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Impact of Land Use/Land Cover Change on Sediment Yield in the Upstream Watershed of Kiri Dam Using SWAT, Remote Sensing and GIS Simulation

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ABSTRACT

Reservoir sedimentation is a major challenge affecting the sustainability and operational efficiency of water-sources infrastructure in Nigeria. Kiri Dam, located on the Gongola River in Adamawa State, has experienced progressive storage-capacity loss due to sediment deposition, largely driven by increasing human activities within its watershed. This study assessed the impact of land use/land cover change on sediment yield in the upstream watershed of kiri dam using SWAT, remote sensing and GIS (Geographic Information Systems) integrated with the Modified Universal Soil Loss Equation (MUSLE). Land-use/land-cover (LULC) changes between 2003 to 2013 and 2023 were mapped using Landsat imagery and maximum likelihood classification, while hydrological and sediment-yield simulations were conducted using SWAT/MUSLE to quantify sediment yield in the reservoir. The results revealed significant land-cover transformation within the watershed over the 20-years period. Forest/woodland and savanna/shrub areas declined by 2,146 km² and 705 km, from 6,305 km² in 2003 to 4,159 km² in 2023 The study concludes that upstream land-use changes, particularly agricultural expansion, vegetation clearance, and land degradation, are the primary drivers of increased sediment yield and reservoir sedimentation in Kiri Dam. It recommends the implementation of integrated watershed-management measures like afforestation, soil-conservation practices, riparian-buffer restoration, and targeted erosion-control interventions in priority sub-basins to reduce sediment inflow and prolong the reservoir's operational lifespan.

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INTRODUCTION

Reservoirs are the basis for water management, irrigation, flood control and hydropower production. They promote industry and socio-economic development by providing a reliable supply of water for domestic, agricultural and industrial use. But one of the major problems that impact on their sustainability and effectiveness is sedimentation. Sedimentation is the accumulation of silt, organic debris and particles, including heavy metals, when degraded soil elements from the watershed are carried by surface runoff and deposited in reservoirs. This reduces the storage capacity of the reservoir over time, affects the water quality, dam infrastructure, increases risk of flooding and reduces the operational life of the reservoir (Wang et al., 2022; Ding et al., 2025).

Agriculture, deforestation, grazing, and settlement growth are examples of human activities in upstream catchments that greatly accelerate the delivery of sediment into reservoirs and contribute to soil erosion (Attulley et al., 2022). Sedimentation does not only reduce storage volume, but it also affects water quality, reservoir ecology, and contaminant dynamics. Sediment can act as both a sink and a source for nutrients and heavy metals, increasing turbidity,

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altering nutrient cycling, degrading aquatic habitat, and concentrating pollutants that pose risks for human and ecosystem health. (Adamu and Edward, 2023; Williams, 2023).

The reservoir of the Kiri Dam, which is situated in the Shelleng Local Government Area of Adamawa State, Nigeria, is becoming more and more vulnerable to upstream land degradation. Only a few empirical studies have measured the impact of upstream activities on the sedimentation dynamics of the lower Benue Basin, despite the dam's significance for irrigation, hydropower, fisheries, and water supplies (Adamu and Edward, 2023).

Advances in hydrological modeling technologies such as SWAT (Soil Water Assessment Tool) allow for full watershed assessments, land use monitoring and sediment yield calculations, while remote sensing and GIS provide effective tools for tracking spatial and temporal changes in land use and land cover(Daramola et al,.2022). Recent advances in hydrological modeling technologies such as SWAT (Soil Water Assessment Tool) provide for detailed watershed analyzes, land use monitoring and sediment yield estimations; remote sensing techniques and GIS provide effective tools for tracking spatial and temporal changes in land use and land cover. (Adeogun et al, 2020). This study aims to analyze land use and land cover changes in the Kiri dam upstream watershed using remote sensing data and to simulate sediment yield and transportation using the SWAT model and GIS. (Adamu and Edward, 2023).

Study Area

Kiri Dam, situated in Adamawa State, Nigeria, was constructed on the Gongola River. The dam experienced hydrological impacts following the establishment of the Dadin Kowa dam, which was originally erected by the Savanna Sugar Company and is currently managed by the Upper Benue River Basin Development Authority (UBRBDA). (Gambo et al, 2025) Construction commences in 1976 and was completed in 1981, with commissioning in 1982. The dam has a nominal catchment area of 57,200 km^{2,} which was later reduced, following the construction of Dadin Kowa dam, and the actual DEM-delineated watershed used in the analysis is approximately 24,898 km². The dam is located in the community of Kiri in Adamawa State's Shelleng Local Government Area. It is located 170 meters above sea level at latitude 9° 53' 5"N and longitude 12° 0' 32"E. The dam is situated about 35 kilometers upstream from where the Gongola and Benue rivers converge. A lowland landscape with large floodplains and alluvial marshes characterizes the surrounding area. The region's geology consists of alluvial deposits covering Cretaceous strata, as well as sedimentary rocks including shale and thin bands of limestone and lignite. The region has a single rainfall peak, usually in August or September, and a tropical continental climate (Gambo et al, 2025).].

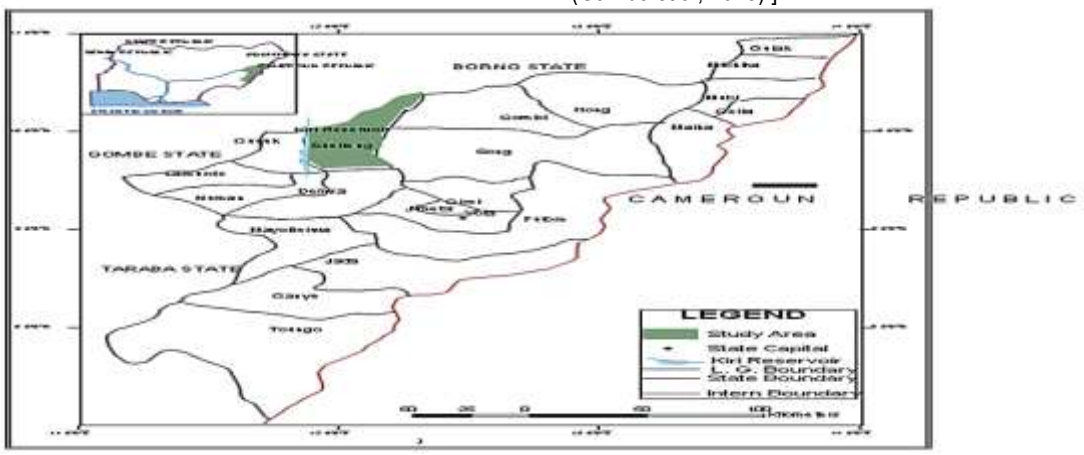


Figure 1.0: Map of the study area (Source: Google Map)

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MATERIALS AND METHOD

The research employed remote sensing, geographical data, soil information, meteorological and hydrological datasets, along with ground-reference data, to assess land use and land cover (LULC) alterations and to simulate sediment yield in the Kiri Dam's upstream watershed. The watershed's physiographic features were defined, the drainage system and sub-basins were mapped, and slope data was obtained utilizing a 30m Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM). Soil information, encompassing soil texture, depth, and hydrological characteristics, was obtained from the Harmonized World Soil Database (HWSD). Meteorological parameters comprised daily precipitation, peak and lowest temperatures, wind velocity, and solar irradiance, whereas hydrological and sediment concentration metrics were utilized for model calibration and validation. The LULC classification and accuracy assessment were supported by ground-reference information and high-resolution imagery from Google Earth.

Landsat 7, 8 and 9 images of 30 m spatial resolution for mapping LULC in 2003–2023 was used. Pre-processing of the imagery included re-projection, geometric correction, radiometric and atmospheric correction, and subsetting to the study watershed.(Conde et al., 2019). To carry out supervised maximum likelihood classification, training samples were taken from high-resolution photography and ground reference data. Forest, agricultural land, built-up, bare land, and aquatic bodies were the categories into which the resulting LULC maps were divided. Ground-truth points, confusion matrix, overall classification accuracy, and Kappa coefficient were used to evaluate the classification accuracy. Then the LULC change and transition between different periods were quantified using post classification comparison.[3] ArcSWAT interface was used to develop the Soil and Water Assessment Tool (SWAT 2012) for hydrological and sediment modeling. The watershed was delineated and stream networks and sub-basins were generated and hydrologic response units (HRUs) were generated by integrating DEM, LULC, soil and slope data sets. Temperature and daily rainfall data were used to prepare climatic inputs which were processed and loaded into the model. The LULC maps classified were used in SWAT to represent the spatial distribution of land cover in the watershed.

The SWAT model was calibrated using streamflow data for 2003–2015 and validated for 2016–2023. Sediment concentration was evaluated over the same calibration and validation periods. Model performance was assessed using the Nash–Sutcliffe Efficiency (NSE), coefficient of determination (R^2), percent bias (PBIAS), and root mean square error (RMSE).

RESULTS AND DISCUSSION

This section deals with the data collected for the assessment. The results were discussed one after the other as shown below:

Land-Use / Land-Cover Change (2003 – 2023)

The land use/land cover (LULC) of the study area was classified into seven (7) major classes. The number of pixels and the corresponding ground area occupied by each land use/land cover class are presented in Figure 3.1, while their respective area coverage is summarized in Table 1.

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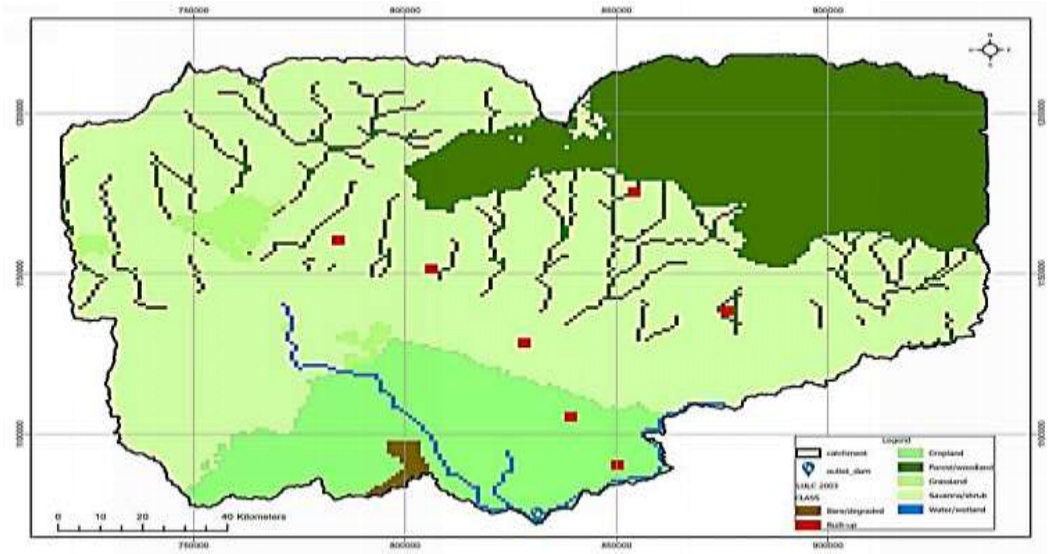


Figure3.1 Classified Land use / land cover map of Kiri Watershed for year 2003

The 2023 classified land use/land cover (LULC) map reveals significant shifts in land use during the course of the 20-year study period. Urban areas (0.9%), agricultural land (24.4%), barren or degraded land (0.7%), wooded areas (16.7%), aquatic or wetland regions (0.7%), savanna or shrub land (55.3%), and grassland (1.3%) were among the seven main land use and land cover groups found by the evaluation. Savanna and shrubland constitute the dominant land cover types, covering approximately 55.3% of the total study area. Agricultural land accounts for the second largest share of land use at 24.4%, followed by forested areas at 16.7%. The remaining land cover classes built-up land, grassland, bare/degraded land, and water/wetland collectively account for less than 4% of the total area, indicating relatively limited spatial coverage.

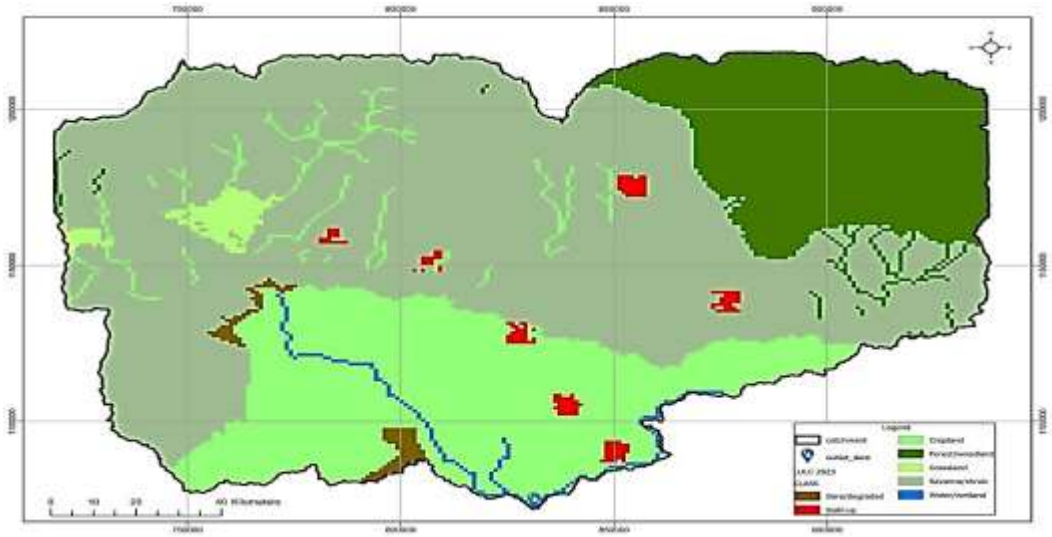


Figure 3.2 Classified Land use / land cover map of Kiri Watershed for year 2023

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The analysis of land use/land cover (LULC) in the Kiri Dam watershed for the period 2003 to 2023 indicates a clear transition from a natural vegetation-dominated landscape to a human-dominated system. Figures3.1 and 3.2) and change detection map (Figure3.3) indicate that the same pattern of savanna-belt land conversion as reported elsewhere in Nigeria [2], woodland and savanna, once the dominant land covers have been progressively converted, especially in accessible upland and lowland zones, to cropland and, to a lesser extent, built-up and bare/degraded areas. Cropland expansion is strongest around the lower valley and reservoir fringe, suggesting strong agricultural pull from soil fertility and water supply. At the same time, fragmentation of vegetation cover, emergence of degraded patches on sandy soils, and gradual settlement expansion highlight increasing anthropogenic pressure across the watershed.

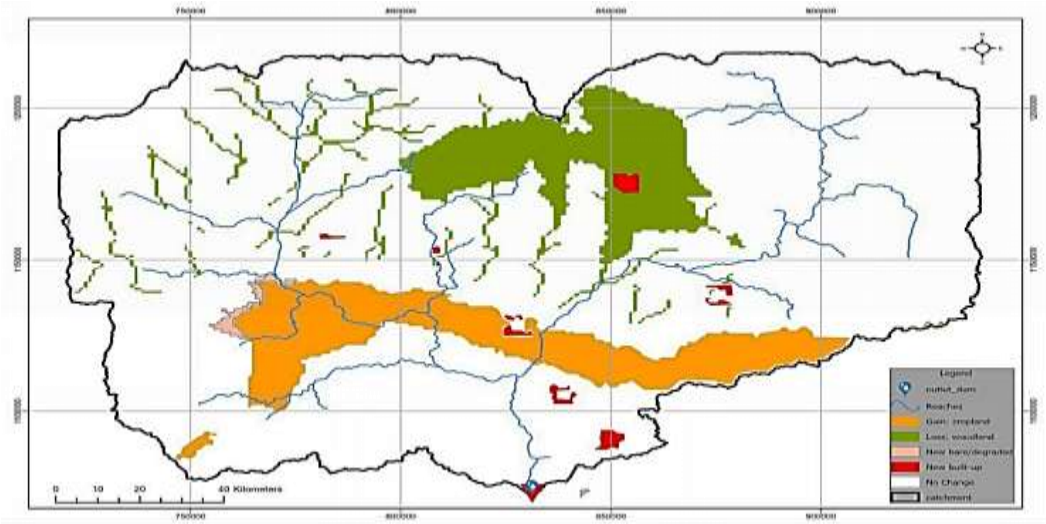


Figure3.3 LULC transitions (2003–2023), cropland gain, woodland loss, new built-up and new bare/degraded land.

Significant changes in land cover and use between 2003 and 2023 are illustrated in Table 1. The biggest increase was in cropland which increased by 2,697 km2 from 3,368 km² (13.5%) to 6,065 km² (24.4%). This indicates extensive agricultural expansion during the study period. Built-up areas also grew from 63 km2 (0.3%) to 225 km2 (0.9%), showing rising settlement and urbanization. Forest woods, however, decreased the most, by 2,146 km2, from 6,305 km2 in 2003 to 4,159 km2 in 2023, which indicates significant deforestation.Then savannah/shrub and grassland, transformation of natural vegetation into farming and towns. Water/wetland remained stable during the study period, while bare/degraded land slightly increased, indicating increasing environmental degradation. Overall, human activities have caused significant changes to the landscape, and the findings suggest the necessity for sustainable land-use planning and conservation.

Land Use/Land Cover Change (2003–2023)

The watershed was categorized into seven LULC classes: forest/woodland, savanna/shrubland, cropland, grassland, built-up land, water/wetland and bare/degraded land. In 2003, the dominant class was savanna/shrubland (58.1 %), followed by forest/woodland 2023 (25.3 %) and cropland (13.5 %). Savanna/shrubland continued to be the dominant land cover type in (55.3%), cropland increased to 24.4%, and forest/woodland decreased to 16.7%.

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Table 1. Land use/land cover areas and net change (2003–2023)

LULC class	2003 area (km²)	2003 (%)	2023 area (km²)	2023 (%)	Net change (km²)
Forest/woodland	6,305	25.3	4,159	16.7	-2,146
Savanna/shrubland	14,458	58.1	13,753	55.3	-705
Cropland	3,368	13.5	6,065	24.4	+2,697
Grassland	404	1.6	320	1.3	-84
Built-up	63	0.3	225	0.9	+162
Water/wetland	185	0.7	185	0.7	0
Bare/degraded	109	0.4	185	0.7	+76

The greatest gain was in cropland, which expanded by 2,697 km², and the greatest loss was in forest/woodland, which contracted by 2,146 km². Development land increased by 162 km2 and semi-natural land by 76 km2. These changes constitute a significant alteration of natural flora to agricultural and residential land uses

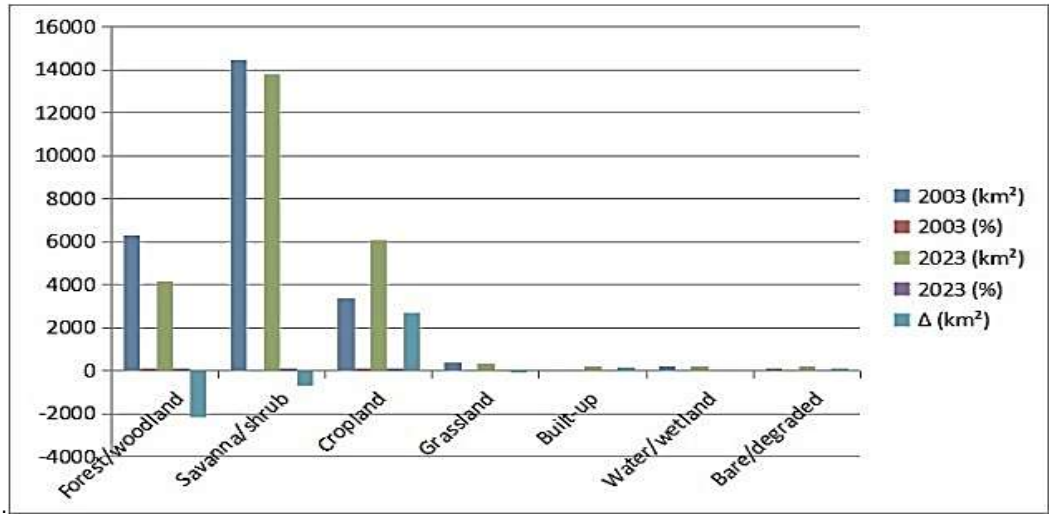


Figure 3.4: Land use/cover area by class with net change (Δ km²)

Watershed Characteristics

The delineated DEM watershed is said to be about 24,898 km 2. The drainage pattern is dendritic and runoff from different parts of the watershed converges to the outlet at Kiri Dam. The land varies from fairly level plains to steeper upland areas. The slope distribution as shown indicates that about 79.9% of the catchment is gentle class (≤6°), 12.5% is moderate (approximately 6-15°) and 7.6% is steep or rugged (>15°). Steeper areas are especially important for runoff production and erosion risk. Thus, the watershed delineation provides a suitable spatial context for subsequent SWAT model simulations, ensuring that streamflow and other hydrological processes are accurately simulated within the Kiri Dam catchment [8].

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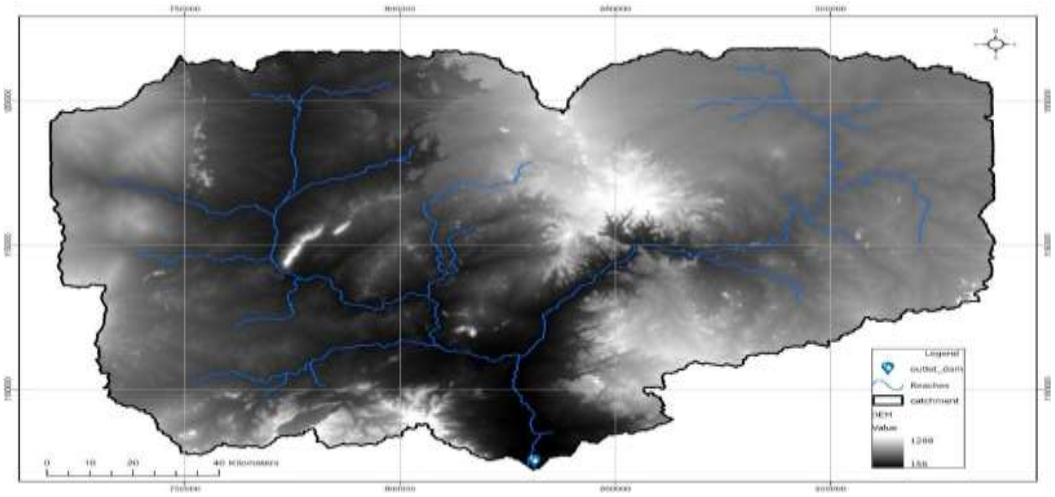


Figure3.5: Digital Elevation Model and extracted drainage network used for watershed delineation

Slope

The slope layer represents the steepness of the terrain (in degrees) over a shaded-relief base. The catchment lies in gentle terrain: some four-fifths of the area is at slopes of some 6 degrees or less, in the broad plains that cover most of the north, west and center. Relief is concentrated in a rugged upland massif through the center and south-centre of the catchment the darkest, most dissected ground with scattered ridges and inselbergs elsewhere. These steeper zones, which make up a small portion of the area, are the runoff-generating and erosion-prone parts of the landscape and are located at the stream headwaters.

Table 2: Approximate relief distribution (tonal split of the slope raster; indicative)

Relieve class (approx. slope)	% of catchment	Area
Gentle (≈ ≤ 6°)	79.90%	20,075
Moderate (≈ 6–15°)	12.50%	3,142
Steep / rugged (> ≈ 15°)	7.60%	1,912

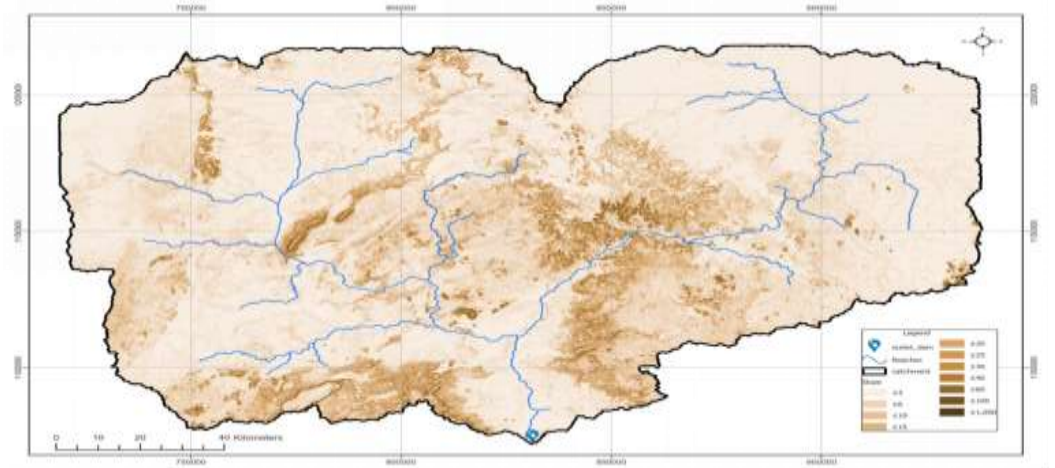


Figure 3.6: Slope / relief of the catchment. Pale = gentle plains; dark brown = steep, dissected terrain; blue = reaches; outlet dam at the south.

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Slope (relief) parameters of Kiri Dam catchment are shown in Figure 3.6. Geography of the catchment is diverse; areas of gentle dissection (dark brown tints) to mild plains (light shades). The steep slopes are mainly in the central and eastern parts of the watershed where the higher velocities of runoff and soil erosion are expected. The drainage network (blue lines) carries runoff and eroded sediments to the catchment outlet, which is located at the southernmost point of the Kiri Dam.

Soils

Four soil associations occupy the catchment in broad, roughly west–east belts that grade from the uplands in the north to the valley floor at the outlet in the south.

Table3: Soil associations within the catchment

Soil Type	Setting	Percentage (%)	Area(km²)
Luvisols	Central belt; fertile, clay-enriched	33.8%	8,506
Leptosols (upland)	Northern uplands; shallow, stony	33.6%	8,433
Lixisols (sandy)	South-central belt; sandy, low-fertility	20.9%	5,258
Fluvisols (alluvial)	Southern valley floor near outlet	7.5%	1,885

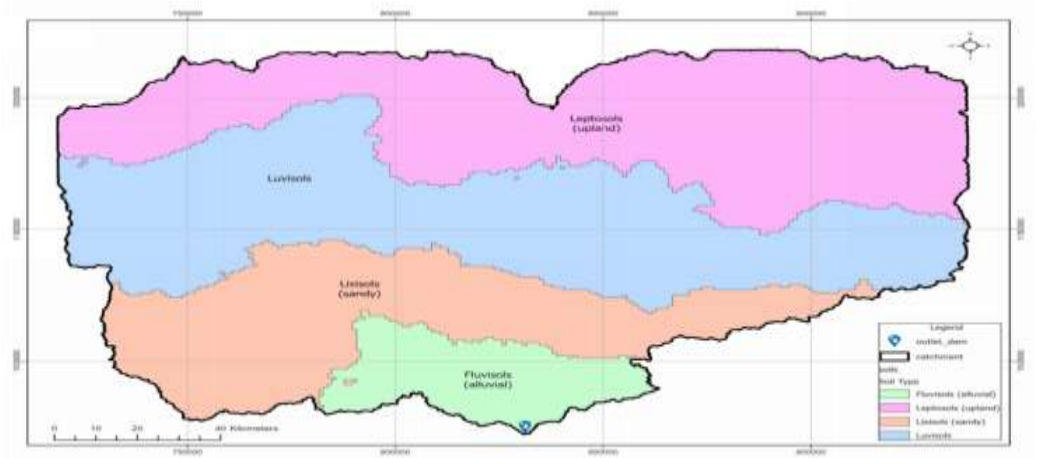


Figure 3.7: Soil associations: Leptosols (upland, pink), Luvisols (blue), Lixisols (sandy, orange) and Fluvisols (alluvial, green).

Every association has its own unique way. Leptosols are stony, shallow highland soils with limited storage capacity. Once the cover is gone they are easily eroded and rapidly lose water. Most of the productive agriculture in the middle belt is on Luvisols which are the most fertile and structurally stable . Lixisols are sandy, low-activity soils that are naturally some of the most erodible in the watershed and are susceptible to surface crusting, poor infiltration and rill erosion. On the valley floor near the exit are young, fertile alluvial soils called fluvisols. They are mainly a depositional environment. They trap the silt that is transported from upstream.

Sediment Yield and Model Performance

The SWAT performance was evaluated for both streamflow and suspended sediment concentration using the observed and simulated data for the calibration and validation periods. The results give quantitative evidence that the model can reproduce the sediment and watershed hydrologic responses. The classified 2023 land use/land cover (LULC) map shows the major

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changes in land use during the 20-year study period.

The assessment identified seven major land use and land cover categories including urban areas (0.9%), agriculture land (24.4%), barren or degraded land (0.7%), forested areas (16.7%), aquatic or wetland areas (0.7%), savanna or shrub land (55.3%) and grassland (1.3%). Savanna and shrubland are the dominant land cover types, making up approximately 55.3 % of the total study area.

Table 4: Streamflow performance statistics during calibration and validation.

Metric	Calibration (2003–2015)	Validation (2016–2023)
Mean observed flow (m^3/s)	9.42	8.76
Mean simulated flow (m^3/s)	9.18	9.09
NSE	0.58	0.52
R^2	0.62	0.58
PBIAS (%)	+2.5	−3.8s
RMSE (m^3/s)	1.8	2.1

Sediment concentration performance was less successful than stream flow performance but was still quantitatively useful for the assessment of sediment dynamics. The mean observed suspended sediment concentration (SSC) during calibration was 86.4 mg/L, and the mean simulated concentration was 79.3 mg/L. During validation, observed mean was 82.7 mg/L and simulated mean was 92.7 mg/L. The NSE decreased from 0.42 for calibration to 0.35 for validation and the R^2 ranged from 0.43 to 0.42. The PBIAS ranged from +8.2 % to −12.1 % and the RMSE increased from 12.5 to 14.2 mg/L. The results indicate that the model was able to capture some of the temporal variation in sediment concentration, but with more uncertainty than the streamflow simulation.

Table5: Sediment concentration performance statistics during calibration and validation

Metric	Calibration (2003–2015)	Validation (2016–2023)
Mean observed SSC (mg/L)	86.4	82.7
Mean simulated SSC (mg/L)	79.3	92.7
NSE	0.42	0.35
R^2	0.43	0.42
PBIAS (%)	+8.2	−12.1
RMSE (mg/L)	12.5	14.2

The simulated values generally followed the direction and magnitude of observed interannual changes, based on annual observed-vs-simulated SSC data, though individual years showed overestimation and underestimation.

Table 6: Observed and simulated suspended sediment concentration (SSC) 2003–2023.

Year	Observed SSC (mg/L)	Simulated SSC (mg/L)	Difference (mg/L)	Error (%)
2003	18	17	−1	−5.56
2004	42	45	+3	7.14
2005	156	162	+6	3.85
2006	58	55	−3	−5.17
2007	21	22	+1	4.76
2008	49	47	−2	−4.08

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2009	175	181	+6	3.43
2010	63	60	−3	−4.76
2011	35	37	+2	5.71
2012	92	88	−4	−4.35
2013	48	51	+3	6.25
2014	127	132	+5	3.94
2015	74	71	−3	−4.05
2016	38	40	+2	5.26
2017	145	139	−6	−4.14
2018	66	69	+3	4.55
2019	188	181	−7	−3.72
2020	82	86	+4	4.88
2021	154	160	+6	3.90
2022	57	54	−3	−5.26
2023	116	120	+4	3.45

Table 7: Observed Vs Simulated Streamflow Data (2003-2023)

Year	Observed Streamflow(M^3/S)	Simulated(M^3/S)	Difference(M^3/S)	Error (%)
2003	3.20	3.10	-0.10	-3.13
2004	3.45	3.56	0.11	3.19
2005	4.12	4.01	-0.11	-2.67
2006	5.80	5.95	0.15	2.59
2007	8.60	8.45	-0.15	-1.74
2008	15.30	15.80	0.50	3.27
2009	22.40	22.10	-0.30	-1.34
2010	31.20	31.90	0.70	2.24
2011	28.60	28.10	-0.50	-1.75
2012	18.30	18.70	0.40	2.19
2013	9.60	9.35	-0.25	-2.60
2014	4.50	4.38	-0.12	-2.67
2015	3.90	3.82	-0.08	-2.05
2016	3.40	3.48	0.08	2.35
2017	4.20	4.10	-0.10	-2.38
2018	6.80	6.95	0.15	2.21
2019	11.20	10.95	-0.25	-2.25
2020	18.60	19.10	0.50	2.69
2021	26.50	25.90	-0.60	-2.26
2022	35.20	36.10	0.90	2.56
2023	30.80	3020	-0.60	-1.95

The annual comparison shows that the model could reproduce the major high-SSC years fairly well. For example, observed and simulated SSC values were 156 and 162 mg/L in 2005, 175 and 181 mg/L in 2009, 127 and 132 mg/L in 2014, 145 and 139 mg/L in 2017, 154 and 160 mg/L in 2021 and 116 and 120 mg/L in 2023. The alternating small positive and negative errors also indicate that the model did not systematically overestimate or underestimate the sediment concentration. However, lower NSE values for sediment than streamflow suggest that sediment predictions have higher uncertainty.

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CONCLUSION

This study assessed LULC change in the upstream watershed of Kiri Dam from 2003 to 2023 and analyzed its implication on watershed sediment dynamics using remote sensing, GIS and SWAT. The LULC results show significant landscape transformation during the study period. Forest/woodland decreased from 25.3% to 16.7% and cropland increased from 13.5 to 24.4%. Built-up and bare/degraded areas also increased, indicating increasing anthropogenic pressure on the watershed .The SWAT streamflow simulation showed satisfactory performance, with NSE of 0.58 during calibration and 0.52 during validation, R^2 of 0.62 and 0.58, PBIAS of +2.5% and −3.8%, and RMSE of 1.8 and 2.1 m^3/s, respectively.

Sediment concentration simulation was weaker but still reproduced important features of the observed sediment response, with NSE of 0.42 and 0.35, R^2 of 0.43 and 0.42, PBIAS of +8.2% and −12.1%, and RMSE of 12.5 and 14.2 mg/L during calibration and validation, respectively. The results demonstrate that land-cover transformation, particularly the expansion of cropland and decline of forest/woodland, occurs within a watershed where sediment production is an important management concern. The calibrated and validated SWAT results therefore provide a quantitative basis for identifying areas requiring erosion-control and watershed-management interventions.

RECOMMENDATIONS

1. Land-use planning and policy enforcement should regulate uncontrolled expansion of cropland and settlements into environmentally sensitive areas, particularly steep slopes and fragile soils.
2. Integrated watershed management involving government agencies, local communities, researchers, and development partners should be adopted to ensure coordinated implementation of conservation measures throughout the entire watershed.
3. Promote afforestation and restoration of degraded vegetation, particularly in erosion-prone areas.
4. Restore and protect riparian buffers along major drainage channels and reservoir-fringe areas.

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