Fluvial Geomorphological Characterization of River Magarya in the Upper Gongola Basin, Northeastern Nigeria: An Integrated Dem, Saga-GIS and Field Approach

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Abstract
River longitudinal profiles provide important insights into landscape evolution, tectonic processes, lithology, and human impacts; however, the geomorphology of many tributaries within the Gongola Basin in northeastern Nigeria remains undocumented. This study examines the geomorphological characteristics along the 30.1 km longitudinal profile of River Magarya in Akko LGA, Gombe State, through an integrated application of remote sensing, GIS, and field-based measurements. The catchment was delineated from a 30m SRTM DEM using Golden Surfer 24 and SAGA GIS 7.8, incorporating a Machine Vision approach. GPS and ranging poles were used to measure longitudinal and cross-profiles in the upper, middle, and lower river courses. Landforms were identified through the geomorphon algorithm and verified by manual field observation. Changes in land use/land cover between 1993 and 2023 were evaluated through supervised Landsat classification in ArcGIS 10.8. The findings indicate that the catchment encompasses 130.2km², including 5 sub-catchments and 112 tributaries with a combined stream length of 140.2km. Elevation decreases from 630m at the source to 275m at the confluence, producing an average gradient of 11.8m/km. Cross-profile results identify a flat-bottomed, sand-filled valley in the upper course, measuring 19.3 m in width and 4.9 m in depth, which developed on friable Kerri-Kerri sandstone; a gorge in the middle course, measuring 73.2 m wide and 34.6-47 m high; and a broad, U-shaped lower-course valley containing point bars.

Nine geomorphons were classified automatically, whereas 29 landforms were identified manually. The built-up area expanded from 4.4% to 18.8%, thick vegetation decreased from 18.5% to 9.3%, and open spaces grew from 17.9% to 41%. The study concludes that lithological differences among the Pindiga, Gombe Sandstones, Yolde, and Keri-Keri formations exert strong control over channel morphology along River Magarya, with this influence compounded by intense anthropogenic pressure associated with urban expansion and deforestation. On the basis of the identified characteristics, the study recommends constructing check dams and gabions in the gorge section to regulate runoff and limit downstream sedimentation; afforesting the flat-bottomed upper course with vetiver grass and economic trees to stabilize the friable sandstone; enforcing a 100 m buffer zone that prohibits sand mining, rice mills, and farming along the middle and lower courses; and implementing community-based watershed management to regulate urban expansion and fuelwood extraction.

Keywords: *Fluvial geomorphology, longitudinal profile, Geomorphons, Catchment delineation, Land Use Land Cover, Gongola Basin, River Magarya*

Introduction

The term geomorphology originates from the Greek words – geo (earth), morphos (form) and logos (discourse), and refers to the scientific study of landforms and the processes responsible for their formation (Faniran and Jeje, 2002). In its contemporary interpretation, the discipline extends beyond the historical description of landform development to examine the complex intra- and interrelationships between form and process. Landforms are surface features of the earth characterized by distinctive morphologies that reflect the predominance of particular geomorphic processes during their formation (Filip and Vit, 2008). Within fluvial environments, the river longitudinal profile is the simplest yet one of the most informative morphological representations. It depicts the configuration of a river channel from its source to its mouth and contains substantial information about the geomorphology of the drainage basin (Karthika and Mohana, 2013).

The concave form of longitudinal profiles is regarded as a persistent and nearly universal characteristic, regardless of climatic conditions, channel length, or lithology. River channels are closely connected to their catchments, and at the macroscale, the geographic position of a catchment reflects the combined influence of climate, geology, topography, soil cover, and land use. These characteristics consequently govern the transfer of water and sediment into the channel. Under undisturbed conditions, channel morphology changes progressively over centuries to millennia, exhibiting the conventional downstream pattern of vertical incision in the youthful upper course, lateral erosion and sediment transport in the mature middle course, and deposition in the old lower course (Chris, 1993). Rivers modify their gradients to achieve a flow velocity at which erosion and deposition are in balance, a state known as a graded profile or equilibrium slope (John, 1941). When a river reach receives a load below its transport capacity, the river erodes its bed and banks; conversely, an excessive load promotes aggradation until equilibrium velocity is reached (Wanah, 2017; Wanah and Abdullahi, 2018).

This natural balance is increasingly disturbed by anthropogenic activities. Because virtually all river basins are now influenced by human intervention, the principal controls of channel morphology - water and sediment flux, bank strength, and base level - are subject to alteration. Certain channels, including bedrock-lined or armored cobble-bed rivers with cohesive, vegetated banks, are comparatively resistant to change. Other channels are highly sensitive, such that a

threshold exceeded in a controlling variable may initiate substantial instability. In the Nigerian Sudan Savanna, intensive grazing, fuelwood harvesting, urban expansion, cultivation along river corridors, sand extraction, and the establishment of local rice mills have modified catchment vegetation, raised runoff coefficients, and increased sediment delivery. These changes have, in turn, affected channel width, depth, gradient, and planform (Steve and Gabriola, 2014; Grabowski et al., 2022). During high-flow events, the irregular movement of water and sediment generates physical forces that operate on the channel bed, banks, and riparian vegetation, producing a range of morphological features, including gorges, interlocking spurs, potholes, rapids, meanders, point bars, and natural levees.

Although longitudinal profile analysis is fundamental to flood-risk assessment, hydrological modeling, engineering design, and watershed management, the geomorphology of many tributaries in the Gongola Basin of Northeastern Nigeria remains undocumented. Like other parts of Nigeria, Gombe State is repeatedly affected by flooding during periods of intense rainfall, resulting in farmland loss, infrastructure damage, and community displacement. Characterizing longitudinal profiles, gradients, cross-profile geometry, and landform assemblages is therefore necessary for locating flood-prone channel reaches and developing suitable mitigation measures. However, the limited studies available for the region have addressed the subject only within a restricted scope. For example, Wanah and Abdullahi (2018) described the longitudinal profile of River Bagadaza in Akko Local Government Area, emphasizing gradient and broad land-use patterns as the principal factors shaping the profile, while giving limited consideration to the systematic identification and spatial arrangement of erosional and depositional landforms along the channel continuum.

River Magarya, a 30.1 km tributary within the Gongola system in Akko LGA, illustrates this deficiency. Field observations indicate that the river traverses four significant geological formations of the Upper Benue Trough - Pindiga, Yolde, Gombe Sandstone and Kerri-Kerri - and includes deeply buried ancient rocks, friable sandstones that form atypical flat-bottomed, sand-filled valleys rather than conventional V-shaped valleys, a structurally controlled gorge with overhanging cliffs, and extensive U-shaped depositional valleys containing point bars and natural levees downstream. Nevertheless, its catchment has not been delineated; its long profile and three-segment cross-profiles have not been quantified; its landforms have not been classified with the modern automated geomorphon approach of Jasiewicz and Stepinski (2013); and changes in its three-decade Land Use Land Cover have not been related to channel adjustment.

Accordingly, this study was undertaken to address this gap through a comprehensive characterization of the geomorphological features along River Magarya. The study investigates whether the geomorphological features along River Magarya have been identified and characterized, examines the morphometric properties of its catchment, and determines the factors controlling its longitudinal and cross-profile morphology. Specifically, it aims to delineate the catchment and sub-catchments from SRTM DEM data using SAGA GIS and a Machine Vision approach; characterize longitudinal and cross-profiles along the upper, middle, and lower courses; classify landforms through an automated geomorphon algorithm and manual field identification; and evaluate Land Use Land Cover change between 1993 and 2023. The resulting baseline dataset, comprising elevations from 275 m to 630 m, an average gradient of 11.8 m/km, nine automatically identified geomorphons, twenty-nine manually recognized landforms, and rapid built-up expansion from 4.4% to 18.8%, will provide an essential scientific foundation for hydrological modeling, flood mitigation, and sustainable watershed management under the

Nigeria Erosion and Watershed Management Project (NEWMAP), as well as for comparable savanna environments.

Description of Study Area

River Magarya is located between Latitudes 10°13' and 10°16'N and Longitudes 11°05' and 11°12'E in Akko Local Government Area, Gombe State, Nigeria. The river is a fourth-order tributary of River Jarkwami, which forms part of the Gongola River system in the Upper Benue Trough. Its main channel extends 30.1 km from its source near the Akko hills to its confluence at Dumbe. The area has an AW (Tropical Savannah) climate, characterized by mean annual rainfall of 850-900 mm, a mean temperature of 32°C, and a rainy season lasting from May-October. Elevation varies from 275 m at Dumbe, the lowest point, to 630 m at the source, while intermediate elevations range from 399-550 m.

Geologically, River Magarya traverses four formations (Obaje, 2009; Mbimbe et al., 2019; Ikusemoran et al., 2018): (a) Kerri-Kerri Formation: This is the youngest formation in the Gongola arm and is predominantly flat lying. It consists of whitish gray sandstone, siltstone and claystone and is highly vulnerable to fluvial erosion. (b) Gombe Sandstone: Comparable to the Bima Formation, this unit contains interbeds of coal, lignite and coaly shale and is exposed at Pantami and along the upper course. (c) Pindiga Formation: Laterally equivalent to the Gongila Formation, it records a Turonian-Santonian full marine incursion and comprises dark/brown carbonaceous shale and limestone, which occur as stratified layers along the upper course. (d) Yolde Formation: This Cenomanian transitional/coastal marine formation consists of sandstone, limestone, shale and claystone and is exposed along the middle course.

The soils comprise ferruginous tropical soils, sandy loam, lithosols and vertisols. The vegetation consists of Guinea Savanna, characterized by *Parkia biglobosa, Adansonia digitata, Azadirachta indica*, and *Butyrospermum paradoxum*, with areas of derived savanna resulting from fuelwood collection and cultivation. Economic activities comprise farming, particularly rice and maize production on alluvial floodplains, irrigation at Dumbe, sand mining, rice-parboiling mills, mechanical workshops, and residential expansion from Gombe Metropolis into Bye-Pass, Riyad, Bomala, and Nasarawo.

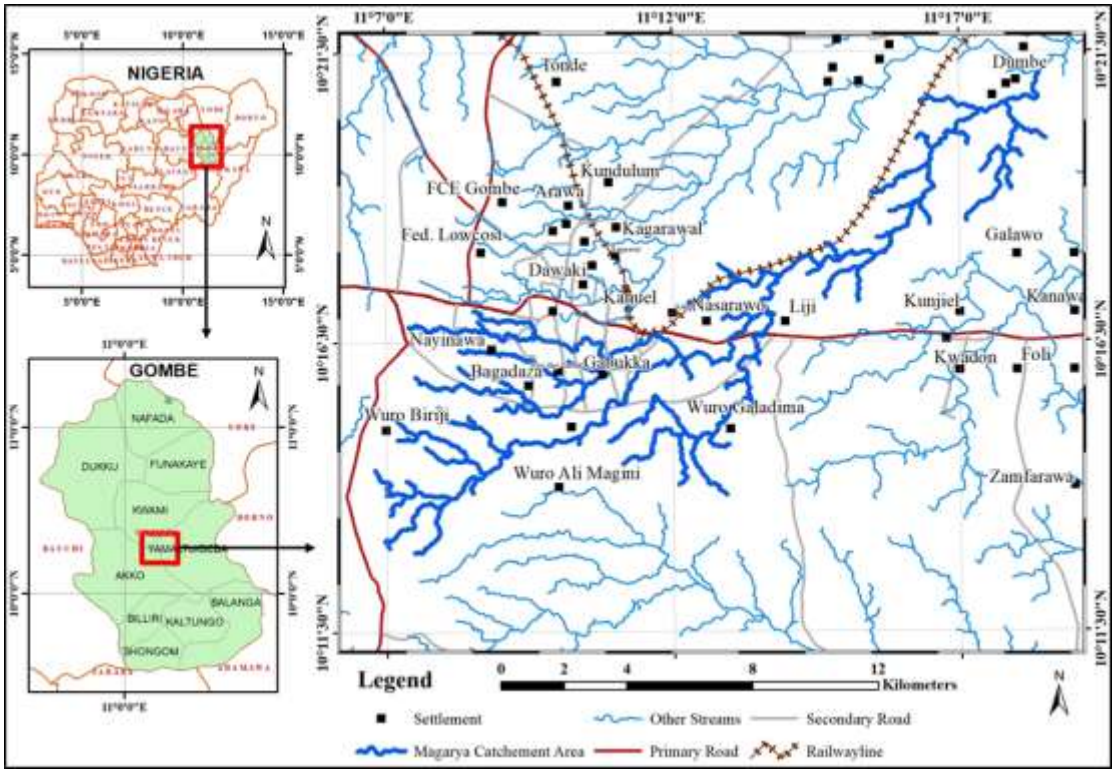


Figure 1: Map of the Study Area Showing Magarya River Catchment

Methodology

The study drew on both primary and secondary sources of data. Primary data consisted of Global Positioning System coordinates recorded at the source and mouth of River Magarya, longitudinal profile measurements obtained with a 100 m tape and ranging pole, field photographs, and ground-truthing data for Land Use Land Cover. Secondary data included the Shuttle Radar Topography Mission Digital Elevation Model with a 30 m resolution; topographic maps 151NE Akko and 152NE Gombe at a scale of 1:50,000; Landsat Thematic Mapper imagery from 1993; Enhanced Thematic Mapper Plus imagery from 2003; Operational Land Imager imagery from 2013 and 2023; a geological map produced by the Nigeria Geological Survey Agency; and relevant literature. The hardware comprised a laptop, Garmin 78 GPS, ranging pole, 100 m tape, digital camera and smartphone. The software packages employed were ArcGIS 10.8, SAGA GIS 7.8, Golden Surfer 24, Google Earth Pro, Microsoft Excel and Word.

Catchment delineation was performed using a Digital Elevation Model derived from the topographic maps. In SAGA GIS, the drainage network and watershed basins were delineated with the Terrain Analysis tools for Channel Network and Drainage Basins. A three-dimensional representation of the Digital Elevation Model was generated in Golden Surfer 24 using the Machine Vision approach developed by Conrad (2019). The sub-catchments were designated A to E, and stream ordering followed Strahler (1957). Morphometric variables, including area, length, and tributary count, were calculated; the drainage pattern was identified, and Horton's (1945) laws were evaluated.

Longitudinal and cross-profile analyzes were conducted by plotting elevation against the distance from the source to produce the long profile. Three cross-profile locations were selected: Point A on the upper youthful course, Point B on the middle mature course, and Point C on the

lower old course. Channel gradient was computed by dividing the Vertical Interval by the Horizontal Equivalent, and the average gradient was determined. Valley forms were classified according to Leopold et al. (1964).

Geomorphological mapping employed both automated and manual methods. Automated classification was conducted with the Geomorphons module in SAGA GIS, following Jasiewicz and Stepinski (2013). Ten landform classes: flat, peak, ridge, shoulder, spur, slope, hollow, footslope, valley, and pit were identified. Field-based identification involved observing and measuring landforms and recording their locations with GPS at 32 points. These were categorized as erosional landforms, including gorges, potholes, rapids, interlocking spurs, overhanging cliffs, rock outcrops, mass-wasting features, boulders and meanders, and depositional landforms, including point bars, natural levees, sand dunes, flat-bottomed valleys, slumped materials, gravel and pebbles.

Land Use Land Cover change detection employed Landsat imagery from 1993, 2003, 2013 and 2023. Supervised classification based on the Maximum Likelihood algorithm was used to divide the study area into five classes: Built-up, Light Vegetation, Open Spaces, Rock Outcrop and Thick Vegetation. Changes and rates of change were calculated, while accuracy was evaluated through ground truthing.

River Magarya Catchment and its Morphometry

The River Magarya catchment was delineated over an area of 130.2 km² and comprises 5 sub-catchments and 112 tributaries as shown in Figure 2 and Table 1 respectively, with a combined stream length of 140.2 km. The drainage network exhibits a dendritic pattern, which develops where the underlying geology lacks distinct structural control. The tributaries converge at acute angles of less than 90°, a configuration characteristic of the flat-lying Kerri-Kerri formation. This drainage pattern reflects relatively uniform lithology and has important implications for flood response. Although dendritic networks generally have longer lag times than trellis systems, the high drainage density may promote more rapid runoff concentration.

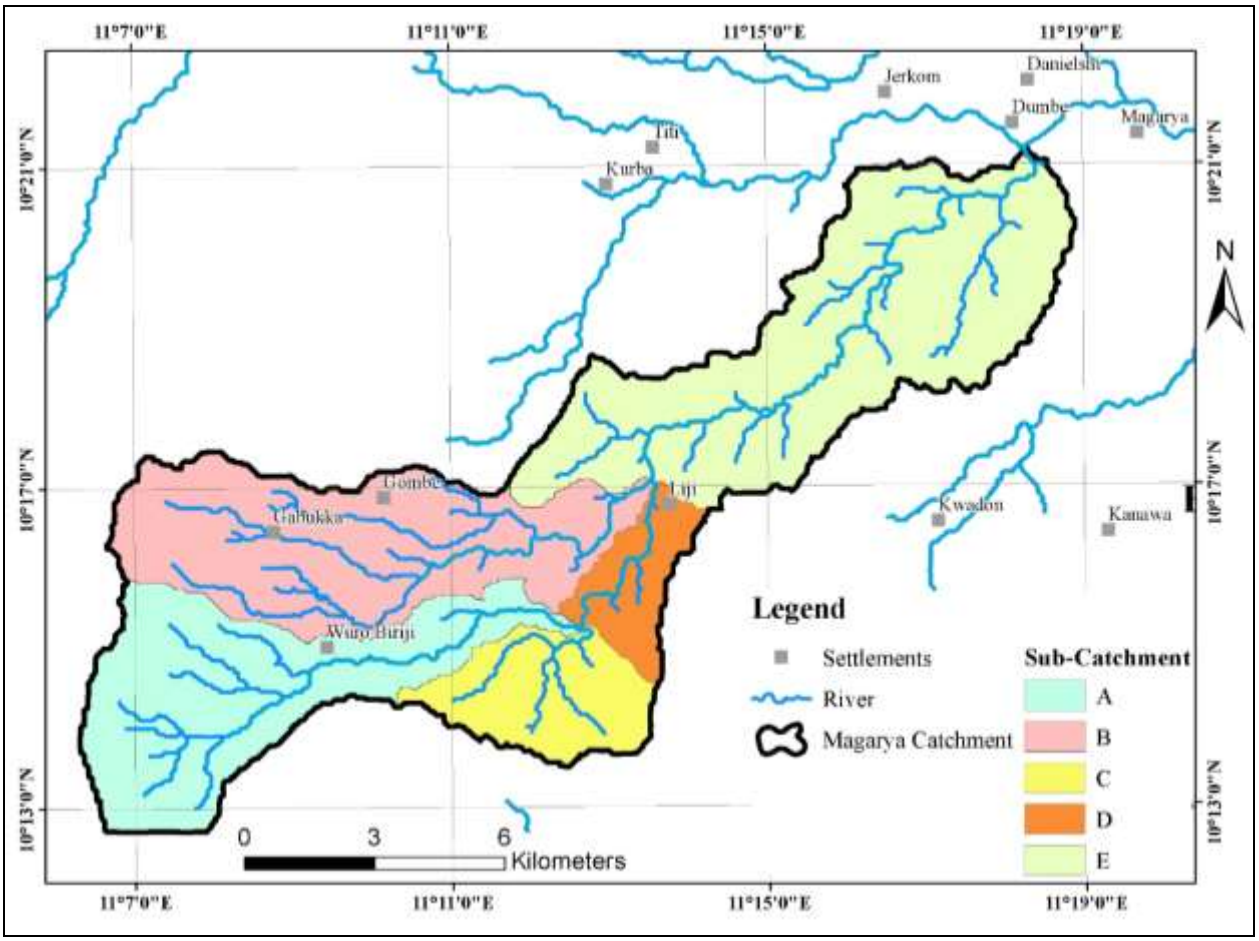


Figure 2: River Magarya Subatchments

Table 1: Morphometry of River Magarya Catchment

Sub catchment	Number of Tributaries	Area of the Catchment	Percentage	Length of the catchment	%
A	21	29.88km^2	22.95%	30.31km	21.6%
B	27	33.94km^2	26.07%	43.51km	31.0%
C	9	11.99km^2	9.2%	10.83km	7.75%
D	10	6.84km^2	5.2%	11.53km	8.22%
E	45	47.5km^2	36.4%	44,10km	32.44%
Total	**112**	**130.21km^2**	**100%**	**140.28km**	**100%**

Sub-catchment E is the largest, containing 45 tributaries and accounting for 36.4% of the catchment. This distribution is consistent with Horton's law of stream numbers, which states that the number of streams in each order follows an inverse geometric sequence as stream order increases (Horton, 1945). The delineation identifies hydrologically significant units that are

relevant to water resources management, flood modeling, and military operations. With an area of 130.2 km², the catchment is smaller than the neighboring Bagadaza catchment (198 km²) documented by Wanah and Abdullahi (2018), yet it has a greater drainage density (1.08 km/km² compared with 0.86 km/km²), suggesting greater runoff potential and helping explain flooding in the study area. In contrast to the Cher Basin Rivers described by Larue (2019), which exhibited convex hypsometric curves in Triassic sandstones and indicated disequilibrium, Magarya has a concave profile characteristic of mature rivers in sedimentary terrain approaching equilibrium, although knickpoints occur because of variations in rock resistance.

Drainage density of 1.08 km/km² is moderate to high for a semi-arid region, indicating relatively impervious subsurface conditions, sparse vegetation and mountainous relief. Gregory and Walling (1973) noted that high drainage density accelerates flood peaks. This finding has implications for sedimentation in Dadin Kowa Reservoir, since Magarya supplies the reservoir through Morom. Sub-catchment E, which covers 36.4% of the area, contributes the greatest proportion of runoff and sediment and should therefore receive priority for soil conservation under the Nigeria Erosion and Watershed Management Project.

Longitudinal Profile Analysis

The longitudinal profile is concave, with irregularities in the form of knickpoints resulting from lithological variation and anthropogenic activity. Although concavity is regarded as a universal characteristic irrespective of climate or lithology (Leopold et al., 1964), the presence of knickpoints reflects differences in the resistance of Pindiga sandestone compared with Kerri-Kerri sandstone and the Yolde Formation. Elevation declines from 630 m at the source to 275 m at the mouth, while gradients were recorded as 10 m/km and 8.2 m/km for segments A and B respectively with an average of 11.8 m/km. This implies that, for every 10 km, there is 11.8 m fall. High velocity at upper course erodes bed and banks, transporting debris to lower course forming depositional landforms (Sinha & Parker, 1996).

The profile was subdivided into three segments (Figures 3 and 4) that broadly correspond to Davisian stages (upper or young, middle or matured and lower or old), although they have been modified.

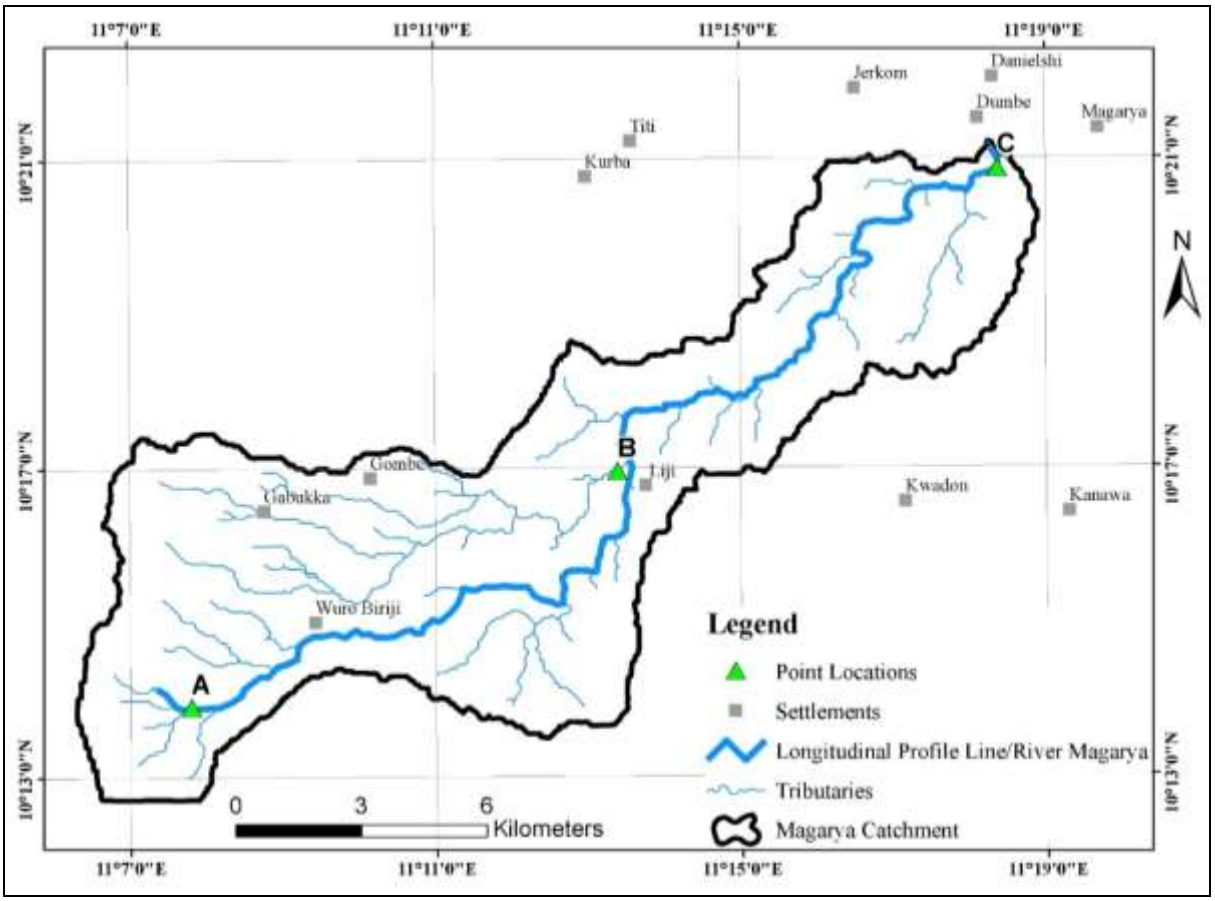


Figure 3: The Long profile subdivided into three segments

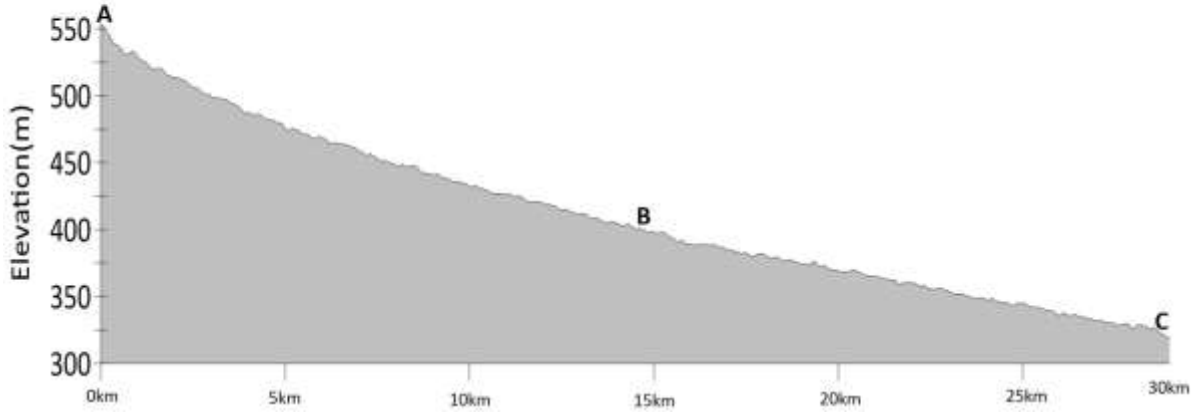


Figure 4: Logitudinal Profile of River Magarya

The longitudinal profile substantially enhances understanding of the geomorphic attributes that define the cultural landscape and provide a basis for crop production and socio-economic development, as asserted by Wanah and Abdullahi (2017). The gradient is important for

engineering and hydrological purposes; bridge design along the Akko-Gombe road must account for the 11.8 m/km gradient and the gorge depth.

Cross Profile Analysis

Table 2: Cross-Profile Analysis of River Magarya

Location	Elev. (M)	Width (M)	Depth (M)	Valley shape	Dominant process	Lithology
A	522.40	19.30	4.90	Flat-bottomed sand-filled	Vertical erosion	Keri-Keri, Gombe sandstond and Pindiga
B	399.80	73.23	3.20	V-shaped gorge	Lateral erosion and Mass wasting	Yolde and Pindiga
C	333.72	129.32	5.51	Broad U-shaped	Deposition and Meandering	Alluvium and Keri-Keri

As depicted in Table 2 and Figure 5, cross-profile A does not exhibit the ideal V-shaped form; instead, it has a flat floor filled with sand deposits. This contrasts with the Davisian ideal of a V-shaped valley and suggests lithological control. The unconsolidated sandstone of the Kerri-Kerri Formation collapses rapidly, as reported for the Bagadaza River by Wanah and Abdullahi (2018). This finding indicates that the Davis model requires modification when applied to the Cretaceous sediments of the Gongola Basin, where friable sandstone cannot sustain steep V-shaped valley walls. Consequently, the walls collapse and produce a flat-bottomed valley. This result is consistent with Ikusemoran et al. (2018), who identified the Kerri-Kerri Formation as highly vulnerable to fluvial erosion. The presence of sand within the flat-bottomed valley also suggests substantial sediment supply from upstream deforestation and sand mining.

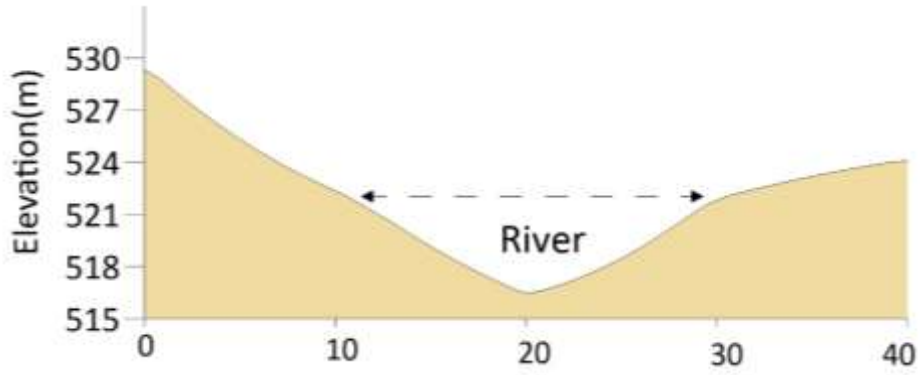


Figure 5: Cross Profile at Point A

Cross-profile B displays a deeply incised gorge, 34.6-47 m high and 50-70 m wide, formed through differential erosion of Pindiga shale and Yolde sandstone. Hydraulic action undercuts the valley sides, causing them to collapse. Gorge development is significant because the resistant carbonaceous shale and limestone of the Pindiga Formation form a cap rock, while the

underlying Yolde Formation is eroded, producing overhangs. Filip and Vit (2008) describe this process as differential erosion. The gorge provides a suitable location for an irrigation dam, as observed at Dumbe.

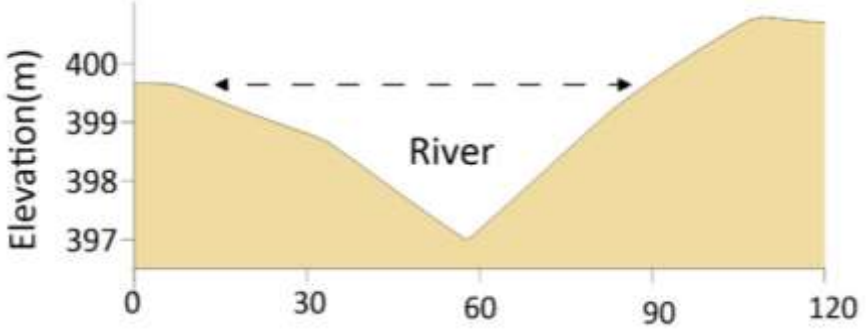


Figure 6; Cross Profile at Point B

Cross-profile C exhibits a broad U-shaped valley with an extensive floodplain, low flow velocity, suspended silt, point bars, and natural levees. This profile corresponds to the old-age stage, characterized by the predominance of deposition. Flood events produce natural levees through vertical accretion, with well-sorted sand, silt, and clay; the deposits are thickest and coarsest near the channel and become thinner and finer with increasing distance. Point bars develop opposite cut banks through lateral channel migration, forming acute meander ridges composed of sand, gravel, silt, clay, and nutrients. These geomorphic features are suitable for fadama agriculture, as reported by Adamu et al. (2015).

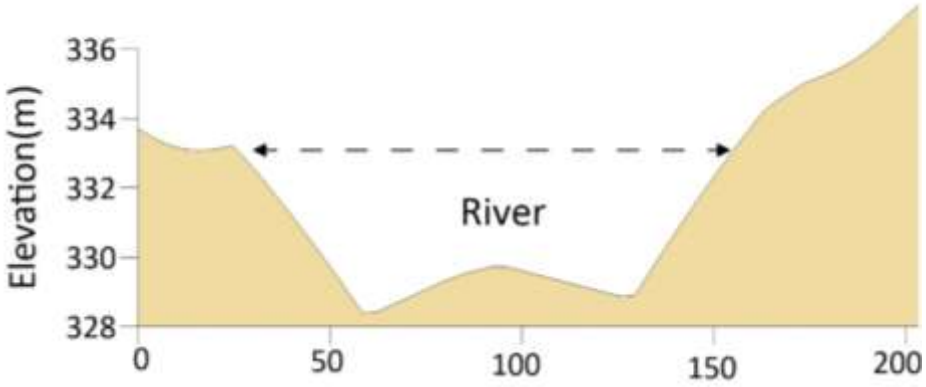


Figure 7: Cross Profile at Point C

Geomorphological Features (Geomorphons)

Geographic Information System-based analysis conducted with SAGA classified the landscape into 9 geomorphons: depression, flat, footslope, hollow, ridge, shoulder, slope, spur, and valley (Table 3 and Figure 8). Flat and valley forms are predominant across the alluvial plains, whereas ridges and peaks are associated with the Basement Complex and Bima Sandstone hills. Nevertheless, the automated classification did not capture some micro-forms because the Digital Elevation Model had a 30 m resolution.

Table 3: Summary of Erosional and Depositional featuress along River Magarya

River Stage	Erosional Landforms	Depositional Landforms	Process
Upper (A)	Interlocking spurs, Gorge (10-15 m deep, 50-70 m length), Exposed Pindiga & Gombe Sandstone, Overhanging cliff, Rock outcrops, Rapids	Flat-bottomed valley, Sand deposits, Kerri-Kerri exposure	Downcutting, collpse, and hydraulic action
Middle (B)	Rapids without falls, Potholes, Plunge pools, Undermining, Landslides, Rock outcrops (Yolde Fm), Mass wasting, Boulders, Meanders	Slumped materials, Collapsed banks, Gravel	Lateral erosion, mass wasting, and abrasion
Lower (C)	Meanders (Sinuos), Cut banks	Natural levees, Point bars, Gravel, Pebbles, Sand dunes, Ridges, Floodplain, Sand mining pits	Deposition and lateral migration

A notable feature is the gorge in the upper course, which measures 10-15 m in depth and 50-70 m in length from the base to the hills. It developed through differential erosion of Pindiga and Yolde sandstones. Hydraulic action causes undermining, which ultimately results in collapse. The presence of rapids without waterfalls suggests high flow velocity; however, the resistant Pindiga limestone inhibits waterfall development. Rapids occur where the channel traverses resistant bedrock. Potholes develop through the abrasion caused by pebbles rotating within eddies, indicating turbulent flow, while plunge pools form at the bases of rapids. Overhanging cliffs provide shelter for criminal elements and animals, creating a security concern. Sediment deposition produces a relatively flat bed, as observed in the upper course and confirmed by Wanah (2017). Boulders and materials from collapsed banks are transported and subsequently deposited, creating a recurring cycle of erosion and deposition.

Undermining may cause slumping that obstructs the channel, after which flowing water removes the blockage, forming a recurring hydrological cycle. Meanders are characteristic of the middle course because of lower flow velocity, although they may also occur in the lower course. Natural levees develop through vertical sediment accumulation during flood events and are composed of well-stratified, well-sorted sand, silt, and clay. The deposits are thickest and coarsest near the channel and become thinner and finer with increasing distance. Point bars occur opposite concave cut banks and consist of laterally migrating, sharply defined meander ridges composed of sand, gravel, silt, and clay. Their nutrient-rich, finer sand particles and trapped debris make them suitable for crop cultivation.

The nine-class Geomorphon classification corresponds with the 10 common landforms identified by Jasiewicz and Stepinski (2013). However, manual interpretation identified an additional 20 microforms, including potholes and plunge pools, that the automated method failed to detect because of resolution limitations. Accordingly, integration of the two approaches is superior, as recommended by Andrea et al. (2005) and Stepinski and Jasiewicz (2011). These features have several implications, including irrigation dam sites in gorges, small-scale fishing and hydroelectricity, grazing, tourism, wind protection, and military concealment. Overhanging cliffs and gorges provide strategic hiding places for military operations, a feature also observed in the Kaltungo hills. The influence of lithology is evident. The Pindiga Formation produces rapids and

gorges because of its resistance, whereas the friable Kerri-Kerri Formation forms flat-bottomed valleys. Coal intercalations within the Gombe Sandstone contribute to the development of overhangs, while the Yolde Formation promotes undermining. These findings support Thornbury's (1968) principle that geologic structure is the dominant control on landform evolution.

Land Use Land Cover Change Detection (1993-2023)

Five Land Use and Land Cover (LULC) classes were identified. Built-up areas expanded exponentially, largely as a result of state creation in 1996, rural-to-urban migration, and the arrival of Internally Displaced Persons fleeing insurgency (Gadiga & Galtima, 2017; Bibi, 2020).

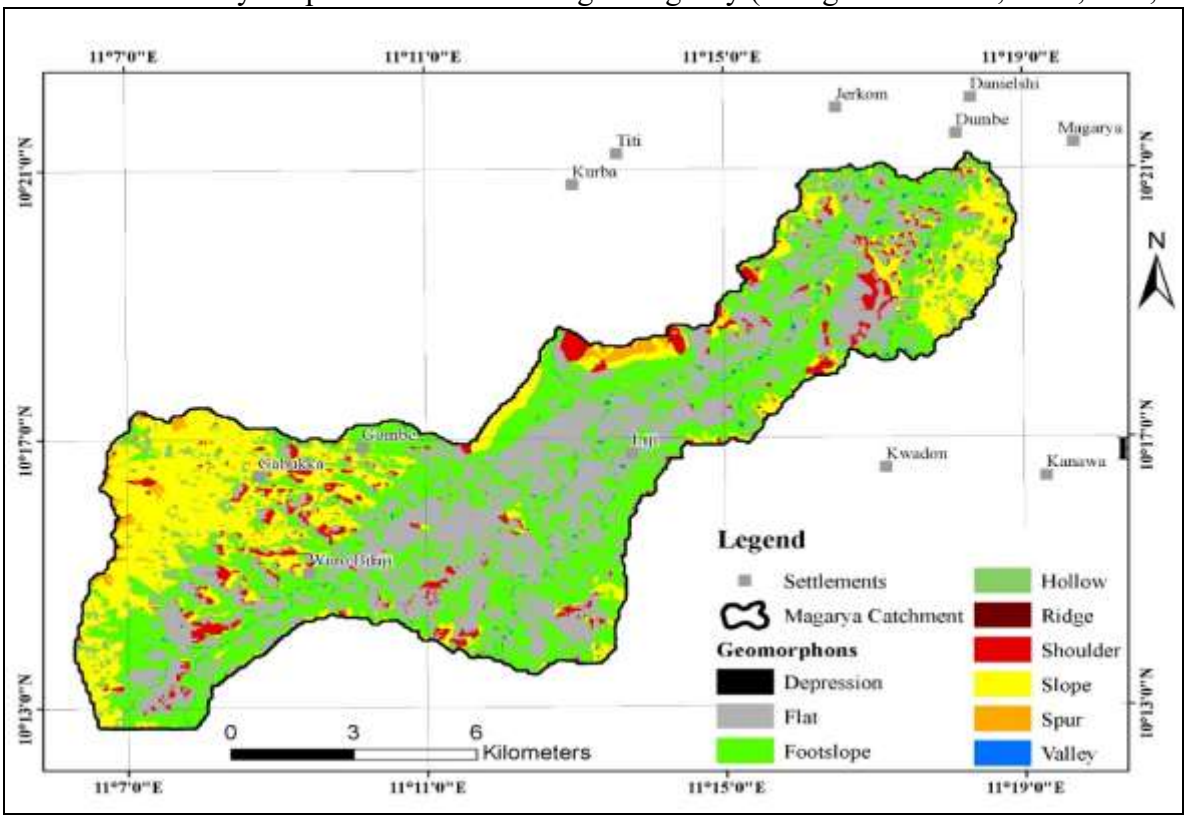


Figure 8: Geomorphons Map

Table 4: Land Use Land Cover Percentage (1993-2023) River Magarya Catchment

LULC	1993		2003		2013		2023	
	Area(sqkm)	%	Area(sqkm)	%	Area(sqkm)	%	Area(sqkm)	%
Built-up	5.79	4.44	9.46	7.27	17.63	13.54	24.56	18.86
Light vegetation	60.51	46.47	45.37	34.84	48.16	36.99	26.70	20.50
Open spaces	23.31	17.91	29.31	22.51	32.39	24.88	53.42	41.02
Rock outcrop	16.41	12.60	16.20	12.44	16.14	12.39	13.38	10.28
Thick vegetation	24.18	18.57	29.88	22.94	15.89	12.20	12.16	9.34
Total	130.21	100.00	130.21	100.00	130.21	100.00	130.21	100.00

Built-up areas increased by 63.6% (93-03), 86.3% (03-13), and 39.3% (13-23). The greatest increase occurred between 2003 and 2013, driven by the infrastructure boom that followed state

creation and by population influxes from neighboring states affected by insecurity associated with the Boko Haram insurgency, banditry, kidnapping, terrorism, and political crises (Gadiga, 2017). Light vegetation declined by 25% (93-03), increased by 6.2%, and then decreased by 44.6%. Open spaces expanded by 25.7%, 10.5%, and 64.9%, respectively, largely because of deforestation for fuelwood and construction. Thick vegetation increased by 23.5% (93-03), reflecting rejuvenation during 1983-1993, before declining by 46.8% and 23.5% in the subsequent periods.

The increase in built-up land cover from 4.4% to 18.8% is consistent with the 133% increase reported by Gadiga and Galtima (2017) in Gombe Metropolis between 1991 and 2003 following state creation. Thick vegetation declined by 49.7%, primarily because of fuelwood demand from rice-parboiling mills along the river, indicating unsustainable resource use. Open spaces expanded from 17.9% to 41% because of indiscriminate tree felling for fuel energy and construction. Rock outcrops decreased by 17.7% as a result of mining-related blasting and anthropogenic geomorphic processes.

Anthropogenic activities observed include irrigation at Dumbe, where the low-gradient channel mouth, natural levee, point bars, and channel sinuosity are suitable for rice cultivation; mechanical workshops along the bank, which contribute to oil pollution; and residential buildings constructed on the bank. Although boulders and concrete with larger grain sizes have been arranged to mitigate degradation, they reduce channel capacity. Rice mills along the bank contribute to deforestation and husk pollution, while sand mining in the middle course accelerates bank collapse and causes undercutting. Lumbering in the lower segment, C, reduces riparian vegetation that helps stabilize the banks. According to Ward and Tockner (2001), vegetation removal exposes soil to erosive forces and increases sediment transport, as observed in the study area.



Figure 9: Irrigation Activities at the Lower course of the River

This trend has climatic implications, including increased temperatures and global warming, and hinders progress toward Sustainable Development Goal 13 (Climate Action) and Goal 15 (Life on Land). The loss of resources is more psychologically stressful than their gain (Stevan, 1989), underscoring the importance of conservation efforts to prevent further losses. These changes accelerate economic activity, stimulate industrial expansion and urbanization, and ultimately produce adverse effects on rainfall variability and drought conditions (Bibi, 2020). The expansion of built-up areas and open spaces increases runoff, decreases infiltration, and raises

peak flood discharge in Magarya, thereby contributing to flooding in Gombe State. The reduction in dense vegetation diminishes interception, increases surface runoff, and elevates sediment delivery to the Morom and Dadin Kowa Reservoirs, consequently reducing their storage capacity.

Conclusion

The River Magarya catchment, covering 130.2 km² with a channel length of 30.1 km is a sinous river, exhibits a conventional three-stage evolutionary pattern shaped by four geological formations and intensified by anthropogenic pressure. Its channel is characterized by an average gradient of 11.8 m/km, elevations ranging from 275-630 m, 9 automated geomorphons, and 29 manually identified landforms, including gorges 34.6-47 m high, interlocking spurs, rapids without falls, potholes, plunge pools, overhanging cliffs, rock outcrops, meanders, point bars, and natural levees. Rather than forming a V-shaped valley, the upper course contains a flat-bottomed valley because of the friable Kerri-Kerri sandstone. The middle course forms a gorge as a result of differential erosion between the Pindiga and Yolde formations, whereas the lower course consists of a broad U-shaped valley with a floodplain. Land Use Land Cover analysis indicates substantial anthropogenic transformation over three decades, including a 327% increase in built-up areas, a 49.7% reduction in thick vegetation, and a 129% increase in open spaces.

The dataset establishes a baseline for (i) hydrological simulation and flood modeling, using 5 sub-catchments as hydrological units, (ii) locating irrigation dams at the Dumbe gorge sites, (iii) reducing flood risk through check dams in flat areas vulnerable to erosion, (iv) analyzing terrain for military training and identifying strategic hideouts, (v) designing the Akko-Gombe bridges with consideration of channel gradient and gorge depth, and (vi) supporting watershed management under the Nigeria Erosion and Watershed Management Project.

The complexity and diversity of the landforms underscore the need for a balanced approach to implementation, thereby promoting peaceful coexistence with the natural environment. It is important to sensitize people to the need to preserve the cultural landscape and accommodate its use when communities fall back on it for continued utilization. The findings demonstrate the validity of monitoring gully erosion at the catchment scale. The resulting maps are valuable tools for planners, decision-makers, and engineers, enabling them to make affordable, timely, and rational decisions that help prevent or reduce devastating impacts.

Recommendations

Drawing on the findings of this study, several interconnected recommendations are proposed to support the sustainable management of the River Magarya catchment. First, for hydrological modeling and water resources planning, the Upper Benue River Basin Development Authority should adopt the five delineated sub-catchments as hydrological units for Soil and Water Assessment Tool (SWAT) modeling. This approach will facilitate accurate discharge estimation and flood forecasting across the 130.2 km² basin. Second, with respect to conservation and flood risk reduction, the gorge and valley areas at Dumbe should receive priority protection from the Nigerian Conservation Foundation and the Federal Ministry of Environment because of their overhanging cliffs and substantial incision depths ranging from 34.6 to 47 m. Accordingly, the Nigeria Erosion and Watershed Management Project (NEWMAP) should introduce structural interventions, including check dams, alongside biological measures, such as afforestation, in the flat and exposed upper catchment. The limited vegetation cover in this area leaves the friable Kerri-Kerri sandstone particularly vulnerable to erosion. This requirement is further

demonstrated by the observed Land Use Land Cover changes, including a 327% increase in built-up area and a 49.7% reduction in thick vegetation between 1993 and 2023.

Moreover, effective regulatory enforcement is essential. The National Environmental Standards and Regulations Enforcement Agency (NESREA) should implement stringent controls on sand mining and construction within riparian zones by maintaining a 100 m setback along the riverbanks and regulating blasting near rock outcrops that can destabilize channel slopes. These measures should be reinforced through community-based sustainable land management. The local communities of Doma, Nasarawo, Dumbe and Akko should participate actively in planning and decision-making, since their traditional knowledge and practices may support conservation strategies that are both more effective and culturally appropriate. For long-term sustainability, permanent hydrological monitoring stations should be installed at Points A, B, and C along the upper, middle and lower courses to continuously assess discharge, sediment load and cross-profile changes. The resulting data would support siltation control through upstream afforestation and regulated sand mining.

Finally, subsequent research should extend beyond morphometric assessment to incorporate sedimentological analyzes using X-Ray Diffraction (XRD) and X-Ray Fluorescence (XRF), two-dimensional hydrodynamic modeling, and discharge validation using current meter, Acoustic Doppler Current Profiler (ADCP) and weir methods to quantify the contribution of groundwater baseflow. The strategic significance of the gorge and the overhanging cliffs along the upper and middle reaches, which provide natural concealment, necessitates detailed terrain mapping to support military training and security operations. These efforts should be complemented by public awareness campaigns led by the National Orientation Agency (NOA) and NESREA to encourage responsible land use, watershed conservation, and protection of the cultural landscape.

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