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Infiltration Control and Precipitation Management: Panacea for Soil Erosion, Erosion Wadis and Aggradation of Orogodo River in Agbor Metropolis

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ABSTRACT: Globally, water is the most potent agent of soil erosion. Its potency at room temperature depends on the flow energy. Water induced soil erosion involve breakdown, and transport of broken-down soil aggregates from place of origin to where the displaced particles are deposited, thus stagnant water has very low erosive potentials. Currently, one of the major sources of colossal plagues in Agbor metropolis is soil degradation through soil erosion. Prominence of soil erosion in the metropolis is attributable to high infiltration density, severe rainfalls and long steep topography. This paper examines infiltrations, severe rainfall, topography and urbanization effects on soil erosion, and Orogodo River sustenance in Agbor metropolis. The metropolis mean annual precipitation (1787 mm) was estimated from Delta State annual rainfall data (2005–2015). Curve number method and Pythagoras theorem apply to estimate the metropolis runoff volume and topography gradient. Newton's laws of motion apply to estimate runoff acceleration, velocity, force, kinetic energy, and momentum. Volume of sediment deposits in Orogodo River for 28 years (1998−2026) was estimated using the rational method. Research findings reveal Agbor metropolis runoff potentials: flow volume, velocity, acceleration, kinetic energy, force, and momentum is [(779580863.3) m^3, (2.5) m/s, (0.026) m/s^2, (2.43619E+12) J, (20269102449) N and (3.82964E+13) $kgms^{-1}$]. Outstanding runoff potentials and unethical waste management aggravate soil erosion, while debris transport downslope is fast sinking Orogodo River. Residents should establish samba and channel courtyard runoffs to it, adopt ethical waste management and provide drainage systems with concrete slab covers to prevent waste deposition into it.

KEYWORDS: Soil; urbanization; soil erosion; Orogodo River; infiltration; waste management

1. Introduction

Agbor metropolis, Delta State, Nigeria, lies at elevations ranging from approximately 94 to 217 m above sea level, with an average elevation of about 160 m. The area is underlain by the Miocene–Recent Benin Formation, formerly known as the Coastal Plain Sands, which extends across a substantial part of the coastal region of Nigeria. The formation consists predominantly of unconsolidated, friable sands with gravelly units and discontinuous clay lenses. In Agbor, lateritic soil generally occurs within the upper few meters, followed by fine-grained sands approximately 9–58 m thick and deeper medium- to coarse-grained sandy layers containing intermittent clay lenses. The principal aquifer occurs within these deeper sandy beds, generally at depths exceeding 60 m [1,2]. The elevation and topographic characteristics of the study area are presented in Figure 1.

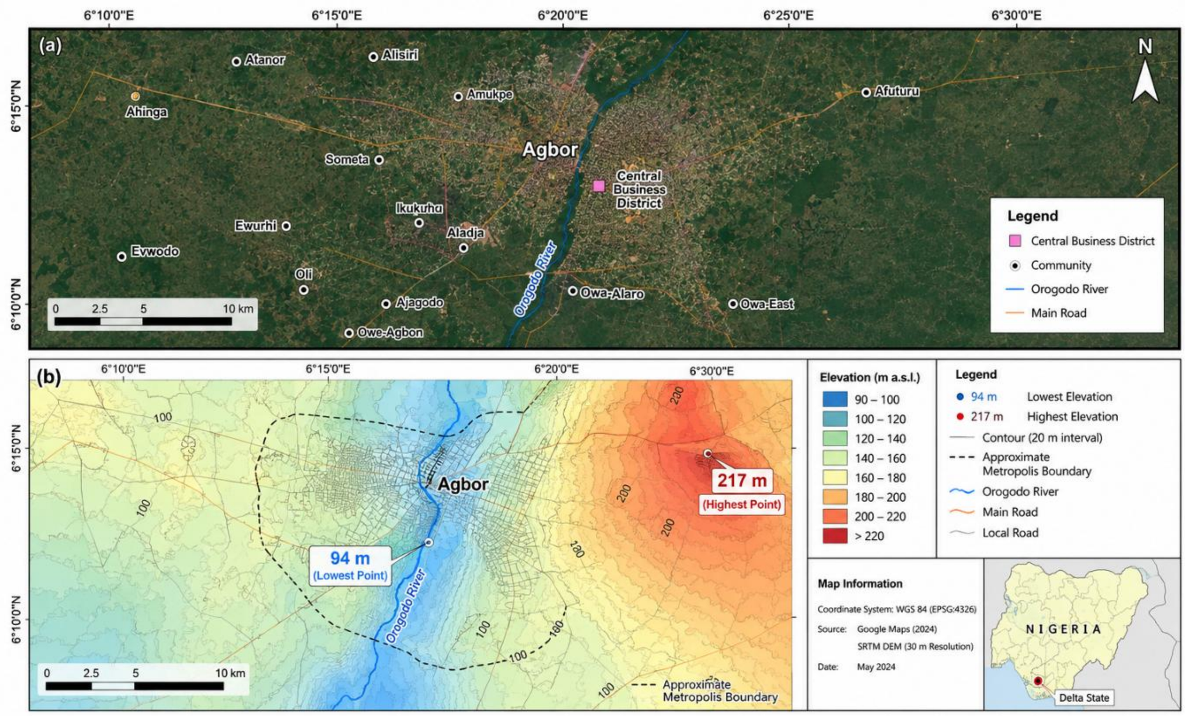

Figure 1. Topographic map of Agbor metropolis (a) Area of Agbor (b) Agbor metropolis lowest and peak highest points.

Despite relatively favorable natural drainage conditions and the absence of significant river-induced flooding, Agbor has increasingly experienced land degradation associated with water-driven soil erosion. Early and moderate manifestations include exposed building foundations and tree roots, damaged unpaved roads, sheet erosion, and the development of erosion rills. Representative field evidence of these conditions is presented in **Figure 2**, illustrating how progressive removal of surface soil exposes vegetation roots and structural foundations and promotes the transition from sheet to rill erosion.

More severe forms of erosion have developed into large gullies in several parts of the metropolis, particularly around the Midoma/Iweriebor and Alibuba areas. As shown in **Figure 3**, these gullies have expanded into developed areas, damaged or threatened residential buildings and infrastructure, and contributed to the abandonment of some properties. The severity of these features demonstrates that soil erosion in Agbor has progressed beyond localized surface degradation and has become an important environmental, agricultural, economic, health, and public-safety concern.

Previous approaches to soil erosion management in Agbor have generally been reactive, with investigations and remedial measures often initiated after significant erosion events have occurred. Many interventions have concentrated on increasing the length, width, and depth of drainage channels and expanding drainage networks to convey runoff downslope toward the Orogodo River. Although improved drainage is important, the continued occurrence and expansion of erosion features suggest that drainage infrastructure alone cannot adequately address the problem. Such approaches may overlook the combined effects of population growth, urbanization, rainfall, topography, reduced infiltration, waste management practices, and human activities.

Population growth and urban expansion are particularly important drivers of these changes. Several decades ago, extensive vegetation and larger areas of permeable land facilitated rainfall infiltration and reduced surface runoff within the metropolis. Increasing population and associated urban development have progressively converted these surfaces into buildings, paved roads, roofs, and other infrastructure. This transformation reduces the area available for infiltration and increases the proportion of rainfall converted into surface runoff [3–10]. Soil compaction associated with development can further decrease porosity and infiltration capacity, while topographic gradients provide the energy required for accumulated runoff to move downslope. Consequently, increasing urbanization, impervious surface coverage, rainfall intensity, runoff volume, and slope characteristics can collectively increase erosion susceptibility.

Rainfall and topography represent the major natural controls on water-driven erosion in Agbor. Rainfall supplies the water responsible for soil detachment and transport, while slope gradient and length influence runoff velocity and erosive energy [11,12]. However, natural processes alone cannot adequately explain the recent intensification of erosion. Human activities, including vegetation removal, housing and infrastructure development, road construction, soil compaction, and alteration of natural drainage pathways, can substantially accelerate erosion beyond natural rates [13–15]. Current erosion conditions in Agbor should therefore be understood as the result of interactions between natural environmental processes and increasing anthropogenic pressures.

Solid-waste management may further intensify the problem. Improperly disposed waste can accumulate within drainage channels and obstruct runoff pathways, causing water to overflow onto adjacent exposed surfaces. Transported solid particles may also contribute to surface abrasion during high-flow conditions. Consequently, increasing drainage dimensions without simultaneously addressing waste disposal and human behavior may provide only temporary improvements. Sustainable erosion management therefore requires not only engineering interventions but also effective environmental management, appropriate policies, enforcement, and community participation.

Soil erosion is particularly concerning because soil formation occurs extremely slowly compared with the rate at which soil can be removed. Previous studies have reported that the formation of only a few centimeters of productive soil may require hundreds to thousands of years [16–28]. Soil can therefore be regarded as effectively non-renewable on a human timescale. Its degradation can reduce agricultural productivity, impair ecosystem services, damage infrastructure, and increase socioeconomic losses, making soil protection and conservation essential components of sustainable land and urban management. The magnitude of the local problem is further demonstrated by previous investment in erosion-control projects.

The Delta State Nigeria Erosion and Watershed Management Project reportedly committed substantial resources to mitigating the Midoma/Iweriebor erosion site, including engineering works covering several kilometers [29]. Nevertheless, erosion remains evident in Agbor. The surface and rill erosion documented in Figure 2 indicates continuing localized soil loss, particularly around exposed surfaces and infrastructure.

Figure 2. Sheet erosion showing (a) exposed tree roots (b) Exposed house foundation. (c) Sheet erosion developing into rill erosion on an earth road off Odeh Street; (d) and (e) Houses damaged and abandoned due to Midoma/Iweriebor erosion wadi. (f) Damaged and deserted house along Midoma/Iweriebor erosion wadi (g) Damaged and deserted houses on the cliff of Midoma erosion wadi and rill developing into new gully in the erosion gully under salvage.

At a more advanced stage, the gully systems presented in Figure 3 demonstrate how concentrated runoff can produce substantially greater physical and socioeconomic impacts, including damage to buildings and infrastructure. The coexistence of these different erosion forms emphasizes the need to identify and manage the underlying erosion drivers rather than relying exclusively on remedial measures after severe gully development has occurred. Globally, water-driven soil erosion remains one of the major threats to soil function and land sustainability. Although extensive research has established many fundamental mechanisms controlling soil erosion, local erosion processes are strongly influenced by interactions among climate, soil properties, land use, topography, and human activities [30–32]. Therefore, erosion-control strategies developed for one environment may not adequately address conditions occurring elsewhere. Effective management requires location-specific assessment of erosion drivers and the mechanisms through which these factors interact. For Agbor metropolis, an important knowledge gap remains in understanding the combined relationships among population growth, urbanization, infiltration conditions, rainfall, runoff generation, topography, waste management, and human activities. Previous interventions have largely emphasized drainage infrastructure rather than an integrated evaluation of these interacting factors. Sustainable mitigation must also consider institutional and behavioral factors because engineering structures may perform poorly when drainage channels are obstructed by waste or when uncontrolled development continues to increase runoff generation.

Figure 3. Erosion gullies in Agbor metropolis: (a) rill-to-gully development at Midoma; (b) abandoned houses along the Midoma/Iweriebor erosion wadi; (c–d) aerial views of the Alibuba erosion wadi; (e) affected houses along the gully perimeter; (f) downstream section of the Alibuba wadi; (g) sand deposits across F222 (F109); and (h) soil and waste deposits along F222 (F109).

Soil erosion cannot be completely eliminated because it is a naturally occurring geomorphic process. Management should instead aim to maintain erosion at levels that do not significantly compromise soil functions, ecosystem services, infrastructure, or future land productivity. This requires combining engineering measures with appropriate land-use planning, waste management, vegetation protection, community participation, and effective environmental governance.

Accordingly, this study examines the causes, mechanisms, and impacts of soil erosion and gully development in Agbor metropolis. It estimates runoff potential and evaluates the relationships among population growth, urbanization, infiltration conditions, rainfall, topography, and soil erosion. The study further considers the influence of waste management and human activities and proposes integrated measures for mitigating soil degradation and erosion. By examining these factors collectively, the study seeks to provide a more preventive and sustainable framework for erosion management in Agbor metropolis rather than relying primarily on reactive interventions after severe erosion has occurred.

2. Materials and Methods

2.1. Study Area and Geographical Characteristics.

Agbor metropolis is located between approximately 6°06′–6°21′ N and 6°04′–6°21′ E and extends across Ika North East and Ika South Local Government Areas (LGAs), Delta State, Nigeria. It serves as the administrative headquarters of Ika South LGA and is an important economic and political center of the Ika region. The metropolis covers an estimated area of approximately 144 km² (35,583 acres) and is characterized by two elevated topographic zones separated by the Orogodo River valley. The Orogodo River traverses the metropolis and receives surface runoff from numerous drainage outlets and tributaries [33]. The terrain ranges from approximately 94 m above sea level around the river valley to a maximum elevation of 217 m, with an average elevation of approximately 160 m (Figure 1b). The horizontal distance between the major elevated areas and the Orogodo River is approximately 5 km, while the average topographic gradient is approximately 1:39 (0.026 or 2.6%). Groundwater occurs at approximately 114–128 m below the ground surface based on local borehole information. Agbor experiences a subequatorial climate characterized by distinct wet and dry seasons and rainforest vegetation. Annual rainfall is approximately 2,000–3,000 mm, with most precipitation occurring during the wet season. Ambient temperatures generally range from 24 to 32 °C. The urban landscape comprises residential and commercial areas together with extensive paved and unpaved road and drainage networks. These characteristics influence rainfall infiltration, runoff generation, and the susceptibility of exposed surfaces to erosion.

2.2. Field Observation and Data Collection.

Field observations and environmental surveillance conducted between 1998 and 2026 were used to evaluate changes in urban development, drainage conditions, waste management, erosion occurrence, and human activities within Agbor metropolis. Particular attention was given to urban expansion, residential and commercial development, road and drainage construction, the condition of the Orogodo River, solid-waste disposal, and community environmental practices. Roads and associated drainage systems were classified into two categories according to their orientation relative to the prevailing topographic gradient. Category A comprised roads and drainage channels running approximately parallel to the slope, whereas Category B included those running laterally or longitudinally across the dominant slope direction. Approximate lengths of paved and unpaved roads were determined using vehicle odometer readings during field surveys.

Selected Category A roads included Imudia, Isede, Convent, Okobi, Efezomor, Powerline, A232, Oruboh, Okwuokenye, Eboh, Kingsley, and Board roads/streets. Category B observations included Abude–Memeh, Ajuebon–Ehiabor, Dr. Whyte–Winners Chapel, Deeper Life, Morka, Odeh–Cemetery, Mariere–Osian, Baleke–Agraka, Hill–Obiazikwor, Alihame, Owanta, and Owa-Ekei roads. These locations were inspected at irregular intervals before, during, and after rainfall events to identify runoff pathways, drainage obstruction, erosion development, and sediment accumulation. Additional field measurements included the width of the Orogodo River channel and floodplain and the accumulation of sediments within and adjacent to the river. The approximate groundwater depth used in the topographic assessment was obtained from a borehole located along Okwuokenye Street, off Odeh Street, Agbor. Differences in elevation and horizontal distance between the elevated terrain and the Orogodo River were used to characterize the average topographic gradient.

2.3. Rainfall and Runoff Estimation.

Mean rainfall information for Delta State was used to estimate rainfall intensity for the runoff analysis. Based on a mean annual rainfall of 1,787 mm during 2005–2015 and the assumption that rainfall was uniformly distributed over approximately seven months of the year, the rainfall intensity adopted for the analysis was 0.112 in h^{-1}. Runoff was evaluated for five representative land-cover conditions: (i) forest vegetation, (ii) townhouse/residential development, (iii) commercial areas, (iv) earth roads, and (v) paved roads. These categories were selected to represent the progressive transformation of permeable natural surfaces into increasingly impervious urban surfaces.

2.4. SCS Curve Number Method.

Surface runoff depth was estimated using the Soil Conservation Service Curve Number (SCS-CN) approach [34–36]:

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \quad (1)$$

where is runoff depth, is rainfall depth, is initial abstraction, and is the potential maximum retention after runoff begins.

The potential maximum retention was calculated from the Curve Number (CN) as:

$$S = \frac{1000}{CN} - 10 \quad (2)$$

where S is expressed in inches when the conventional imperial form of the equation is used. Initial abstraction was assumed to be 20% of the potential maximum retention:

$$I_a = 0.2S \quad (3)$$

Substituting Equation (3) into Equation (1) gives:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \quad (4)$$

for $P>0.2S$; otherwise, $Q=0$.

Initial abstraction represents rainfall losses occurring before runoff generation, including interception by vegetation, surface storage, evaporation, and infiltration. The parameter represents the potential retention capacity of the surface and is related to land use, soil characteristics, and antecedent moisture conditions through the CN.

2.5. Curve Number Adjustment for Antecedent Moisture Conditions.

Curve Numbers corresponding to Antecedent Moisture Condition II (AMC II) were obtained from standard CN tables [37, 38]. To represent wet or worst-case conditions, the AMC II values were converted to AMC III using the adopted conversion factors. The resulting values of were then calculated using Equation (2). Table 1 summarizes the CN conversion rather than presenting each calculation separately in the text. The decreasing values from forest vegetation to paved surfaces represent the reduction in potential rainfall retention associated with increasing surface imperviousness.

Table 1. Curve Number (CN) and retention parameters for different land-cover conditions.

Land-cover condition	CN (AMC II)	Conversion factor	CN (AMC III)	S (in.)
Forest vegetation	70	1.210	84.700	1.81
Townhouse/residential	90	1.070	96.300	0.38
Commercial area	94	1.042	97.948	0.21
Earth road	91	1.063	96.773	0.33
Paved road	98	1.014	99.372	0.06

2.6. Runoff Volume Estimation.

The Rational Method was additionally applied to estimate peak runoff discharge from the contributing urban surfaces [35, 35, 39]:

$$Q_p = CiA \quad (5)$$

where Q_p is peak runoff discharge, C is the runoff coefficient corresponding to the land-use or surface condition, i is rainfall intensity, and A is the contributing drainage area. The notation Q_p is used here to distinguish peak discharge calculated using the Rational Method from runoff depth (Q) calculated using the SCS-CN method.

Runoff estimates were compared among forest, residential, commercial, earth-road, and paved-road conditions to evaluate changes associated with urbanization. The relative contributions of these surface categories before and after urban development were subsequently summarized graphically.

2.*7. Estimation of Runoff Hydraulic and Erosive Potential.*

The potential physical effects of runoff were evaluated using basic relationships for velocity, momentum, force, and kinetic energy [37, 39]. Runoff velocity associated with elevation difference was estimated as:

$$v = \sqrt{2gh} \quad (6)$$

where is velocity (m s^{-1}), is gravitational acceleration (9.81 m s^{-2}), and is the elevation difference (m).

Runoff momentum was estimated as:

$$M = mv \quad (7)$$

where is momentum (kg m s^{-1}), is the mass of runoff water (kg), and is runoff velocity.

The corresponding force was expressed as:

$$F = ma \quad (8)$$

where is force (N) and is acceleration (m s^{-2}).

Runoff kinetic energy was calculated as:

$$KE = \frac{1}{2}mv^2 \quad (9)$$

where is kinetic energy (J). These parameters were used as indicators of the potential capacity of runoff to detach, transport, and redistribute soil and sediment along the topographic gradient.

2.8. Data Analysis and Comparison of Urbanization Conditions.

The calculated runoff characteristics were compared across the five land-cover categories to assess the influence of urbanization on runoff generation and erosion potential. Forest vegetation represented the relatively permeable reference condition, whereas residential development, commercial areas, earth roads, and paved roads represented progressively modified urban surfaces. Changes in runoff contribution associated with these land-cover conditions were summarized using graphical analysis to illustrate the potential shift in runoff generation before and after urbanization.

3. Results and Discussions

3.1. Population Growth and Urbanization Trends.

Population growth and urbanization in Nigeria have increased substantially over the past seven decades. As shown in Figure 4a, the national population increased from approximately 37.2 million in 1950 to more than 220 million by 2023, accompanied by a marked expansion of the urban population. In 1950, only about 10.5% of Nigerians lived in urban areas, compared with approximately 54.8% by 2023. This long-term trend demonstrates the continuing demographic transition from predominantly rural settlement toward increasingly urbanized development [6,10,40,41].

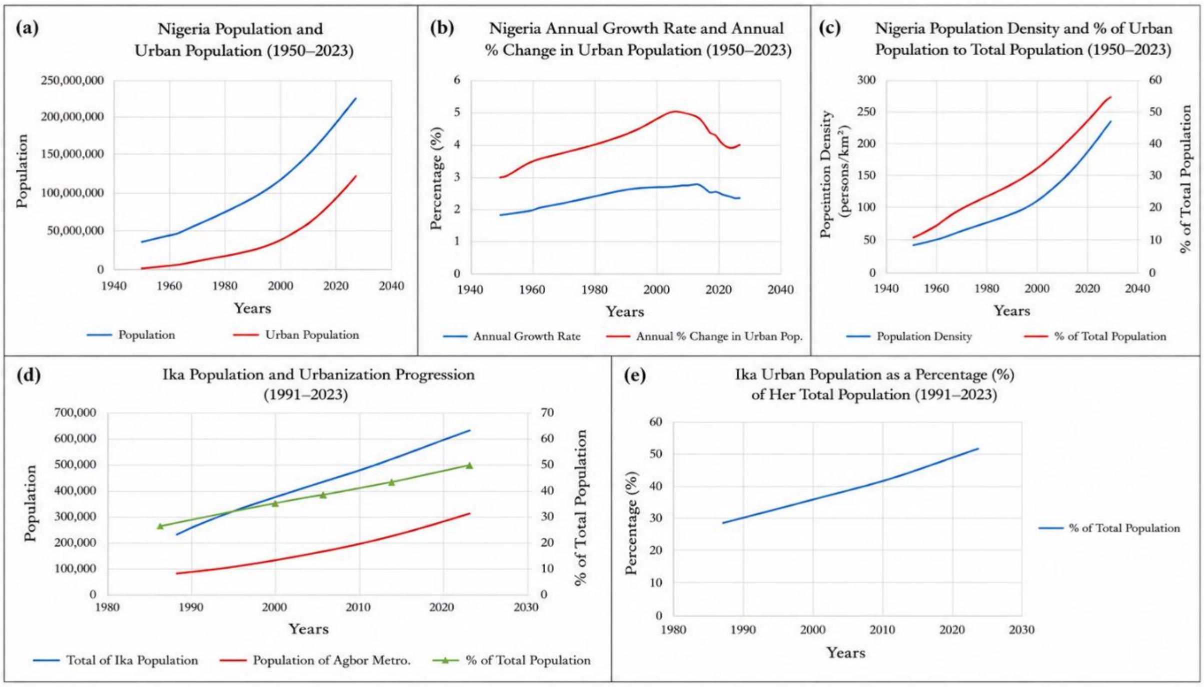

Figure 4. Population growth and urbanization trends in Nigeria and Agbor metropolis: (a) national population and urban population, (b) annual population growth rate and urban population change, (c) population density and urban population share, (d) population and urbanization progression in Agbor, and (e) Agbor urban population as a percentage of the total Ika population..

The rate of this demographic change has varied over time. Figure 4b shows that the annual population growth rate increased gradually before reaching relatively high levels during the 2000s and early 2010s. It subsequently declined from approximately 2.66% in 2014 to 2.41% in 2023. However, this decline represents a reduction in the *rate* of growth rather than a decrease in the total population. The annual percentage change in the urban population followed a similar pattern, reaching its highest level during the period of rapid urban expansion before declining in recent years. Despite this moderation, continued population growth places increasing pressure on housing, transportation, drainage, waste management, and other urban infrastructure.

The demographic transition is also evident from changes in population density and urban population share. As presented in Figure 4c, Nigeria's population density increased from approximately 40 persons km^{-2} in 1950 to about 242 persons km^{-2} in 2023. Over the same period, the proportion of the population living in urban areas increased from approximately 10.5% to 54.8%. These parallel trends indicate increasing concentration of people and development within urban areas. From an environmental perspective, such growth generally requires conversion of vegetated and permeable surfaces into residential areas, commercial facilities, roads, and other built infrastructure, thereby increasing the proportion of impervious land.

A comparable trend occurred within Agbor metropolis. Figure 4d shows the progression of the total population of the Ika area together with the population of Agbor metropolis between 1991 and 2023. The population of Agbor increased from approximately 67,379 in 1991 to 313,066 in 2023, indicating substantial urban expansion over approximately three decades. This growth can be attributed to a combination of natural population increase, migration from surrounding settlements, and the progressive incorporation of peripheral communities into the expanding metropolitan area.

The increasing concentration of the Ika population within Agbor is more clearly demonstrated in Figure 4e. The proportion of the combined population of Ika North East and Ika South LGAs residing within Agbor metropolis increased from approximately 28.6% in 1991 to 51.9% in 2023. Thus, more than half of the population of the two LGAs is now concentrated within the metropolitan area. This expansion has increased demand for residential buildings, commercial facilities, roads, drainage networks, schools, healthcare facilities, and other urban infrastructure.

Overall, Figure 4a–e demonstrates that population growth and urbanization in Agbor broadly reflect the demographic transition occurring at the national level. The environmental significance of these trends lies in the associated transformation of land cover. Expansion of buildings, roads, compacted surfaces, and other infrastructure progressively reduces vegetation cover and infiltration-capable areas. Consequently, a larger proportion of rainfall can be converted into surface runoff, particularly during intense rainfall events. The observed demographic and urbanization trends therefore provide an important basis for examining the subsequent relationship among land-cover change, runoff generation, and soil erosion in Agbor metropolis.

3.2. Effects of Land-Cover Change on Runoff Generation.

The hydrological calculations demonstrate substantial differences in runoff potential among the investigated land-cover conditions. Under the forested reference condition, the estimated runoff volume was approximately 146,304 m^3. Individual townhouse, commercial, earth-road, and paved-road conditions generated approximately 11,375, 64,008, 20,483, and 228,600 m^3

of runoff, respectively. The detailed runoff, mass, force, momentum, and kinetic-energy estimates are summarized in Table 2. It indicates that the hydrological effect becomes substantially greater when the individual development units are scaled to represent existing urban conditions. Based on the estimated 26,000 residential units, 6,000 commercial units, and approximately 400 km of earth and paved roads, the calculated total runoff reaches approximately m^3. The largest calculated contributions are associated with residential and commercial development, followed by paved roads. The contrast among these surfaces can be explained by their different infiltration and storage capacities. Vegetated surfaces intercept rainfall, increase surface roughness, support soil porosity, and promote infiltration through plant-root systems. In contrast, roofs, paved roads, compacted soil, and commercial surfaces provide limited opportunities for infiltration. A greater proportion of rainfall is therefore converted directly into surface runoff. The results support the conceptual relationship between increasing imperviousness and increasing runoff potential during urban development.

Table 2. Runoff and associated hydraulic parameters for different land-cover conditions in Agbor metropolis.

Parameter	Forest	Residential	Commercial	Earth road	Paved road	Total
Runoff per unit (m^3)	146,304	11,375	64,008	20,483	228,600	470,770
Total runoff (m^3)	146,304	295,753,536	384,048,000	8,193,024	91,440,000	**779,580,863**
Runoff mass per unit (kg)	1.46×10^8	1.14×10^7	6.40×10^7	2.05×10^7	2.29×10^8	4.71×10^8
Total runoff mass (kg)	1.46×10^8	2.96×10^{11}	3.84×10^{11}	8.19×10^9	9.14×10^{10}	$\mathbf{7.80 \times 10^{11}}$
Force per unit (N)	3.80×10^6	2.96×10^5	1.66×10^6	5.33×10^5	5.94×10^6	1.22×10^7
Total force (N)	3.80×10^6	7.69×10^9	9.99×10^9	2.13×10^8	2.38×10^9	$\mathbf{2.03 \times 10^{10}}$
Momentum per unit (kg m s^{-1})	3.66×10^8	2.84×10^7	1.60×10^8	5.12×10^7	9.14×10^{10}*	9.20×10^{10}*
Total momentum (kg m s^{-1})	3.66×10^8	7.39×10^{11}	9.60×10^{11}	2.05×10^{10}	3.66×10^{13}	$\mathbf{3.83 \times 10^{13}}$
Kinetic energy per unit (J)	4.57×10^8	3.55×10^7	2.00×10^8	6.40×10^7	7.14×10^8	1.47×10^9
Total kinetic energy (J)	4.57×10^8	9.24×10^{11}	1.20×10^{12}	2.56×10^{10}	2.86×10^{11}	$\mathbf{2.44 \times 10^{12}}$

Storm water acceleration for each hillside of the metropolis is 0.026 m/s^2.
Storm water velocity (v) = 2.5 m/s approx. (for the metropolis)

3.3. Changes in Runoff Potential Following Urbanization.

The physical transformation of Agbor associated with urbanization is illustrated in Figure 5a, which provides a view of the developed road environment. Such infrastructure represents an important transition from natural or semi-natural surfaces toward compacted and impervious land cover. This transformation affects rainfall partitioning by reducing the proportion of precipitation that can infiltrate into the soil. The broader extent of urban development is shown in Figure 5b. Expansion of residential, commercial, and transportation infrastructure increases the total area contributing rapid surface runoff. The effect is particularly important where development occurs along sloping terrain because runoff generated from individual properties and roads can combine downslope and increase the volume of water entering drainage channels.

The calculated distribution of runoff under the pre-urbanization condition is presented in Figure 5c. Under predominantly vegetated conditions, surface roughness, plant cover, and root systems would have reduced runoff velocity and promoted infiltration. Although runoff was still generated, vegetation provided greater protection against soil detachment and limited the direct transfer of rainfall energy to exposed soil. In comparison, Figure 5d shows the calculated redistribution of runoff associated with urbanized land-cover conditions. The increased contribution of residential, commercial, and road surfaces demonstrates how urban expansion can shift the hydrological behavior of the metropolis toward greater runoff production. This change is particularly important because the generated runoff must ultimately be accommodated by a limited drainage network and the Orogodo River.

The runoff distribution presented in Figure 5 is consistent with the numerical results in Table 1. Urbanization therefore influences erosion not merely through increased runoff volume but also by concentrating runoff onto fewer available flow pathways. Where drainage capacity is inadequate or obstructed, the resulting overflow can expose road shoulders, unpaved surfaces, and building surroundings to repeated erosive flows.

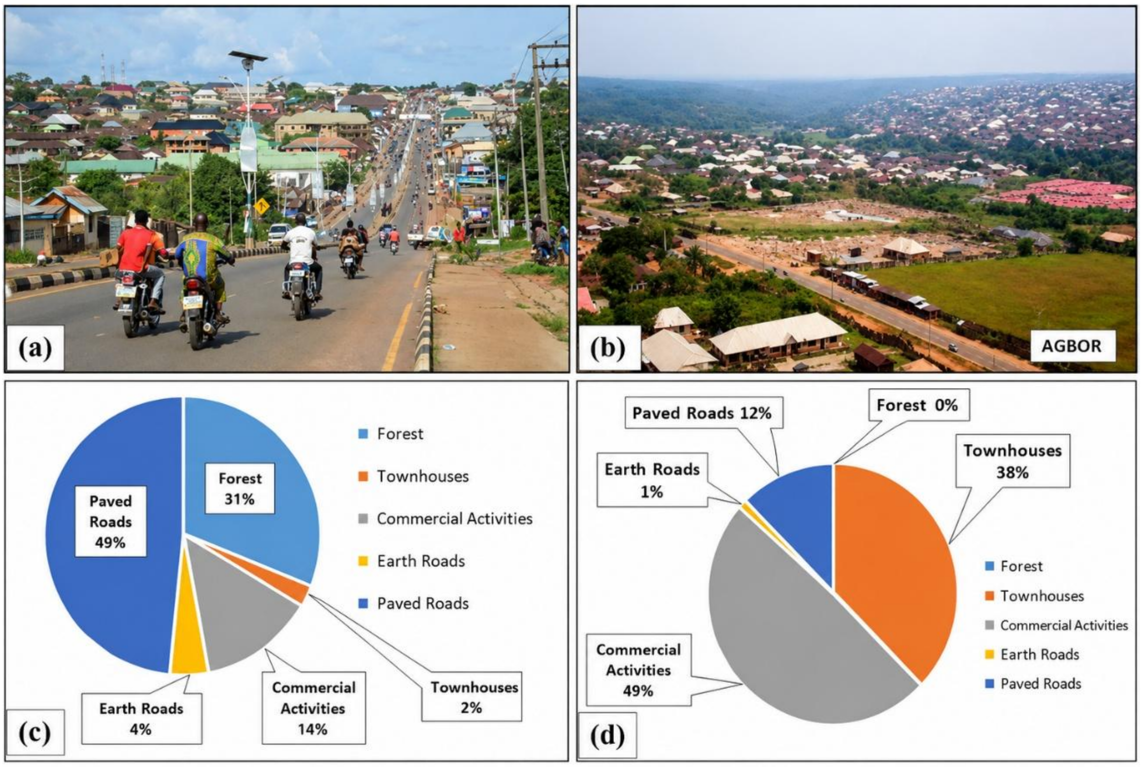

Figure 5. Urban development and runoff potential in Agbor metropolis: (a) view of Old Lagos–Asaba Road, (b) aerial view of Agbor metropolis, and (c–d) runoff potential before and after urbanization, respectively.

3.4. Runoff Force, Momentum, and Erosive Potential.

Urban development also substantially increases the calculated physical energy associated with runoff. Under the forested condition, runoff force, momentum, and kinetic energy were estimated at approximately N, kg m s^{-1}, and J, respectively. Scaling the calculations to current urban conditions produced much larger values, particularly for residential, commercial, and paved-road surfaces, as reported in Table 1. These results are important because the erosive capacity of flowing water depends not only on runoff volume but also on its velocity and associated energy. Increasing runoff mass increases momentum, while increasing velocity produces a particularly strong effect on kinetic energy because velocity is squared in the kinetic-energy relationship. On sloping terrain, concentrated runoff can therefore detach and transport soil particles more effectively than low-volume, low-velocity flow. The estimated average runoff acceleration and velocity for the metropolitan terrain were approximately 0.026 m s^{-2} and 2.5 m s^{-1}, respectively. These values should be interpreted as theoretical indicators of runoff potential rather than direct measurements of flow velocity at every location. Actual field velocities will vary according to rainfall intensity, local slope, surface roughness, drainage geometry, and flow depth.

3.5. Development of Sheet, Rill, and Gully Erosion.

The calculated increase in runoff potential provides a mechanism for understanding the erosion features observed during field surveys. Rainfall impact on exposed soil initially detaches fine particles through splash erosion. Once rainfall exceeds local infiltration and storage capacity, shallow surface flow develops and transports loosened material downslope, producing sheet erosion. As runoff becomes concentrated within small depressions or preferential flow pathways, sheet erosion can develop into rill erosion. Continued flow enlarges these channels, particularly where the underlying soil has already been disturbed by construction, vehicle movement, drainage failure, animal burrows, exposed roots, or other surface disturbances. Under persistent high-volume flow, rills can progressively develop into gullies. The field evidence presented earlier in Figure 2 demonstrates these initial and intermediate stages through exposed roots, exposed building foundations, and rill development along disturbed surfaces. These observations indicate that apparently minor surface erosion can become important when runoff repeatedly follows the same pathways. More advanced erosion is documented in Figure 3, where large gullies have affected buildings and surrounding land in the Midoma/Iweriebor and Alibuba areas. The progression from sheet erosion to rills and eventually to large gullies indicates that erosion in Agbor represents a continuum rather than isolated erosion processes. This interpretation is consistent with the high runoff potentials estimated for the increasingly urbanized landscape.

3.6. Drainage Obstruction, Solid Waste, and Orogodo River Degradation.

Expansion and enlargement of drainage infrastructure have been major responses to flooding and erosion in Agbor. However, these interventions have not fully prevented runoff overflow, flash flooding, or soil erosion. Increasing urban runoff is compounded by solid-waste accumulation within drainage channels, which reduces their effective flow capacity. As shown in Figure 6a, waste can substantially obstruct drainage pathways, increasing the likelihood that stormwater will overflow onto roads and exposed soil during intense rainfall.

Runoff also transports eroded soil, sediment, and solid waste downstream into the Orogodo River. Figure 6b shows sediment accumulation within the river channel, demonstrating the connection between urban runoff, erosion, and river sedimentation. Continued deposition can reduce channel depth and flow capacity, thereby increasing the vulnerability of surrounding areas to flooding.

Long-term field observations indicate considerable modification of the Orogodo River and its floodplain. Sections between F222 (F109), A232, and Old Lagos–Asaba Road were approximately 100 m wide before 1999, whereas some sections currently measure less than 20 m. Accumulation of excavated sediment and other materials along the riverbank is evident in Figure 6c. Such deposition can contribute to channel constriction and progressive floodplain modification. Human activities have further intensified pressure on the river corridor. Figure 6d illustrates the use of a sand-deposited section of the river environment for car-washing activities, while Figure 6e shows development and human occupation close to the river. These activities may restrict natural floodplain functions and potentially introduce additional sediment and pollutants into the river system.

Mechanical maintenance has therefore become necessary to restore and maintain channel capacity. Abandoned or faulty maintenance equipment is shown in Figure 6f, whereas active desilting of the Orogodo River is presented in Figure 6g. Institutional involvement in these restoration activities is further illustrated in Figure 6h. Although desilting can temporarily improve river conveyance, repeated sediment and waste inputs may reduce its long-term effectiveness. Overall, the observations in Figure 6 indicate that drainage obstruction, solid-waste disposal, sediment transport, floodplain modification, and river-channel degradation are interconnected. Sustainable management should therefore combine regular drainage maintenance and desilting with improved solid-waste management, erosion control, floodplain protection, and land-use regulation rather than relying solely on enlargement of drainage infrastructure.

Figure 6. Anthropogenic impacts and management of the Orogodo River: (a) waste accumulation in a drainage channel, (b) sediment deposition in the riverbed, (c) sediment accumulation along the floodplain, (d) car-washing activity on the river floodplain, (e) commercial activities along the river corridor, (f) abandoned faulty swamp buggy in the river flow path, (g) river desilting, and (h) inspection of the desilting operation by Hon.

4. Conclusions

This study identified population growth, urbanization, increasing impervious surfaces, intense rainfall, steep topography, inadequate drainage, and poor waste management as the major factors contributing to runoff-driven soil erosion in Agbor metropolis. Urban expansion has progressively reduced infiltration-capable surfaces, increasing runoff volume and erosive potential. The long topographic gradient further accelerates runoff, promoting the progression of sheet and rill erosion into gullies and wadis. Inadequate waste management aggravates these processes by obstructing drainage systems and increasing sediment and debris transport into the Orogodo River. Although rainfall and topography cannot be readily controlled, runoff generation and human activities can be effectively managed. Sustainable mitigation should prioritize nature-based and preventive measures, including green spaces, vegetative buffers, infiltration trenches, retention ponds, and household infiltration areas to reduce runoff at its source. These measures should be supported by regular drainage maintenance, improved solid-waste management, river dredging and restoration, floodplain protection, and relocation of activities encroaching on the Orogodo River corridor. Stronger urban planning, environmental regulations, enforcement, and community participation are also essential. An integrated approach combining engineering, nature-based solutions, effective governance, and responsible community behavior offers the most sustainable strategy for reducing soil degradation and protecting the Orogodo River.

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Competing Interest

None of the authors declared any conflict of interest.

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