Mechanisms of riverbank failure and channel instability on the Nkisi River, Southeast Nigeria

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Abstract. Sedimentation hazards pose several geoenvironmental problems in active alpine regions and fluvio-deltaic environments. Therefore, this research seeks quantitative knowledge of the mechanisms that trigger riverbank erosion which result in high volumes of sediment yield in the downstream reaches of the Nkisi River. Study of the mechanisms of mass wasting of the riverbanks was motivated by the high rate of siltation and accretion that are currently occurring at the mouth of the Nkisi River, occupying a total surface area of about 40,000 m². Many riverbank stability and erosion assessment studies have been done using a wide range of geomorphometric and geotechnical analyses which consider the shear strength of the bank materials in relation to the geomorphometric characteristics of the riverbanks. With this insight, this research focuses on investigating the potential causes of riverbank retreat on the river, with particular interest on the effects of soil properties in triggering mass failures. Field surveys and laboratory investigations, coupled with Bank Erosion Hazard Index (BEHI) and Bank Stability and Toe Erosion Model (BSTEM) characterized the riverbanks as unstable and conditionally stable, revealing a potentially high rate of sediment loading from the composite banks, with a factor of safety that varies from 0.76 to 1.04.

Keywords: Riverbank retreat, Nkisi River, Stability analysis, BSTEM, BEHI

1. Introduction
Riverbank erosion is one of the major problems affecting sustainable watershed management in many developing countries [1-3]. The phenomenon is common in Southeast Nigeria where numerous hydro-geomorphological processes, in concert with anthropogenic inputs, have exacerbated the magnitude and intensity of several ecohydrological problems including flash floods and gully erosion [4,5]. Every year, several million metric tonnes of sediment are eroded from the upland areas of Southern Nigeria and deposited on the low-lying floodplains of the lower Niger region through a network of river courses and ephemeral storm channels [6,7]. Consequently, the fluvio-deltaic plains of the Southeast and Niger Delta regions have witnessed numerous sedimentation hazards and associated ecohydrological problems including water quality impairments, alteration of aquatic habitats, and the influx of phosphorous and heavy metals into the adjoining streams and rivers courses [8-11].

According to the World Bank-Nigeria Erosion and Watershed Management Project (NEWMAP), gully erosion and associated processes such as riverbank retreat are the major environmental challenges affecting the Southeast region of Nigeria, causing estimated annual damage of over 100 million US dollars [12]. Furthermore, the prevalence of riverbank erosion in these densely populated areas of Southeast Nigeria has been aggravated by the unfavourable interactions between human activity and the natural environment [13]. The geoenvironmental hazards posed by these recurring ecohydrological phenomena remain to be fully mitigated notwithstanding that over 500 million US
dollars have been committed by the World Bank assisted project (NEWMAP) in partnership with the Department of Erosion Control, Flood and Coastal Management of the Nigerian Ministry of Environment [12].

Riverbank retreat and gully erosion are so severe in the Southeast and Niger Delta regions that in some localities land loss has been reported to occur at a rate of 2 to 3 m/yr [14]. In addition, the rate of accretion and sedimentation at the confluence of River Niger and River Nkisi is so high that the current estimated total surface area of the accreted sediments is about 40,000 m². Therefore, a comprehensive evaluation and understanding of riverbank processes and mechanisms of channel instability on the Nkisi River and adjoining stream courses are crucial for river hazard assessments, and for evaluating the dynamic changes in watershed-scale sediment budget in relation to riverbank retreat.

2. Materials and Methods

2.1. Study area

The Nkisi River (6°09'56"N, 6°46'37"E), is located on the left (eastern) bank of the Niger River and is almost entirely located in the metropolitan city of Onitsha, in Anambra state, Nigeria. The Nkisi River, which originates from the Awka-Orlu Cuesta, flows through several villages and towns, including Nkpọr, Nsugbe and Ogbunike, and empties into the Niger River (Figure 1). The minimum and maximum mean monthly discharges of the river are estimated to be about 1.4 and 1.8 m³/s, respectively. About 30% of the Nkisi River watershed can be found within the low-lying, flood-dominated, fluvial plains of the lower Niger region, and is mostly typified by agricultural, urban and suburban land cover.

The study area lies in the boundary between the tropical hinterland climate and subequatorial climate of Nigeria, with an average annual rainfall of 1850 mm and peak rainfall in July. Elevation ranges from 91 to 97 m, while groundwater table averages 1.5 to 2 m near the banks of the River Niger and River Nkisi. The study area lies within the Anambra Basin and is entirely underlain by Paleocene to Recent sediments (Figure 2). The Nkisi River displays a low sinuosity index (SI<1.25), with channel width that varies from 22 to 27 m, while the bed slope ranges from 0.005 to 0.0004. The flow regime of the river is unregulated, with a flashy hydrograph that indicates the topographic nature of the terrain within the catchment. The morphology of the river channel has been frequently modified by high rates of incision due to the readily erodible bank sediments which result in a high frequency of transport of suspended sediments. The materials composing the riverbed vary from randomly deposited gravel and medium-grained sands in the upstream reaches of the river to well sorted fine-grained sands, silts and clay in the downstream reaches of the river.

Noticeable changes in the morphodynamics of the river channel began in the last quarter of the 20th century. However, the last two decades have witnessed a sudden increase in the intensity of bank instability and sediment accretion at the mouth of the river. These changes have been attributed to anthropogenic influences brought about by deforestation, artisanal sand mining and overall destruction of the riparian ecosystem within the river catchment. Rapid demographic changes coupled with poor land management practices within Onitsha and environs have resulted in a mean riverbank erosion rate of about 0.3 m per annum.

2.2. Field investigations and laboratory analysis

Field measurements were undertaken from June 2017 to February 2019, where several geomorphometric data (bank height, bank angle, thalweg depth and width, channel width, and bankfull depth) were measured from both sides of the river channel at more than twenty locations along the lower reaches of the river. Undisturbed soil core samples were collected from representative layers within the bank using standard Shelby tube samplers along with disturbed soil samples. Atterberg limits, unconsolidated undrained triaxial tests, particle size distribution, and phase relationship tests were conducted on the retrieved soil samples to evaluate the geotechnical properties of the bank sediments. Characteristic failure mechanisms of the banks were identified including several seepage cavities and tension cracks [15-19]. While the Bank Stability and Toe Erosion Model (BSTEM) and
Bank Erosion Hazard Index (BEHI) were used to evaluate the stability and the erosion potential of the riverbanks.

Figure 1. Location map of the study area.

Figure 2. Geologic map of Anambra state, Southeast Nigeria after Okoyeh et al. [20].
3. Results and Discussion

3.1. Geotechnical and geomorphometric characteristics of the riverbanks

Table 1 summarizes the geotechnical and geomorphometric characteristics of the riverbanks. The river channels are made up of composite banks which comprise a basal layer of highly resistant clay with an average thickness of 0.85 m. The basal layer is overlain on the right by a moderately consolidated reddish-brown lateritic soil with a mean thickness of 2.7 m, and on the left by loosely consolidated alluvial deposits. Bank angle varies from 80 to 110º on the right and 75 to 85º on the left, while the maximum depth and width of the thalweg ranges from 0.6 to 0.9 m and 6 to 18 m, respectively (Figure 3). The bankfull width varies from 27 to 30 m, while bankfull depth remains low (0.5 to 0.8 m) during low river stages and increases to about 3 to 3.5 m during the rainy seasons. Field observations revealed a marked difference in the retreat rates of the composite banks, indicating that the top alluvial sediments retreat faster than the highly resistant basal layer. This marked difference has been ascribed to the different erodibility coefficients and undrained shear strength of the bank sediments. Quick undrained triaxial compression tests conducted on the soil samples reveal an average effective friction angle of 24 kPa, 29 kPa, and 32 kPa for the basal layer, upper-right layer, and upper-left layer, respectively. Atterberg limits test results also show that the mean value of plasticity index of the bank materials are 54, 37, and 24 % for the basal layer, upper-right layer and upper-left layer, respectively.

| Location and Soil Type | Basal layer (clay) | Upper-right layer (silty clay) | Upper-left layer (silt) |
|------------------------|--------------------|-------------------------------|------------------------|
| Thickness (m)          | 0.5-1.2            | 2.2-3.2                       | 1.8-2.2                |
| Bank angle (º)         | 85-90              | 80-110                        | 75-85                  |
| Liquid limit (%)       | 80-88              | 49-60                         | 38-44                  |
| Plastic limit (%)      | 27-33              | 15-20                         | 14-18                  |
| Plasticity index (%)   | 53-55              | 34-40                         | 24-26                  |
| Effective friction angle (kPa) | 23-25            | 27-30                         | 30-33                  |
| Effective cohesion (kPa) | 14-18              | 7-9                           | 2-5                    |
| Bulk density (Mg/m³)   | 1.82               | 1.85                          | 1.89                   |
| Dry density (Mg/m³)    | 1.43               | 1.40                          | 1.56                   |
| Void ratio             | 0.67               | 0.52                          | 0.71                   |

3.2. Stability analysis of the riverbanks

Riverbank stability analysis was conducted using the Bank Stability and Toe Erosion Model (BSTEM, version 5.4). The BSTEM was developed to evaluate the principal factors affecting the stability of riverbanks and to calculate the factor of safety ($FS$) by combining the limit equilibrium method and the unsaturated shear strength properties of the bank materials [21]. The model classifies $FS$ of 1.0 to 1.3 as conditionally stable and less than 1 as unstable. Figure 4 shows the results of the bank stability analysis performed on both sides of the river channel. On the right bank of the river, stability analysis was conducted considering an average bank height of 4 m, mean bank angle of 80º, surface water elevation of 2 m, and water table depth of 1.5 m (Figure 4a). The analysis, which was performed to simulate failure under drawdown conditions, shows that the bank was unstable with a factor of safety of 0.76. Result of the analysis indicates that bank retreat occurred only on the upper moderately consolidated layer and was insignificant on the basal layer, as a result of the different shear strength properties of the two materials composing the bank. The effect of vegetation on the stability of the riverbank was evaluated by running a root-reinforcement model (RRM) with a maximum root depth of 0.7 m (ryegrass, $c_r = 1.75$ kPa). The result gives a safety factor of 0.8, which indicates that a further increase in root depth will ultimately lead to an increase in $FS$. 
Similarly, stability analysis was performed on the left bank of the river considering an average bank height of 2.2 m, bank angle of 75º, surface water elevation of 2 m, and water table depth of 0.2 m.
(Figure 4b). The result shows that the bank was conditionally stable with a safety factor of 1.04, failure volume of 15 m$^3$, and sediment loading of 28,270 kg. By incorporating the root-reinforcement model (RRM) with root cohesion ($c_r$) of 1.07 kPa, the factor of safety considering the effect of vegetation (root cohesion) was calculated to be 1.14. The result further shows that under a flow duration of 24 hrs, maximum lateral retreat and total eroded area (TEA) of the bank were 0.21 m and 0.178 m$^2$, respectively. This signifies the high erodibility of the upper alluvial deposits and the high shear strength characteristics of the basal layer (Figure 4c and 4d).

3.3. Bank Erosion Hazard Index

Bank Erosion Hazard Index (BEHI) was used to assess the erosion potential of the riverbanks following the method presented by Rosgen [22]. To analyze the erosion potential of the banks, the BEHI employs characteristic riverbank metrics such as bank height ratio, root depth ratio, root density, bank angle, and surface protection. The results show high BEHI values of 36.1 and 39.2 for the left and right banks of the river channel (Table 2). Bank angles were generally high as a result of the shear, slab, and alcove-type failures, and undercutting of the lower portion of the upper silty clay layer.

The combination of the high bank angles, together with the low shear strength properties of the bank materials and the absence of natural and artificial surface protection all had an extreme effect on the BEHI values. About 90% of the banks are covered by riparian vegetation. However, root-reinforcement was generally low given that the maximum rooting depth of the riparian vegetation varied from 0.4 to 0.6 m, whereas root density on both banks had an average metric score of 5.65 (moderate). The results thus indicate that the metric scores obtained from the analysis of root depth ratio and root density were generally below the minimum values required to increase the stability of the riverbanks. The results suggest that a minimum root depth of 2 m is required to reduce the bank hazard index from high to low.

The validity of the BEHI results was further evaluated by comparing aerial images of the riparian area from the year 2003 to 2018 (Figure 5). The result indicates that the rate of retreat of the riverbanks and sediment loading rates into the river were consistent with the rate of sediment accretion and increase in the surface area of the deposited sediments at the mouth of the river. Furthermore, there was a marked relationship between the morphodynamic changes in the river channel and the rate of change in the size of the urban population, which signifies possible human-induced impacts on the natural hydrologic disturbance regimes of the river channel.

| Bank Location | Bank Height Ratio (m/m) | Root Depth Ratio (%) | Root Density (%) | Bank Angle (°) | Surface Protection (%) | Total Index |
|---------------|------------------------|----------------------|-----------------|---------------|-----------------------|-------------|
| Left          | 8.4                    | 7.8                  | 5.9             | 6.1           | 7.9                   | 36.1        |
| Right         | 9.5                    | 8.2                  | 5.4             | 8.2           | 7.9                   | 39.2        |

4. Conclusions

This research has provided new insights into the morphodynamic changes in the Nkisi River channel, considering sparse research to date on the application of relevant riverbank hazard assessment methods such as the Bank Stability and Toe Erosion Model (BSTEM) and Bank Erosion Hazard Index (BEHI) in evaluating the mechanisms of riverbank retreat in Nigeria.

Shear failures, occasional slumps and alcove-type failures constitute the primary failure mechanisms of the riverbanks. These failure mechanisms are characteristic features of the loosely to moderately consolidated upper layers of the composite banks. Field investigations followed by bank stability analysis revealed high bank erosion rates and accelerated sediment loading that usually occur during the recession limb of the river hydrograph under rapid drawdown conditions.

The bank metric scores obtained from the BEHI analysis showed some degree of consistency with the results obtained from the bank stability analysis and the estimated volume of eroded materials
from aerial photographs. The validity of the results is evidenced by the continuous buildup of a point bar opposite a cut bank at a meander loop near the mouth of the river (Figure 6). These dynamic erosion processes have cut deep into the abutments of an access bridge located in the area and could have potential effects on the stability of the bridge over time.

The analysis of the riverbank stability simulated during drawdown conditions at flow elevations above the contact between the upper alluvial deposits and the basal resistant clay showed that virtually all the banks were unstable or conditionally stable with $FS$ that ranged from 0.76 to 1.04. However, the conditionally stable banks transitioned to unstable condition at a minimum flow duration of 48 hrs.

It is noteworthy to mention the marked similarity between the field observed bank erosion mechanisms and the results obtained from the riverbank stability analysis, given that mass failures occurred only in the alluvial sediments composing the upper layer of the composite banks.

**Figure 5.** Time series satellite (Google Earth) images of the study area showing changes in the morphodynamics of the river channel and active sedimentation at the mouth of the Nkisi River.

**Figure 6.** (a) Active erosion at a cut bank, and (b) Formation of a point bar at a meander loop near the confluence of River Niger and River Nkisi. Sand bags have been used to minimize the effects of the erosion on the abutments of an access bridge in the area.

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