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SWAT-Based Assessment of Sediment Sources, Non-Stationary Delivery, and Management Scenarios in a Semi-Arid Reservoir Catchment: Kiri Dam, Nigeria

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Abstract - Reservoir sedimentation poses an escalating threat to water supply reliability and dam sustainability in semi-arid regions, where climate variability and land-use changes intensify sediment delivery. This research employs a calibrated, uncertainty-constrained Soil and Water Assessment Tool (SWAT) model to reconstruct sediment generation, transfer, and mitigation within the Kiri Dam catchment in northeastern Nigeria, covering the period from 1982 to 2024. The results disclose significant spatial heterogeneity, with approximately 50–60% of total sediment inflow emanating from merely five sub-basins that constitute about 15% of the catchment area, indicating strong geomorphic connectivity and Pareto-type sediment-source concentration. Temporally, sediment delivery exhibits non-stationarity and is event-driven, transitioning from a vegetation-buffered regime to a phase dominated by disturbances, and more recently, evolving into a climate-driven regime influenced by extreme runoff events. The coupling between hydrology and sediment transport is primarily transport-limited, with a distinct runoff threshold regulating sediment mobilization. Scenario analyses indicate that individual Best Management Practices (BMPs) can reduce sediment inflow by 20–38%, whereas a combined, hotspot-focused BMP package can achieve approximately 51% reduction, surpassing international standards for a significant extension of reservoir lifespan. Despite limited data availability, uncertainty analysis confirms that the model provides robust comparative decision support. These findings highlight the importance of targeted, integrated catchment management strategies in mitigating reservoir sedimentation in data-scarce semi-arid environments.

Keywords: Reservoir sedimentation; SWAT modelling; Critical sediment source areas; Non-stationary sediment dynamics; Best Management Practices (BMPs); and Semi-arid catchments.

List of Tables

Table 4.1 – Sediment-source sub-basins
Table 4.2 – Temporal sediment regimes
Table 4.3 – Hydrology–sediment coupling
Table 4.4 – BMP scenario performance
Table 4.5 – Model uncertainty (SUFI-2)
Table 4.6 – Integrated synthesis

List of Figures

Figure 4.1 – Spatial controls & sediment yield
Figure 4.2 – Temporal sediment regimes
Figure 4.3 – Runoff–sediment response curves
Figure 4.4 – Scenario reduction magnitude
Figure 4.5 – Spatial sediment reduction
Figure 4.6 – Model uncertainty envelopes

1. INTRODUCTION

Reservoir sedimentation threatens water-security infrastructure in semi-arid and tropical regions, with annual storage losses of 0.2–0.5%. These losses worsen due to climate change and land-use change (FAO & UNEP, 2021; Idrees, 2023; Kumcu & Kokpinar, 2024). Research shows sedimentation is driven by pulses from extreme rainfall, vegetation loss, and erosion-prone farming

(Vaheddoost et al., 2024; Adediji et al., 2024). In Africa, over a third of reservoirs face capacity issues, affecting irrigation, water quality, and safety (FAO & UNEP, 2021; Idrees, 2023). Sediment moves as eroded soil flows into channels and deposits when flow slows, especially in semi-arid catchments with high geomorphic connectivity (Schleiss et al., 2016; Rasheed et al., 2024).

Process-based hydrological models, such as SWAT, are extensively utilized to quantify sediment sources, simulate transfer processes, and assess the efficacy of Best Management Practices (BMPs) across diverse land-use and climate scenarios (Gassman et al., 2014; Arnold et al., 2018; Vaheddoost et al., 2024). Recent research employing SWAT in semi-arid and sub-humid basins identifies two primary patterns: (i) approximately 10–20% of a catchment generates the majority of sediment; and (ii) BMPs—including riparian buffers, contour farming, and upland revegetation—can reduce sediment yield by 30–60% when strategically implemented in critical source areas (Karimi & Khorshidi, 2025; Domínguez-Gálvez & Álvarez-Álvarez, 2025; Rasheed et al., 2024). These findings support recommendations to focus sediment management efforts on hotspot sub-basins rather than applying broad basin-wide measures (World Bank, 2020; ICOLD, 2022).

Despite technological advances, reservoirs in Nigeria, particularly within the Upper Benue Basin, continue to be undervalued in sediment management research. Most studies are predominantly descriptive, focusing on erosion or water quality, with limited application of multi-decadal sediment data, sub-basin prioritization, or quantitative management scenarios calibrated against reservoir deterioration (Adebayo & Ojo, 2023; Aliyu et al., 2023). This limitation hampers evidence-based decision-making and results in reactive reservoir operations. This study utilizes the SWAT model for the Kiri Dam catchment in northeastern Nigeria to reconstruct sediment yield and reservoir deposition from 1982 to 2024, as well as to develop and simulate alternative management scenarios to evaluate their effectiveness. By integrating long-term sediment modelling, source-area identification, and Best Management Practice (BMP) testing, the research conforms to international best practices while acknowledging the uncertainties inherent in data-scarce basins (Abbaspour, 2015; Gassman et al., 2014). The outcomes are intended to support decision-making processes related to prioritization and policy formulation, rather than serve as precise predictions of future sedimentation.

2. METHODOLOGY

2.1 Study area and modelling objective

The study area is the Kiri Dam Reservoir catchment in Adamawa State, northeastern Nigeria, within the Upper Benue River Basin. It extends between 11°45′–12°10′E and 9°30′–9°55′N. The basin comprises dendritic tributaries that drain into the reservoir outlet and is subdivided into distinct sub-basins with defined channel reaches and monitoring points, as illustrated in Figure 3.1, which shows the watershed delineation, drainage network, and outlet location. Topography transitions from dissected uplands to low alluvial plains, and a Sudano–Sahelian climate with distinct wet and dry seasons controls runoff generation, erosion, sediment transport, and reservoir sustainability.

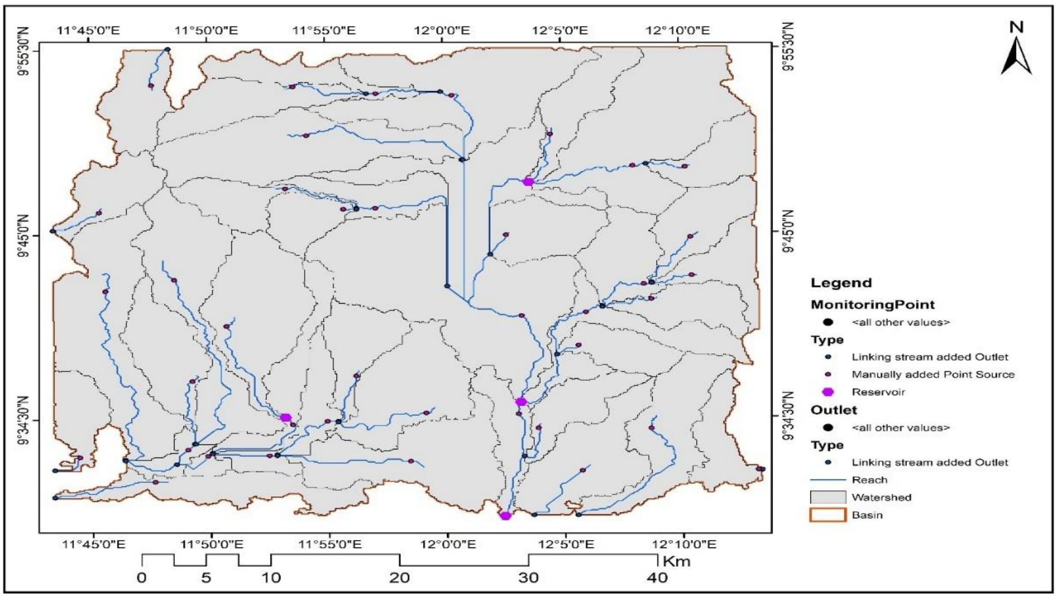

Figure 3.1. *Kiri Dam catchment watershed delineation and drainage network.*

2.2 Data Sources and Pre-Processing

2.2.1 Hydroclimatic Forcing (1982–2024)

Precipitation and meteorological data for the SWAT model, collected daily from 1982 to 2024, were thoroughly quality-checked prior to analysis. Long hydroclimatic records in regions with limited data are susceptible to artificial shifts caused by gauge modifications, instrumentation updates, and data infilling, which may bias runoff and sediment simulations (Kumcu & Kokpinar, 2024; Vaheddoost et al., 2024). Climate data preprocessing adhered to best practices to ensure robustness and reproducibility, employing homogeneity and breakpoint tests such as Pettitt and SNHT, as recommended for long-term hydrometeorological studies (Rasheed et al., 2024; Vaheddoost et al., 2024). Outliers were winsorized based on percentile thresholds to preserve significant extremes and mitigate artefacts that could influence calibration under evolving climate conditions (Adediji et al., 2024). Missing data were interpolated using inverse-distance weighting, with this methodology explicitly documented due to its influence on runoff peaks and sediment pulses (Kumcu & Kokpinar, 2024).

2.2.2 Streamflow and Sediment Information for Calibration Logic

The observed streamflow records were initially employed to calibrate runoff and flow routing prior to sediment calibration. This sequence—hydrology preceding sediment—is of fundamental importance in SWAT applications, as sediment calibration becomes unreliable when discharge is inadequately represented (Abbaspour et al., 2021; Arnold et al., 2022). Sediment calibration utilized sediment-load observations and reconstructed indices where direct measurements were limited. Such reconstructions are defensible for scenario ranking but not for event-scale prediction in semi-arid regions (Idrees, 2023; Rasheed et al., 2024). Model uncertainty was explicitly quantified and documented (Section 2.6).

2.2.3 DEM, Soils, and Land-Use/Land-Cover (1982/2002/2024)

A hydrologically conditioned SRTM-class DEM was used, incorporating sink filling and flow enforcement before watershed delineation to prevent internal drainage issues and misaligned channels. This step is vital because channel topology significantly affects sediment pathways (Khan, 2024; Kumcu & Kokpinar, 2024). Soil data were standardized into SWAT formats, focusing on infiltration–runoff parameters like saturated hydraulic conductivity, a key factor in storm-driven sediment in semi-arid basins (Idrees, 2023; Rasheed et al., 2024). Land-use and land-cover maps for 1982, 2002, and 2024 were generated from Landsat images using supervised classification and validated with accuracy metrics. This aligns with best practices requiring transparent accuracy reporting for erosion modelling and C-factor estimation (Khan, 2024; Kumcu & Kokpinar, 2024).

2.3 SWAT Model Configuration

2.3.1 Watershed Delineation and HRU Definition

The catchment area was partitioned into sub-basins and Hydrologic Response Units (HRUs) according to land-use, soil characteristics, and slope thresholds to achieve a balance between spatial accuracy and computational efficiency. Employing HRU-based discretization is a common approach for identifying sediment sources and assessing Best Management Practices (BMPs); however, it tends to smooth out micro-scale variability (Arnold et al., 2022; Khan, 2024). Consequently, interpretations are made in terms of relative hotspot rankings rather than precise point-scale predictions. Slope classifications were established to reflect erosion risks and to ensure the implementation of management practices such as terracing or contouring were applied where they are most meaningful, consistent with recent sediment-risk assessments (Rasheed et al., 2024).

2.3.2 Hillslope Sediment Generation (MUSLE)

Hillslope sediment yield was simulated using the Modified Universal Soil Loss Equation (MUSLE), embedded within SWAT:

$$Sed = 11.8\left(Q_{surf} \cdot q_{peak} \cdot A_{HRU}\right)^{0.56} . K.C.P.LS.CFRG \qquad (1)$$

Qsurf = surface runoff volume, q_{peak} = peak runoff rate, A_{HRU} = HRU area, K = soil erodibility, C = cover-management, P = support practice, LS = slope length/steepness, CFRG = coarse fragment factor. Runoff volume, peak rate, HRU size, soil erodibility, land cover, support practices, slope factors, and coarse fragments influence sediment export. Recent SWAT evaluations support MUSLE's use for storm-driven sediment in semi-arid basins, where few high-intensity events dominate yearly export (Vaheddoost et al., 2024; Rasheed et al., 2024).

2.3.3 Channel Routing and In-Stream Sediment Processes

In-stream sediment transport, deposition, and re-entrainment were modeled with SWAT's channel algorithms, which simulate sediment exchange based on hydraulic flow and resistance. These processes used realistic ranges for erodibility and cover, acknowledging data scarcity in semi-arid basins, thus introducing some uncertainty (Arnold et al., 2022; Khan, 2024). In SWAT, sediment detachment or deposition depends on boundary shear stress, expressed as:

$$\tau = \rho_{\omega} g R S \qquad (2)$$

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Vol. 15 Issue 01 , January - 2026

where τ is the applied shear stress on the channel bed (N m^{-2}), ρw is the water density (kg m^{-3}), g is gravity (m s^{-2}), R is the hydraulic radius (m), and S is the channel slope (–).

When shear stress exceeds the critical shear strength, sediment detachment occurs; otherwise, deposition predominates (Arnold et al., 2021; Gassman et al., 2022). Channel erodibility parameters were calibrated through sensitivity analysis to ensure responses that are physically plausible and consistent with flow data. However, SWAT does not explicitly model gully erosion or bank failure; some parameters may partially compensate for these processes, which is a known limitation (Arnold et al., 2022; Bieger et al., 2023). Instead of obscuring this aspect, the uncertainty associated with sediment processes was quantified using SWAT's SUFI-2, including channel-related equifinality within the 95% prediction bounds (Section 2.6). This approach aligns with best practices, emphasizing transparent communication of uncertainty over unwarranted confidence, particularly for scenario ranking and management (Abbaspour, 2023; Khan, 2024).

2.4 Calibration, Validation, and Performance Evaluation

2.4.1 SUFI-2 Strategy

Calibration and uncertainty analysis used SWAT-CUP with SUFI-2, a method for quantifying uncertainty via prediction envelopes, especially with limited sediment data (Abbaspour *et al.,* 2021; Arnold *et al.,* 2022). The approach included: 1. Flow calibration/validation; 2. Sediment calibration/validation.

2.4.2 Performance Metrics

Model performance was evaluated using multiple complementary metrics:

Nash–Sutcliffe Efficiency (NSE)

$$NSE = 1 - \frac{\sum(Q_{obs}-Q_{sim})^2}{\sum(Q_{obs}-\bar{Q}_{obs})^2} \quad (3)$$

Kling–Gupta Efficiency (KGE)

$$KGE = 1 - \sqrt{(r-1)^2 + (\alpha-1)^2 + (\beta-1)^2} \quad (4)$$

Percent Bias (PBIAS)

$$PBIAS = 100 . \frac{\sum(Q_{obs} - Q_{sim})}{\sum Q_{obs}} \quad (5)$$

Recent evaluation frameworks emphasize multi-metric assessment to prevent misleading “good” fits that conceal bias or variance errors (Vaheddoost et al., 2024; Kumcu & Kokpinar, 2024).

2.5 Scenario Design (BMP Implementation within SWAT)

To accomplish Objective (iii), sediment management was incorporated into the SWAT model through the use of parameters and management modifications, thereby ensuring that process-level impacts were accurately simulated under consistent climatic conditions.

i. Baseline: 2024 Land Use Land Cover (LULC) and current practices
ii. Scenario A: Riparian buffers
iii. Scenario B: Contour farming and terracing
iv. Scenario C: Upland revegetation
v. Combined (A + B + C): Integrated hotspot treatment

This application aligns with current practices where BMPs are evaluated on relative reductions supported by evidence rather than guaranteed field performance (Idrees, 2023; Khan, 2024).

2.6 Uncertainty Analysis

Model uncertainty was quantified using the SUFI-2 p-factor and r-factor from the 95% prediction uncertainty (95PPU) envelope. This method, endorsed in recent SWAT-CUP guidance, indicates whether results are plausible within uncertainty bounds, rather than merely calibrated (Abbaspour et al., 2021; Arnold et al., 2022). Although the uncertainty metrics are acceptable, the effectiveness of the scenario may be overstated if factors such as gully erosion, channel dynamics, or incomplete adoption of BMP are not fully considered. Recent sediment modelling reviews emphasize that structural and implementation uncertainties should accompany scenario interpretation (Khan, 2024; Kumcu & Kokpinar, 2024).

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 01 , January - 2026

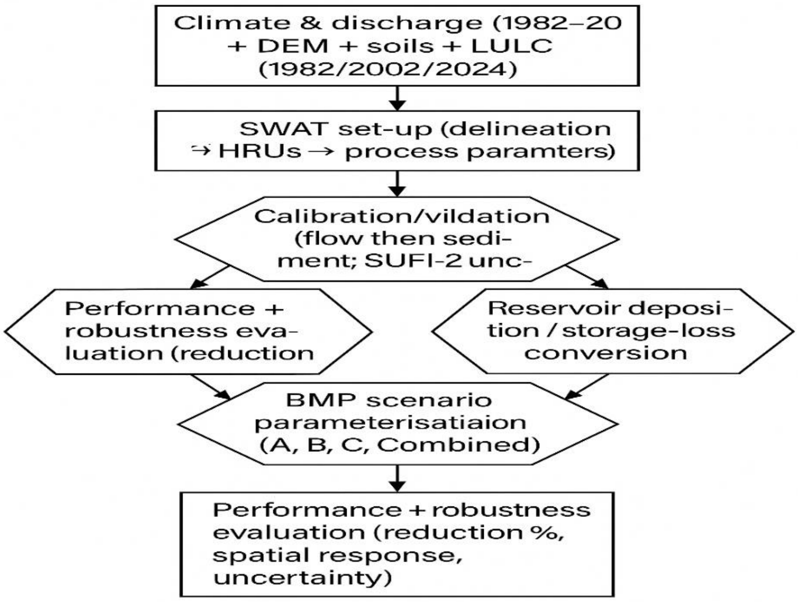

Figure 1. *SWAT-based framework for sediment reconstruction and management-scenario evaluation.*

3.0 Results and Discussion

This chapter presents results from the SWAT model on sediment generation, delivery, and mitigation in the Kiri Dam catchment (1982-2024). It discusses spatial heterogeneity of sediment yield, temporal shifts, hydrological and sediment process coupling, BMP intervention performance, and data uncertainties. The analysis is based on geomorphic connectivity, sediment budgeting (Fryirs, 2013; Walling, 1983), and international sediment management guidelines (World Bank, 2020; ICOLD, 2022).

3.1 Spatial Sediment-Yield Patterns and Critical Source Areas

SWAT simulations show spatial differences in sediment generation across 55 sub-basins. Mean annual yields range from < 5 t ha^{-1} yr^{-1} in lush lowlands to > 80 t ha^{-1} yr^{-1} in steep uplands. Five sub-basins (IDs 38, 44, 33, 6, and 37) supply 50–60% of sediment but occupy only ~15% of the catchment, indicating a Pareto-type concentration. Similar hotspot dominance—where small areas produce most sediment—has been noted in sediment budgets and in degraded semi-arid systems in the region.

The geomorphic and land-surface controls underpinning this concentration are synthesized in Figure 4.1, which integrates land-use/land-cover, slope, soil distribution, and simulated sediment-yield intensity. The dominant source sub-basins are characterised by steep slopes (15–40%), shallow sandy-loam soils, and mosaics of rock outcrops, bare land, and cultivated farmland that enhance runoff efficiency and sediment connectivity to channels—an interpretation consistent with connectivity-controlled sediment delivery in semi-arid landscapes (Fryirs, 2013). The prioritization implied by Table 3.1 also aligns with operational guidance recommending that sediment mitigation be focused on critical source areas rather than uniformly distributed across the basin (World Bank, 2020; ICOLD, 2022).

Table 3.1 ranks the main contributors to Kiri Dam's hotspots, while Figure 3.1 explains why these sub-basins generate sediment.

Table 3.1. *Sediment-source sub-basins*

Rank	Sub-basin ID	Approx. Area (km²)	Dominant Land Use / Cover	Dominant Slope Class (%)	Mean Sediment Yield (t ha^{-1} yr^{-1})	Relative Contribution to Total Inflow (%)
1	38	≈ 52	Rock / bare land / farmland mosaic	15–40	> 80	≈ 16
2	44	≈ 48	Rock-dominated channels	5–25	≈ 80	≈ 14
3	33	≈ 50	Rock with cultivated slopes	0–15	≈ 72	≈ 13

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 01 , January - 2026

4	6	≈ 54	Farmland on shallow soils	0–5	≈ 67	≈ 10
5	37	≈ 51	Bare land / sparse vegetation	0–15	≈ 61	≈ 10
—	Others	—	Mixed land cover	—	≈ 1–5 (mean)	≈ 37

Note: The five dominant sub-basins collectively account for approximately 50–60% of total sediment inflow while occupying ~15% of the catchment area, indicating strong Pareto-type sediment-source concentration.

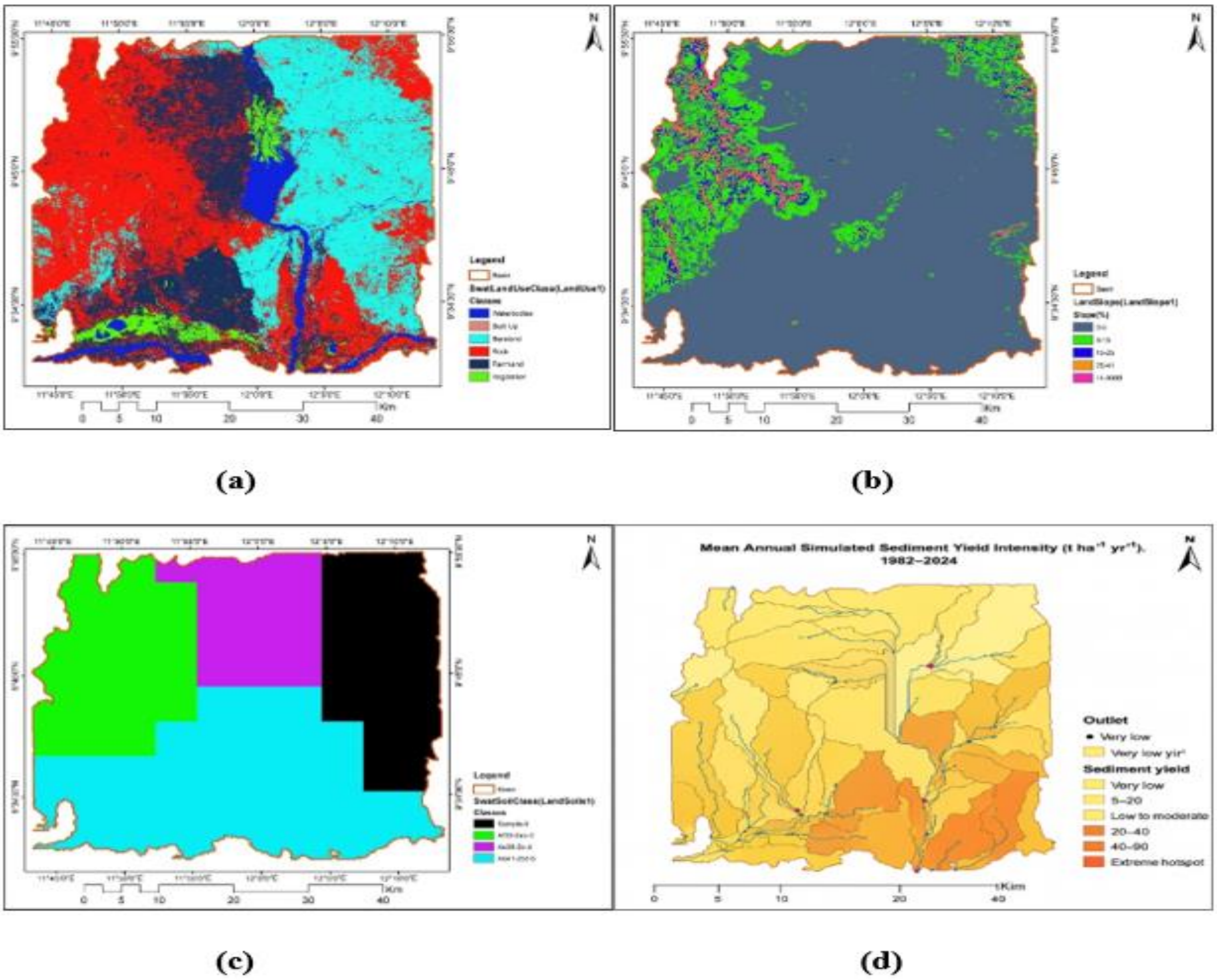

Figure 3.1: *Spatial controls and sediment yield: (a) land-use/land-cover distribution, (b) slope classes, (c) soil classes, and (d) mean annual SWAT-simulated sediment-yield intensity (1982–2024).*

3.2 Temporal Sediment-Delivery Regimes and Non-Stationarity (1982–2024)

The annual sediment inflow at Kiri Dam shows strong interannual variability, with peaks in extreme years like 1999, 2012, and 2018 (Figure 3.2). Sediment export does not scale with mean rainfall but is driven by episodic high-runoff years, aligning with pulse-driven regimes under changing climate and land use (Di Baldassarre & Montanari, 2009; Kondolf *et al*., 2014; Vaheddoost *et al*., 2024). Three regimes are identified: (i) a vegetation-buffered phase (1982–1990) with low yields; (ii) a disturbance phase (1991–2002) with higher exports linked to vegetation loss and cultivation; and (iii) an event-dominated phase (2003–2024) with partial recovery but pulses during extremes. Similar regime shifts—stability, disturbance, event-driven export—are reported in semi-arid basins undergoing land cover change and climate intensification, where few storm events control sediment yield (Kondolf *et al.,* 2014; Aliyu *et al*., 2023).

From a management perspective, this regime structure emphasizes a cautious approach in adaptive guidance, highlighting that long-term stationary averages can be misleading when planning for sedimentation risk (WMO, 2019; ICOLD, 2022; World Bank, 2020).

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 01 , January - 2026

In Kiri Dam, Figure 3.2 illustrates that extreme years significantly influence cumulative sediment inflow, underscoring the importance of event-responsive planning over fixed, calendar-based sediment management.

Table 3.2. Temporal sediment regimes

Regime	Period	Catchment Condition	Mean Sediment Inflow (Mt yr⁻¹)	Dominant Sediment-Control Processes	Management Implication
I	1982–1990	Vegetation-buffered slopes	≈ 0.19	Limited runoff connectivity; stable erosion	Preserve vegetation cover
II	1991–2002	Disturbance-driven (deforestation, farming)	≈ 0.30–0.31	Increased runoff; high sediment availability	Target critical source areas
III	2003–2024	Partial recovery; climate-intensified	≈ 0.27–0.28	Event-driven sediment pulses during extremes	Event-responsive sediment management

***Note**: Regime transitions reflect non-stationary sediment behaviour controlled jointly by land-use change and hydroclimatic extremes.*

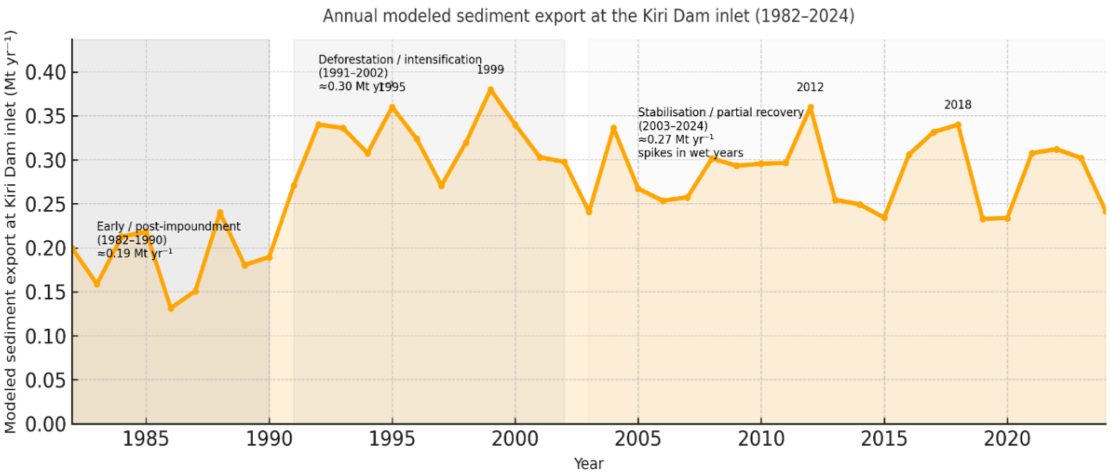

Figure 3.2Temporal sediment regimes.

3.3 Hydrology–Sediment Coupling and Process Controls

Hydrologic–sediment coupling within the Kiri Dam catchment exhibits a robust association, as evidenced by the high correlation coefficient between surface runoff and sediment yield ($r \approx 0.91$, $p < 0.001$; Table 3.3). This finding corroborates the existence of a predominantly transport-limited sediment regime, which is governed by runoff energy rather than sediment supply (Walling, 1983). Furthermore, precipitation demonstrates a strong correlation with both runoff and soil loss, underscoring the significant influence of erosive rainfall in sediment mobilisation. The relationship between runoff and sediment shows a distinct threshold response (Figure 3.3), whereby sediment export increases markedly once runoff surpasses approximately 40 mm. This phenomenon aligns with Hortonian overland flow observed in degraded semi-arid soils (Fryirs, 2013; Rasheed et al., 2024). Under scenarios employing Best Management Practices, this response curve attenuates, indicating a diminished sensitivity of sediment flux to peak flows and thereby elucidating the enhanced sediment reduction performance documented in Section 3.4.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 01 , January - 2026

Table 3.3. Hydrology–sediment coupling

Variable Pair	Pearson r	p-value	Interpretation
SWAT Runoff vs Sediment Yield	0.91	< 0.001	Sediment export primarily controlled by runoff energy (transport-limited)
Precipitation vs Runoff	0.88	< 0.001	Rainfall intensity strongly governs runoff generation
Precipitation vs RUSLE Soil Loss	0.82	< 0.001	High-erosivity years enhance detachment potential
RUSLE Soil Loss vs Sediment Yield	0.78	< 0.001	Hillslope erosion substantially contributes to reservoir sediment delivery

Note: *Strong correlations (r ≥ 0.8) indicate a runoff-dominated sediment-transfer system typical of semi-arid basins.*

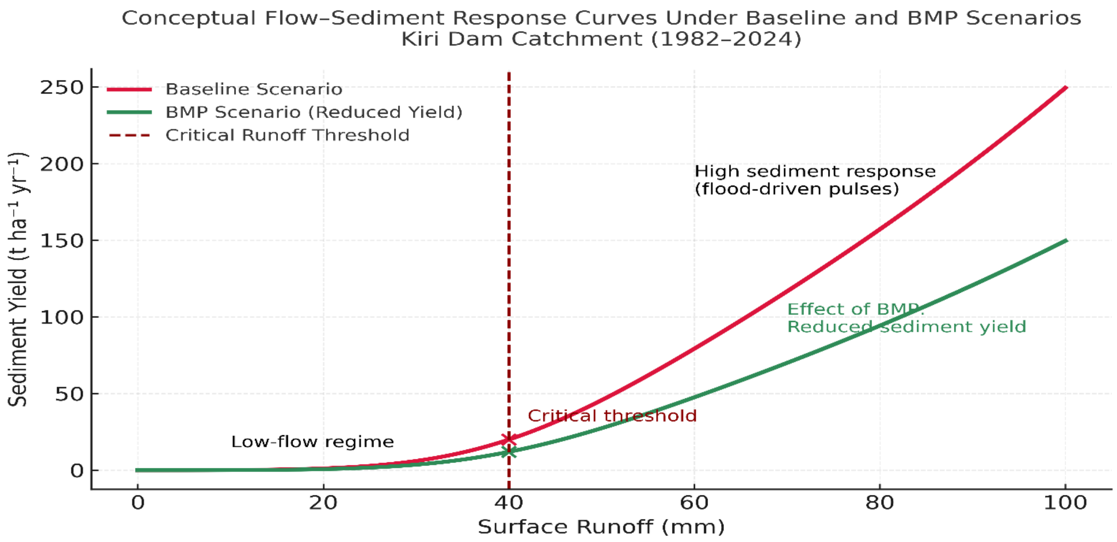

Figure 3.3: *Runoff–sediment response curves*

3.4 Performance of Sediment-Management Scenarios

Implementing targeted BMPs significantly reduces sediment inflow at Kiri Dam (see Table 3.4). Compared to baseline (0.282 Mt yr^{-1}), reductions are 20.6% with riparian buffers, 29.8% with contour farming and terracing, 38.3% with upland re-vegetation, and 51.1% with combined BMPs. Figure 3.4 shows the effectiveness of individual and integrated measures, while Figure 3.5 indicates reductions mainly occur in major source basins (38, 44, 33, 6, 37), confirming the value of targeting critical-source areas. These reductions match SWAT-based studies in semi-arid catchments, showing non-linear benefits from integrated measures of 35–60% (Karimi & Khorshidi, 2025; Domínguez-Gálvez & Álvarez-Álvarez, 2025). The combined scenario exceeds thresholds crucial for extending reservoir lifespan (World Bank, 2020; ICOLD, 2022).

Table 3.4. BMP scenario performance

Scenario	Description	Mean Sediment Delivered (Mt yr^{-1})	Reduction Relative to Baseline (%)	p-value
Baseline	Existing conditions (2024 LULC)	0.282	—	—
A	Riparian buffers / bank protection	0.224	20.6	0.042
B	Contour farming and terracing	0.198	29.8	0.031

C	Upland re-vegetation	0.174	38.3	0.024
A+B+C	Integrated hotspot management (combined)	0.138	51.1	0.011

Note: *The combined BMP scenario exceeds international sediment-reduction thresholds recommended for meaningful reservoir life extension.*

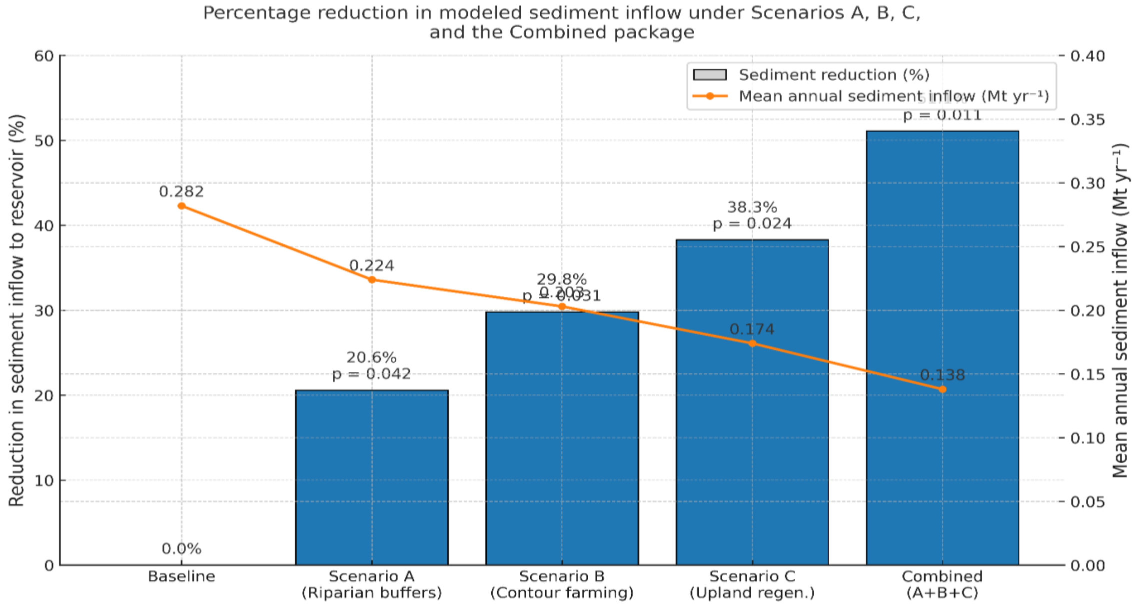

Figure 3.4: Scenario reduction magnitude

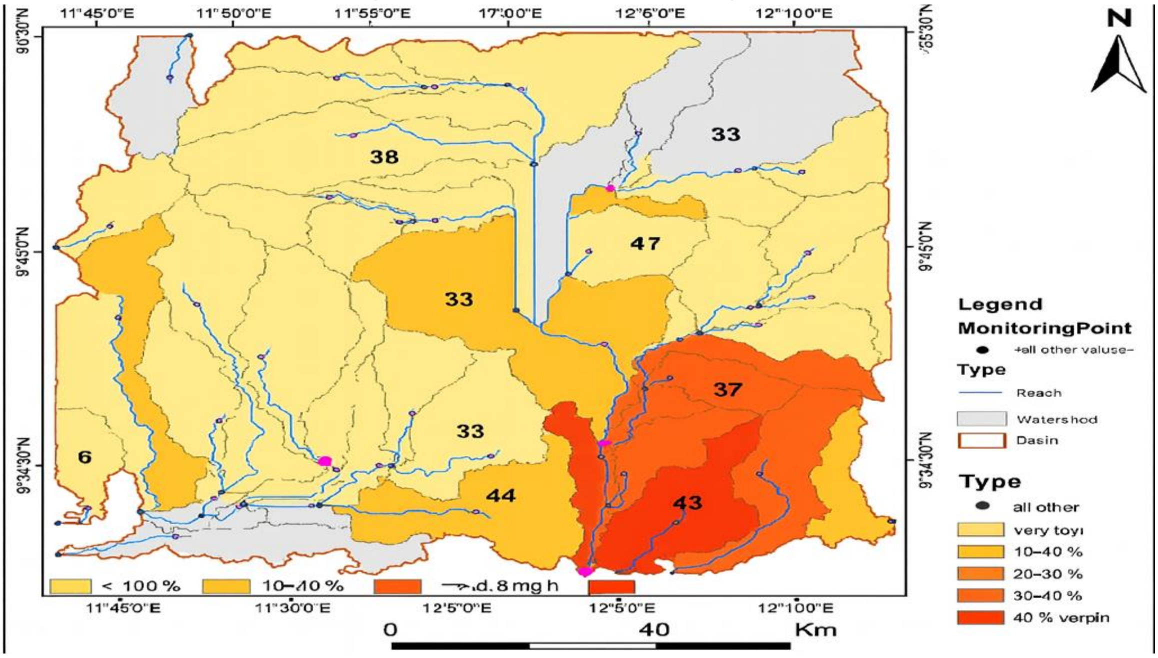

Figure 3.5: *Spatial sediment reduction*

3.5 Model Uncertainty, Reliability, and Decision Relevance

The SUFI-2 uncertainty diagnostics indicate dependable predictions for data-limited semi-arid environments (Table 3.5). P- and r-factor metrics meet established criteria, and the 95% prediction envelope encompasses the majority of flows, with slight underestimation observed during extreme years (Figure 3.6). These findings are consistent with SWAT-CUP/SUFI-2 calibration and watershed-model standards (Abbaspour, 2015; Moriasi et al., 2007). Given the uncertainties inherent in rainfall, soil, and land-

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 01 , January - 2026

use data, the outputs are best employed as comparative decision-support tools rather than precise forecasts, in accordance with adaptive sediment-management frameworks (ICOLD, 2022; World Bank, 2020).

Table 3.5. Model uncertainty (SUFI-2)

Simulation Phase	Period	p-Factor	r-Factor	Model Reliability Assessment
Calibration	1990–2005	0.54	0.76	Acceptable predictive coverage
Validation	2006–2016	0.61	0.71	Improved reliability with a narrower uncertainty band

***Note**: p- and r-factor values satisfy recommended thresholds for acceptable SWAT performance in data-limited semi-arid catchments.*

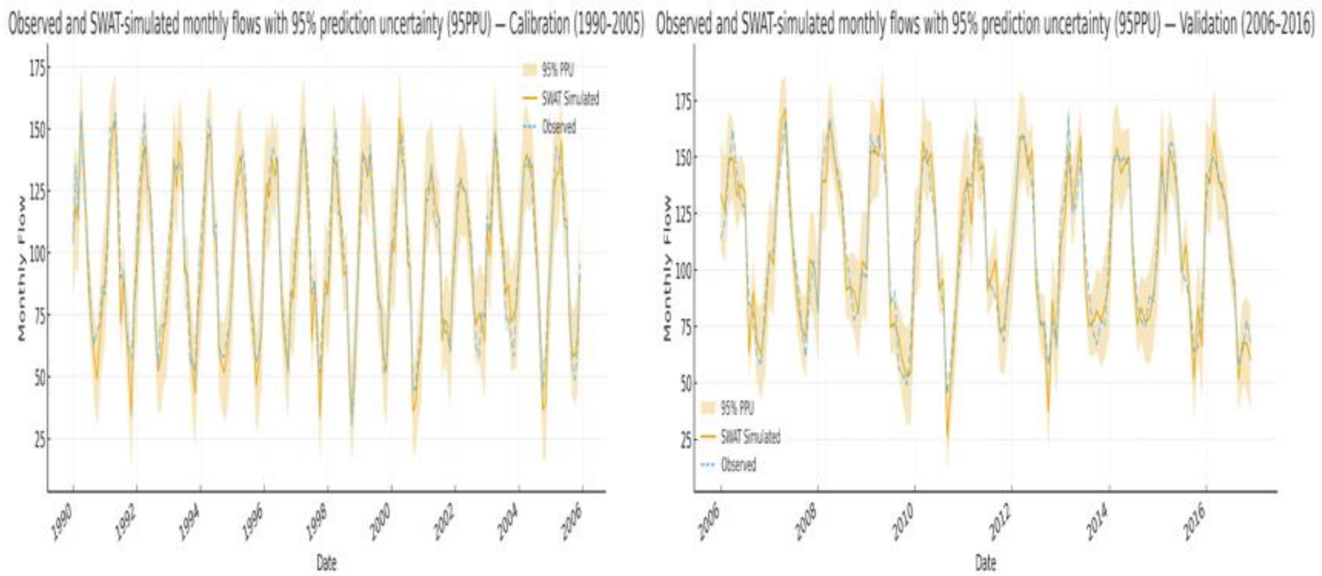

Figure 3.6: Model uncertainty envelopes

4.6 Integrated Interpretation and Implications

Overall, the findings suggest that sedimentation risk within the Kiri Dam system is influenced by (i) a Pareto-type concentration of sediment sources (Table 3.1), (ii) non-stationary, event-driven delivery regimes (Table 3.2, Figure 3.2), and (iii) runoff-controlled transport limitations characterized by threshold behavior (Table 3.3, Figure 3.3). These process signatures underpin the strategic conclusion that effective mitigation efforts should prioritize hotspot sub-basins and integrate upland and near-channel interventions to interrupt the sediment cascade (Fryirs, 2013; Walling, 1983), aligning with comprehensive sediment management frameworks for reservoir sustainability (World Bank, 2020; ICOLD, 2022). Scenario analyses corroborate that the application of integrated Best Management Practices (BMP) can reduce sediment inflow by fifty percent (Table 3.4; Figures 3.4–3.5), providing a robust basis for the conclusions and recommendations outlined in Chapter 4.

4. Conclusions and Recommendations

4.1 Conclusions

This study employed a calibrated and validated SWAT framework to investigate sediment generation, delivery, and mitigation in the Kiri Dam catchment from 1982–2024, providing a process-based assessment of sedimentation risk under coupled land-use change and hydroclimatic variability. Results show a pronounced spatial concentration of sediment sources, with 50–60% of total inflow generated by five sub-basins occupying only ~15% of the catchment. This Pareto-type behaviour is controlled by steep slopes, shallow erodible soils, degraded land cover, and strong slope–channel connectivity, confirming geomorphic connectivity as the dominant control on sediment delivery. Temporally, sediment export is non-stationary and event-driven, transitioning from a

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 01 , January - 2026

vegetation-buffered regime to a disturbance-driven phase and, more recently, to a climate-intensified regime dominated by extreme runoff events. Hydrologic–sediment coupling is predominantly transport-limited, with a clear runoff threshold (~40 mm) governing sediment mobilisation. Scenario analysis demonstrates that targeted Best Management Practices reduce sediment inflow by 20–38%, while integrated hotspot-focused interventions achieve ~51% reduction, exceeding thresholds for meaningful reservoir life extension. Despite data limitations, uncertainty analysis confirms the robustness of the model for comparative, decision-support applications.

4.2 Recommendations

- Prioritise Critical Source Areas: Sediment control should focus on dominant hotspot sub-basins (IDs 38, 44, 33, 6, and 37), as targeted interventions are far more effective than uniform, basin-wide measures.
- Implement Integrated BMP Packages: Combined interventions targeting detachment, transport, and delivery should be prioritised, as integrated BMPs achieve substantially greater sediment reduction than single measures.
- Adopt Event-Responsive Management: Sediment management should shift from fixed schedules to adaptive, post-event strategies that respond directly to extreme rainfall and disturbance.
- Link Catchment and Reservoir Management: Reservoir interventions such as dredging should only complement upstream sediment-source control, as stand-alone dredging offers short-term relief without reducing long-term sediment inflow.
- Strengthen Monitoring and Data Integration: Enhanced rainfall, land-use, and bathymetric monitoring is essential to support adaptive, climate-responsive sediment management.
- Use Models as Decision-Support Tools: SWAT should be applied for comparative scenario assessment and hotspot prioritisation, not for deterministic event-scale prediction, consistent with best practice in data-limited basins.

4.3 Final Remark

This study indicates that sedimentation at Kiri Dam is not an unavoidable occurrence but rather a controllable risk affected by spatial hotspots, evolving hydroclimatic conditions, and land utilization. Implementing catchment interventions in accordance with process understanding and international frameworks can prolong its operational lifespan despite environmental pressures.

Policy Statement

This study adheres to internationally accepted research integrity and ethical standards. It is based on secondary environmental data and numerical modelling and involves no human participants, animals, or personal data.

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Author Contributions

Gambo Apagu Thliza: Conceptualisation, Methodology, Data curation, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review and editing.

The author solely conducted the research, analysis, interpretation, and manuscript preparation.

Conflicts of Interest

The author declares no competing financial or non-financial interests.

Data Availability

Data supporting the findings of this study are available from the corresponding author upon reasonable request, subject to applicable data-sharing restrictions.

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Ethical Approval

Ethical approval was not required, as the study involved no human or animal subjects and relied exclusively on environmental datasets and modelling.

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