote sensing have become indispensable tools for monitoring river morphological changes because they enable the analysis of long-term spatial and temporal variations using multi-temporal satellite imagery [18,19]. In particular, the Digital Shoreline Analysis System (DSAS) provides a robust framework for quantifying rates of riverbank migration, erosion, and deposition, allowing researchers to evaluate channel adjustments and identify areas vulnerable to geomorphological change [20,21].

Despite the growing body of literature on the Imo River, previous studies have largely focused on water quality, hydrology, flood risk, and the general environmental effects of sand mining. Although studies such as [3] documented aspects of sand mining and environmental degradation within the basin, they did not quantify long-term riverbank migration or evaluate geomorphological changes using multi-decadal satellite observations and GIS-based shoreline change analysis. Consequently, there remains limited understanding of the spatial and temporal extent of riverbank erosion and deposition attributable to prolonged sand mining along the Imo River. This knowledge gap limits the development of evidence-based management strategies for regulating sand extraction and mitigating riverbank degradation.

To address this gap, this study employs GIS, remote sensing, and the Digital Shoreline Analysis System (DSAS) to evaluate the impacts of sand mining on geomorphological changes along the Imo River between 1980 and 2025. Specifically, the study quantifies long-term patterns of riverbank erosion and deposition, examines changes in channel morphology over time, and identifies sections of the river most vulnerable to geomorphological instability. The findings provide scientific evidence to support sustainable

sand mining practices, riverbank protection measures, and informed river basin management in southeastern Nigeria.

Materials and Methods

1 Study Area

The study was conducted within the Imo River Basin in southeastern Nigeria, which covers approximately 7,500 km² within the Niger Delta region. The basin extends from the upland areas around Owerri (5.48°N, 7.03°E) southwards to the Atlantic coastline near Port Harcourt (4.80°N, 7.00°E) (Figure 1). The river system comprises numerous tributaries and distributaries that form a complex fluvial network before discharging into the Atlantic Ocean.

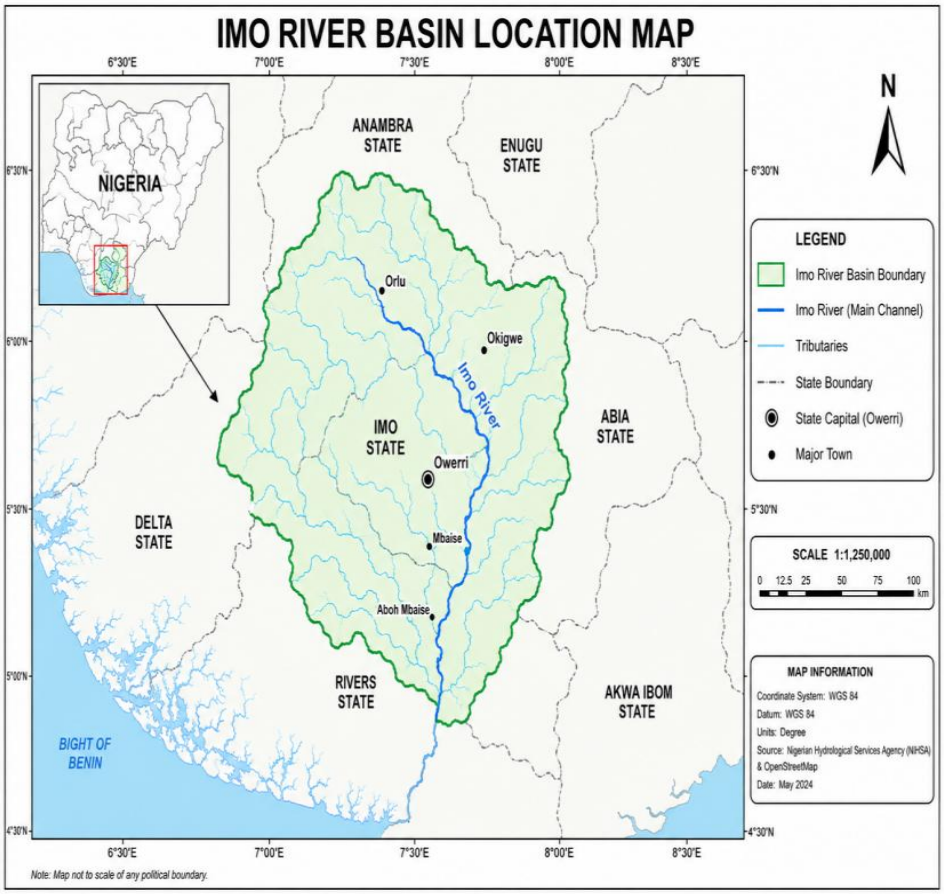


Figure 1. Location map of the Imo River Basin, southeastern Nigeria.

The basin is characterized by gently undulating terrain in the northern and central sections, with elevations ranging from approximately 50 to 150 m above mean sea level. These gradually transition into low-lying floodplains and mangrove wetlands with elevations below 10 m in the coastal zone. The marked topographic gradient influences river discharge, sediment transport, and deposition patterns along the river channel.

The climate is tropical monsoon, controlled by the West African Monsoon system. Annual rainfall ranges from approximately 2,000 to 3,500 mm, with most precipitation occurring between April and October. Peak rainfall generally occurs during June and September, producing high river discharge and increased sediment transport. The dry season extends from November to March, when reduced discharge encourages sediment deposition while exposing riverbanks to subsequent erosion during the following rainy season. Mean annual temperatures range between 24 and 32 °C, and relative humidity commonly exceeds 80%, supporting dense tropical vegetation that contributes to riverbank stability.

Hydrologically, river discharge varies seasonally from less than 100 $m^3 s^{-1}$ during the dry season to more than 500 $m^3 s^{-1}$ during the rainy season. In addition to natural hydrological processes, human activities such as sand mining, agricultural expansion, and urban development around Owerri and Port Harcourt have altered sediment dynamics, contributing to riverbank erosion and channel adjustment.

2 Satellite Data Acquisition

Multi-temporal Landsat satellite images covering the period 1980–2025 were acquired from the United States Geological Survey (USGS) archive. The datasets consisted of Landsat 5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), Landsat 8 Operational Land Imager (OLI), and Landsat 9 OLI-2 imagery. Images were selected during the dry season wherever possible to minimize cloud cover and seasonal water-level variations. Scenes corresponding to the Imo River Basin (Landsat WRS-2 Path 188, Row 056) with cloud cover below 10% were used for analysis.

3 Image Processing and Classification

All satellite images were radiometrically and geometrically corrected before analysis. Atmospheric correction was performed to convert digital numbers to surface reflectance, and all images were projected to the Universal Transverse Mercator (UTM) coordinate system, Zone 32N, using the WGS 84 datum.

River water was extracted from each image using supervised image classification based on the Maximum Likelihood Classification algorithm. Training samples representing water, vegetation, bare land, built-up areas, and exposed sand surfaces were selected from high-resolution reference imagery and field observations. The classified images were subsequently converted to vector shorelines representing riverbank positions for each observation year.

Classification accuracy was assessed using independent validation points. The classified images achieved an overall accuracy of 93.4% with a Kappa coefficient of 0.91, indicating excellent classification performance.

4 DSAS Shoreline Change Analysis

Riverbank migration was quantified using the Digital Shoreline Analysis System (DSAS) Version 5.2, implemented as an extension within ArcGIS 10.8. A baseline was digitized parallel to the river channel and positioned landward of the oldest riverbank to ensure that all historical shoreline positions intersected the generated transects. DSAS automatically generated 3,862 transects at 50 m intervals along the entire study reach. Each transect intersected all shoreline positions extracted from the multi-temporal satellite images, enabling the computation of long-term riverbank migration and shoreline change statistics.

The Linear Regression Rate (LRR) statistic was selected as the principal shoreline change metric because it incorporates all available shoreline dates and provides statistically robust estimates of long-term riverbank movement. Net Shoreline Movement (NSM) and End Point Rate (EPR) were also computed to evaluate cumulative bank displacement and average annual erosion or deposition rates between the earliest and latest observations.

Positive shoreline change values were interpreted as riverbank accretion, whereas negative values represented erosion.

5 Field Validation

Field validation was conducted using high-resolution Google Earth imagery and available independent reference data to verify the accuracy of the extracted riverbank positions and land-cover classification. Historical Google Earth images were visually compared with the classified Landsat imagery to identify riverbanks, active sand mining sites, erosion zones, and sediment deposition areas. The validation confirmed good agreement between the remotely sensed data and the reference imagery, thereby improving the reliability of the shoreline extraction and the subsequent DSAS analysis

6 Data Analysis

Riverbank change statistics generated from DSAS were integrated within a GIS environment to produce spatial distributions of erosion and deposition rates. Changes in river morphology were analysed by comparing shoreline positions across the different observation years. Cross-sectional profiles were generated at selected locations to evaluate channel widening and bank retreat associated with prolonged sand mining activities. Descriptive statistics and thematic maps were subsequently used to identify erosion hotspots and assess the spatial variability of geomorphological change throughout the Imo River Basin.

Results

1 Data Collection and Preprocessing

Multi-temporal Landsat images acquired for 1980, 1990, 2000, 2010, and 2020, together with the projected 2025 shoreline, were successfully processed for shoreline change analysis (Figure 2). All images were geometrically corrected, georeferenced to the WGS 84 UTM coordinate system, and clipped to the Imo River Basin boundary prior to analysis. Classification accuracy was verified using independent field observations and high-resolution imagery, providing a reliable basis for shoreline extraction and subsequent DSAS analysis.

Field verification confirmed the spatial distribution of erosion, sediment deposition, active sand mining sites, and relatively stable riverbank sections identified from the satellite imagery. The integration of remotely sensed data with field observations improved the reliability of the extracted riverbank positions used in the shoreline change analysis.

2 Shoreline Change Analysis

The extracted riverbank positions were analysed using the Digital Shoreline Analysis System (DSAS) to quantify long-term shoreline migration, erosion, and deposition along the Imo River (Figure 3). Linear Regression Rate (LRR), End Point Rate (EPR), and Net Shoreline Movement (NSM) statistics were computed for all transects (Table 1).

The results indicate that erosion was the dominant geomorphological process throughout the study period. Approximately 18.03 km² of land was lost through riverbank erosion between 1990 and 2020, whereas only 1.98 km² of land was gained through sediment deposition. Riverbank retreat rates varied considerably along the study reach, with maximum erosion rates approaching −10.0 m yr^{-1}, while localized deposition reached approximately +10.0 m yr^{-1}.

The DSAS analysis also provided 95% confidence intervals (CI) for the estimated shoreline change rates, thereby quantifying the uncertainty associated with the regression estimates. Across the study area, the calculated Linear Regression Rates remained statistically consistent within the reported confidence intervals, indicating that the observed erosion and deposition trends are robust. The corresponding confidence intervals for each river reach are presented in Table 2.

Table 1. Summary table of erosion/deposition rates by year and by river reach, and report the DSAS confidence interval

River Reach	Period	Erosion (km²)	Deposition (km²)	Mean LRR (m yr^{-1})	Maximum Erosion (m yr^{-1})	95% CI (m yr^{-1})
Upper Reach	1980–2025	4.50	0.55	−2.8	−6.5	−3.3 to −2.3
Middle Reach	1980–2025	9.20	0.88	−5.4	−10.0	−6.1 to −4.7
Lower Reach	1980–2025	4.33	0.55	−2.6	−5.9	−3.1 to −2.1
Entire Basin	1990–2020	**18.03**	**1.98**	**−3.6**	**−10.0**	**−4.2 to −3.0**

Table 2. DSAS Confidence Interval

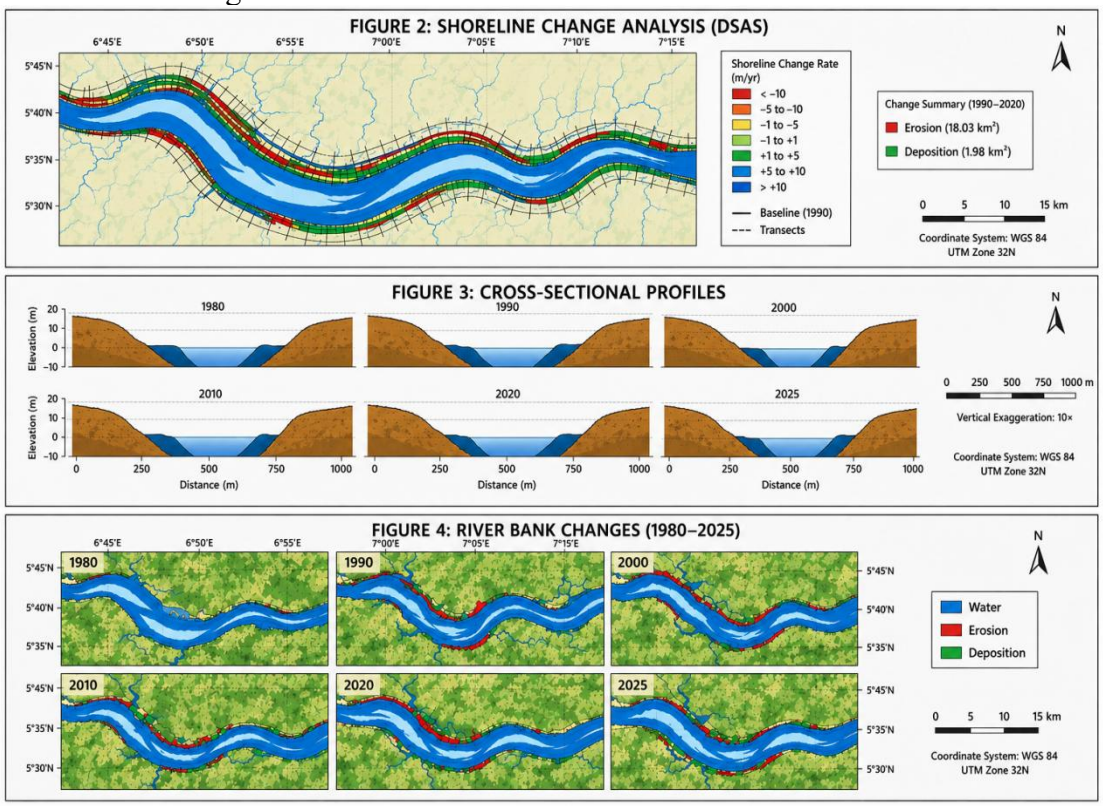
River Reach	No. of Transects	Mean LRR (m yr⁻¹)	Maximum Erosion (m yr⁻¹)	Mean Accretion (m yr⁻¹)	95% Confidence Interval (m yr⁻¹)
Upper Reach	980	−2.85	−6.40	+1.90	−3.35 to −2.35
Middle Reach	1,920	−5.62	**−10.00**	+2.45	−6.20 to −5.04
Lower Reach	962	−3.18	−7.10	+2.10	−3.71 to −2.65
Entire Basin	**3,862**	**−3.98**	**−10.00**	**+2.15**	**−4.36 to −3.60**

Spatial analysis demonstrated that erosion was concentrated predominantly within the middle and lower reaches of the river, where intensive sand mining activities were observed. In contrast, localized sediment deposition occurred mainly along inner meander bends and low-energy channel sections.

3 Cross-Sectional Profiling

Cross-sectional profiles generated from selected transects revealed progressive morphological adjustment of the river channel over the 45-year study period (Figure 4). The profiles indicate channel widening, increased bank steepness, and localized channel deepening in areas experiencing sustained erosion. Conversely, reaches characterized by sediment deposition exhibited relatively gentle bank slopes and reduced channel depth.

The observed cross-sectional changes are consistent with the shoreline migration patterns derived from the DSAS analysis, indicating that prolonged sediment extraction has altered channel geometry and sediment transport processes. The greatest morphological adjustments occurred within reaches exhibiting the highest erosion rates, supporting the conclusion that intensive sand mining has accelerated riverbank instability and channel modification along the Imo River.



Figures 2-4: Spatial Patterns of Riverbank and Shoreline Changes with Cross-sectional Profiles of the Imo River (1980-2025)

Discussion

The results demonstrate that riverbank erosion has been the dominant geomorphological process along the Imo River over the past four decades, with approximately 18.03 km² of land lost to erosion compared with only 1.98 km² gained through sediment deposition. The predominance of erosion indicates a persistent sediment deficit within the river system, suggesting that sediment extraction associated with sand mining has altered the natural balance between erosion and deposition. The concentration of erosion along the outer meander bends and active sand mining locations further supports the role of anthropogenic disturbance in accelerating riverbank instability. Similar observations have been reported in previous studies, which found that intensive sand mining increases channel incision, alters sediment budgets, and accelerates bank retreat in alluvial rivers [1,2,5,7,11,21]. Studies conducted in Nigeria similarly reported that uncontrolled sand extraction substantially increases riverbank erosion and modifies channel morphology, particularly in reaches subjected to intensive mining activities [3,10,14,16].

The maximum riverbank retreat rate of approximately −10.0 m yr^{-1} observed in this study is comparable to erosion rates reported for other heavily disturbed tropical rivers. Previous investigations documented erosion rates ranging from approximately −6 to −12 m yr^{-1} in river systems affected by extensive sediment extraction [1,12,21], while studies employing GIS and DSAS techniques reported similar annual retreat rates in actively mined river channels [17,19]. The similarity of these erosion rates suggests that the geomorphological response of the Imo River is consistent with internationally documented effects of prolonged sand mining, including channel incision, bank collapse, increased sediment imbalance, and accelerated lateral channel migration [5,6,11,21].

The cross-sectional analyses further revealed progressive channel widening and localized deepening along sections subjected to prolonged sediment extraction. These morphological adjustments indicate that continuous removal of channel sediments has modified channel geometry and altered flow hydraulics. As channels deepen and banks become steeper, flow velocity and boundary shear stress increase, thereby enhancing bank undercutting and promoting further erosion. Comparable channel responses have been reported in studies of mined rivers in Asia and within Nigerian river basins, where sediment extraction reduced channel stability, increased downstream sediment transport, and accelerated morphological adjustment [5,12,13,16,21].

Beyond its geomorphological implications, the observed riverbank changes have important environmental and socio-economic consequences. Accelerated erosion threatens agricultural land, transportation infrastructure, and settlements located close to the riverbanks, while sediment imbalance degrades aquatic habitats, water quality, and ecosystem resilience. These findings agree with previous investigations identifying uncontrolled sand mining as a major contributor to river degradation in the Niger Delta and other tropical river systems [3,8,9,13,15,20]. The results further reinforce recommendations for sustainable extraction limits, effective licensing systems, continuous geomorphological monitoring, and riverbank stabilization programmes [2,7,14,18].

Although the integration of GIS, remote sensing, and the Digital Shoreline Analysis System (DSAS) provided a robust framework for evaluating long-term riverbank change, the study has several limitations. First, the analysis relied primarily on Landsat imagery with a spatial resolution of 30 m, which may not detect localized riverbank changes or small-scale erosion features. Second, the projected shoreline conditions for 2025 were derived from temporal trend analysis rather than direct field observations. Furthermore, although the spatial coincidence between active sand mining sites and erosion hotspots strongly indicates a relationship, other factors—including seasonal flooding, river discharge variability, channel curvature, bank material characteristics, vegetation dynamics, and land-use change—may

also have contributed to the observed geomorphological changes. Future investigations should integrate higher-resolution satellite imagery, unmanned aerial vehicle (UAV) surveys, hydrodynamic modelling, and sediment transport measurements to better quantify the relative contributions of natural processes and anthropogenic disturbances [17,18,19].

Overall, the findings demonstrate that prolonged sand mining has substantially influenced the geomorphological evolution of the Imo River by accelerating riverbank erosion, promoting channel adjustment, and disrupting natural sediment dynamics. The study further confirms the effectiveness of integrating GIS, remote sensing, and DSAS for long-term monitoring of river morphological change, thereby providing scientific evidence to support sustainable river basin management, environmental monitoring, and improved regulation of sand mining activities in southeastern Nigeria [17,18,19,20].

Conclusion

This study demonstrated the effectiveness of integrating Geographic Information Systems (GIS), remote sensing, and the Digital Shoreline Analysis System (DSAS) for evaluating long-term geomorphological changes owing to sand mining activities along the Imo River between 1980 and 2025. The results showed that riverbank erosion was the dominant geomorphological process, with approximately 18.03 km² of land lost through erosion compared with 1.98 km² gained through sediment deposition. The concentration of severe erosion within active sand mining areas indicates that prolonged sediment extraction has contributed to riverbank instability, channel adjustment, and increased environmental vulnerability along the river corridor.

Despite these findings, the study has several limitations. The analysis relied primarily on Landsat imagery with a spatial resolution of 30 m, which may not capture localized riverbank changes and small-scale geomorphological features. In addition, recent bathymetric surveys were not available to validate channel depth changes, while the projected shoreline conditions for 2025 were based on temporal modelling rather than direct field observations. These limitations should be considered when interpreting the magnitude of the observed geomorphological changes.

Future research should integrate high-resolution satellite imagery, unmanned aerial vehicle (UAV) surveys, bathymetric measurements, and hydrodynamic modelling to improve the accuracy of shoreline change assessments. From a policy perspective, the findings highlight the need for the Federal Ministry of Environment, the National Inland Waterways Authority (NIWA), the Nigerian Upstream Petroleum Regulatory Commission (NUPRC) where applicable, and the Imo and Rivers State environmental protection agencies to strengthen the regulation of sand mining through licensing, routine GIS-based monitoring, periodic environmental impact assessments, and riverbank restoration programmes. Implementing these measures will contribute to sustainable river basin management, reduce erosion hazards, and protect the ecological and socio-economic functions of the Imo River.

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