Journal of Natural Resources and Environmental Management
http://dx.doi.org/10.29244/jpsl.16.4.550

RESEARCH ARTICLE

Land Use/Cover Dynamics in the Ruhuhu River Basin, Tanzania (1990–2023): A Multi-temporal Satellite Imagery and Machine Learning Analysis

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Article History
Received
8 September 2025
Revised 2 July 2026
Accepted 11 July 2026

Keywords
land use land cover change, Ruhuhu River Basin, remote sensing, Google Earth Engine, ecosystem

ABSTRACT

This study presents the first multi-decadal analysis of Land Use and Land Cover (LULC) dynamics in the Ruhuhu River Basin, Tanzania, over a 34-year period (1990–2023). Multi-temporal satellite imagery from Landsat 5 TM, Landsat 8 OLI, and Sentinel-2 MSI was classified using the Random Forest algorithm within Google Earth Engine into six LULC categories: water, barren land, forest, grassland, farmland, and shrubland. The classification accuracies were robust (overall accuracy: 81.60–98.70%; Kappa: 80.02–87.40%). The results revealed a sharp decline in forest cover from 56.92% to 28.60%, coupled with significant expansions in farmland (2.99% to 21.40%) and barren land (5.29% to 14.00%), driven by agricultural intensification and coal mining. These transformations have far-reaching implications for the ecological integrity of Lake Nyasa, including disrupted hydrological cycles, biodiversity loss, and reduced ecosystem services. This study provides spatially explicit evidence to support integrated land management and conservation strategies in the Ruhuhu catchment and similar sub-Saharan African river basins.

Introduction

River basins are recognized for their critical ecological roles as natural zones of interaction between terrestrial and aquatic ecosystems [1]. They form complex systems that host diverse natural processes essential for supporting water and nutrient cycles, provision of habitat, and climate regulation, collectively underpinning human well-being [2]. They also form essential ecological corridors, sustaining a wide array of flora and fauna while supporting crucial socioeconomic activities such as agriculture, fishing, and hydropower generation [3].

Despite their importance, river basins are threatened by numerous challenges triggered by both anthropogenic pressures and natural phenomena [4]. These challenges include climate change, anthropogenic activities, and natural disasters [5]. Previous studies have highlighted several interconnected drivers contributing to river basin degradation, including changes in Land Use and Land Cover (LULC) [6]. Other drivers include overpopulation, livestock encroachment, agricultural expansion, mining, industrialization, illegal logging, and urbanization [7]. Collectively, these factors accelerate the degradation of river basins, resulting in severe deterioration of aquatic ecosystems, decline in riparian vegetation, wetland loss, and fragmentation of aquatic life [8].

Building on the existing body of literature, changes in land use and cover in water basins are significantly associated with the degradation of water sources, triggering water pollution, and affecting the overall management of river basins [9]. Land-use activities such as agricultural intensification, mining, and other environmentally unfriendly activities conducted within water basins directly disturb river systems [10]. Changes in land use and cover within river basins directly influence hydrological cycles, reduce aquatic productivity, and trigger cascading effects, such as intensified flooding and increased water scarcity [11]. These changes jeopardize livelihoods, food security, and public health, especially in vulnerable communities that are highly dependent on natural-resource-based economies [12].

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Case studies from various regions have demonstrated the pervasive nature of river basin degradation driven by LULC change. In China's Upper Huai River Basin, land-use changes driven by agriculture and urban development have led to notable ecosystem imbalances [13]. In Egypt, urban and agricultural expansion has contributed to vegetation loss and exacerbated water scarcity in the Nile Basin [14]. In Ethiopia, agricultural intensification in the Upper Ribb Watershed within the Lake Tana sub-basin has been linked to a 29.95% expansion of farmland at the expense of shrublands, which decreased by 34.20% % [15]. In Kenya, a study of the River Lumi Riparian Ecosystem revealed a 52.7% and 36.6% decline in forest and riparian vegetation, respectively, between 1987 and 2019 [16]. More recently, Selamu et al. [17] documented that farmland expanded by 37.41% and built-up areas by 230.45% in Ethiopia's Jema River Sub-basin between 1994 and 2024, using a comparable GEE-based Random Forest framework, underscoring the regional scale of this challenge.

Tanzania, like many other sub-Saharan regions, faces similar challenges of rapid land use and cover change within numerous river basins. The Ruhuhu River Basin, located within the Lake Nyasa/Malawi/Niassa catchment, is the largest tributary of Lake Nyasa, with a catchment area of 14,070 km², and approximately 20% of Lake Nyasa's inflow originates from the Ruhuhu catchment [18,19]. The basin is among the most sensitive aquatic ecosystems in the Lake Nyasa system, providing critical spawning habitat for endemic fish species such as Opsaridium microlepis (locally known as "Mbasa"), a freshwater salmon endemic to Lake Nyasa/Malawi/Niassa [20]. Recent research has further demonstrated that anthropogenic activities along Lake Nyasa catchments are altering the habitat and genetic diversity of this species, highlighting the urgency of land management interventions [21].

Despite the ecological and economic significance of the Ruhuhu River Basin, a notable gap persists in the systematic, cost-effective, and time-sensitive monitoring of LULC dynamics in this region [22]. The absence of up-to-date land use and cover dynamics information hampers informed management and decision-making, weakens the implementation of sustainable management strategies, and results in fragmented policy responses. Understanding spatial and temporal land use and cover dynamics is essential for developing conservation and restoration interventions tailored to river basins [23]. The emergence of cloud computing and the Google Earth Engine (GEE) has demonstrated promising achievements in geospatial technology [24].

Therefore, to fill these research gaps, this study presents the first multi-decadal (1990–2023) analysis of LULC dynamics in the Ruhuhu River Basin, Tanzania. The general objective was to assess land use and cover and its dynamic transitions across six LULC categories; water, barren land, forest, grassland, farmland, and shrubland, between 1990 and 2023, using multi-temporal satellite imagery and the Random Forest algorithm within the Google Earth Engine platform [25].

Materials and Methods

Study Area

The study area was the Ruhuhu sub-basin, situated within the Ruhuhu water catchment of Lake Nyasa in the Ruvuma region in the southern part of Tanzania [26]. Geographically, it lies between latitudes 9°30'00" S and 11°0'00" S and longitudes 34°30'00" E and 36°0'00" E, covering 1,410,556.63 ha (Figure 1). Demographically, the Ruhuhu sub-basin is estimated to have a population of over 689,000 by 2035, up from 401,500 people recorded in 2012 [19]. The basin forms ecologically important spawning sites for more than 300 endemic fish species in Lake Nyasa [19]. Geologically, it forms part of the Karoo Basin of south-central Africa [18], which provides access to coal deposits. This study area was selected because of the current pressing environmental stress observed in the Ruhuhu River Basin, where coal mining activities have increasingly led to direct disruptions of the natural ecosystem.

Remote Sensing Data and Sensor Selection

This study utilized freely available remote sensing datasets from Landsat 5 TM, Landsat 8 OLI, and Harmonized Sentinel-2 MSI, configured within the Worldwide Reference System (WRS) scene of path 167, row 67 [27]. The four study years (1990, 2005, 2013, and 2023) were selected based on three complementary criteria: (1) image quality whereby only years with cloud-free or near-cloud-free (<5% cloud cover) imagery of sufficient quality for the entire basin extent were considered viable; (2) socioeconomic periodization, the years correspond to distinct phases of land use pressure in the Ruhuhu Basin, representing the pre-liberalization baseline (1990), the post-structural adjustment and early mining expansion period (2005), the peak coal mining boom (2013), and the current state with intensified agriculture and mining (2023); and (3) data availability, the selected years align with available national census data (2002, 2012) and population projections, enabling demographic cross-referencing of LULC drivers.

Landsat 5 TM imagery was used for the 1990 and 2005 study periods, Landsat 8 OLI for 2013, and Harmonised Sentinel-2 MSI for 2023, reflecting the operational periods of each satellite platform. To ensure spatial consistency across all study periods, all Sentinel-2 imagery (native resolution: 10 m) was resampled to a spatial resolution of 30 m within the Google Earth Engine environment prior to classification, matching the Landsat spatial resolution [28]. The dataset attributes are presented in Table 1.

Table 1. Remote sensing datasets used for Land Use and Land Cover (LULC) classification in the Ruhuhu River Basin, Tanzania, for the study years 1990, 2005, 2013, and 2023. The table presents the data type, acquisition period, spatial resolution, data source (Google Earth Engine), and Worldwide Reference System (WRS) path/row for each satellite sensor, illustrating the multi-sensor approach adopted to ensure temporal coverage across the 34-year study period.

Data types	Acquisition date	Resolution	Source	Path/row
Landsat 5 TM	Medium (1990, 2005)	Raster (30)	Https://code.earthengine.google.com/	Path 167/ Row 67
Landsat 8 OLI	Medium (2013)	Raster (30)	Https://code.earthengine.google.com/	Path 167/Row 67
Sentinel 2	Medium (2023)	Raster (10)	Https://code.earthengine.google.com/	Path 167/Row 67
Study area	2023	Vector	Lake Nyasa Water Body (LNWB)	Path 167/ Row 67

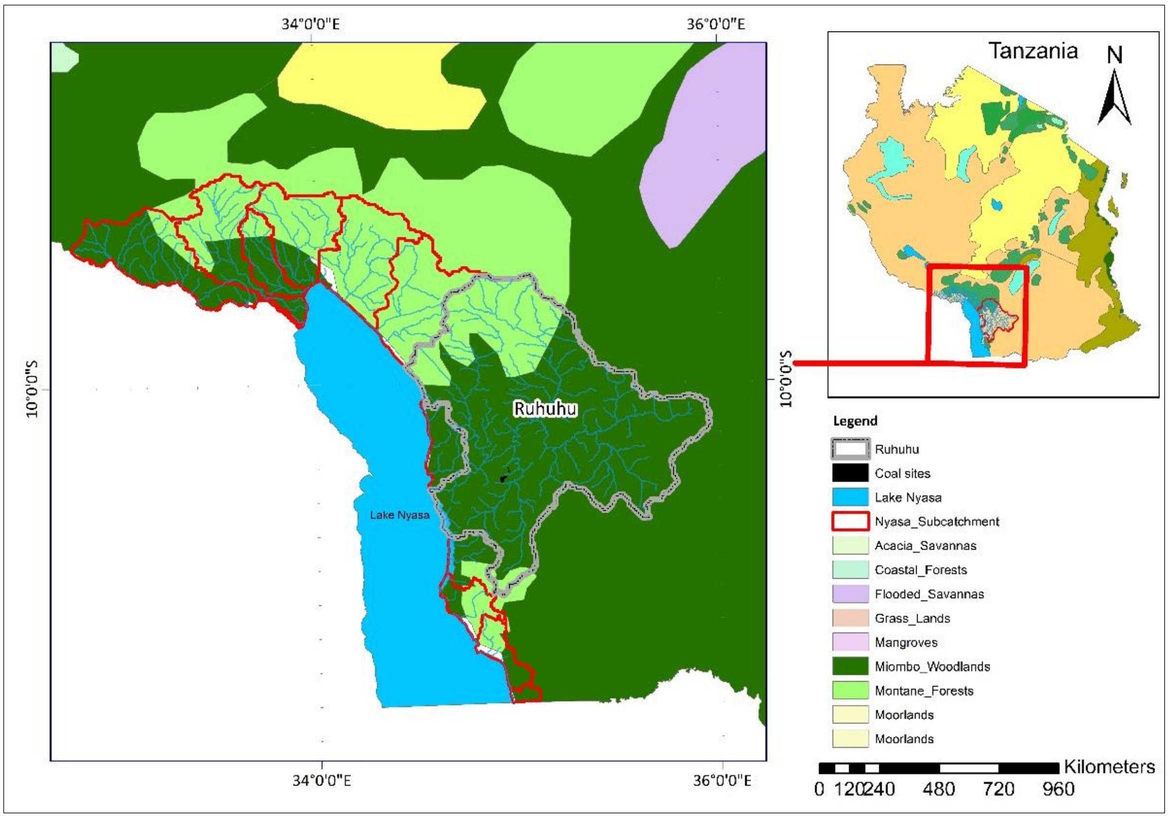

Figure 1. Map of the study area showing the location of the Ruhuhu River Basin within the Lake Nyasa Catchment in the Ruvuma region, southern Tanzania. The basin covers 1,410,556.63 ha and lies between latitudes 9°30’00” S and 11°0’00” S and longitudes 34°30’00” E and 36°0’00” E, representing the largest tributary of Lake Nyasa and a globally significant biodiversity hotspot subject to increasing anthropogenic pressure from coal mining and agricultural expansion.

Training Data Collection

Training sample collection was conducted using the Open Foris Collect Earth tool, a platform embedded within Google Earth Pro and sponsored by FAO [29]. The collection of training samples involved the manual digitization of features identified using high-resolution images and ancillary datasets within Google Earth Pro. The digitized polygons and points were exported to ArcGIS 10.8 as KML files, converted to shapefiles (retaining the WGS 84 geographic coordinate system), and uploaded to the Google Earth Engine as training samples.

Within the Google Earth Engine, imported shapefiles were converted to geometry using an automated machine procedure; consequently, the number of training samples generated varied by year: 12,228, 12,186, 10,825, and 2,767 for the years 1990, 2005, 2013, and 2023, respectively. The lower sample count for 2023 is a structural constraint of the GEE automated geometry conversion. The 2023 classification accuracy (OA = 83.09%, KC = 80.89%) remained above the widely accepted 80% threshold, demonstrating that the classification remained statistically reliable. The split algorithm was applied to divide the training samples into training (60%) and validation (40%) datasets. The distribution of the training samples is presented in Table 2.

Table 2. Distribution of training and validation samples used for Land Use and Land Cover (LULC) classification in the Ruhuhu River Basin, Tanzania, for the study years 1990, 2005, 2013, and 2023. The table shows the total number of collected samples and their allocation into training (60%) and validation (40%) subsets using a split algorithm, illustrating the variation in sample size across study years and the structural constraint that resulted in a lower sample count for 2023 due to the automated Google Earth Engine geometry conversion process.

Year	Number training samples		
	Collected samples	Training sample	Validation samples
1990	12,228	7,426	4,802
2005	12,186	7,330	4,856
2013	10,825	6,421	4,404
2023	2,767	1,929	838

LULC Classification

This study applied a supervised classification method using the Smile Random Forest (SRF) algorithm embedded in the Google Earth Engine [30]. Six LULC categories were developed, consistent with those applied in previous studies and first listed under the UNFCCC Good Practice Guidelines [29]. The Water category included rivers, lakes, swamps, small and large dams, and wetlands. The Forest category comprised forest plantations and natural Miombo woodlands. The Barren Land category encompassed abandoned farms, mining sites, built-up areas, rocks, outcrops, sand, beaches, and residential areas. The Grassland category referred to areas with short vegetation, grass near rivers, and grazing land. The Shrubland category included shorter vegetation with low foliage coverage. Finally, the Farmland category represented seasonal and perennial crops [31]. This classification scheme was selected for its alignment with established international frameworks and its applicability to the diverse land cover types characteristic of the Ruhuhu River Basin.

Accuracy Assessment

The confusion matrix approach was applied for the accuracy assessment [32]. This study applied Overall Accuracy (OA) and Kappa Coefficient (KC) as primary accuracy metrics [33], with a threshold of ≥80% for both metrics, as established in previous studies [34]. In addition, per-class producer's accuracy (PA) and user's accuracy (UA) were calculated for all six LULC categories across all four study years. All four study years exceeded the 80% threshold for both OA and KC, confirming the reliability of the classification.

Results and Discussion

Results

LULC Distribution and Changes (1990–2023)

This study identified six major LULC categories: water (W), barren land (BL), forest (F), grassland (G), farmland (FM), and shrubland (S), which indicated differences in dynamism over the 34-year study period. Figure 2 shows the temporal and spatial distributions of the six LULC categories. Table 3 presents the area (ha) and percentage of each LULC category estimated in the Ruhuhu River Basin between 1990 and 2023.

Forest cover was the dominant LULC category in 1990 (56.92%), subsequently increasing to 62.9% in 2005, significantly decreasing to 21.8% in 2013, and slightly recovering to 28.6% by 2023. Shrubland was the second most dominant LULC category in 1990 (29.2%), decreasing to 22.8% in 2005, dramatically increasing to 52.4%

in 2013—reflecting the transitional shrubland phase characteristic of degraded Miombo woodland ecosystems—and subsequently decreasing to 32.2% by 2023 as shrubland areas were progressively converted to farmland and barren land. Barren land increased from 5.29% (1990) to 14.00% (2023). Farmland expanded from 2.99% (1990) to 21.40% (2023). Water bodies remained relatively stable, between 0.56% and 0.66%, throughout the study period.

Table 3. Accuracy assessment results for the Land Use and Land Cover (LULC) classification of the Ruhuhu River Basin, Tanzania, for the study years 1990, 2005, 2013, and 2023, including per-class Producer's Accuracy (PA) and User's Accuracy (UA) for all six LULC categories. The table demonstrates that all four study years exceeded the widely accepted 80% threshold for both Overall Accuracy (OA) and Kappa Coefficient (KC), confirming the statistical reliability of the Random Forest classification applied within the Google Earth Engine platform.

LULCC	1990		2005		2013		2023	
categories	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
Water	8,100.29	0.57	9,353.76	0.66	7,932.98	0.56	8,125.35	0.58
Barren	74,633.77	5.29	93,768.60	6.65	94,638.01	6.71	196,961.90	14.00
Forest	802,836.60	56.9	886,990.15	62.9	307,557.19	21.80	403,407.20	28.60
Grass	71,023.60	5.04	81,707.10	5.79	46,255.82	3.28	46,412.12	3.29
Farm	42,147.82	2.99	16,580.68	1.18	215,234.48	15.30	301,825.37	21.40
Shrub	411,814.56	29.2	322,156.35	22.8	738,938.14	52.40	453,824.69	32.20
Total	1,410,556.63	100.00	1,410,556.63	100.00	1,410,556.63	100.00	1,410,556.63	100.00

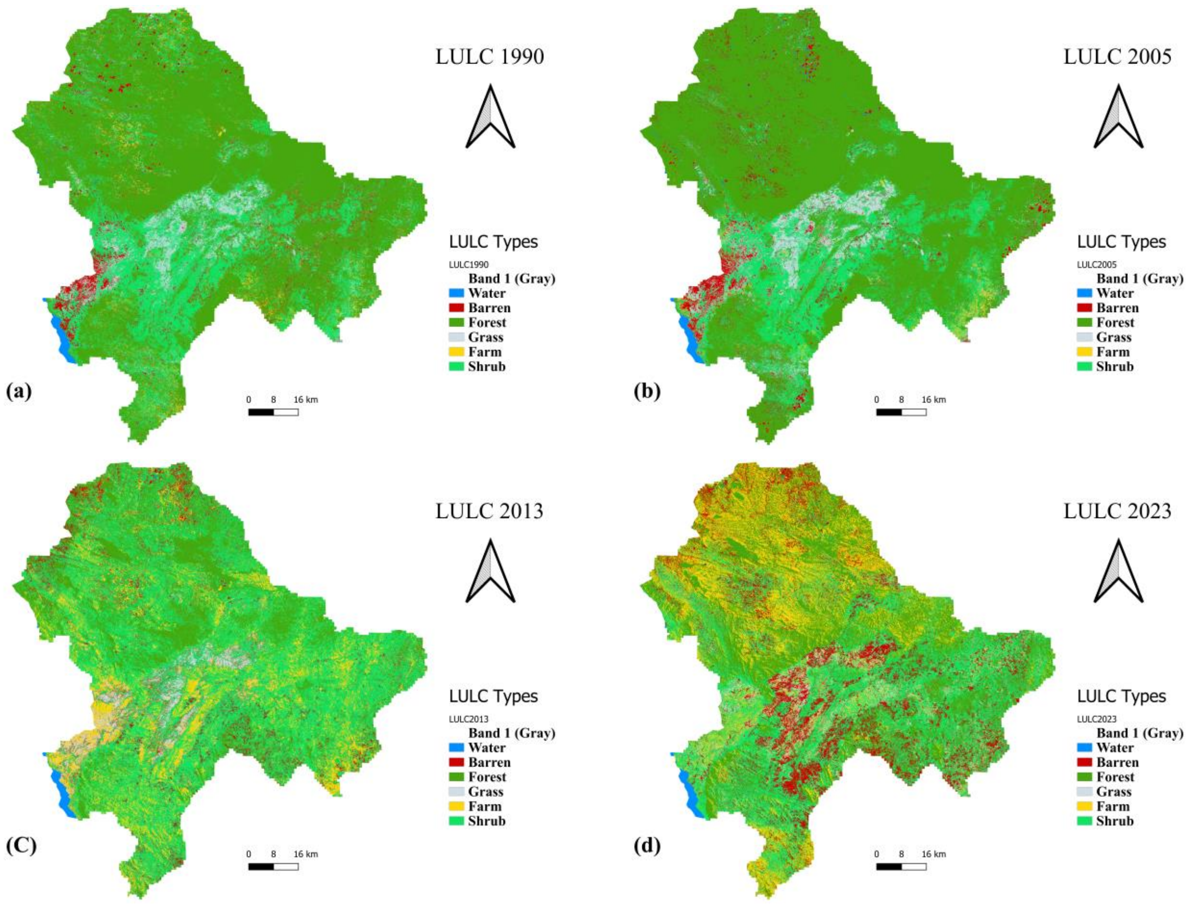

Figure 2. Spatial and temporal distribution of the six Land Use and Land Cover (LULC) categories which are water, barren land, forest, grassland, farmland, and shrubland in the Ruhuhu River Basin, Tanzania, for the years (a) 1990, (b) 2005, (c) 2013 and (d) 2023, classified using the Random Forest algorithm within Google Earth Engine. The maps illustrate a dramatic decline in forest cover from 56.92% in 1990 to 28.60% in 2023, concurrent with significant expansions in farmland (from 2.99% to 21.40%) and barren land (from 5.29% to 14.00%), reflecting the intensification of agricultural activities and opencast coal mining across the basin over the 34-year study period.

LULC Transition Matrix (1990–2023)

The results of the LULC transition matrix analysis revealed complex patterns of land use and cover transformation over the 34-year study period (Table 4; Figure 3). Water bodies experienced a net reduction of 8,509.32 ha, with the most substantial conversions occurring to barren land (489.42 ha), forest (546.39 ha), and farmland (299.97 ha). Barren land underwent significant alterations, with 81,351 ha transitioning to other land cover types, predominantly forests (12,532.23 ha) and shrublands (34,816.31 ha). A considerable portion of the forest area (814,765.6 ha) changed, with the largest shifts occurring to farmland (208,741.2 ha) and shrubland (189,707.9 ha). Grassland was modified over 66,079.33 ha, mainly converting to shrubland (23,955.47 ha) and farmland (13,039.92 ha). Farmland experienced changes in 42,502.4 ha, with the most substantial conversions to barren land (14,008.23 ha) and shrubland (16,115.13 ha). Shrubland underwent alterations in 399,212.2 ha, primarily transforming into barren land (83,830.3 ha) and farmland (59,119.54 ha).

Table 4. Area in hectares (ha) and percentage cover for each of the six Land Use and Land Cover (LULC) categories (water, barren land, forest, grassland, farmland, and shrubland) quantifies within the Ruhuhu River Basin, Tanzania, for the study years 1990,2005, 2013, and 2023. The table reveals a dramatic decline in forest cover from 56.92% (802,836.60 ha) in 1990 to 28.60%(403,407.20 ha) in 2023, concurrent with significant expansions in farmland (from 2.99% to 21.40%) and barren land (from 5.29% to 14.00%), reflecting the intensification of agricultural activities and coal mining across the basin over the 34-year study period.

LULC type	Water	Barren	Forest	Grass	Farm	Shrub	Total
Water	6,831.09	489.42	546.39	96.03	299.97	246.42	8,509.32
Barren	106.11	15,884.01	12,532.23	2,927.34	15,085.17	34,816.31	81,351.16
Forest	721.80	66,054.58	340,334.70	9,205.47	208,741.20	189,707.90	814,765.60
Grass	134.01	17,045.10	1,837.62	10,067.22	13,039.92	23,955.47	66,079.33
Farm	33.75	14,008.23	5,425.38	967.77	5,952.15	16,115.13	42,502.40
Shrub	353.43	83,830.30	43,263.35	23,187.59	59,119.54	189,458.00	399,212.20
Total	8,180.19	197,311.60	403,939.70	46,451.42	302,237.90	454,299.20	1,412,420.00

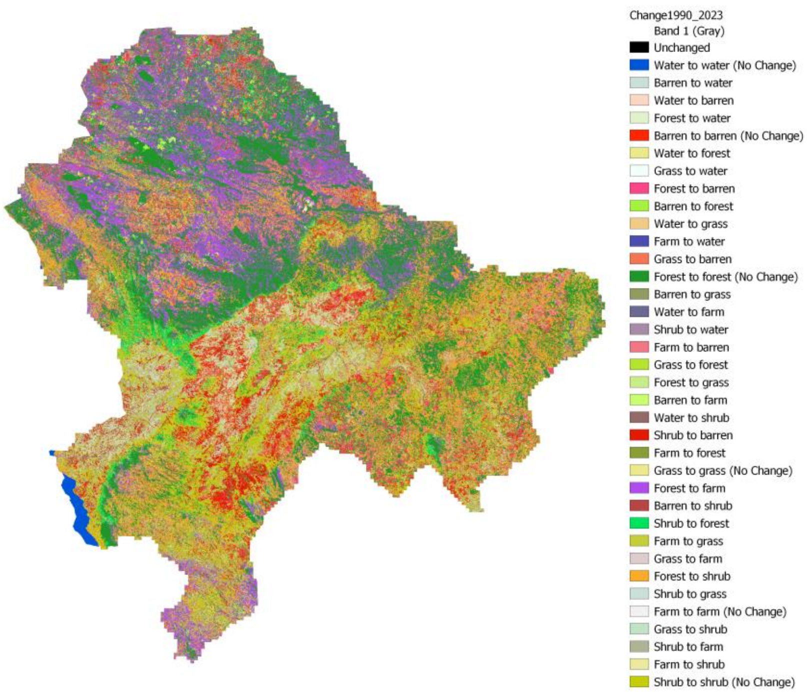

Figure 3. Map showing the primary Land Use and Land Cover (LULC) transition trajectories in the Ruhuhu River Basin, Tanzania, for the overall study period from 1990 to 2023, with colour-coded zones indicating the dominant conversion pathways between LULC classes across the 1,410,556.63-ha of the basin. The map illustrates that the most significant transitions involved the conversion of forest to farmland (208,741.2 ha) and barren land (66,054.58 ha), and the transformation of shrubland to barren land (83,830.3 ha) and farmland (59,119.54 ha), reflecting the combined pressures of agricultural expansion and opencast coal mining across the basin.

Discussion

The LULC analysis and change matrix (1990–2023) revealed substantial land use and land cover transformations within the Ruhuhu River Basin. Forestland experienced the greatest decline, while shrubland and farmland expanded considerably. In addition, barren land increased at an alarming rate. These findings indicate a complex pattern of land use and land cover change over the past three decades within the basin. The observed trends are consistent with broader land use transformations reported across sub-Saharan Africa, where agricultural expansion [33], population growth, and changing land management practices have contributed to forest loss [34], vegetation degradation, and the conversion of natural ecosystems into croplands and other land uses [35].

Expansion of Barren Land

Barren land in the Ruhuhu River Basin expanded substantially from 5.29% in 1990 to 14.00% in 2023, indicating increasing land-surface exposure and disturbance within the study area. This expansion may be associated with several processes, including mining-related land disturbance, settlement expansion, abandoned agricultural fields, exposed rocks, and coal outcrops. Settlement expansion may have contributed to this trend, as urbanization is widely recognized as a major driver of LULC change in Africa [35]. Urban growth is associated with the transformation of natural and agricultural landscapes into residential areas and other human-modified land uses, thereby altering land-cover patterns and increasing landscape disturbance [36]. Furthermore, rapid urban expansion in sub-Saharan Africa has been linked to the conversion of farmland to urban uses and substantial changes in peri-urban landscapes [37].

Coal mining is another driver of increased barren land within the Ruhuhu Basin. The Ruhuhu Basin is a coal-bearing basin containing several coal sub-basins, including Mchuchuma, Ngaka North, Mbalawala, and Lumecha [38]. Furthermore, Ruhuhu is known as an intracratonic Karoo basin containing thick Karoo sediments interbedded with coal deposits [39]. The increase in barren land may therefore partly reflect the physical disturbance associated with coal extraction and related infrastructure. This interpretation is supported by studies showing that opencast and surface mining commonly transform vegetated land into exposed mining land [10,40–42]. Similarly, coal-mined landscapes in central India experienced forest-cover loss and increasing land degradation vulnerability due to mining expansion [42]. Therefore, the observed expansion of barren land in the Ruhuhu River Basin is consistent with documented impacts of opencast and surface mining, where vegetation clearance, soil removal, excavation, and mine infrastructure increase exposed and degraded land surfaces.

Intensification of Farmland

This study revealed a substantial increase in farmland, with the category expanding by 18.41% over the study period, in addition to an intact farmland area of 5,952.15 ha. The observed expansion is consistent with broader land-use trends reported across sub-Saharan Africa [35], where agricultural expansion is a major component of LULC change. Population growth and the increasing demand for food have been identified as key underlying drivers of agricultural expansion in the region [35], resulting in the conversion of natural vegetation and other land-cover types into cropland [36]. The increase in farmland within the Ruhuhu River Basin may therefore reflect a growing demand for agricultural production associated with demographic growth in the basin.

The findings are also consistent with land-use dynamics reported in the Matengo Highlands, which form an important part of the Ruhuhu River Basin. Research has shown that increasing population pressure and land scarcity in the highlands have encouraged movement into less densely populated areas and the cultivation of previously uncultivated woodland landscapes [43,44]. Furthermore, population pressure and increasing human activities in the Matengo Highlands have contributed to environmental degradation and deforestation [44]. Therefore, the expansion of farmland observed in the Ruhuhu River Basin is likely associated with growing agricultural demand, population pressure, and the continued conversion of natural landscapes into agricultural land, a pattern that has been widely documented across both the Matengo Highlands and sub-Saharan Africa more broadly.

Decline of Forest Cover

Forest cover was reduced by 28.32% during the study period. The change matrix analysis indicated that 340,334.70 ha of forest remained intact, while the majority of the forest area was converted to farmland (208,741.20 ha) and barren land (66,054.58 ha), signifying deforestation and forest degradation, respectively. Miombo woodlands dominate much of the vegetation cover within the Ruhuhu River Basin and provide important ecosystem services and livelihood resources for rural communities [45]. Consequently, continued loss of Miombo woodland may have implications for local livelihoods, carbon storage, and water regulation within the basin. Continued deforestation and woodland degradation may reduce carbon storage capacity and affect ecosystem functions that support local livelihoods [46].

The marked increase in shrubland observed in 2013 may indicate the expansion of disturbed or regenerating vegetation following woodland degradation. Previous studies have shown that anthropogenic disturbances influence the structure and recovery dynamics of Miombo woodlands, with regeneration occurring through the establishment and development of regenerating stands following the cessation of disturbance [47]. The subsequent decline in shrubland between 2013 and 2023 coincided with the expansion of farmland (15.3% to 21.4%) and barren land (6.71% to 14.0%), suggesting that some shrub-dominated areas may have been converted to agricultural land or other disturbed land-cover classes. Furthermore, the high Kappa coefficient obtained for the 2013 classification (KC = 87.40%) provides confidence that the observed expansion of shrubland represents a real land-cover change rather than a classification artifact.

Regional Contextualisation

The findings of this study are consistent with LULC change patterns reported in other East African river basins and catchments. In Tanzania's Wami River Basin, woodland, bushland, and grassland were converted substantially to cultivated land, with cultivated-land expansion linked especially to population growth and agriculture [34]. Similar patterns were reported in the Sigi River watershed, where extensive deforestation and rapid small-scale cultivation expansion occurred across foothill and escarpment areas [48]. In Ethiopia, studies of the Gilgel Gibe watershed and Tana sub-basin also documented agricultural expansion alongside forest or vegetation-cover decline [11], with measurable implications for runoff, groundwater recharge, evapotranspiration, and water yield [11]. At the regional scale, forest-cover loss is commonly associated with increased stream discharge and surface runoff, although catchment responses vary [49]. Collectively, these studies indicate that the Ruhuhu River Basin reflects broader East African trends of agricultural expansion, forest-cover decline, and increasing pressure on watershed hydrological functions.

Drivers and Implications of Anthropogenic Land Expansion

The major drivers of LULC changes in the Ruhuhu River Basin include rapid population growth, intensified crop cultivation in the lowland and Matengo Highlands, expansion of the built-up area, expansion of opencast coal mines in the Ngaka, Ludewa, Peramiho, and Mbuyula sub-basins, and increased demand for firewood and charcoal for fuel. Climate change, including increased drought frequency and prolonged drought duration, has also been associated with LULC changes in the region [36]; however, further studies are needed to disentangle the effects of climate change from the more direct anthropogenic drivers observed in this study.

The LULC changes documented in this study have profound implications for the Ruhuhu River Basin and wider Lake Nyasa ecosystem. Forest degradation contributes to altered hydrological cycles, increased carbon emissions, heightened soil erosion, and significant biodiversity loss, particularly affecting Miombo woodlands, which support over 8,500 plant species of which 54% are endemic [50]. The Ruhuhu River Basin is the largest tributary of Lake Nyasa/Malawi/Niassa [26] and a critical spawning area for freshwater salmon and other endangered fish species [15]. Chavula et al. [19] have further documented the multifaceted challenges facing the Lake Malawi/Niassa/Nyasa basin, including sedimentation, water quality degradation, and declining fish stocks, all of which are exacerbated by upstream LULC change.

Policy Implications and Management Recommendations

The findings of this study have direct implications for land management policies in the Ruhuhu River Basin and Tanzania. Based on the documented LULC changes and their drivers, five evidence-based management interventions are recommended. First, the establishment of legally protected riparian buffer zones along the Ruhuhu River and its major tributaries is necessary to prevent further encroachment of farmland and mining activities into sensitive riparian ecosystems. Second, the integration of REDD+ payment mechanisms would provide economic incentives for community-led forest conservation and reforestation in Miombo woodland areas [51]. Third, strengthening community-based forest management (CBFM) programmes, particularly in the Litumbandyosi-Gesimasowa Game Reserve buffer zones, is essential for empowering local communities as stewards of forest resources. Evidence from Tanzania shows that CBFM plays an important role in sustaining community forests by increasing awareness and local participation in conservation activities [52]. Fourth, stricter environmental impact assessment (EIA) requirements and mandatory post-mining land rehabilitation obligations for opencast coal mining operations in the Ngaka, Ludewa, and Mbuyula sub-basins are required to mitigate ongoing ecosystem degradation [41]. Fifth, the promotion of climate-smart agriculture and agroforestry practices in the Matengo Highlands would reduce pressure on natural forest boundaries while simultaneously improving food security for the growing population [53,36].

Limitations

This study has several limitations. First, the training sample size for 2023 (n = 2,767) was substantially lower than those for other years (>10,000), which is a structural constraint of the automated GEE geometry conversion process. Although the 2023 classification accuracy remains above the accepted threshold, future studies should consider stratified random sampling approaches within GEE. Second, the use of multiple satellite sensors across study periods introduced potential spectral differences that were mitigated by resampling all imagery to a common 30 m resolution and applying consistent pre-processing procedures. Third, this study did not quantitatively disentangle the relative contributions of climate change and direct anthropogenic drivers. Fourth, the "barren land" category encompasses a heterogeneous mix of land cover types, which may limit the specificity of the interpretations regarding individual land-use drivers.

Conclusion

This study provides the first multi-decadal, spatially explicit analysis of LULC dynamics in the Ruhuhu River Basin, Tanzania, over a 34-year period (1990–2023). The findings reveal a basin undergoing profound ecological transformation driven by the convergence of rapid population growth, agricultural intensification, and a coal mining boom, which induced pressures that are emblematic of the broader land transformation crisis facing sub-Saharan Africa's river basins. The most significant finding was the net loss of 28.32% of the basin's forest cover, primarily converted to farmland (208,741.20 ha) and barren land (66,054.58 ha). This loss of Miombo woodland represents a direct threat to Tanzania's commitments under the National Forest Policy, the Sustainable Development Goals (particularly SDG 13: Climate Action and SDG 15: Life on Land), and the ecological integrity of Lake Nyasa, one of the world's most biodiverse freshwater ecosystems. The concurrent expansion of farmland (from 2.99% to 21.40%) and barren land (from 5.29% to 14.00%) underscores the urgency of integrated land management interventions that simultaneously address food security, mining regulations, and forest conservation. The five policy recommendations proposed in this study provide a concrete, evidence-based framework for action. Future research priorities include hydrological modelling to quantify the water balance implications of the documented LULC changes, carbon stock assessment to inform REDD+ programme design, and socioeconomic impact studies to evaluate the livelihood consequences of ecosystem service loss for communities dependent on the Ruhuhu River Basin.

Author Contributions

HSF: Conceptualization, Methodology, Writing of Original Draft; **SJN:** Analysis, Validation, Writing & Editing, Visualization; **FM:** Review & Editing.

AI Writing Statement

During the preparation of this work, the author(s) used grammar software to improve clarity and language editing. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Conflicts of Interest

There are no conflicts to declare.

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