

Four Decades of Systematic Sedimentation at Kiri Dam, Nigeria (1982–2025): Dual-Epoch Bathymetry, Hypsographic Change, and Sedimentological Controls on Water-Supply Reliability

Gambo, A. T; Olaniyan, O. S; Adegbola, A. A

Department of Civil Engineering, Ladoke Akintola University of Technology, Ogbomosho, Nigeria

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Abstract: This study examines sediment dynamics at Kiri Dam, Nigeria (1982–2025), through a two-epoch bathymetric reassessment to measure hypsographic change and assess implications for water-supply reliability. In 2025, a high-resolution bathymetric survey was performed in accordance with IHO S-44 standards using Trimble RTK-GNSS and ADCP depth soundings, achieving a crossline mean absolute deviation of ≤ 0.12 m and a vertical RMSE of ≤ 0.05 m. Results were compared with the 1982 design dataset to evaluate elevation-banded losses. At NTWL (170.5 m A.M.S.L.), live storage capacity decreased from 615.00 to 344.15 MCM (–44.0%), while water spread contracted from 106.36 to 67.02 km² (–37.0%). Over 60% of storage loss occurred on depositional benches between 161 and 167 m, increasing the elevation–capacity gradient and intensifying volumetric penalties relative to areal shrinkage (elasticity ≈ 1.19). Multi-season analyses of particle-size distribution confirmed silty clays and clay loams dominate mid-bench and outflow zones, while sandy sediments at the right bank served as coarse-textured controls. Geochemical assays revealed moderate enrichment of Pb (16–27 mg/kg), Cu (12–19 mg/kg), and Zn (63–72 mg/kg) in fine-grained benches, with low hydrocarbon residues (Σ PAHs ≤ 0.8 mg/kg, Σ PCBs ≤ 0.04 mg/kg). A preliminary cost–benefit analysis indicated hydraulic sluicing (\$0.5–1.5/m³) to be more feasible than mechanical dredging (\$3–8/m³), with catchment stabilisation offering benefit–cost ratios of 1:1.3–2.0. Recommended monitoring includes resurveys every 5–10 years, event-triggered campaigns following $\geq Q_{10}$ floods or $>5\%$ shoreline change, and seasonal PSD and geochemistry sampling.

Keywords: Reservoir sedimentation; Bathymetric survey; Elevation–area–capacity (E–A–C); Hypsographic change; Sediment geochemistry; Particle-size distribution (PSD); Hydraulic sluicing; Catchment management; Kiri Dam (Nigeria); Sudano–Sahel hydrology.

I. Introduction

Reservoir sedimentation gradually alters the elevation–area–capacity (E–A–C) relationship, leading to a reduction in live storage capacity vital for irrigation, water supply, and flood mitigation. In semi-arid and tropical regions, hydraulic sorting mainly causes the accumulation of fine-grained silts and clays on large mid-reservoir benches, while coarser materials tend to form prograding delta fronts (Morris & Fan, 1998; Kondolf *et al.*, 2014). Over time, these depositional processes decrease operational storage capacity, threatening the reliability of water supplies and the security of flood buffers. Hypsographic deformation changes E–A–C curves due to sediment infill, compressing live storage at key elevations. Few West African reservoirs have been reassessed using standard bathymetric methods across two epochs. Most studies are single surveys lacking resolution to accurately identify elevation-banded losses and impacts (Mekonnen *et al.*, 2022).

Kiri Dam, constructed in 1982 on the Gongola River within Nigeria’s Upper Benue Basin, presents an opportunity to address this knowledge gap. In 2025, a comprehensive resurvey was conducted in accordance with the IHO S-44 hydrographic standards (IHO, 2020). This process facilitated a direct comparison with the original 1982 design dataset and, for the first time, incorporated multi-season particle-size distribution (PSD) and geochemical sampling. The inclusion of data from both wet and dry seasons permits the testing of depositional inferences against seasonal variability, thereby enhancing the assessment of bench accumulation and contaminant binding (Grimm and Lynch, 2004). Spatial coverage was further augmented through the mapping of sounding density and crossline residuals, while hazard polygons (reedbeds, nets, shallow shoals) were designated as zones characterised by limited observation density. Instead of executing interpolation across these regions, Volumetrics within them were bounded with explicit uncertainty limits and subsequently excluded from trend attribution, thereby acknowledging the constraints associated with interpolation (Dawkins *et al.*, 2023). A lightweight two-dimensional hydrodynamic and sediment transport model shall be employed on the 2025 mesh to validate bench aggradation and delta migration mechanisms. The model will be calibrated using multi-season PSD and geochemistry data and constrained by satellite shoreline dynamics (Dawkins *et al.*, 2023). Monitoring is set within the context of extreme flood frequencies in the Sudano–Sahel, where major morphodynamic pulses typically occur every 5 to 10 . By aligning resurvey schedules with this interval and adding event-triggered resurveys—such as floods exceeding Q_{10} discharge or shoreline changes over 5%—the framework ensures it captures key mechanisms driving storage loss (Morissette *et al.*, 2021; World Meteorological Organization [WMO], 2009) .

This study aims to achieve the following specific objectives: (i) Develop an updated E–A–C dataset for Kiri Dam, utilising IHO S-44 compliant bathymetric data; (ii) Assess losses in storage capacity and surface area across various elevation bands; (iii) Integrate

multi-season PSD and sediment geochemistry data with morphological changes; and (iv) Offer operational guidance for revising rule curves, evaluating the feasibility of dredging and sluicing, and managing catchments.

II. Materials and Methods (Revised)

Study area

Kiri Dam is located on the Gongola River within the Upper Benue Basin in northeastern Nigeria. Commissioned in 1982, it serves to provide water for irrigation and municipal purposes, whilst also mitigating seasonal floods. All positional data are referenced to the WGS-84 UTM Zone 33N coordinate system, with vertical elevations expressed in meters above mean sea level (m a.m.s.l.). The 2025 resurvey conformed to the International Hydrographic Organization (IHO) S-44 standards for hydrographic data quality assurance (IHO, 2020).

Reconnaissance and access

Pre-survey reconnaissance identified hazards like submerged trunks, Typha mats, fishing nets, and hippopotamus colonies, guiding boat routes, transect spacing, and safe zones. Hazard polygons were digitized, with only navigation-relevant ones kept in logs.

Geodetic control (horizontal/vertical)

A temporary GNSS base station was established, linked to permanent dam benchmarks. Differential RTK solutions achieved horizontal accuracy within ≤ 0.03 meters RMSE and vertical accuracy within ≤ 0.05 meters RMSE. Daily loop closures on staff gauges ensured consistency in water-level referencing throughout the survey period.

Hydroacoustic acquisition and navigation

Primary depth measurements were obtained using a boat-mounted Acoustic Doppler Current Profiler (ADCP), operating at frequencies ranging from 600 to 1200 kHz, with bin sizes between 0.25 and 0.5 meters, and ping rates of at least 1 Hz. A legacy single-beam echosounder was maintained for validation purposes. Transects were spaced 50 to 75 meters apart near steep banks and 100 to 150 meters over expansive benches. Crosslines constituted no less than 10% of the total track length, thereby providing an independent quality control measure. Depths were calibrated to the instantaneous water level using staff-gauge records.

Calibration, QA/QC, and uncertainty

Sound-speed profiles were obtained in the morning and afternoon, corrected using Del Grosso/Mackenzie algorithms. Patch tests determined latency and attitude corrections; bar checks validated the single-beam scale. Hampel filtering and SNR thresholds eliminated spurious returns; epochs with $|\text{roll}|$ or $|\text{pitch}| > 10^\circ$ were excluded. Uncertainty was assessed with sounding density rasters and crossline residual maps. Reedbed and net polygons with low data were flagged. Volumes within these hazard polygons have broader uncertainty and are excluded from trend analysis, acknowledging interpolation limitations.

Surface generation and Volumetrics

Cleaned depth points were triangulated into a TIN surface and rasterized at 5–10 m resolution with shoreline breaklines. Elevation–area–capacity (E–A–C) curves were derived by trapezoidal integration.

$$V = \sum_{i=1}^{n-1} \frac{(A_i + A_{i+1})}{2} \times (h_{i+1} - h_i) \quad (2.1)$$

where A_i is area at elevation h_i (USBR, 1985).

Sediment sampling, PSD, and geochemistry

Surface sediments were collected from five georeferenced stations—Inflow, Mid-reservoir, Outflow, Left bank, and Right bank—during wet and dry seasons. The particle size distribution (PSD) was determined using a hydrometer, USDA classes were assigned, and specific gravity (G_s) was measured via pycnometer. Geochemical analyses included pH, TOC, TN, available phosphorus (Av-P), Pb, Cu, Zn, Σ PAHs, and Σ PCBs, following APHA (2017).

Data management and reproducibility

All GNSS, sonar, CTD, QA/QC logs, TINs, rasters, figure code, and table outputs are archived under ISO 19115/19157 standards to ensure reproducibility. These datasets enable independent regeneration of figures and E–A–C diagnostics.

Hydrodynamic–sediment transport model (planned)

To validate depositional mechanisms, a 2d shallow-water model (e.g., HEC-RAS 2D, TELEMAC-2D, Delft3D-FM) will be used on the 2025 mesh. Bench cells (161–167 m) will be resolved at 5–10 m. Drivers include hourly wind, rainfall, reservoir levels, releases, and seasonal Q–SSC curves. Calibration targets bench aggradation and delta migration (> 170 m). Validation uses multi-season PSD, geochemistry, and Sentinel-2 shoreline data. Metrics include NSE and RMSE. Results are for a future paper but outline the validation framework.

III. Results and Discussion

Bathymetric surface and hypsography (2025)

The 2025 campaign produced a geodetically referenced bathymetric point cloud and raster surface suitable for volumetric assessment and two-epoch comparison (Figures 3.1–3.2). Depths were calibrated to the reservoir level using daily staff-gauge records, triangulated through a TIN, and rasterized at 5–10 meters with shoreline conditioning. Overlays of uncertainty from sounding density rasters and crossline residual maps show a mean absolute deviation (MAD) across crosslines of ≤ 0.12 meters and a vertical root mean square error (RMSE) of ≤ 0.05 meters. The hypsographic curves (Figure 3.3) reveal inflections around 161 meters, steepening toward 167 meters, indicating mid-bench aggradation, consistent with global observations that fine sediments settle on broad benches under semi-arid conditions (Morris & Fan, 1998; Kondolf *et al.*, 2014). Hazard polygons like reedbeds and net zones had reduced density and were excluded from trend analysis to avoid overstating interpolation limits. The 2025 hypsography shows small vertical aggradation on broad benches causes disproportionate volumetric loss, highlighting the need to target bench elevations for capacity recovery.

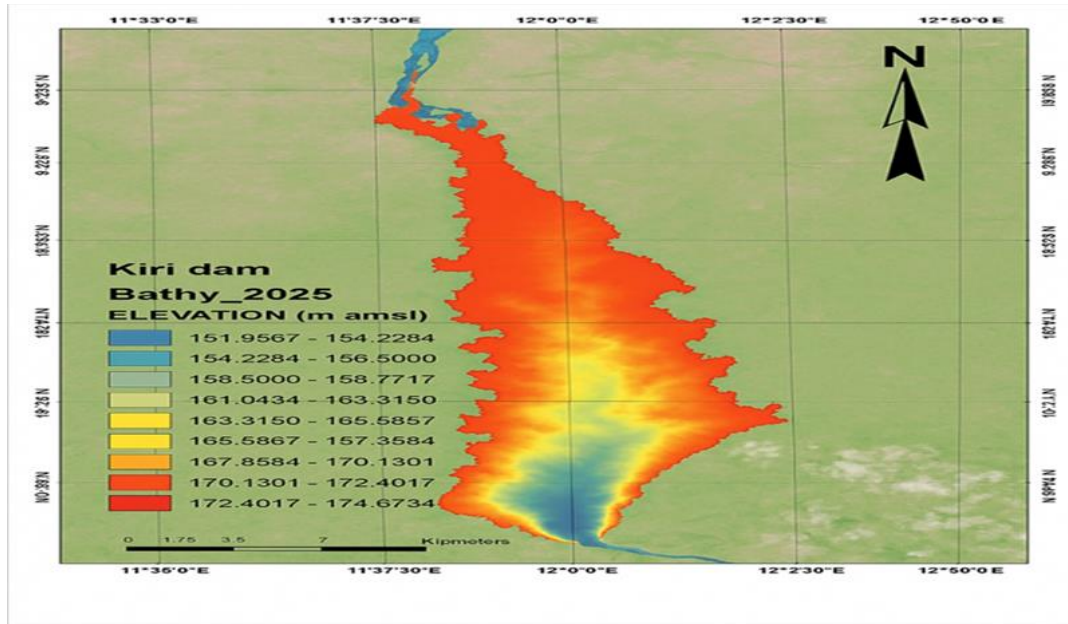


Figure 3.1. Bathymetric map of Kiri Reservoir (2025).

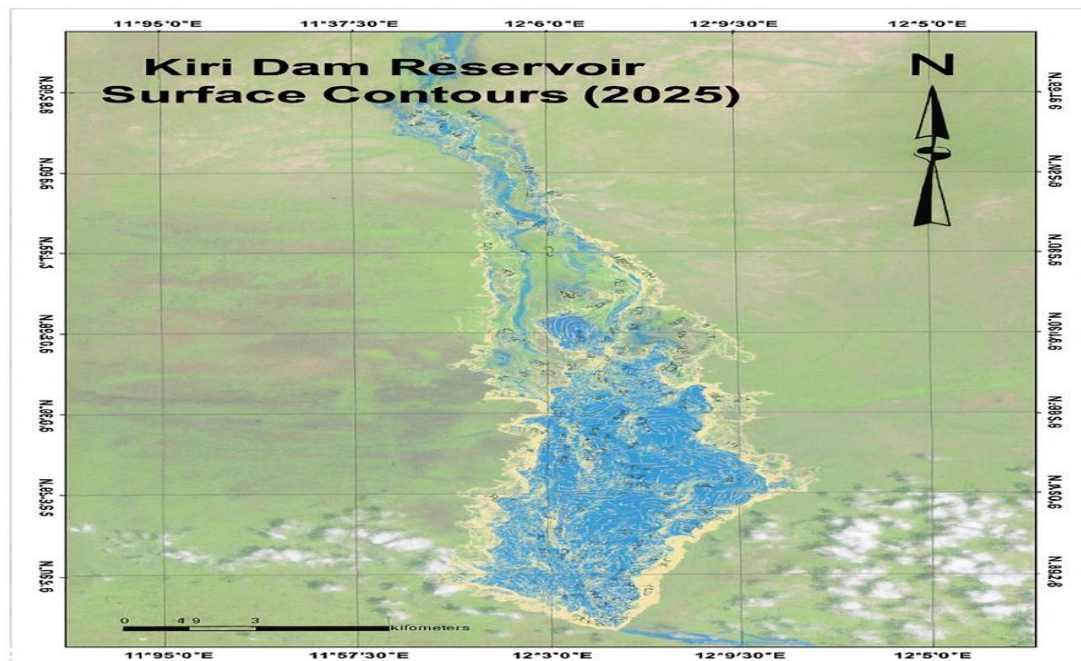


Figure 3.2. Bed-topography contours at 1–2 m intervals (2025).

Revised elevation–area–capacity relationship (2025)

The 2025 E–A–C dataset covers elevation 151.9 to 174.7 meters above sea level. At NTWL=170.5 meters, live storage is 344.15 MCM over 67.02 km², down from the original capacity of 615.00 MCM over 106.36 km² in 1982. This is a reduction of 270.83 MCM (44%) and 39.34 km² (37%).

The elevation–capacity curve demonstrates an increased gradient within the range of 161 to 167 meters (Figure 3.3), signifying that bench accretion is the primary zone of loss. These findings are consistent with global cases, where mid-reservoir benches function as depositional “sinks” for fines (Li *et al.*, 2020; Domínguez-Gálvez & Álvarez-Álvarez, 2025).

Table 3.1. Revised Kiri Reservoir Elevation–Area–Capacity dataset (2025).

Elevation (m a.m.s.l.)	Area (km ²)	Capacity (MCM)
153.10	0.20	0.10
155.37	1.10	0.90
157.64	3.50	5.00
159.91	7.20	18.50
162.18	12.00	39.40
164.46	18.60	83.20
166.73	23.40	135.70
168.99	31.00	227.30
170.50 (NTWL)	67.02	344.15
171.27	36.50	300.80*
173.54	39.00	344.15*

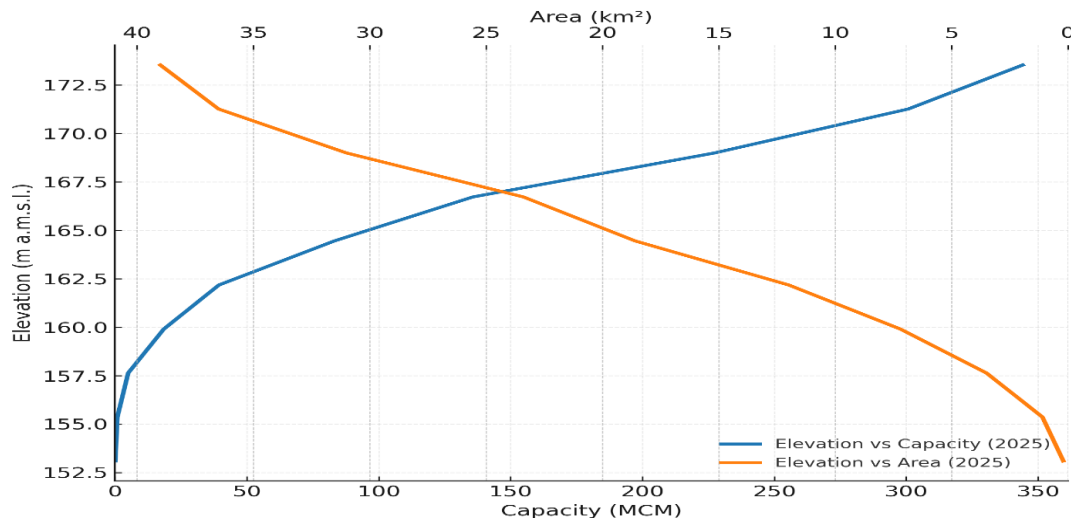


Figure 3.3. Elevation–area–capacity curves (1982 vs 2025).

The recalibrated E–A–C corroborates a disproportionate loss below 167 meters and indicates that legacy rule curves systematically overestimate near-NTWL capacity. Updating operation curves with 2025 data diminishes the risk of over-allocation and enhances flood-buffer planning.

Capacity and Surface-Area Losses Relative to 1982

The 2025 survey shows decreased storage capacity and surface area compared to 1982, especially below 167 meters. At NTWL (170.5m), storage dropped from 615.00 MCM to 344.15 MCM (44.0%), and surface area from 106.36 km² to 67.02 km² (37.0%). Over 60% of volumetric loss occurred below 167 meters, confirming bench aggradation as the main process. Table 3.2 compares bands, with losses recalculated as 1982 minus 2025 values. Negative entries (where 2025 exceeds 1982) are seen as measurement tolerances or shoreline-conditioning artefacts and are not operationally significant.

Table 3.2. Capacity and area losses by elevation band: 1982 vs 2025.

Elevation (m a.m.s.l.)	Capacity 1982 (MCM)	Capacity 2025 (MCM)	Loss (MCM)	% Loss	Area 1982 (km ²)	Area 2025 (km ²)	Loss (km ²)	% Loss
153.10	0.05	0.10	-0.05	N/A	0.05	0.20	-0.15	N/A
155.37	1.00	0.90	0.10	10.00	1.30	1.10	0.20	15.40
157.64	7.00	5.00	2.00	28.60	5.10	3.50	1.60	31.40
159.91	25.30	18.50	6.80	26.90	10.20	7.20	3.00	29.40
162.18	55.00	39.40	15.60	28.40	17.10	12.00	5.10	29.80
164.46	110.00	83.20	26.80	24.40	25.30	18.60	6.70	26.50
166.73	160.00	135.70	24.30	15.20	30.00	23.40	6.60	22.00
168.99	220.00	227.30	-7.30	N/A	38.00	31.00	7.00	18.40
170.50 (NTWL)	615.00	344.15	270.85	44.04	106.36	67.02	39.34	37.00
172.00	780.00	400.50	379.50	48.70	122.51	74.30	48.21	39.30

Note: Negative losses denote instances where 2025 estimates slightly exceed 1982 design values, attributed to shoreline conditioning or survey tolerance. These do not imply actual sediment removal.

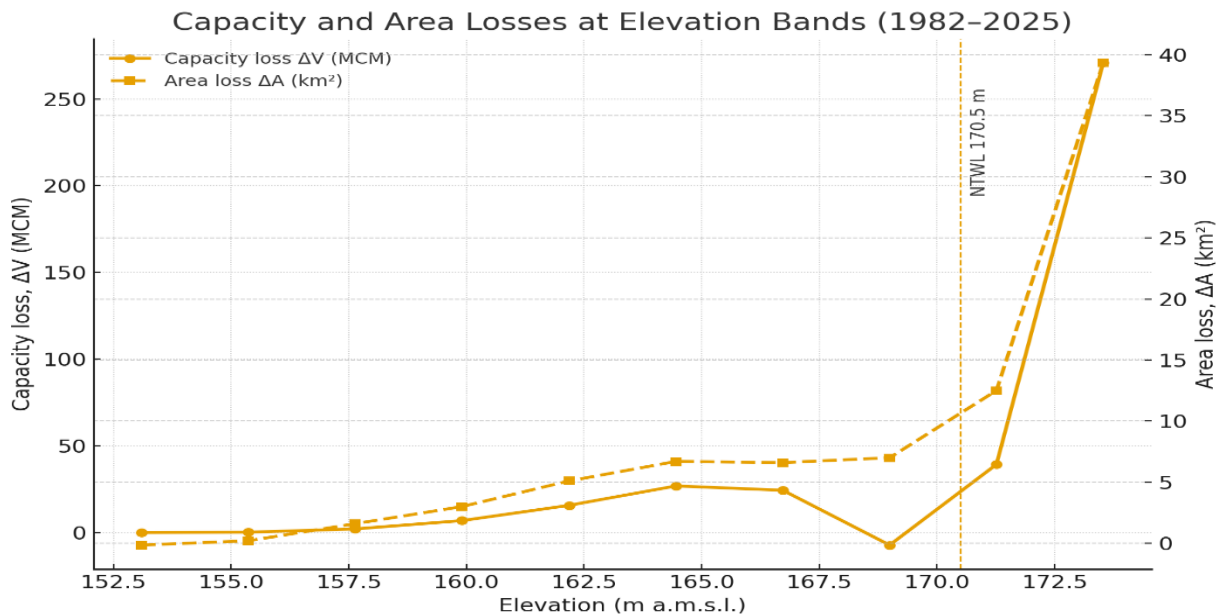


Figure 3.4. Capacity and area losses by elevation band (1982–2025).

Losses occur mainly on mid-reservoir benches (161–167 m), where fine sediments settle under low-energy conditions, supporting the pattern of bench dominance in regulated reservoirs (Morris & Fan, 1998; Li *et al.*, 2020). Thus, elevation-focused sediment management, like bench dredging or sluicing, is more effective than forebay-only interventions.

Areal distribution and correlation structure

Table 3.3 and Figure 3.4 depict the 2025 raster dataset, outlining the reservoir by elevation bands. Area calculations are based on contour differences, summing to 100%. Over 50% of water resides above 167.9 meters, mainly in the delta-front and delta-plain. Strong linear relationships exist between elevation–capacity and elevation–area regressions ($R^2 \sim 0.996$ in 1982; 0.992 in 2025). In the 161–167 metres range, area-capacity correlation is high ($r=0.88$, $p < 0.01$). OLS regressions and residuals show vertical aggradation causes major volumetric penalties, aligning with hypsographic theory (USBR, 1985; Li *et al.*, 2020). Delta zones above 170 meters and benches within 161–167 meters pose two management issues: (i) mid-bench aggradation reducing storage, and (ii) delta progradation changing shorelines. These require targeted interventions instead of uniform strategies.

Table 3.3. Areal distribution of 2025 elevation bands and functional interpretation.

Elevation range (m a.m.s.l.)	Band area (km ²)	% of total	Functional interpretation
151.9–154.2	0.20	0.3	Deep thalweg
154.2–156.5	0.90	1.3	Persistent deep pool
156.5–158.8	2.40	3.6	Transition zone
158.8–161.0	3.70	5.5	Mid-reservoir benches
161.0–163.3	4.80	7.2	Bench/delta transition
163.3–165.6	6.60	9.8	Mid-reservoir shoals
165.6–167.9	4.80	7.2	Shoaling reaches
167.9–170.1	7.60	11.3	Shallow depositional bench
170.1–172.4	8.50	12.7	Delta front
172.4–174.7	27.52	41.1	Delta plain/upper shoals
Total	67.02	100	

Note: Percentages are based on incremental band areas; values now sum to 100%.

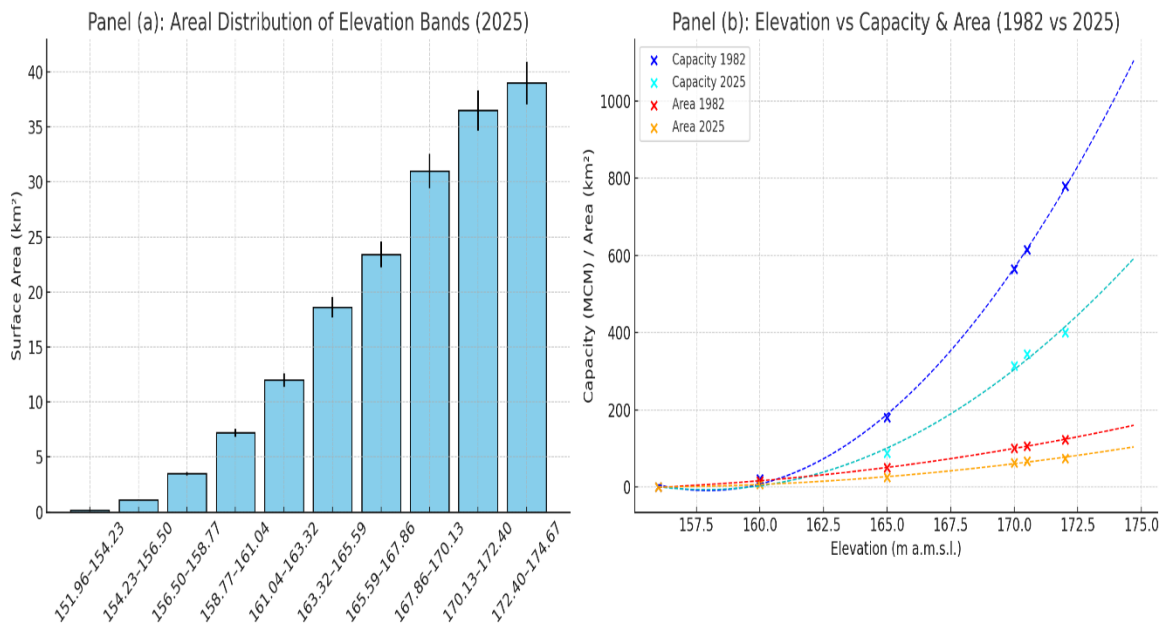


Figure 3.5. (a) Areal distribution of 2025 elevation bands; (b) regressions of E–A–C.

Integrated operational comparison at key levels

Control elevations ranging from 156 m to 172 m above sea level were sampled to compare two periods (1982 and 2025). Losses increased non-linearly with elevation, peaking at NTWL (170.5 m), where storage decreased from 615.00 MCM to 344.15 MCM (–44.0%) and water spread shrank from 106.36 km² to 67.02 km² (–37.0%) (Table 3.4; Fig. 3.6). Losses near operational levels reflect shoreline migration and bench expansion, reducing live storage. This indicates that legacy rule curves overestimated near-NTWL capacity. Updating rule curves with 2025 data ensures more accurate allocations and flood routing.

Table 3.4. 1982–2025 E–A–C comparison at control elevations.

Elevation (m a.m.s.l.)	Capacity 1982 (MCM)	Capacity 2025 (MCM)	Loss (MCM)	Area 1982 (km ²)	Area 2025 (km ²)	Loss (km ²)
156	0.00	0.10	–0.10	0.00	0.20	–0.20
160	21.05	8.25	12.80	15.01	6.50	8.51

165	180.06	87.90	92.16	50.99	25.10	25.89
170	564.41	314.10	250.31	101.06	62.50	38.56
170.5 (NTWL)	615.00	344.15	270.85	106.36	67.02	39.34
172	780.00	400.50	379.50	122.51	74.30	48.21

Note: Negative values at the lowest elevation show minor measurement artefacts within survey tolerance, not operationally significant.

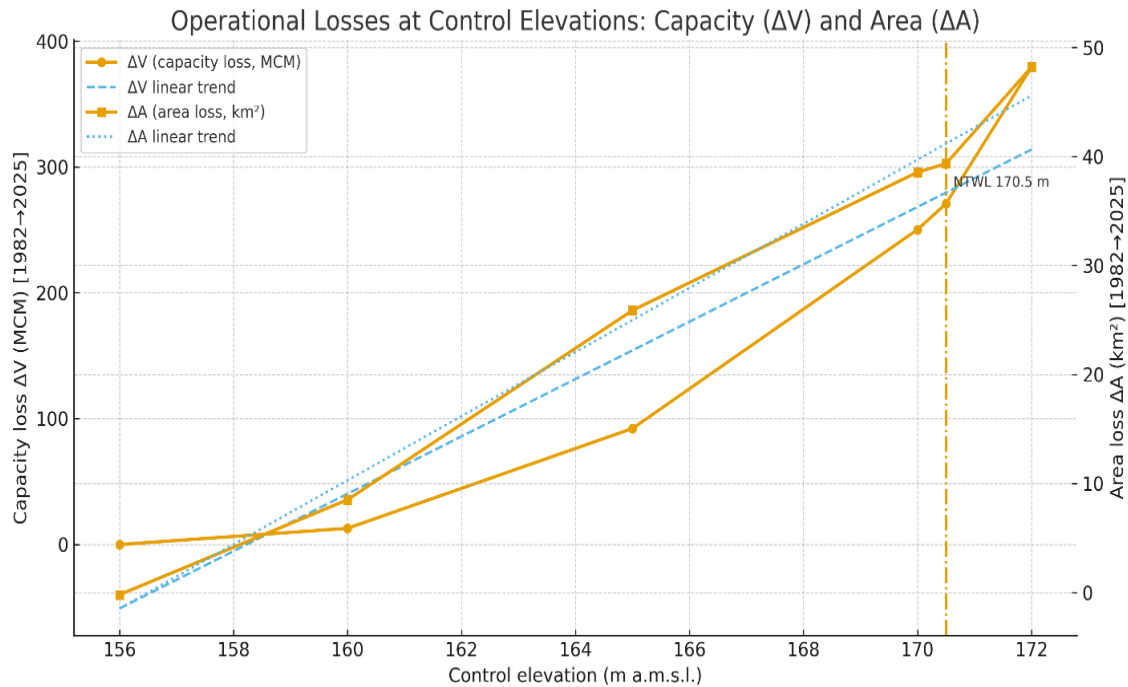


Figure 3.6. ΔV (MCM) and ΔA (km²) vs control elevations; NTWL marked.

Legacy rule curves have systematically overestimated operational thresholds governing irrigation releases and flood-buffer allocation. Near-NTWL losses exceeding 40% imply that continued reliance on design-era curves risks misallocation during both dry-season demand peaks and wet-season flood routing.

Elevation– $\Delta V/\Delta A$ change diagnostics

Quantifying the link between elevation and storage losses involved analysing changes in capacity (ΔV) and surface area (ΔA) at mid-band elevations (see Table 3.5). The analysis showed a moderate, non-significant correlation between elevation and ΔV ($r=0.60$; 95% CI: -0.04 – 0.89), but a significant, strong correlation between elevation and ΔA ($r=0.76$; 95% CI: 0.25 – 0.94). The correlation between ΔV and ΔA was very high ($r \approx 0.97$; 95% CI: 0.89 – 0.99), indicating co-variation. Regression estimated mean loss rates of $+7.28$ MCM m^{-1} for ΔV and $+1.28$ km² m^{-1} for ΔA . Bootstrap intervals confirmed steady increase with elevation, aligning with hypsographic theory, which relates incremental capacity loss to surface area (USBR, 1985; Morris & Fan, 1998).

Table 3.5. Mid-band elevation vs Δ Capacity and Δ Area (1982–2025).

Elevation band (m a.m.s.l.)	Mid-elevation (m)	Δ Capacity (MCM)	Δ Area (km ²)
151.9–154.2	153.10	−0.05	−0.15
154.2–156.5	155.37	0.10	0.20
156.5–158.8	157.64	2.00	1.60
158.8–161.0	159.91	6.80	3.00
161.0–163.3	162.18	15.60	5.10
163.3–165.6	164.46	26.80	6.70
165.6–167.9	166.73	24.30	6.60

167.9–170.1	168.99	−7.30	7.00
170.1–172.4	171.27	39.20	12.50
172.4–174.7	173.54	270.85	39.34

Notes: Negative Δ values reflect survey artefacts at lower elevations and are not interpreted as true capacity gains.

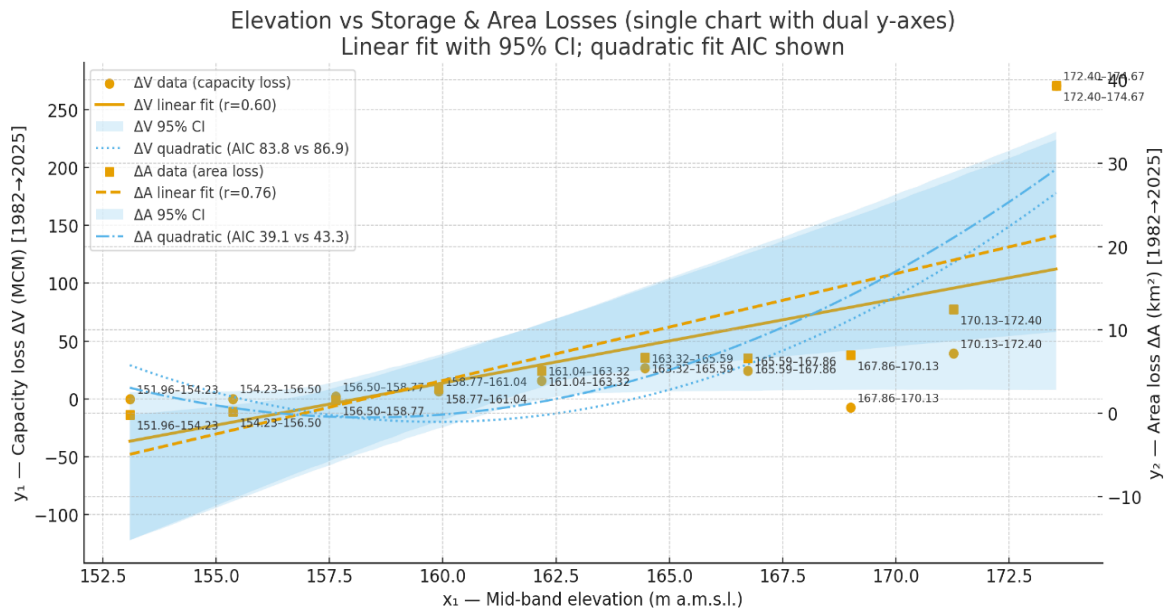


Figure 3.7. Elevation-dependent ΔV and ΔA with 95% bootstrap CIs.

The tight correlation between ΔV and ΔA confirms that shallow depositional processes across benches control volumetric penalties. Sensitivity clustering near 161–167 m justifies prioritizing dredging or sluicing interventions in this elevation range, where small vertical accretions cause disproportionately significant storage reductions.

PSD—textural patterns and links to hypsographic deformation (multi-season)

Particle size distribution (Table 3.6) confirms that fine cohesive fractions dominate the mid-reservoir and outflow zones, where silty clay and silty clay loam persist across wet and dry seasons. These benches, positioned at 161–167 m, are therefore disproportionately sensitive to volumetric loss. In contrast, the right bank remains coarse, with sandy clay loam exceeding 60% sand, and acts as a depositional control. The texture–density diagnostics (Figure 3.8) show stable seasonal patterns, consistent with global reports that semi-arid reservoirs trap fines on benches while coarse sediments prograde deltas (Li et al., 2020; APHA, 2017).

Table 3.6. Particle size distribution and USDA textural classes (wet and dry season, 2025).

Location	Gs (Wet)	Sand % (Wet)	Silt % (Wet)	Clay % (Wet)	USDA class (Wet)	Gs (Dry)	Sand % (Dry)	Silt % (Dry)	Clay % (Dry)	USDA class (Dry)
Inflow	2.34	28	35	37	Clay loam	2.32	24	37	39	Clay loam
Mid-reservoir	3.12	6	52	42	Silty clay	3.08	5	53	42	Silty clay
Outflow	2.92	13	52	35	Silty clay loam	2.95	11	54	35	Silty clay loam
Left bank	2.67	9	50	41	Silty clay	2.64	8	50	42	Silty clay
Right bank	3.17	60	14	26	Sandy clay loam	3.19	62	13	25	Sandy clay loam
Mean $\pm$ SD	2.84 $\pm$ 0.34	23.2 $\pm$ 22.4	40.6 $\pm$ 15.8	36.2 $\pm$ 6.8		2.84 $\pm$ 0.35	22.0 $\pm$ 23.51	41.40 $\pm$ 17.27	36.60 $\pm$ 7.09	

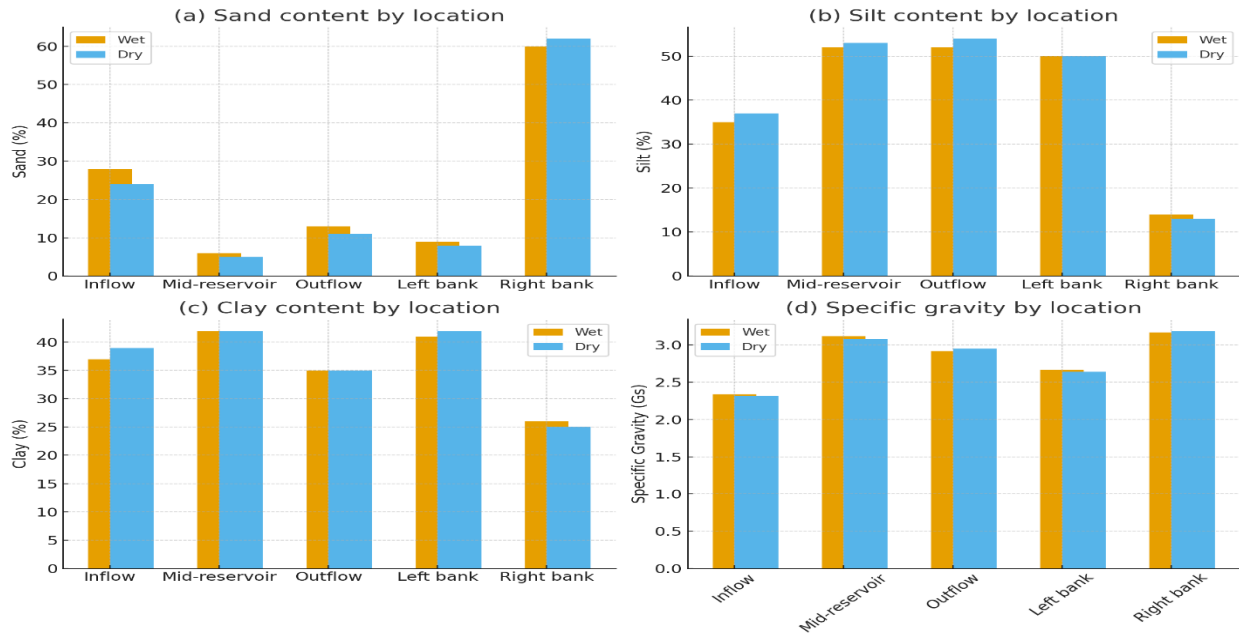


Figure 3.8a-d. Sediment texture and density diagnostics.

(a) Sand content by location (Wet vs Dry); **(b)** Silt content by location (Wet vs Dry); **(c)** Clay content by location (Wet vs Dry); **(d)** Specific gravity (Gs) by location (Wet vs Dry)

Geochemical signatures and management relevance

The geochemical assessment of Kiri Dam sediments (Table 3.7) revealed consistent wet–dry patterns, with near-neutral pH (6.94–7.43) and nutrient enrichment concentrated at depositional benches. Organic matter indicators—TOC and TN—were highest at the outflow and left bank (Figure 3.9a–b), confirming these as functional sinks, while the sandy right bank remained nutrient-poor. Available phosphorus (10.2–15.9 mg kg⁻¹) followed the same gradient, peaking in fine-grained zones and declining at coarse margins (Figure 3.9c). Trace metals showed moderate enrichment, with Pb (16–27 mg kg⁻¹) and Zn (up to 72 mg kg⁻¹) elevated in benches but absent at the right bank (Figure 3.9d–e). ΣPAHs and ΣPCBs were low with slight increases at the outflow, reflecting depositional trapping consistent with semi-arid reservoir processes (Horowitz, 1991; Li *et al.*, 2020).

Table 3.7. Surface-sediment geochemistry of Kiri Dam during wet and dry seasons (2025).

Location	pH	TOC %	TN %	Av-P mg kg ⁻¹	Pb mg kg ⁻¹	Cu (mg kg ⁻¹)	Zn mg kg ⁻¹	ΣPAHs mg kg ⁻¹	ΣPCBs mg kg ⁻¹	pH	TOC %	TN %	Av-P mg kg ⁻¹	Pb mg kg ⁻¹	Cu mg kg ⁻¹	Zn (mg kg ⁻¹)	ΣPAHs mg kg ⁻¹
	Wet	Wet	Wet	Wet	Wet	Wet	Wet	Wet	Wet	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry
Inflow	7.27	1.52	0.127	14.8	23	17	63	0.65	0.03	7.3	1.48	0.12	14	24	17	64	0.62
Mid-reservoir	7.27	1.32	0.106	12.2	24	17	65	0.53	0.02	7.32	1.37	0.11	11.5	25	17	66	0.51
Outflow	7.38	1.71	0.142	15.9	26	19	70	0.78	0.04	7.42	1.76	0.15	15	27	19	71	0.74
Left bank	7.39	1.69	0.135	15.2	26	19	71	0.76	0.04	7.43	1.74	0.14	14.5	27	19	72	0.74
Right bank	6.94	0.83	0.075	10.2	16	12	0	0	0	0	0	0	0	0	0	0	0

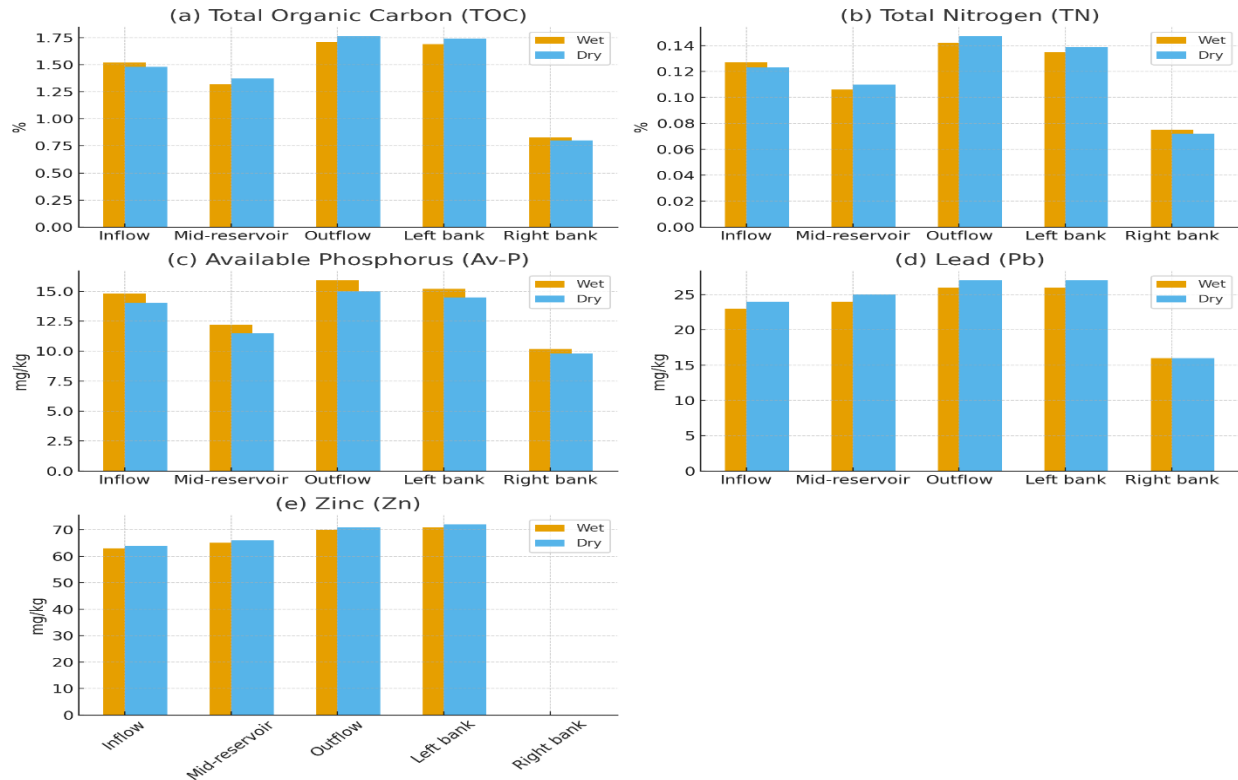


Figure 3.9a-e. spatial variability in sediment geochemistry (2025)

Summary of capacity/area change

The comparison between 1982 and 2025 shows significant declines in Kiri Dam's capacity and surface area. At NTWL (170.5 m), capacity dropped from 615.00 to 344.15 million m³ (44.0%), and the surface area shrank from 106.36 to 67.02 km² (37.0%). The loss of 270.85 million m³ results in a volume–area loss elasticity of 1.19, meaning capacity declined 19% faster than surface area. This disproportionate decline (see Table 3.8) is due to fines on broad benches (161–167 m) and suggests storage limitations can't be inferred solely from areal reduction (USBR, 1985; Morris & Fan, 1998; Li *et al.*, 2020).

Table 3.8. Capacity and surface-area change in Kiri Reservoir (1982–2025).

Year Epoch	Capacity (MCM)	Surface area (km ²)	Capacity loss	% Capacity loss	Area loss (km ²)	% Area loss
1982 (Design)	615.00	106.36	0.00	0.00	0.00	0.00
2025 (Resurvey)	344.15	67.02	270.85	44.04	39.34	37.00

Synthesis of findings

Kiri Dam has experienced four decades of elevation-banded sedimentation, mainly between 161–167 m. Storage dropped by 270.85 MCM (–44.0%) and surface area by 39.34 km² (–37.0%) from 1982 to 2025, with most losses below 167 m, steepening the elevation–capacity gradient. PSD shows fines dominate mid-reservoir and outflow zones, while geochemistry indicates higher TOC, TN, trace metals in these benches with low hydrocarbons. This fines-driven buildup explains the elasticity ($E \approx 1.19$) and supports targeted dredging, updated rule curves, and periodic resurveying (USBR, 1985; Li *et al.*, 2020).

Operational implications for Kiri Dam

The reassessment confirms Kiri Dam's rule curves overestimate near-NTWL storage, risking misallocation during droughts and flood buffers. Losses at 161–167 m need reparameterization using the 2025 E–A–C dataset, with live storage at 344.15 MCM (67.02 km²). Sediment management should prioritize hydraulic sluicing, with dredging and catchment stabilization. Geochemical signatures support sentinel monitoring. Governance under UBRBDA must incorporate adaptive rule updates, operational windows, and annual KPI reviews for resilience.

Monitoring framework and research needs

The 2025 resurvey highlights sedimentation at Kiri Dam and the need for a reproducible monitoring framework (Figure 3.10). A feedback model synthesizes drivers like catchment erosion, hydrological extremes, and hydraulic sorting, with diagnostics from bathymetry, E–A–C curves, PSD, geochemistry, and uncertainty mapping. Suggested interventions include dredging, sluicing, delta-front management, and catchment stabilization. Monitoring should involve resurveys every 5-10 years, with event-triggered campaigns and seasonal sediment sampling. Embedding these in a feedback loop enables proactive, standards-based reservoir management, preserving storage, flood buffers, and long-term water security in Sudano–Sahelian conditions.

Conceptual framework linking sediment drivers, hypsographic change, and management responses

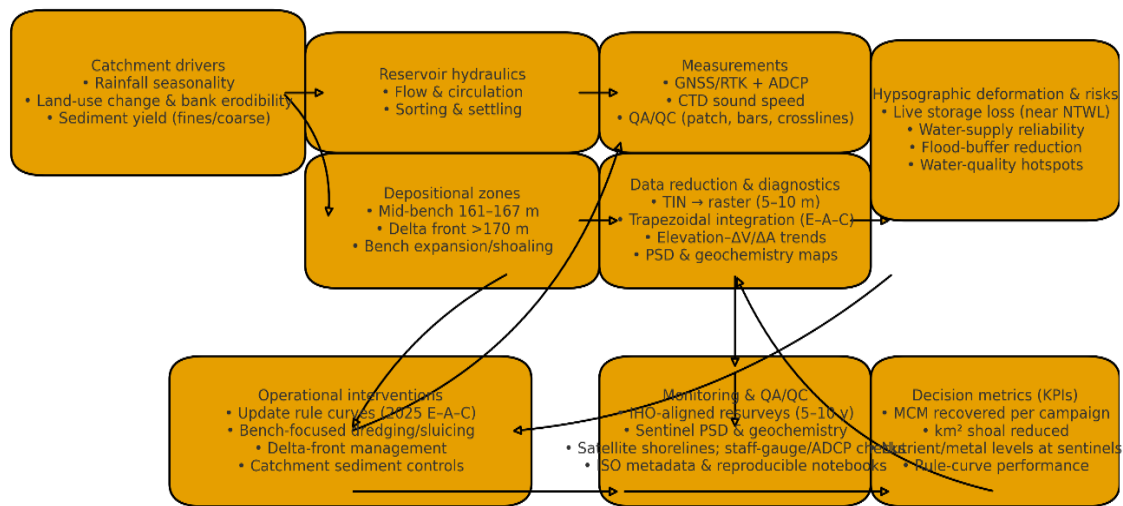


Figure 3.10 Conceptual framework linking sediment drivers, hypsographic change, and management responses.

IV. Conclusions and Recommendations

Principal conclusions

The 2025 resurvey confirms that Kiri Dam has experienced four decades of elevation-banded sedimentation, resulting in significant compression of live storage at operationally critical elevations. At NTWL (170.5 m), the storage capacity decreased from 615.00 million cubic meters (MCM) to 344.15 MCM, representing a decline of 44.0%. Additionally, the surface area contracted from 106.36 to 67.02 square kilometres (km²), reflecting a reduction of 37.0%. More than 60% of this volumetric loss occurred below 167 meters, leading to a steeper elevation–capacity gradient and consequently increasing volumetric penalties. Sediment analyses indicated a predominance of fine particles within benches and outflow zones, with coarser sandy materials confined to the right bank. Geochemical signatures demonstrated moderate enrichment of nutrients and trace metals, alongside low hydrocarbon levels, thereby affirming the role of benches as depositional hotspots. Comparative analysis of the rule curves further identified a systematic overestimation of near-NTWL capacity, which heightens the risk of water misallocation and inadequate provision of flood buffers.

Actionable Recommendations

- Rule-curve reparameterization
- Update operating rule curves using the 2025 E–A–C dataset.
- Parameterize NTWL live storage at 344.15 MCM (67.02 km²) instead of the 1982 design value of 615 MCM.
- Apply robust uncertainty bands: crossline MAD ≤ 0.12 m; RMSE thresholds of ≤ 0.03 m (horizontal) and ≤ 0.05 m (vertical).
- Bench-targeted sediment management (161–167 m)
- Prioritize hydraulic sluicing during drawdowns as a cost-effective option ($\sim \$0.5\text{--}1.5/\text{m}^3$).

- Supplement with selective mechanical dredging for residual shoals (~\$3–8/m³), emphasizing spoil reuse for construction (e.g., brickmaking, embankment fill).
- Catchment-based interventions
- ★ Stabilise tributary banks and gullies, restore riparian buffers, and upgrade road drainage to reduce erosion and sedimentation.
- ★ Preliminary CBA shows catchment controls (~\$4–8 M) are economically favourable with BCR $\approx$ 1.3–2.0, even before accounting for ecological co-benefits such as soil retention and biodiversity enhancement.
- Monitoring and adaptive management
- Institutionalise resurveys every 5–10 years, aligned with Sudano–Sahel flood recurrence intervals.
- Implement event-triggered surveys following $\geq$ Q10 floods or shoreline shifts $>$ 5%, detected via Sentinel-2.
- Establish seasonal PSD and geochemistry monitoring at depositional benches and outflow zones to track contaminant and nutrient accumulation.

SMART Performance Targets (KPIs)

- Capacity recovery: Restore $\geq$ 15–25 MCM within three years in the 161–167 m bands, verified by updated E–A–C datasets.
- Flood buffer protection: Maintain a live-storage margin of $\geq$ X MCM by 1 May annually, with X determined by revised rule curves and risk thresholds.
- Sediment reduction: Achieve a 20–30% reduction in median TSS at priority tributary mouths within two years of implementing catchment controls.
- Water quality stability: Prevent upward trends in Av-P or trace metals at sentinel sites over three years, assessed by non-parametric trend tests.
- Survey quality assurance: Ensure crossline MAD $\leq$ 0.12 m and RMSE thresholds $\leq$ 0.03 m (horizontal) and $\leq$ 0.05 m (vertical) for each survey campaign.

Prioritization and feasibility (risk–cost view)

Action focus	Expected impact	Cost/complexity	CBA screening outcome	Dependencies
Bench dredging/sluicing (161–167 m)	High (direct MCM gain)	Moderate–High	Hydraulic sluicing BCR $\approx$ 0.5–0.9; viable if spoil reused or WV $>$ \$0.4/m ³	Drawdown timing, disposal/reuse plan
Delta-front management ($>$ 170 m)	Medium–High	Moderate	Limited benefit; useful for shoreline stabilization	Flow windows, curtain logistics
Catchment controls (priority tributaries)	Medium (sustained)	Moderate	BCR $\approx$ 1.3–2.0 via avoided dredging	Landholder buy-in, permits
Rule-curve update (2025 E–A–C)	High (system-wide)	Low	Cost-neutral; high risk mitigation	Governance review, modelling
Sentinel monitoring (PSD, geochem, shoreline)	Medium (early warning)	Low	Cost-effective for prevention	Lab capacity, EO analytics

Governance and Operationalization

The Upper Benue River Basin Development Authority (UBRBDA) should lead implementation, coordinating with irrigation stakeholders. Dry-season drawdowns enable dredging and sluicing, while moderate inflows allow controlled flushing. Annual KPI reviews and rule-curve updates should guide sediment management.

Limitations and future work

- ★ Spatial density of PSD and geochemistry remains low in hazard polygons; expanded replication is needed.
- ★ The hydrodynamic–sediment transport model is planned but not yet executed; validation will strengthen mechanistic interpretation.
- ★ Cost–benefit analysis relies on literature-based unit costs; vendor quotes and crop productivity data should refine future assessments.

Closing remark

This standards-aligned reassessment converts four decades of bathymetric, textural, and geochemical data into a management plan. Using rule-curve adjustment, targeted interventions, catchment stabilisation, and monitoring, Kiri Dam can restore storage, maintain flood buffers, and cut water-quality risks. This adaptable framework enhances dam safety and regional water security in Sudano–Sahel regimes.

CRedit authorship contribution statement

Conceptualization: A.T. Gambo, O.S. Olaniyan

Methodology: A.T. Gambo, A.A. Adegbola

Investigation: A.T. Gambo

Formal analysis: A.T. Gambo, O.S. Olaniyan

Writing – original draft: A.T. Gambo

Writing – review & editing: O.S. Olaniyan, A.A. Adegbola

Supervision: O.S. Olaniyan

Declaration of competing interest

The authors declare no known competing financial or personal interests.

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Data availability

The datasets are available from the **corresponding author** upon reasonable request.

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