Gully Erosion in the Lateritic Landscapes of Southeastern Nigeria: A Multidisciplinary Review of Controlling Mechanisms, Spatial Variability, And Integrated Mitigation Strategies

Tamunoene Kingdom Simeon Abam[1], Gordon T Amangabara[2], Sylvia D Kingdom-Abam[3], Victoria Sunday Igbani[4]

[1]Institute of Geosciences and Environmental Management, Rivers State University, Port-Harcourt, Nigeria.

[2]Department of Environmental Management Federal University of Technology, Owerri

[3]Groundscan Services Nigeria Limited Lydia Abam Lane, off Dr Peter Odili Road, Trans Amadi Industrial Layout, Port-Harcourt, Nigeria

[4]Department of Geology, University of PortHarcourt, Nigeria

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ABSTRACT

Gully erosion is one of the most destructive forms of land degradation in southeastern Nigeria, where extensive lateritic terrains, intense seasonal rainfall, and increasing anthropogenic disturbances have accelerated landscape degradation, reduced agricultural productivity, damaged critical infrastructure, and displaced vulnerable communities. Despite decades of research and substantial investments in erosion control, gully expansion continues unabated, largely because existing studies have tended to examine hydrological, geotechnical, geomorphological, or land-use factors in isolation, resulting in limited understanding of the complex interactions governing gully initiation, evolution, and spatial variability. This review synthesizes current knowledge on the mechanisms, controlling factors, spatial distribution, and mitigation strategies of gully erosion in the lateritic landscapes of southeastern Nigeria, with emphasis on the interactions between geological, geotechnical, hydrological, geomorphological, and anthropogenic processes. Evidence from field observations and published studies demonstrates that gully initiation is triggered when concentrated surface runoff generated by high-intensity rainfall exceeds the critical shear strength of exposed lateritic soils, while subsequent expansion is governed by the coupled effects of hydraulic scour, headward erosion, seepage, toe undercutting, and gravity-induced slope failures. The severity and morphology of gullies vary considerably across the region owing to differences in lithology, topography, soil composition, groundwater conditions, and land-use practices. Areas underlain by highly permeable, cohesionless, sand-rich lateritic formations exhibit the most rapid gully growth because of their low plasticity, weak structural integrity, and high susceptibility to collapse during repeated wetting–drying cycles. Conversely, soils with higher clay content and greater cohesion exhibit relatively lower rates of gully development. The review further highlights that rapid urbanization, deforestation, poorly designed drainage systems, uncontrolled runoff from roads, and unsustainable agricultural practices significantly amplify natural erosion processes. The synthesis reveals important limitations in existing predictive and management approaches, including inadequate integration of geotechnical and hydrological processes, insufficient field validation of susceptibility models, limited consideration of anthropogenic drivers, and weak translation of scientific findings into engineering practice and public policy. Effective long-term mitigation therefore requires an integrated framework that combines geotechnical characterization, hydrological modelling, high-resolution geospatial monitoring, engineered drainage systems, bioengineering techniques, sustainable land-use planning, and community participation. Such a multidisciplinary approach provides a stronger scientific basis for improving gully erosion prediction, designing resilient control measures, and enhancing environmental sustainability across southeastern Nigeria and other tropical lateritic regions experiencing similar erosion challenges.

Keywords: Gully erosion, geology, south east Nigeria, land use, runoff, mechanism, mitigation

INTRODUCTION

Gully erosion is among the most severe manifestations of land degradation worldwide and constitutes a major environmental, engineering, and socio-economic challenge, particularly in tropical and subtropical regions characterized by highly weathered soils and intense seasonal rainfall. Beyond the irreversible loss of fertile land, gully erosion alters watershed hydrology, accelerates sediment delivery to rivers and reservoirs, damages critical infrastructure, threatens human settlements, and undermines sustainable agricultural production. The increasing frequency of extreme rainfall events associated with climate variability, coupled with rapid urbanization, deforestation, and unsustainable land-use practices, has further accelerated gully initiation and expansion in many developing countries (Zhao et al., 2021; Ghosh et al., 2021; Jaafari et al., 2022).

Southeastern Nigeria represents one of the global hotspots of gully erosion owing to its unique combination of geological, geomorphological, climatic, and anthropogenic conditions. The region is characterized by deeply weathered lateritic soils developed predominantly over the Ajali Sandstone, Nanka Sands, Benin Formation, Ogwashi–Asaba Formation, and Imo Shale. These formations are highly susceptible to erosion because they are dominated by loose, highly permeable sandy materials with relatively low cohesion and plasticity. Combined with annual rainfall ranging from approximately 1,900 to 2,200 mm, steep and undulating terrain, increasing population pressure, rapid urban expansion, and widespread vegetation removal, these geological conditions create an environment that is exceptionally vulnerable to gully initiation and rapid landscape degradation (Okagbue & Ezechi, 1988; Ocheli et al., 2021; Egbueri & Igwe, 2021).

The socio-economic consequences of gully erosion in southeastern Nigeria are profound. Hundreds of active gullies have destroyed roads, bridges, residential buildings, public utilities, and farmlands, while simultaneously disrupting transportation networks, increasing production costs, displacing communities, and reducing agricultural productivity. In severely affected states such as Anambra, Enugu, Abia, and Imo, numerous communities continue to experience extensive land loss and recurring infrastructure failures despite significant investments in erosion control programmes (Francisca et al., 2023; Alhassaan et al., 2024; Ali et al., 2025). The Agulu–Nanka gully complex alone covers approximately 1,100 km², with some gully heads retreating by as much as 20–50 m annually, making it one of the largest and fastest-growing gully systems in Africa (Obiadi et al., 2011). Estimates further indicate that economic losses attributable to gully erosion exceed US$100 million annually through damage to infrastructure, loss of agricultural land, reduced property values, and increased maintenance costs (Nwankwoala, 2019).

Recognition of the severity of the problem has stimulated extensive research over the past five decades. Early investigations focused primarily on the geomorphological evolution of gullies and their relationship with land use (Grove, 1949; Ofomata, 1975a, 1975b, 1987), whereas more recent studies have increasingly employed remote sensing, Geographic Information Systems (GIS), geotechnical investigations, and machine learning techniques to map gully distribution and predict erosion susceptibility (Arabameri et al., 2020; Ocheli et al., 2021; Emeh et al., 2023; Wang et al 2023; Fagbohun et al., 2024). Advances in geospatial technologies have significantly improved the identification of erosion-prone areas, while geotechnical investigations have enhanced understanding of the influence of soil plasticity, cohesion, permeability, particle-size distribution, and shear strength on gully development (Chikwelu & Ogbuagu, 2014; Nwankwoala & Igbokwe, 2020).

Despite these advances, effective prediction and sustainable control of gully erosion remain elusive. Most previous studies have concentrated on individual components of the erosion system, including rainfall characteristics, soil properties, topographic variables, land-use change, or spatial susceptibility modelling, without adequately considering the dynamic interactions among these controlling factors. Process-based models provide valuable insights into hydraulic and sediment transport processes but require extensive site-specific data that are rarely available in developing countries. Conversely, empirical and machine-learning models generally achieve high predictive accuracy for identifying susceptible locations but often provide limited understanding of the underlying physical mechanisms controlling gully initiation, enlargement, and long-term evolution (Poesen et al., 1998; Wei et al., 2022). Consequently, many mitigation measures have been implemented based primarily on erosion symptoms rather than on the governing geotechnical and hydrological processes responsible for gully development.

Furthermore, existing studies have rarely integrated geological characteristics, geotechnical behaviour, hydrological processes, geomorphological evolution, and anthropogenic influences within a single conceptual framework capable of explaining why gullies exhibit markedly different morphologies, rates of expansion, and failure mechanisms across southeastern Nigeria. Equally important, relatively little attention has been devoted to translating scientific understanding into engineering design criteria, land-use planning, and policy interventions that can effectively reduce long-term erosion risk. This disconnect between scientific research and practical implementation partly explains why numerous erosion-control projects have achieved only limited or temporary success.

The development of gully erosion is inherently a coupled hydro-geotechnical process. Gully initiation begins when concentrated runoff generates hydraulic shear stresses that exceed the critical shear strength of the soil, causing progressive detachment of soil particles and the formation of rills that subsequently evolve into gullies. As incision progresses, side slopes become increasingly unstable due to toe erosion, seepage, elevated pore-water pressures, tension cracking, and repeated wetting–drying cycles, resulting in rotational failures, slab collapse, and rapid headward retreat. The relative contribution of these mechanisms is strongly influenced by lithology, soil composition, groundwater conditions, slope morphology, rainfall intensity, vegetation cover, and human activities, particularly poorly designed drainage systems, road construction, sand mining, and deforestation (Carey, 2006; Ocheli et al., 2021; Egbueri & Igwe, 2021).

Given the increasing environmental and economic costs of gully erosion and the limitations of existing approaches, there is a pressing need for a comprehensive synthesis that integrates current knowledge across multiple disciplines. Such an integrated perspective is essential for identifying the dominant controls on gully initiation and evolution, improving susceptibility assessment, and developing more effective and sustainable mitigation strategies.

Accordingly, this review critically synthesizes current knowledge on the mechanisms, spatial distribution, controlling factors, and mitigation of gully erosion in the lateritic terrains of southeastern Nigeria. Particular emphasis is placed on the interactions among geological, geotechnical, hydrological, geomorphological, climatic, and anthropogenic processes that govern gully development. The review also evaluates the strengths and limitations of existing predictive models and erosion-control measures and proposes an integrated framework to support improved engineering design, land-use planning, environmental management, and policy formulation for sustainable erosion control in southeastern Nigeria and other tropical lateritic environments.

METHODOLOGY

This study adopted an integrated review and field-based investigation approach to synthesize current knowledge on the mechanisms, controlling factors, spatial distribution, and mitigation of gully erosion in the lateritic terrains of southeastern Nigeria. The methodological framework combined systematic review of published literature with field observations and geotechnical investigations to provide a comprehensive understanding of the hydro-geotechnical processes governing gully initiation and evolution.

The first stage involved an extensive desk-based review of peer-reviewed journal articles, conference proceedings, government technical reports, engineering consultancy reports, geological maps, and unpublished academic studies relating to gully erosion in southeastern Nigeria and comparable tropical environments. Particular emphasis was placed on studies addressing geological controls, soil properties, rainfall characteristics, hydrological processes, geomorphology, land-use change, erosion susceptibility modelling, and mitigation strategies. The reviewed literature was critically synthesized to identify areas of consensus, methodological limitations, knowledge gaps, and emerging research directions.

To complement the literature review, reconnaissance surveys and detailed field investigations were undertaken at representative gully erosion sites across southeastern Nigeria. Site selection was based on the severity of erosion, geological setting, accessibility, and spatial distribution across the major lateritic formations. Field investigations included visual assessment of gully morphology, measurements of gully geometry, documentation of slope failure mechanisms, drainage characteristics, land-use conditions, vegetation cover, and evidence of anthropogenic disturbances such as road construction, sand mining, deforestation, and poorly designed drainage systems. Local knowledge obtained through interactions with community members also provided valuable information on the historical development and progression of selected gullies.

Geotechnical investigations were conducted to characterize the engineering properties of soils controlling gully development. Field and laboratory investigations included borehole drilling, disturbed and undisturbed soil sampling, Standard Penetration Tests (SPT), Cone Penetration Tests (CPT), in-situ vane shear tests, stratigraphic logging, particle-size distribution analysis, Atterberg limits, and other index property determinations. These tests provided information on soil classification, sand-clay proportions, plasticity, cohesion, permeability, and shear strength, which are fundamental parameters influencing soil erodibility and slope stability.

The field observations, laboratory results, and published evidence were subsequently integrated using a comparative analytical approach. Relationships among lithology, topography, rainfall, hydrological processes, soil characteristics, and human activities were examined to explain variations in gully morphology, mechanisms of initiation, rates of expansion, and regional susceptibility. Rather than evaluating individual factors independently, the study adopted a systems perspective that emphasizes the interactions among geological, geotechnical, hydrological, geomorphological, climatic, and anthropogenic controls. This integrated analytical framework forms the basis for evaluating existing mitigation measures and proposing more effective strategies for sustainable gully erosion management in southeastern Nigeria.

Description of Study area

Aspects of land form, climate and geology are described as attributes that are implicated in gully development. Southeastern Nigeria is characterized by two seasons in the year, namely: the wet and dry seasons. The total annual precipitation decreases from 2200mm in the south end to 1900mm in the north (Adeola *et al* 2016). The hottest months as are January to March with temperature averaging 27^{o}C. The relative humidity is generally high throughout the year, reaching a maximum of 90% recorded during the rainy season.

Although the area has a variety of land forms, there is a significant flat and low-lying part, generally less than 200m above sea-level. The low-lying plain is the southward extension of the coastal plain sands. The central part is characterized by undulating land surface with many hills with an average height of between 170m and 180m above sea-level.

The superficial geology of the region is characterized by sedimentary formations, including the Benin Formation, Ogwashi-Asaba Formation, and Recent Alluvium as exemplified in Figures (1 to 3) for Anambra, Imo, Ebonyi and Abia States.

These formations overlie the older Imo Shale. The Benin Formation, the most dominant, is composed of sandstone and sandy sediments. Underlying the Benin Formation is the Ogwashi-Asaba Formation, which consists of sandstones, shales, and clays. The Recent Alluvium, found along river channels, includes unconsolidated sands, gravels, and silts.

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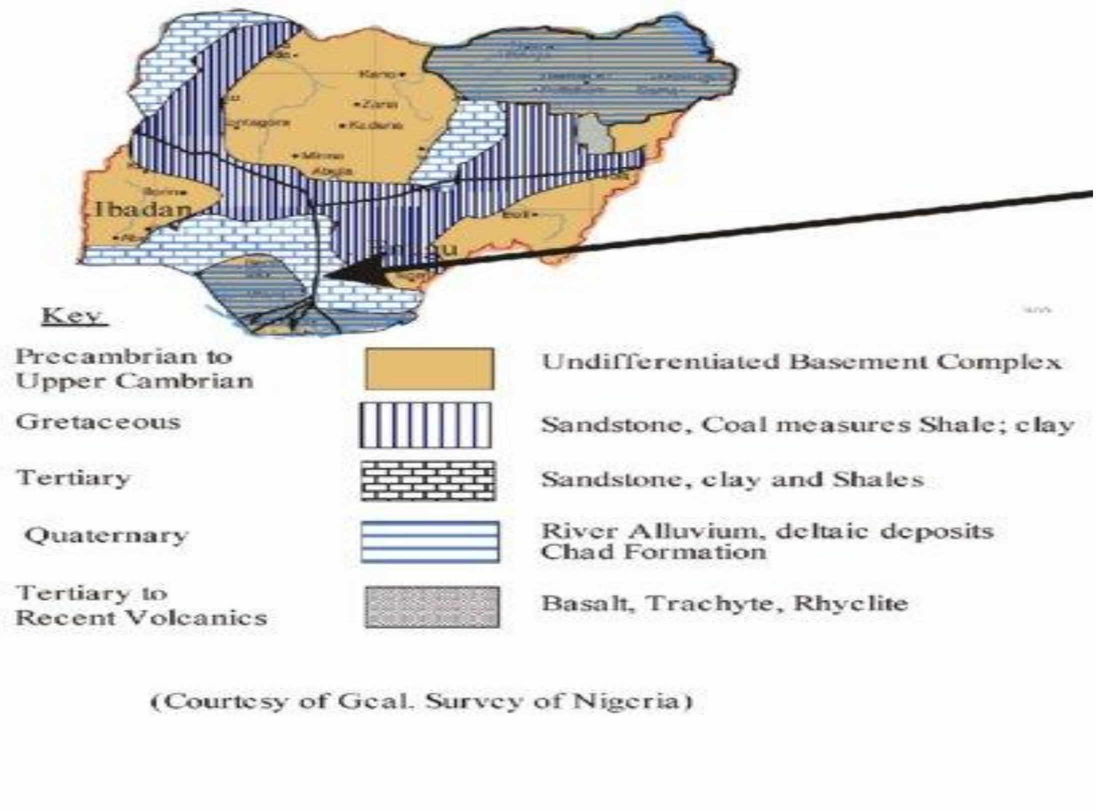

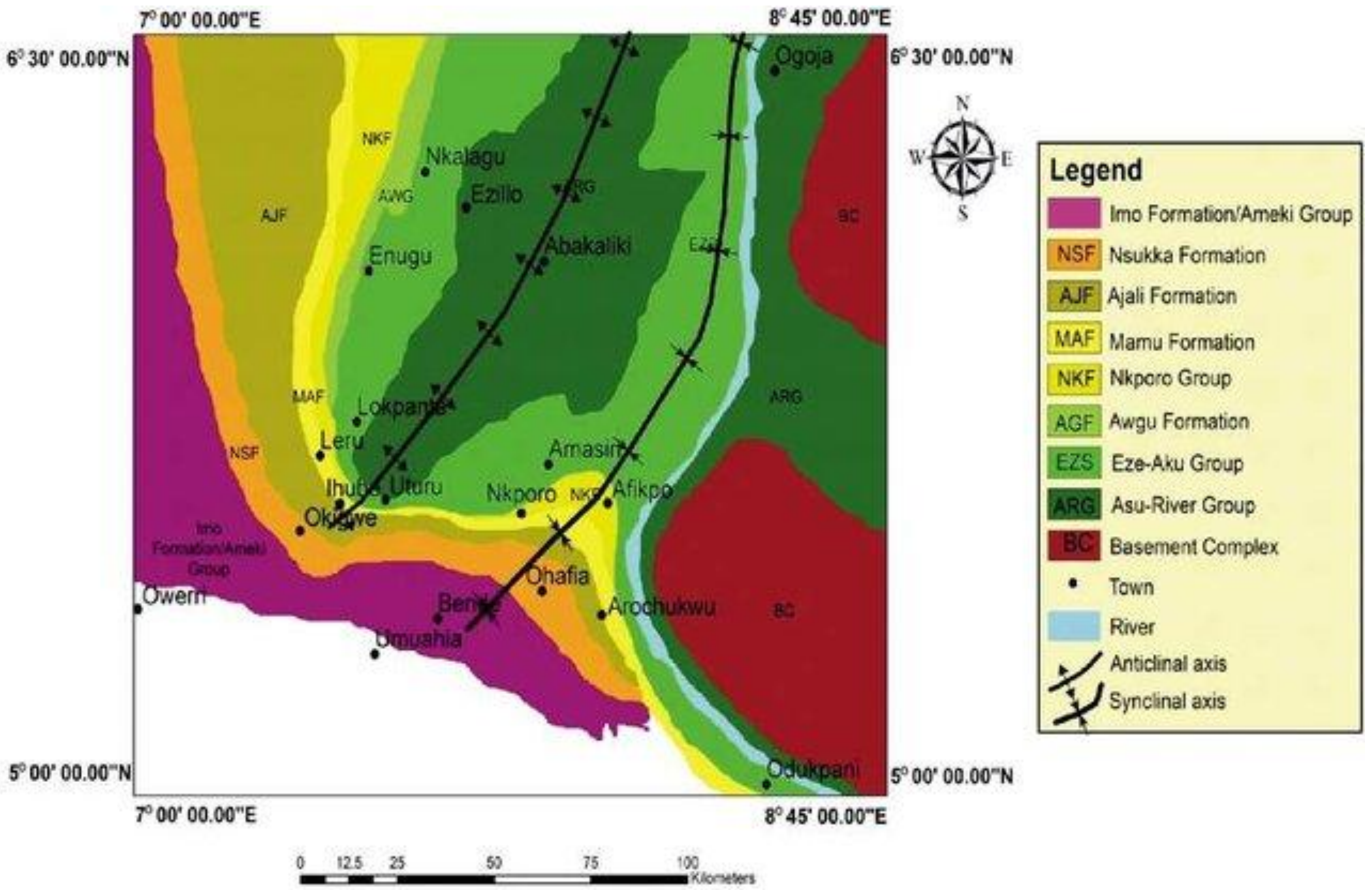

Fig.(1) Geology of South-East Nigeria (after Igwe and Obasi; 2021)

Over the years, these soil formations have been subjected to tropical/subtropical weathering and a process of lateritization resulting in iron – aluminum -enrichment of the soil.

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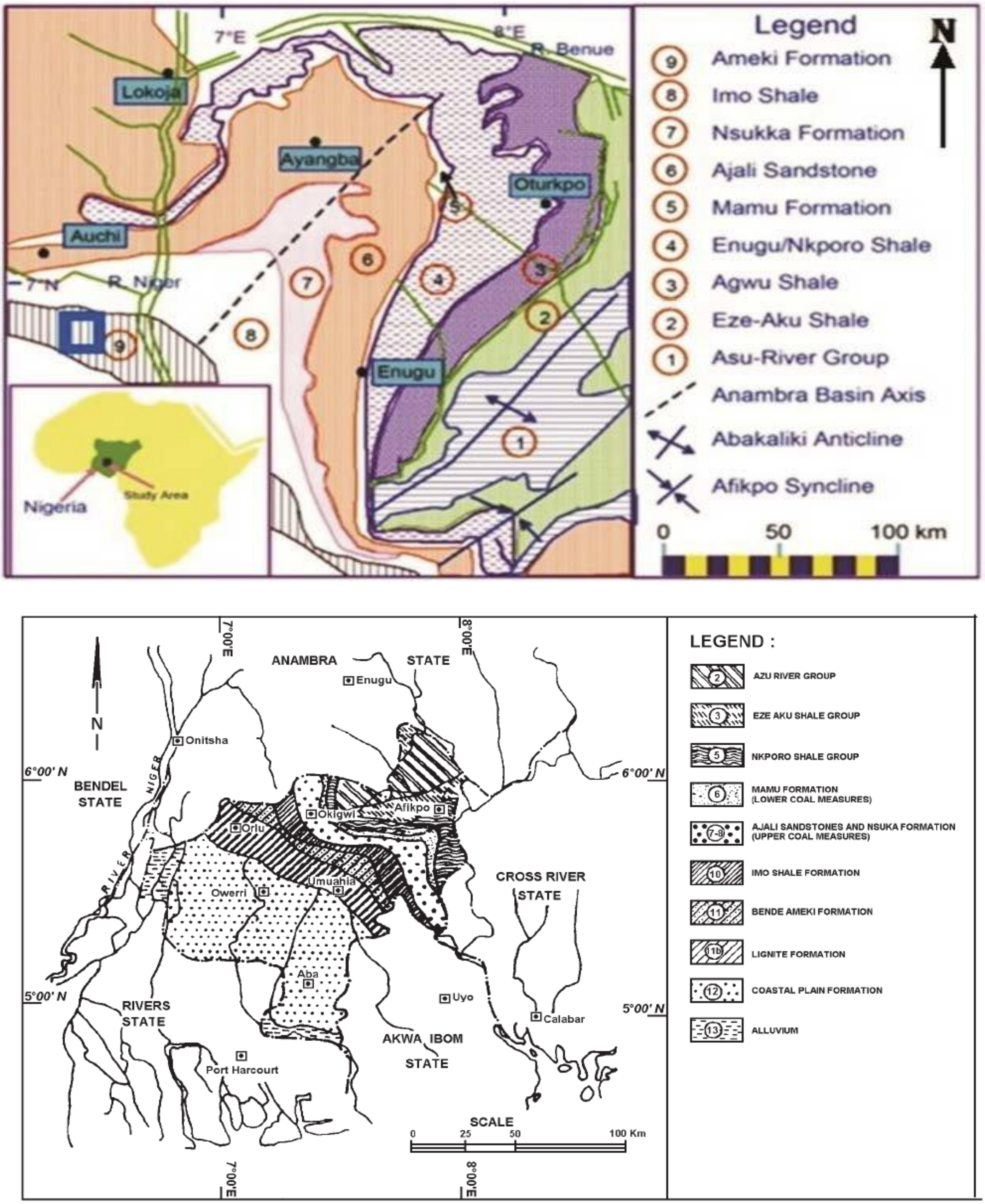

Fig. (2): Geological maps of Anambra and Imo States (after Dim et al; 2019)

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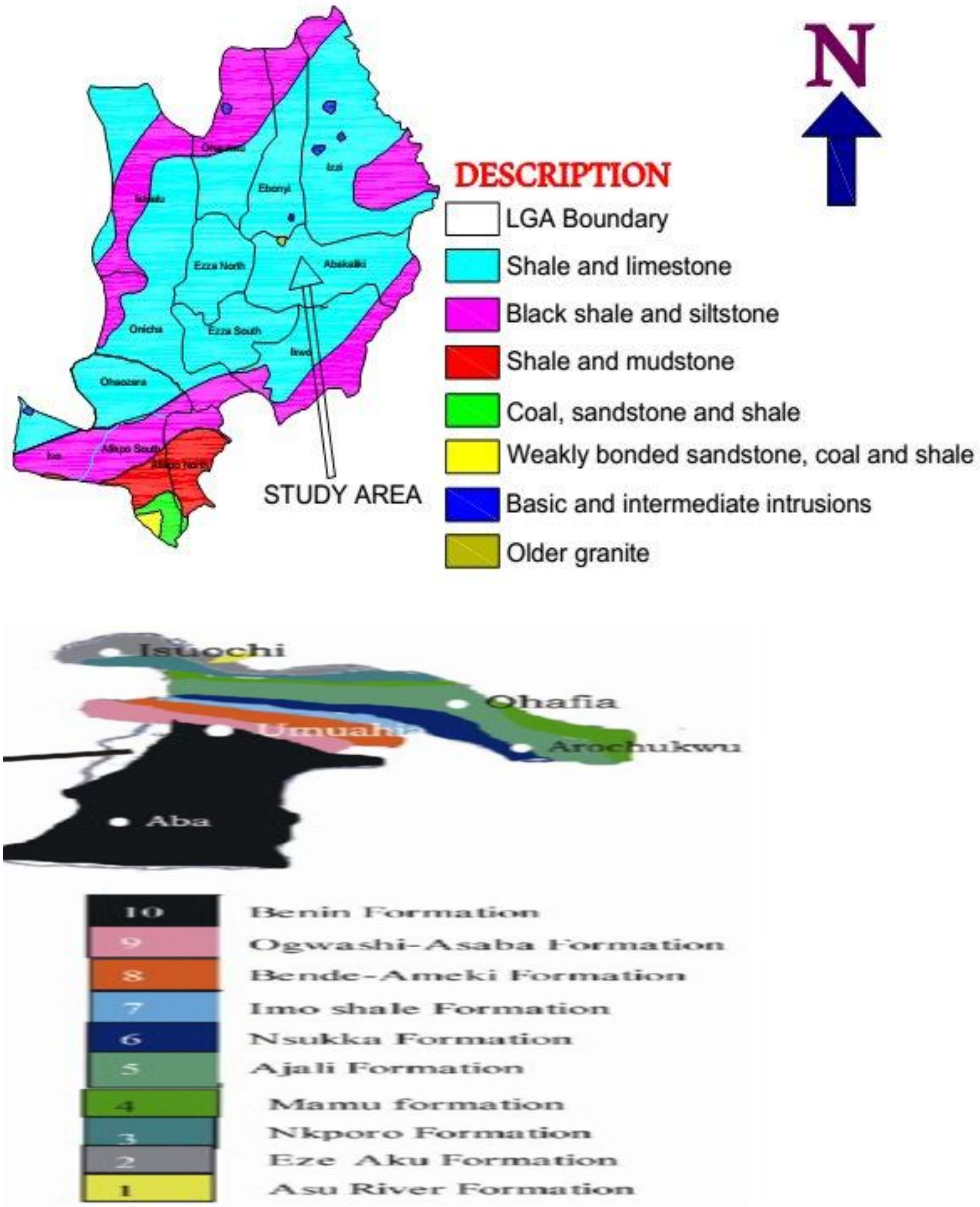

Fig. 3: Geological map of Ebonyi and Abia States (after Salahudeen and Aghayan (2018) for Ebonyi, Magnus Uzoma Igboekwe1, Cyril Ngozi Nwankwo; (2011) for Abia)

RESULTS AND DISCUSSION

Geological and Geotechnical Controls on Gully Development

Field investigations confirmed that lateritic soils constitute the dominant surficial deposits across southeastern Nigeria, with thicknesses ranging from approximately 8 to 40 m. Borehole records from Umudike, Onitsha, Enugu, and Owerri indicate that these lateritic materials overlie predominantly sandy sedimentary formations, thereby exerting a strong control on the initiation, morphology, and long-term evolution of gullies.

The results demonstrate that soil composition is the most important predisposing factor controlling gully erosion within the study area. Areas underlain by loose, highly permeable, sand-rich lateritic soils consistently exhibit the greatest erosion intensity because these materials possess low plasticity, weak cohesion, poor aggregation, and limited resistance to hydraulic detachment. Although Standard Penetration Test (SPT) values indicate relatively high frictional resistance in many locations, the low clay fraction substantially reduces inter-particle bonding, making the soils highly vulnerable once concentrated runoff develops. Consequently, hydraulic erosion rapidly removes the supporting material, triggering progressive wall collapse and headward retreat.

Particle-size analyses reveal marked regional variations in soil composition. Severe gully erosion in Anambra and Enugu States is associated with soils containing more than 90% sand, whereas soils from Abia and Imo generally contain between 72 and 80% sand with relatively higher clay fractions. Ebonyi State exhibits the lowest gully erosion intensity because its clay-rich soils possess greater cohesion and lower permeability. These findings indicate that the spatial distribution of gully erosion closely follows the regional geological framework and confirm that increasing clay content enhances soil resistance by improving cohesion and reducing seepage-induced instability. This observation agrees with previous investigations by Okagbue and Ezechi (1988), Chikwelu and Ogbuagu (2014), Ocheli et al. (2021), and Egbueri and Igwe (2021), all of whom identified soil texture and engineering properties as primary determinants of gully susceptibility.

Rather than acting independently, geological conditions determine the mechanical behaviour of soils under hydraulic loading. Consequently, lithology should be regarded as the principal predisposing factor, while rainfall and runoff constitute the triggering mechanisms responsible for gully initiation.

Mechanisms Governing Gully Initiation and Expansion

Field observations indicate that gully development results from coupled hydraulic and geotechnical processes rather than from surface runoff alone. Gully initiation begins when high-intensity rainfall generates concentrated overland flow whose hydraulic shear stress exceeds the critical shear strength of exposed lateritic soils. Initial surface incision develops into rills that progressively enlarge into permanent gullies through repeated rainfall events.

Once formed, gullies evolve through several interacting mechanisms. Continuous scour at the gully head promotes headward retreat, while toe erosion progressively removes lateral support from side slopes. As infiltration increases, pore-water pressures rise within the soil profile, reducing effective stress and shear strength. These processes promote tension cracking, rotational failures, slab collapse, and mass wasting, which collectively account for much of the observed gully widening. Consequently, hydraulic erosion and slope instability should not be viewed as separate processes but as mutually reinforcing mechanisms governing gully evolution.

Differences in soil composition explain the contrasting gully morphologies observed across southeastern Nigeria. In Anambra, where groundwater commonly occurs at greater depths and sandy formations dominate, gullies are characteristically deep and narrow with steep V-shaped cross-sections approaching the natural angle of repose. Conversely, in Imo and parts of Abia, relatively higher clay contents favour the development of tension cracks and rotational failures, producing broader U-shaped gullies with more frequent wall collapses. These observations demonstrate that gully geometry reflects the interaction between soil mechanics and hydrological conditions rather than topography alone.

Influence of Soil Engineering Properties

Laboratory analyses demonstrate that engineering properties exert significant influence on erosion susceptibility. Low plasticity indices, limited cohesion, high permeability, and coarse-grained textures collectively reduce the ability of soils to resist hydraulic forces. Although iron oxide cementation contributes to the apparent strength of lateritic soils under dry conditions, repeated wetting weakens this cementation and progressively destroys soil structure.

The relationship between coarse sand content and gully development observed during this investigation supports earlier experimental findings that increasing sand content accelerates gully widening, deepening, and headward migration. Highly permeable soils also facilitate rapid infiltration, increasing seepage pressures beneath gully walls and promoting internal erosion before visible slope failures occur. Consequently, engineering parameters

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such as plasticity index, permeability, cohesion, particle-size distribution, and shear strength should be considered essential variables in erosion susceptibility assessments.

These findings further suggest that many existing erosion-control projects fail because they primarily address surface runoff while neglecting the geotechnical weaknesses governing slope instability. Sustainable mitigation therefore requires simultaneous control of hydraulic loading and improvement of soil mechanical stability.

Topographic and Hydrological Controls

Topography strongly influences the concentration and velocity of surface runoff. Steeper slopes increase flow velocity and stream power, thereby enhancing the erosive capacity of runoff and accelerating sediment transport. However, slope alone does not determine erosion severity. Rather, severe erosion occurs where steep terrain coincides with weak geological formations and highly erodible soils.

Hydrological processes interact closely with geological controls. High rainfall intensity generates concentrated runoff capable of initiating erosion, whereas permeable sandy soils encourage infiltration, subsurface flow, and piping. This dual influence explains why many gullies continue to expand even after surface runoff has diminished. Consequently, hydrological processes provide the energy for erosion, whereas geological and geotechnical properties regulate the rate and style of gully evolution.

Regional Variability of Gully Characteristics

Marked regional differences were observed in gully morphology, dimensions, and estimated soil loss. Some gullies exceeded 60 m in depth, while estimated soil losses reached tens of thousands of tonnes. These variations cannot be explained solely by rainfall because climatic conditions are broadly similar across southeastern Nigeria. Instead, the findings demonstrate that regional geological variability largely determines erosion intensity. An assessment of the distribution and intensity (Table 1) generally indicates a broad severity sequence approximately as:

Anambra → Enugu → Imo → Abia → Ebonyi

with Anambra showing the most extensive/severe gully problem among the southeastern states. However, this ranking should be treated as a regional generalization rather than a fixed state-wide rule, because gully susceptibility varies considerably within each state.

Table (1) Regional pattern of gully erosion intensity and concentration

Region	Expected gully susceptibility	Principal controlling factors
Anambra	Very high	Friable sedimentary formations, highly erodible soils, concentrated runoff, steep slopes, intense human disturbance
Enugu	Very high–high	Dissected terrain, weak/friable formations, slopes, runoff concentration
Imo	High	Highly erodible soils, rainfall/runoff, drainage modification and land-use change
Abia	High	Sandy/friable materials, slope, concentrated drainage and anthropogenic disturbance
Ebonyi	Moderate overall, locally high	More resistant/older formations in some areas, but susceptible lithologies and steep terrain can produce severe local gullies

The predominance of deep V-shaped gullies in the Nanka and Ajali Sandstone formations reflects high permeability and negligible cohesion, whereas broader U-shaped gullies occurring within more cohesive formations indicate greater influence of mass movement processes. These morphological differences have important engineering implications because stabilization measures effective for shallow rotational failures may be ineffective where deep hydraulic incision dominates.

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Effects of Wetting–Drying Cycles and Human Activities

Seasonal wetting–drying cycles further weaken lateritic soils by disrupting soil aggregates, increasing permeability, reducing cohesion, and promoting crack development. Much of the deterioration occurs during the first few seasonal cycles, after which the weakened soil becomes increasingly susceptible to hydraulic erosion and repeated slope failures. These climatic effects explain the accelerated expansion frequently observed during successive rainy seasons.

Human activities significantly amplify these natural processes. Deforestation, uncontrolled urban expansion, poor agricultural practices, road construction, sand mining, and inadequate drainage systems increase runoff generation while simultaneously reducing soil resistance. Poorly designed roadside drainage is particularly important because it converts diffuse runoff into concentrated high-energy flows capable of rapidly initiating gullies. The interaction between anthropogenic disturbances and naturally weak geological conditions explains why erosion rates are considerably higher in developed catchments than in relatively undisturbed landscapes.

Implications for Gully Erosion Management

The results demonstrate that effective gully management must be founded on an integrated hydro-geotechnical understanding of erosion processes. Mitigation measures designed solely to intercept runoff are unlikely to succeed where slope instability and seepage dominate gully expansion. Likewise, vegetation restoration alone cannot stabilize deep gullies developed within highly permeable sandy formations unless hydraulic loading is simultaneously controlled.

Accordingly, erosion-control programmes should integrate detailed geotechnical characterization, improved drainage design, slope stabilization, groundwater management, revegetation, and continuous geospatial monitoring. Such multidisciplinary approaches address both the triggering mechanisms and the underlying geological controls responsible for long-term gully development and therefore offer greater prospects for sustainable erosion management in southeastern Nigeria.

Major Findings

The review demonstrates that gully erosion in southeastern Nigeria is governed by complex interactions among geological, geotechnical, hydrological, geomorphological, climatic, and anthropogenic factors rather than by any single controlling variable.

The principal findings are summarized as follows:

1. Geological formations exert the primary control on regional gully susceptibility. Highly permeable, sand-rich lateritic soils developed over the Ajali Sandstone, Nanka Sands, and Benin Formation exhibit significantly greater erosion susceptibility than clay-rich formations because of their low cohesion, low plasticity, and high permeability.

2. Concentrated surface runoff generated during high-intensity rainfall provides the hydraulic energy required for gully initiation; however, subsequent expansion is controlled predominantly by hydro-geotechnical interactions involving seepage, pore-water pressure development, toe erosion, tension cracking, and gravity-induced slope failures.

3. Spatial differences in gully morphology across southeastern Nigeria reflect regional variations in geology and soil engineering properties. Deep V-shaped gullies dominate highly sandy formations, whereas broader U-shaped gullies occur in formations with relatively greater clay content and increased mass movement activity.

4. Repeated wetting–drying cycles progressively degrade the engineering properties of lateritic soils by reducing cohesion, increasing permeability, weakening aggregate stability, and accelerating slope instability.

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5. Human activities—including deforestation, uncontrolled urbanization, poor drainage design, inappropriate road construction, sand mining, and unsustainable agricultural practices—substantially accelerate natural erosion processes by increasing runoff concentration and reducing soil resistance.

6. Current susceptibility models successfully identify erosion-prone locations but remain limited in their ability to simulate coupled hydro-geotechnical processes responsible for long-term gully evolution. Consequently, model predictions should be complemented with field investigations and geotechnical characterization.

7. Many existing erosion-control projects achieve only temporary success because they focus primarily on runoff diversion while neglecting the geological and geotechnical mechanisms responsible for progressive slope instability.

8. Sustainable erosion management requires an integrated watershed-scale framework combining engineering design, hydro-geotechnical characterization, ecosystem restoration, geospatial monitoring, land-use regulation, and community participation.

Mitigation and Control Measures

The findings of this review demonstrate that successful gully erosion management in southeastern Nigeria requires an integrated watershed-scale approach that addresses both the triggering hydraulic forces and the underlying geological and geotechnical conditions controlling gully initiation and expansion. Control measures designed without a clear understanding of the dominant erosion mechanisms frequently fail because they address only the symptoms rather than the causes of gully development.

Hydro-Geotechnical Site Characterization Before Intervention

Comprehensive geological, geotechnical, hydrological, and geomorphological investigations should precede every erosion-control project. Site characterization should include detailed mapping of lithology, groundwater conditions, slope geometry, drainage networks, soil stratigraphy, particle-size distribution, permeability, shear strength, and plasticity. These parameters enable identification of the dominant failure mechanisms and provide the engineering basis for selecting appropriate stabilization measures.

Watershed-Based Stormwater Management

Because concentrated runoff is the principal trigger for gully initiation, runoff management should extend beyond individual gullies to the entire drainage basin. Integrated stormwater management should include:

- detention and retention basins to attenuate flood peaks;
- infiltration trenches and recharge structures;
- vegetated swales and bio-retention systems;
- properly lined interceptor drains;
- energy dissipators at drainage outlets;
- check dams and drop structures designed to reduce flow velocity.

Treating runoff at the catchment scale substantially reduces hydraulic loading on vulnerable slopes.

Geotechnical Slope Stabilization

Engineering stabilization measures should be selected according to the governing failure mechanism rather than applying uniform solutions to all erosion sites.

Where rotational failures dominate, stabilization may require:

- soil nailing;
- mechanically stabilized earth systems;
- reinforced earth walls;
- anchored retaining structures;
- geogrids and geotextiles;
- controlled slope regrading.

Conversely, where hydraulic scour dominates, channel lining, grade-control structures, riprap protection, gabions, articulated concrete blocks, and stepped spillways are more appropriate.

Groundwater and Seepage Control

Many deep gullies continue expanding because of subsurface seepage rather than surface runoff alone. Effective stabilization therefore requires groundwater management through:

- horizontal drains;
- subsurface interceptor drains;
- relief wells;
- toe drains;
- drainage blankets;
- seepage cut-off trenches where appropriate.

Reducing pore-water pressure significantly improves slope stability and minimizes progressive wall failures.

Bioengineering and Ecosystem Restoration

Vegetation should complement—not replace—structural measures. Deep-rooted indigenous species, bamboo, vetiver grass, and other suitable bioengineering plants improve soil reinforcement through root binding while simultaneously reducing runoff velocity, enhancing infiltration, and restoring ecosystem services.

Large-scale reforestation of degraded catchments should prioritize native vegetation capable of adapting to local climatic and geological conditions.

Climate-Resilient Infrastructure Design

Future drainage infrastructure should explicitly consider projected increases in rainfall intensity associated with climate change. Culverts, bridges, roadside drains, and urban stormwater systems should therefore be designed using updated hydrological analyses incorporating extreme rainfall scenarios, rather than relying solely on historical rainfall records.

Nature-based solutions should be integrated with conventional engineering structures to improve long-term resilience.

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Land-Use Planning and Risk Zoning

High-resolution susceptibility maps derived from GIS, remote sensing, LiDAR, and machine-learning models should be incorporated into regional land-use planning. Development should be restricted within highly susceptible zones, while environmental impact assessments should become mandatory for major infrastructure projects, urban expansion, quarrying, and sand mining activities occurring within erosion-prone catchments.

Real-Time Monitoring and Early Warning Systems

Advances in Earth observation technologies now permit continuous monitoring of gully evolution. Unmanned aerial vehicles (UAVs), LiDAR surveys, InSAR, high-resolution satellite imagery, rainfall radar, and Internet-of-Things (IoT) monitoring systems should be integrated to establish an early warning system capable of detecting rapid gully expansion before catastrophic failures occur.

Machine-learning algorithms can further improve prediction of high-risk locations and optimize maintenance scheduling.

Community Participation and Institutional Strengthening

Long-term sustainability requires active participation of local communities. Community-based watershed management programmes should promote sustainable farming practices, maintenance of drainage systems, controlled grazing, regulated sand mining, and environmental education.

Institutional coordination among federal, state, and local governments should be strengthened through dedicated watershed management authorities responsible for erosion monitoring, engineering standards, policy implementation, and periodic inspection of drainage infrastructure.

Towards an Integrated Hydro-Geotechnical Management Framework

The evidence synthesized in this study demonstrates that no single mitigation measure can effectively control gully erosion across southeastern Nigeria because erosion processes differ according to geology, hydrology, topography, and land use. Accordingly, future interventions should adopt a hydro-geotechnical framework that integrates watershed hydrology, engineering geology, geotechnical design, geomorphology, ecosystem restoration, geospatial technologies, and community participation. Such multidisciplinary strategies offer the greatest potential for reducing erosion hazards, protecting infrastructure, and improving environmental resilience under changing climatic conditions.

CONCLUSION

This review provides a comprehensive synthesis of the mechanisms governing gully erosion within the lateritic terrains of southeastern Nigeria by integrating geological, geotechnical, hydrological, geomorphological, climatic, and anthropogenic perspectives. The evidence demonstrates that gully erosion is fundamentally a coupled hydro-geotechnical process in which geological conditions determine landscape susceptibility, hydrological processes initiate erosion, and slope instability governs long-term gully expansion. Consequently, the magnitude and spatial variability of gully erosion across southeastern Nigeria are controlled not only by rainfall intensity but also by the interaction between soil engineering properties, groundwater conditions, terrain morphology, vegetation cover, and human disturbances.

A major contribution of this study is the demonstration that regional geological variability explains much of the observed differences in gully morphology, erosion intensity, and progression across southeastern Nigeria. Highly permeable, sand-rich lateritic formations exhibit rapid hydraulic incision and deep gully development, whereas relatively cohesive clay-rich formations experience slower rates of expansion dominated by rotational failures. This finding highlights the importance of incorporating detailed geological and geotechnical characterization into erosion susceptibility assessment and engineering design.

The review also identifies significant shortcomings in existing prediction and management approaches. Current models frequently emphasize spatial prediction while insufficiently representing the coupled physical processes that govern gully evolution. Likewise, many erosion-control projects fail because interventions are implemented without adequate consideration of site-specific geological, hydrological, and geotechnical conditions. Future predictive frameworks should therefore integrate process-based modelling, high-resolution geospatial datasets, machine learning, field monitoring, and engineering geology to improve predictive capability and decision-making.

From an engineering and policy perspective, sustainable gully erosion management cannot rely on isolated structural measures or revegetation programmes alone. Instead, long-term resilience requires watershed-based stormwater management, hydro-geotechnical slope stabilization, groundwater control, climate-resilient drainage infrastructure, ecosystem restoration, geospatial monitoring, risk-informed land-use planning, and strong institutional coordination supported by active community participation.

As climate change, urbanization, and population growth continue to intensify erosion hazards, future research should focus on developing hybrid predictive models that combine physical process simulation with artificial intelligence, continuous remote sensing, and long-term field observations. Such interdisciplinary approaches will improve understanding of gully dynamics, enhance engineering practice, and support evidence-based policies for sustainable land management in southeastern Nigeria and other tropical lateritic environments facing similar environmental challenges.

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