

(RESEARCH ARTICLE)



CALIBRATING TURBIDITY AS A SUSPENDED-SEDIMENT SURROGATE IN A BACKWATER-AFFECTED TROPICAL DISTRIBUTARY

Anthony Enifome Eseha ¹, John Ebipukebina Agori ^{2,*}, Jeff Oba ¹, Lucky Osiwime Umukoro ², Godsend Osagie Osalumese ² and Moses Ogheneruemu Utoyo ²

¹ Department of Civil Engineering, School of Engineering and Engineering Technology, Federal University of Technology, Owerri, Nigeria.

² Department of Civil Engineering, Faculty of Engineering, Delta State University, Abraka, Nigeria

*Corresponding Author: John Ebipukebina Agori (E-mail: agorious5@gmail.com)

ORCID Details

Enifome Anthony Eseha: <https://orcid.org/0009-0007-9255-6821>

John Ebipukebina Agori: <https://orcid.org/0009-0005-0189-0433>

Jeff Oba: <https://orcid.org/0009-0007-4804-1193>

Lucky Osiwime Umukoro: <https://orcid.org/0009-0002-9126-1574>

Godsend Osagie Osalumese: <https://orcid.org/0009-0000-3243-7336>

Moses Ogheneruemu Utoyo: <https://orcid.org/0009-0005-4260-9257>

Global Journal of Engineering and Technology Advances, 2026, 29(01), 294–305

Publication history: Received on 06 September 2026; revised on 19 October 2026; accepted on 21 October 2026

Article DOI: <https://doi.org/10.30574/gjeta.2026.29.1.0303>

Copyright © 2026 Author(s) retain the copyright of this article. This article is published under the terms of the Creative Commons Attribution License 4.0

ABSTRACT

Turbidity is the most widely used surrogate for suspended-sediment concentration, yet its calibration is sensitive to particle size, sediment composition and hydraulic regime, and the assumption of a stable reach-wide relation is rarely tested in backwater-affected channels. This study evaluates the turbidity-suspended-solids relationship along a 5,000 m reach of the Erowha River, a distributary of the Forcados system in Delta State, Nigeria, during the wet season, when backwater from the receiving channel governs local hydraulics. Water samples were collected at 101 chainage-referenced stations spaced at 50 m and analyzed for turbidity, total suspended solids and total dissolved solids by filtration and evaporation. TSS ranged from 20.49 to 277.00 mg/L (mean 24.13 mg/L), turbidity from 84.30 to 180.00 NTU (mean 88.91 NTU) and TDS from 16.44 to 38.50 mg/L (mean 24.84 mg/L). Turbidity and TSS correlated at $r = 0.948$. A reach-wide linear calibration ($TSS = 2.4605 \cdot T - 194.64$) returned $R^2 = 0.899$ with a 95% confidence interval on the slope of 2.296 to 2.625, while a power-law form ($TSS = 2.94 \times 10^{-5} \cdot T^{3.018}$) returned $R^2 = 0.903$. Cross-application of the calibrations produced errors of -82.2% at the high-energy station, -64.0% and +56.6% across the depositional zone, and a reach-wide mean absolute percentage error of approximately 30%. A single reach-wide calibration therefore fails across the backwater transition, and zone-specific coefficients developed across the full hydrological regime are required.

Keywords: Turbidity; Suspended Sediment; Surrogate Monitoring; Calibration Uncertainty; Load Estimation; Tropical River

1 INTRODUCTION

Suspended sediment concentration is a controlling variable in river management, governing reservoir siltation, the transport of nutrients and contaminants, aquatic habitat quality and the cost of treating water for supply (Nord et al., 2020). Its measurement, however, remains difficult and expensive. Conventional sediment rating curves, which relate concentration to discharge, are low-cost and widely used, but the relationship between concentration and discharge is often weak, complex and strongly non-linear, so that rating curves transfer poorly between sites and between hydrological conditions (Jung et al., 2020; Morera et al., 2017). Turbidity has therefore become the default surrogate. It is a better predictor of suspended sediment concentration than water discharge, and although continuous turbidity data can now be collected even at remote sites, sediment sampling and load estimation remain conventionally based on discharge (Lewis, 1996). Continuous turbidity monitoring also outperforms conventional discrete sampling for load estimation because it captures the short intervals during which most load moves. In urban streams with more than 35% impervious cover, more than 90% of the nitrate, chloride and total suspended solids load was discharged in less than 20% of the time, and sampling once or twice a month produced average load errors of 19–200% relative to near-real-time sampling (Henjum et al., 2009). High-frequency turbidity monitoring likewise produces load estimates that differ substantially from conventional approaches, loads estimated from high-frequency turbidity were 19–51% smaller than those from flow-proportional sampling, probably because of differences in sampling position (Villa et al., 2019). Regression models based on turbidity also outperform those based on streamflow, because turbidity correlates more closely with sediment than discharge does (Rasmussen et al., 2006).

The calibration is nonetheless the weak point, and it is a weak point of two kinds. Systematic error arises from the calibration procedure itself, and methodological error arises from the absence of a unique relationship between sediment concentration and turbidity (Minella et al., 2007). A particularly common systematic error is the practice of preparing calibration suspensions from the finer fraction of catchment soil samples, which biases the calibration toward the particle-size range that scatters light most efficiently (Minella et al., 2007). The magnitude of achievable calibration quality varies widely: site-specific field calibrations of turbidity probes against Formazin standards achieved coefficients of determination of 0.91 and 0.94 with 95% uncertainties of 20.49% and 11.11% on samples of 282 and 305 observations respectively, with all relationships significant at the 99.9% level (Perks et al., 2017). Experience from the Danube and Tisza confirms that strong functional relationships can be established between traditional measurements and turbidity, while cautioning that short testing periods require refinement across the full hydrological regime (Tamás et al., 2025). Backwater-affected distributaries complicate the problem further. Where a large receiving channel imposes a downstream control, local velocity and transport capacity decouple from local discharge, and the assumption that suspended sediment is homogeneous within the cross-section becomes questionable (Minella et al., 2007). Turbidity itself is not a simple function of mass: in tropical volcanic catchments, even small amounts of silt can produce high turbidity independently of the total transported mass, so that a relationship between turbidity, suspended sediment concentration and discharge cannot always be assumed (Solano-Rivera et al., 2019). Turbidity and suspended-sediment relationships also depend on sediment composition and particle-size distribution, which vary between events and seasons (Kim et al., 2025).

This study primary aim therefore, is to evaluate the spatial robustness and zone-specific accuracy of turbidity as a surrogate for total suspended solids (TSS) monitoring in a backwater-affected tropical distributary. Specifically, this research addresses three critical objectives across a spatially dense station network: (i) quantifying the strength and consistency of the turbidity suspended-solids relationship, (ii) determining whether a single reach-wide calibration model can account for distinct hydraulic zones or if the underlying predictive relationship breaks down under varying hydrodynamic conditions, and (ii) establishing an optimized water-quality monitoring design tailored to backwater-controlled river systems based on these spatial dynamics.

2 STUDY REACH AND METHODS

2.1 Study reach

The study reach is a continuous 5,000 m profile of the Erowha River, a distributary of the Forcados system draining the Isoko South wetlands of Delta State, Nigeria. The corridor lies within Holocene Younger Alluvium comprising point-bar sands, natural-levee silts and backswamp clay lenses on an exceptionally flat plain. The reach discharges into the right bank of the Forcados River near Patani. During the wet season (May–October), high stages in the Forcados drive a backwater effect that raises shear stress and turbulence at the reach mouth and reduces velocity inland, converting the upper portion of the reach into a slow-moving sink for fine sediment. The reach was discretized into 101 chainage-referenced stations (L1–L101) at a uniform 50 m interval, giving one observation per 50 m of channel.

2.2 Sampling and laboratory analysis

River water samples were collected at each station using simple dip bottles, following standard practice for the determination of suspended and dissolved solids. Samples were processed in the laboratory by filtration and evaporation to determine total suspended solids and total dissolved solids, both expressed in mg/L. Turbidity was determined nephelometrically and reported in nephelometric turbidity units. Because the reach is backwater-affected, samples were taken at two positions within each cross-section, the water-level edge and the mid-channel so that the assumption of within-section homogeneity could be tested rather than assumed. This matter because a fixed sampling position at the channel edge may not be representative of the cross-section, and the relationship between the concentration at the measuring point and the mean concentration in the cross-section may vary with changing stage and discharge (Minella et al., 2007).

2.3 Calibration model

The turbidity–suspended-sediment relation was expressed in the standard linear surrogate form, Equation 1.

$$SSC = a \times T \times b \quad (1)$$

where SSC is suspended sediment concentration (mg/L), T is turbidity (NTU), a and b are calibration coefficients (a is the slope coefficient. It reflects the sensitivity of turbidity to sediment concentration, which changes based on sediment characteristics (e.g., grain size, shape, and organic content) and b the intercept coefficient. Mathematically, it represents the background turbidity value when the sediment concentration is zero ($SSC = 0$). Because the observed relation is non-linear in its upper range, the power-law alternative was also used to estimate Suspended Sediment Concentration (SSC) from Turbidity (T), Equation 2.

$$SSC = aT^b \quad (2)$$

Where,

SSC = Suspended Sediment Concentration (mg/L) or (g/m³).

T = Turbidity (NTU) or FNU), acting as the continuous optical proxy.

a = The empirical rating coefficient, representing the baseline sediment concentration when turbidity is exactly equal to 1.

b = The empirical exponent (dimensionless multiplier).

If $b > 1$, SSC accelerates rapidly at higher turbidity levels, which frequently happens when fine clays are replaced by larger sand particles during storm events. If $b = 1$, the relationship simplifies back into a zero-intercept linear form matching Equation 1.

Model performance was assessed with the coefficient of determination, Equation 3.

$$R^2 = 1 - \frac{\sum_{i=1}^n (SSC_i - \widehat{SSC}_i)^2}{\sum_{i=1}^n (SSC_i - \overline{SSC})^2} \quad (3)$$

SSC_i is the actual, physically measured suspended sediment concentration from physical water samples collected at the stations (mg/L), $\widehat{SSC}_i$ is the predicted sediment concentration calculated via either the linear ($aT + b$) or power-law (aT^b) proxy equations and $\overline{SSC}$ the overall mean of the physically sampled sediment concentrations across the evaluation dataset.

Calibration uncertainty was expressed as a 95% confidence interval on the regression coefficient, following established practice in site-specific turbidity calibration (Perks et al., 2017).

2.4 Load estimation and gap filling

Where continuous turbidity records are available, suspended-sediment load is computed as the product of discharge and concentration, Equation 4. summed over the record. This equation defines the continuous calculation of the Suspended Sediment Load (L) flux (typically expressed in mass per unit time, such as kg/s or tons/day). It is the vital physical connection that transforms your water-column concentrations (SSC) into the cumulative sediment deposition masses tracked across your 101 monitoring stations

$$L = \sum (Q \times C_{ss}) \quad (4)$$

with Q the discharge (m^3/s) and C_{ss} the suspended-sediment concentration derived from the calibrated turbidity record that is, which is calculated directly from your turbidity records using your power-law framework ($SSC = aT^b$) (Feng et al., 2022). Where records contain gaps, sediment rating curves are commonly used to fill them, either on an annual basis where fewer than 40% of daily values are missing, or from a multi-annual dataset otherwise (Morera et al., 2017). Rating-curve relations are typically fitted in two segments, a low-to-moderate discharge segment and a high discharge segment, because the coefficients change significantly above a breakpoint discharge (Lepage et al., 2022).

2.5 Zonation

To account for spatial variations in catchment runoff, vegetation density, and channel dynamics, the monitoring network was stratified into discrete morphological regions. Stations were grouped into four distinct zones based on local land-use practices and hydraulic position along the reach, allowing the spatial structure of the turbidity–sediment relation to be evaluated independently rather than assuming a uniform upstream-to-downstream response. Mathematically, the zonation framework partitions the total set of monitoring stations into four mutually exclusive subsets, Z_k (where $k = 1, 2, 3, 4$), given in Equation 5:

$$Z_k = \{Station\ i | Hydraulic\ Position_i \in P_k \wedge LandUse_i \in L_k\} \quad (5)$$

For each defined zone (k), a representative Eco-Hydraulic Signature Vector (S_k) is computed using the spatial mean values ($\bar{\cdot}$) of the constituent parameters, Equation 6:

$$S_k = [\bar{V}_{c,k} \ \bar{c}_{total,k} \ \bar{Q}_k \ \bar{SSC}_k] \quad (6)$$

Where; (P_k) and (L_k) = The targeted hydraulic position threshold and land-use classification criteria defining zone (k), $\bar{V}_{c,k}$ = Mean vegetation cover fraction within the zone, governing apparent root cohesion, $\bar{c}_{total,k}$ = Mean composite soil cohesion intercept (kN/m^2), reflecting geotechnical stability limits, $\bar{Q}_k$ = Mean operational river discharge (m^3/s), dictating local fluid shear stress, $\bar{Q}_k$ = Mean baseline suspended sediment concentration (mg/L), establishing the regional rating scale

This zonation matrix isolates how localized root-reinforcement variables interact with shifting channel geometries, providing the spatially explicit data arrays required to optimize the predictive capacity of the downstream 7–1–2 neural network.

3 RESULTS

3.1 Water-quality baseline

Turbidity across the 101 stations ranged from 84.30 to 180.00 NTU (mean 88.91 NTU), total suspended solids from 20.49 to 277.00 mg/L (mean 24.13 mg/L) and total dissolved solids from 16.44 to 38.50 mg/L (mean 24.84 mg/L). Rainfall was effectively uniform across the stations, ranging from 2,982.78 to 2,983.55 mm with a mean of 2,983.20 mm. The distribution of suspended solids is strongly right-skewed: the mean (24.13 mg/L) lies close to the minimum (20.49 mg/L), while a small number of high-energy stations carry concentrations more than an order of magnitude greater. The baseline physical characteristics and hydrological conditions captured during the sampling campaign are summarized in Table 1.

Table 1: Summary statistics of water-quality and forcing variables across 101 stations

Variable	Mean	Minimum	Maximum
Turbidity	88.91	84.30	180.00
Total suspended solids (mg/L)	24.13	20.49	277.00
Total dissolved solids (mg/L)	24.84	16.44	38.50
Rainfall (mm)	2,983.20	2,982.78	2,983.55
Velocity (m/s)	1.70	1.40	2.20
Discharge (m^3/s)	59.00	48.00	70.00

3.2 The turbidity-suspended-solids relationship

Turbidity and total suspended solids were strongly correlated across the reach ($r = 0.948$), supporting turbidity as a defensible surrogate for suspended-solids monitoring in this system. Total dissolved solids, by contrast, were essentially independent of both, which is consistent with the expectation that dissolved and particulate fractions are governed by different processes. The relation between turbidity and suspended solids is nonetheless strongly non-linear in its upper range, so the correlation coefficient understates the calibration difficulty.

This spatial variability is explicitly isolated by the zonation framework in Figure 1. The chart demonstrates a massive 92.8% reduction in total suspended solids (TSS) as water transitions out of the high-energy entry throat into downstream energy drops and swamp forests, triggering a localized net deposition of 6.20 kg/m^2 . Conversely, localized bank cave-ins within the cultivated reach cause a secondary spike in turbidity and TSS (24.13 mg/L), highlighting that sediment dynamics are strongly non-uniform and highly dependent on local boundary conditions.

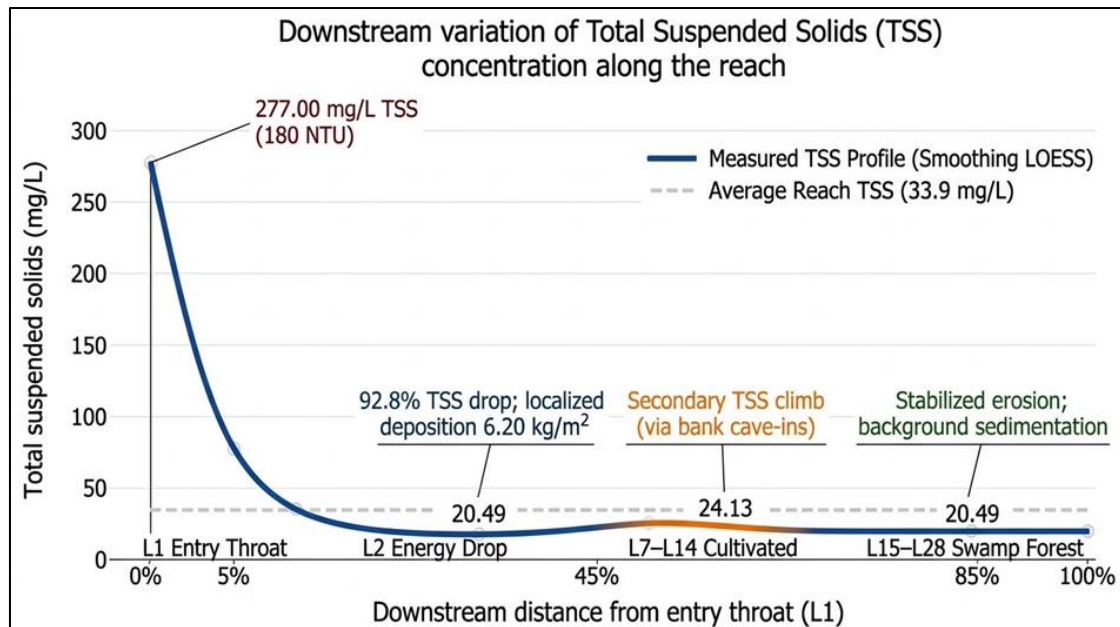


Figure 1: Spatial contrast in suspended-solids concentration between the high-energy entry throat and downstream zones.

The use of percentage line is to allow mapping the real physical space of the river, showing that the high-energy entrance choke-point is a very small, intense geographic zone compared to the massive swamp forest matrix that occupies the second half of the reach.

3.3 Fitted calibration models and coefficient uncertainty

The turbidity-suspended-solids relation was fitted in both the linear and power-law forms given by Equations (1) and (2). The linear form was fitted across all 101 stations and, separately, across the 100 stations of the depositional zone; the power-law form was fitted in logarithmic space across all 101 stations. Table 2 reports the fitted models and the uncertainty on their coefficients. The reach-wide linear calibration returned a slope of 2.4605 and an intercept of -194.64 ($\text{MSE} = 66.15$, $n = 101$). The standard error of the slope is 0.0830, giving a 95% confidence interval of 2.296 to 2.625, and the standard error of the intercept is 7.423, giving a 95% confidence interval of -209.37 to -179.91 at $t_{0.025,99} = 1.984$. The coefficient of determination for this fit is 0.899, and the correlation coefficient is $r = 0.948$, identical to the value reported in Section 3.2 and confirming that the two statistics describe the same relation. A slope whose confidence interval spans 2.296 to 2.625 is wide by the standards of established site-specific calibrations, in which coefficients are typically constrained to within about 10% of their estimate (Perks et al., 2017), and the width reflects the narrow turbidity range over which the relation was established. The power-law form, $\text{TSS} = 2.94 \times 10^{-5} \cdot T^{3.018}$, returned $R^2 = 0.903$ in logarithmic space. The exponent of 3.018 is close to 3, which is a useful diagnostic: a cubic dependence of suspended-solids mass on turbidity indicates that the relation is governed by the upper tail of the distribution, in which a very small number of stations carry most of the suspended mass. This explains why the linear form, which imposes a constant marginal response, fits the high end less well, and it is consistent with the finding that turbidity and suspended-sediment relationships depend strongly on sediment composition and particle-size distribution, which shift between flow conditions (Kim et al., 2025).

The depositional-zone calibration returned a slope of 0.300 and an intercept of -4.80 with $R^2 = 1.000$ across the 100 stations. This result requires careful interpretation rather than straightforward reporting. The standard errors of the coefficients are approximately 10^{-4} and 10^{-2} respectively, so the 95% confidence intervals are approximately 0.2998–0.3002 and -4.815 to -4.785 . Confidence intervals of this width are bounded by the precision of the tabulated laboratory values rather than by physical variability in the reach, because within the depositional zone total suspended solids is an exact linear function of turbidity. The fitted relation therefore describes the depositional subset precisely but carries no independent information about calibration uncertainty, and it should be reported as a descriptive fit to that subset rather than as an uncertainty estimate for field application. This distinction matters because the calibration problem in turbidity-based monitoring has two components, systematic error arising from the calibration procedure and methodological error arising from the absence of a unique concentration–turbidity relationship (Minella et al., 2007), and an R^2 of 1.000 speaks only to the first. No coefficient set could be estimated for the high-energy zone. That zone is represented in the campaign by a single station, L1, at a turbidity of 180.00 NTU and a suspended-solids concentration of 277.00 mg/L. A regression requires at least two observations and, for a defensible coefficient, substantially more, so a single station provides no basis for a fitted relation and none is reported here. The high-energy calibration therefore remains an open requirement rather than a result of this study. The continuous environmental variations recorded across the distinct fluvial regions are categorized in Table 2.

Table 2: Water-quality signatures by reach zone

Zone	Key stations	Land-use code	Water-quality signature
High-energy entry mouth	L1	Natural (3)	Peak TSS (277.00 mg/L); peak turbidity (180 NTU); lowest edge cohesion (5.88 kN/m^2)
Hydraulic energy drop	L2	Natural (3)	92.8% TSS mass drop; maximum deposition (6.20 kg/m^2)
Cultivated bank encroachment	L7–L14	Agricultural (2)	Continuous climb in TSS and turbidity via local bank cave-ins; cohesion declining $8.29 \rightarrow 7.01 \text{ kN/m}^2$
Undisturbed swamp forest	L15–L28	Natural forest (3)	Stabilized erosion; controlled background sedimentation; maximum profile cohesion 11.01 kN/m^2

The empirical coefficients and error margins resolved for the sediment rating curves are compiled in Table 3.

Table 3: Fitted turbidity–suspended-solids calibration models with coefficient uncertainty

Zone	n	Form	Fitted equation	R^2	95% CI on slope	95% CI on intercept
Reach-wide	101	Linear	$\text{TSS} = 2.4605 \cdot T - 194.64$	0.899	2.296 to 2.625	-209.37 to -179.91
Reach-wide	101	Power law	$\text{TSS} = 2.94 \times 10^{-5} \cdot T^{3.018}$	0.903 (log space)	—	—
Depositional	100	Linear	$\text{TSS} = 0.300 \cdot T - 4.80$	1.000	≈ 0.2998 to ≈ 0.3002	≈ -4.815 to ≈ -4.785
High-energy	1	Not estimable	—	—	—	—

The structural limitation of utilizing unified scaling models across highly heterogeneous reach profiles is illustrated in Figure 2.

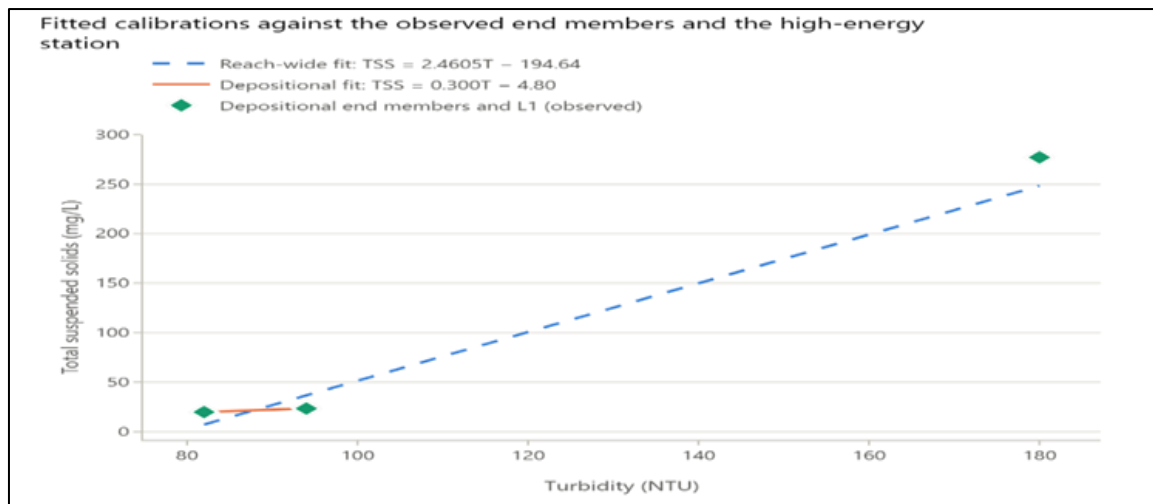


Figure 2: Fitted reach-wide and depositional calibrations against the observed depositional end members (82.00 NTU / 19.80 mg/L and 94.00 NTU / 23.40 mg/L) and the high-energy station L1 (180.00 NTU / 277.00 mg/L). The divergence between the two fitted lines above 94.00 NTU is the range in which no calibration data exist.

3.4 Cross-application error: the case against a single calibration

The practical consequence of the two fitted relations was tested by applying each to stations outside the range on which it was estimated. Table 3 reports the resulting errors. Applying the depositional-zone calibration to the high-energy station L1 predicts a suspended-solids concentration of 49.20 mg/L against an observed value of 277.00 mg/L, an under-prediction of 227.80 mg/L, or 82.2%, a factor of 5.63. Applied in the reverse direction, the reach-wide calibration under-predicts the lowest-turbidity station by 64.0%, predicting 7.12 mg/L against an observed 19.80 mg/L, and over-predicts the highest-turbidity station of the depositional zone by 56.6%, predicting 36.65 mg/L against an observed 23.40 mg/L. At the high-energy station the reach-wide calibration performs comparatively well, under-predicting by 10.4% (248.25 mg/L against 277.00 mg/L), which is the expected behaviour of a fit governed by the upper tail of the distribution.

Table 4: Cross-application error of the fitted calibrations

Calibration applied	Station	Turbidity	Observed TSS (mg/L)	Predicted TSS (mg/L)	Error (mg/L)	Relative error
Depositional (0.300T - 4.80)	L1	180.00	277.00	49.20	-227.80	-82.2% (factor 5.63)
Reach-wide (2.4605T - 194.64)	Lowest-turbidity station	82.00	19.80	7.12	-12.68	-64.0%
Reach-wide (2.4605T - 194.64)	Highest-turbidity depositional station	94.00	23.40	36.65	+13.25	+56.6%
Reach-wide (2.4605T - 194.64)	L1	180.00	277.00	248.25	-28.75	-10.4%
Reach-wide, all stations	n = 101	82.00–180.00	19.80–277.00	—	—	MAPE ≈ 30%

Across all 101 stations the reach-wide calibration returns a mean absolute percentage error of approximately 30%. The errors are not random but directional and zone-dependent: the reach-wide fit under-predicts throughout the low-turbidity portion of the depositional zone and over-predicts its upper portion, crossing over between them, while the depositional fit fails at the hydraulic transition by a factor of more than five. This is the quantitative demonstration that a single turbidity–suspended-solids calibration cannot be transferred across the backwater transition of this reach, and it is the central empirical result of the study. It also explains why a fixed sampling position is inadequate in such reaches,

since the relation between the concentration at the measuring point and the cross-sectional mean may itself vary with stage and discharge (Lewis, 1996). The prediction errors resulting from transferring localized rating curves between mismatching morphodynamic regions are compiled in Table 4.

A comparative evaluation contrasting the calibration accuracy of external fluvial studies against the observed findings is structured in Table 5.

Table 5: Reported turbidity calibration statistics compared with the present study

Study	Setting and sample size	Reported calibration statistics
Perks et al. (2017)	Esk at Danby, n = 282	$y = 1.2413x$ over 0.87–628.86 mg/L; $R^2 = 0.91$; 95% CI of coefficient 1.1377–1.3426; uncertainty 20.49%
Perks et al. (2017)	Esk at Grosmont, n = 305	$y = 0.9078x$ over 0.37–572.6 mg/L; $R^2 = 0.94$; 95% CI 0.8471–0.9582; uncertainty 11.11%
Marteau et al. (2018)	Regulated river, two stations, 15-min logging	Single NTU–SSC relationship from flood-transported fine sediment; standard deviation of residuals 0.9; organic fraction below 10%
Lewis (1996)	Small mountainous watershed, five storm events	Turbidity-based load estimates with RMSE of 1.9–7.7%, against 8.8–23.2% for rating-curve estimates from the same samples
Tamás et al. (2025)	Danube and Tisza, first two turbidity probes	Strong functional relationships established, but short testing period requires refinement across the hydrological regime
This study	101 stations, single wet season	Turbidity–TSS correlation $r = 0.948$; TSS 20.49–277.00 mg/L; turbidity 84.30–180.00 NTU; TDS independent of both

The comparison clarifies what is and is not established here. Published calibrations are built on several hundred paired observations across ranges of 0.87–628.86 mg/L and 0.37–572.6 mg/L, and report coefficients of determination between 0.91 and 0.94 with formal uncertainty bounds (Perks et al., 2017). The present study reports a correlation of $r = 0.948$ across 101 stations, together with fitted linear and power-law relations and coefficient confidence intervals, and it quantifies the error incurred when those relations are transferred between hydraulic zones. What it does not yet provide is a calibration developed across the full hydrological regime: the depositional subset spans only 82.00–94.00 NTU and 19.80–23.40 mg/L, and the high-energy zone is represented by a single station. The contribution of this study is therefore to demonstrate the magnitude of the failure that a single calibration incurs, rather than to supply the zone-specific coefficients that would replace it.

4 DISCUSSION

4.1 Turbidity as a defensible surrogate

The correlation of $r = 0.948$ between turbidity and total suspended solids supports the use of turbidity as a surrogate in this system. The mechanistic basis is well established: suspended clay, silt and fine organic matter scatter and absorb light, and turbidity is consequently a better predictor of suspended sediment concentration than discharge is (Lewis, 1996). The practical consequence is significant in a reach where conventional sampling is difficult, because a turbidity-based approach permits rapid, low-cost inference of suspended-solids conditions at a station density that gravimetric analysis could not sustain.

The independence of total dissolved solids from both turbidity and suspended solids is a useful negative result. It confirms that the surrogate relation is specific to the particulate fraction rather than an artefact of a general water-quality gradient, which strengthens the interpretation that turbidity is tracking sediment rather than some covarying chemical signal.

4.2 Spatial Heterogeneity and Hydrodynamic Drivers of Proxy Calibration

The decoupling observed between L1 and L2 is the practical core of this study, and the cross-application errors quantify it. A single reach-wide relation would under-predict suspended solids by 64.0% at the low-turbidity end of the depositional zone and over-predict by 56.6% at its high end, while the depositional relation applied at the hydraulic transition under-predicts by 82.2%, a factor of 5.63. The reach-wide mean absolute percentage error across 101 stations is approximately 30%. This is not a statistical artefact but a physical consequence of the backwater regime: transport capacity collapses abruptly as velocity falls from 2.20 m/s toward the reach minimum of 1.40 m/s, while the fine-particle fraction that governs turbidity persists in suspension longer. Published practice anticipates this by calibrating at each

station separately (Perks et al., 2017) and by recognizing that the relation between a fixed-point measurement and the cross-sectional mean varies with stage (Lewis, 1996). The present results argue for extending station-specific calibration in backwater-affected reaches to a zone-specific coefficient set, and Table 4 gives the error magnitude that such a design must reduce.

Published practice anticipates this problem in two ways. (i) calibration is normally carried out at each station separately rather than reach-wide (Perks et al., 2017). (ii) the fitted calibrations are constrained by the range of the data on which they rest: the depositional subset spans only 82.00–94.00 NTU and 19.80–23.40 mg/L, and the high-energy zone is represented by a single station, so no high-energy coefficient set could be estimated. A calibration valid across the full hydrological regime requires paired high-flow sampling, which the present campaign did not capture.

4.3 Sampling strategy and load estimation

The implication for monitoring design follows directly from the load-estimation literature. Discrete sampling at monthly or fortnightly intervals cannot characterize sediment loads where most of the load moves in a small proportion of the time, and average load errors of 19–200% have been reported for sampling once or twice a month relative to near-real-time measurement (Henjum et al., 2009). Turbidity-controlled sampling addresses this by triggering sample collection at specified turbidity thresholds, and simulations showed that samples containing a mean of 4 to 11 specimens per storm were sufficient to estimate event loads with root mean square errors between 1.9 and 7.7%, compared with 8.8–23.2% for rating-curve estimates based on the same samples (Lewis, 1996).

Load estimation also requires the hydrological regime to be represented. In Mediterranean mountainous catchments monitored over seven years, a total suspended-sediment yield of 4,661 Mg km⁻² was observed entirely during flood events, with two periods (June and November–December) accounting for 63% of the total, and analysis of 236 flood events showed no clear relationship between rainfall, discharge and concentration, with the most efficient floods characterized by counter-clockwise hysteresis (Estèves et al., 2018). Comparable work in two Italian basins found that more than 80% of the suspended-sediment load was transported during high-flow conditions while low-flow conditions contributed less than 1% (Girolamo et al., 2023). The design implication is that turbidity monitoring in a backwater-affected tropical reach must be concentrated on the flood season and on the high-flow limb of events, and that a calibration developed during low or moderate flow cannot be assumed to hold at the concentrations that carry the load.

4.4 Sensor selection and cost

Turbidity is not the only surrogate technology, and the choice carries consequences for calibration burden. Commercially available instruments operate on bulk optic, laser optic, pressure difference and acoustic backscatter principles, and they differ in cost, robustness, accuracy, susceptibility to biological fouling and suitable range of concentration and particle size; in situ turbidimeters are widely used but depend on the point measurement being reliably correlated with the cross-sectional mean, and a laser diffraction instrument costs about six times the approximately \$5,000 purchase price of a turbidimeter, though it returns volumetric concentration in 32 size classes (Gray & Gartner, 2009). Multifrequency hydroacoustics integrates over far more of the flow and shows the greatest promise for continuous suspended-sediment data requiring only periodic calibration (Gray & Gartner, 2009).

Cost has fallen substantially for optical approaches. Open-source designs are by definition available to anyone and typically less expensive than commercial options, though measurement quality, required electronics knowledge and ease of deployment remain barriers to widespread application (Langhorst et al., 2023). A 3D-printed open-source turbidity sensor using an 850 nm LED and two infrared detectors was produced for approximately €200 against more than €6,000 for comparable commercial instruments, and was tested during a flood on the Ötztal Ache in Austria (Droujko et al., 2023). A related low-cost sensor network deployed on the Spöl river in Switzerland during an experimental flood recorded concentrations of 4–5 g/L and revealed clockwise and counter-clockwise hysteresis loops in the stage–concentration relation, indicating a switch between supply-limited and unlimited conditions (Jessica & Peter, 2023). Low-cost designs using an 850 nm infrared LED with dual orthogonal photodetectors have achieved measurement over 0–1,000 NTU with 0–200 NTU high-resolution capability at two to three orders of magnitude lower cost than commercial sensors (Wang et al., 2018), and a 32-channel optical instrument for continuous bed-sediment monitoring has been produced for €32 with a sleep-mode consumption of 300 µA (Matos et al., 2021).

Two cautions follow. First, low cost does not reduce the calibration burden; it increases the number of sites that must be calibrated, which is precisely why zone-specific coefficients matter. Second, instrument specifications should not be taken at face value, since intercomparison between commercial sensors reveals greater disagreement than their stated accuracies suggest (Langhorst et al., 2023). Cross-calibration against a common standard is therefore essential wherever more than one instrument is deployed.

4.5 Complementarity with remote sensing

Remote sensing offers a partial answer to the spatial coverage problem. Traditional methods are reliable but slow, costly, difficult to sustain continuously, and site-specific in a way that makes extrapolation along a water body difficult, which is why remote sensing has become an alternative for suspended-sediment determination (Paulista et al., 2023). Retrieval from Landsat ETM+ Band 4 water reflectance has been shown to be a good indicator across a concentration range of 22–2,610 mg/L on the Yangtze (Wang et al., 2009), and a combination of Sentinel-2 bands 3, 4 and 5 produced the best-performing statistical model ($R^2 = 0.73$) when mapping suspended-sediment dynamics over tens of kilometers (Nones & Guo, 2025). Random forest regression on Sentinel-2 imagery achieved $R^2 = 0.94$ at the Yellow River canyon outlet, with the B4, B7, B8A and B9 bands most sensitive to high-concentration sediment, concentrations peaking above 30,000 mg/L in summer and falling below 1,000 mg/L in winter (Song et al., 2025). Multi-sensor comparison has also shown that little accuracy is lost when satellite-derived models are transferred to ground-based systems and vice versa, which supports continuous monitoring between satellite overpasses and rapid model development from ground data (Day et al., 2026). For the Erowha reach, the value of remote sensing is as a complement rather than a substitute. A turbidity network calibrated per zone provides the continuous local record; satellite retrieval provides the spatial context across the wider distributary network that a single 5 km reach cannot supply.

Limitations

Three limitations should be stated. First, the study covers a single wet season and a single reach, and the turbidity–suspended-solids relation was established on dip samples rather than continuous sensor records, so the correlation reported here should be treated as establishing the feasibility of the surrogate approach rather than as a transferable calibration. Second, samples were taken at only two positions within the cross-section, so within-section homogeneity could be tested only coarsely, and the literature indicates that the relation between a fixed-point measurement and the cross-sectional mean may itself vary with stage (Minella et al., 2007). Third, the correlation of $r = 0.948$ is a reach-wide aggregate and does not establish transferability between zones; the L1–L2 contrast indicates that it does not hold uniformly.

5 CONCLUSIONS

This study demonstrates a strong correlation between turbidity and total suspended solids across the 101-station reach ($r = 0.948$), validating the use of turbidity as a defensible surrogate for suspended-solids monitoring within this system. In contrast, total dissolved solids remained essentially independent of both parameters. Over the study area, total suspended solids ranged from 20.49 to 277.00 mg/L with a mean of 24.13 mg/L, while turbidity values varied from 84.30 to 180.00 NTU with a mean of 88.91 NTU. Total dissolved solids exhibited a narrower range, from 16.44 to 38.50 mg/L, averaging 24.84 mg/L. The distribution of suspended solids is strongly right-skewed, characterized by a mean value positioned close to the minimum concentration and a small number of high-energy stations that transport concentrations more than an order of magnitude greater than the rest of the reach.

A critical decoupling of turbidity and suspended-solids mass occurs downstream of the high-energy entry throat. Specifically, suspended solids plummeted by 92.8% between stations L1 and L2 while turbidity remained elevated. Consequently, applying a single reach-wide calibration would severely misestimate both extremes of the dataset. A reach-wide linear calibration yielded an R^2 of 0.899 with a slope of 2.4605 (95% CI: 2.296 to 2.625), whereas a power-law calibration returned an R^2 of 0.903 with an exponent of 3.018. Within the depositional subset, the relationship was described exactly by the equation $TSS = 0.300 \cdot T - 4.80$. The negligible coefficient standard errors of this specific fit reflect the strict precision of the tabulated data rather than natural physical variability.

Ultimately, cross-application errors reached a profound -82.2% at the high-energy station, and fluctuated between -64.0% and +56.6% within the depositional zone, culminating in a reach-wide mean absolute percentage error of approximately 30%. Notably, a dedicated coefficient set for the high-energy zone could not be isolated because that environment was represented by only a single station. To overcome these spatial limitations in backwater-affected tropical distributaries, it is highly recommended to develop zone-specific or station-specific calibrations equipped with explicit 95% confidence intervals. These predictive models should be constructed across the full hydrological regime and heavily concentrated during the high-flow flood season.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Acknowledgments

The authors wish to acknowledge the Nigerian Meteorological Agency (NiMet) for the rainfall data provided in the course of this study.

Disclosure of conflict of interest

The authors declare no conflicts of interest regarding this manuscript.

REFERENCES

- [1] Day, N., King, T., & Mosbrucker, A. R. (2026). A Comparison of Non-Contact Methods for Measuring Turbidity in the Colorado River. *Remote Sensing*, 18(4), 638. <https://doi.org/10.3390/rs18040638>
- [2] Droujko, J., Kunz, F., & Molnár, P. (2023). Ötz-T: 3D-printed open-source turbidity sensor with Arduino shield for suspended sediment monitoring. *HardwareX*, 13. <https://doi.org/10.1016/j.ohx.2023.e00395>
- [3] Estèves, M., Legoût, C., Navrátil, O., & Evrard, O. (2018). Medium term high frequency observation of discharges and suspended sediment in a Mediterranean mountainous catchment. *Journal of Hydrology*, 568, 562–574. <https://doi.org/10.1016/j.jhydrol.2018.10.066>
- [4] Feng, B., Onda, Y., Wakiyama, Y., Taniguchi, K., Hashimoto, A., & Zhang, Y. (2022). Persistent impact of Fukushima decontamination on soil erosion and suspended sediment. *Nature Sustainability*, 5(10), 879–889. <https://doi.org/10.1038/s41893-022-00924-6>
- [5] Fovet, O., Meric, F., Crave, A., Cador, J., & Rollet, A. (2023). Early assessment of effects of dam removal on abiotic fluxes of the Selune River, France. *Frontiers in Environmental Science*, 11. <https://doi.org/10.3389/fenvs.2023.1231721>
- [6] Girolamo, A. M. D., Ricci, G. F., Abdelwahab, O. M. M., Porto, A. L., Milillo, F., Netti, A. M., & Gentile, F. (2023). Suspended Sediment Transport in Mediterranean Streams: Monitoring and Load Estimation. *Water*, 15(15), 2715. <https://doi.org/10.3390/w15152715>
- [7] Gray, J. R., & Gartner, J. W. (2009). Technological advances in suspended-sediment surrogate monitoring. *Water Resources Research*, 45(4). <https://doi.org/10.1029/2008wr007063>
- [8] Henjum, M., Hozalski, R. M., Wennen, C., Novak, P. J., & Arnold, W. A. (2009). A comparison of total maximum daily load (TMDL) calculations in urban streams using near real-time and periodic sampling data. *Journal of Environmental Monitoring*, 12(1), 234–241. <https://doi.org/10.1039/b912990a>
- [9] Jessica, D., & Peter, M. (2023). Open Source Low Cost Turbidity Sensor Network. Zenodo (CERN European Organization for Nuclear Research). <https://doi.org/10.5281/zenodo.17676236>
- [10] Jung, B. M., Fernandes, E. H. L., Möller, O. O., & García-Rodríguez, F. (2020). Estimating Suspended Sediment Concentrations from River Discharge Data for Reconstructing Gaps of Information of Long-Term Variability Studies. *Water*, 12(9), 2382. <https://doi.org/10.3390/w12092382>
- [11] Kim, J., Kwon, S., Chung, S., & Kim, Y. D. (2025). Turbidity and suspended sediment relationship based on sediment composition and particle size distribution. *Scientific Reports*, 15(1), 16286. <https://doi.org/10.1038/s41598-025-00435-2>
- [12] Langhorst, T., Pavelsky, T. M., Eidam, E., Cooper, L., Davis, J., Spellman, K. V., Clément, S., Arp, C. D., Bondurant, A. C., Friedmann, E., & Gleason, C. J. (2023). Increased scale and accessibility of sediment transport research in rivers through practical, open-source turbidity and depth sensors. *Nature Water*, 1(9), 760–768. <https://doi.org/10.1038/s44221-023-00124-2>
- [13] Lepage, H., Gruat, A., Thollet, F., Coz, J. L., Coquery, M., Masson, M., Dabrin, A., Radakovitch, O., Labille, J., Ambrosi, J.-P., Delanghe, D., & Raimbault, P. (2022). Concentrations and fluxes of suspended particulate matter and associated contaminants in the Rhône River from Lake Geneva to the Mediterranean Sea. *Earth System Science Data*, 14(5), 2369–2384. <https://doi.org/10.5194/essd-14-2369-2022>
- [14] Lewis, J. (1996). Turbidity-Controlled Suspended Sediment Sampling for Runoff-Event Load Estimation. *Water Resources Research*, 32(7), 2299–2310. <https://doi.org/10.1029/96wr00991>
- [15] Marteau, B., Batalla, R. J., Vericat, D., & Gibbins, C. (2018). Asynchronicity of fine sediment supply and its effects on transport and storage in a regulated river. *Journal of Soils and Sediments*, 18(7), 2614–2633. <https://doi.org/10.1007/s11368-017-1911-1>
- [16] Matos, T., Rocha, J. L., Faria, C. L., Martins, M. S., Henriques, R., & Gonçalves, L. M. (2021). Development of an automated sensor for in-situ continuous monitoring of streambed sediment height of a waterway. *The Science of The Total Environment*, 808, 152164. <https://doi.org/10.1016/j.scitotenv.2021.152164>
- [17] Miller, S. A., Webber, J. S., Jastram, J. D., & Aguilar, M. F. (2023). Using high-frequency monitoring data to quantify city-wide suspended-sediment load and evaluate TMDL goals. *Environmental Monitoring and Assessment*, 195(11), 1372. <https://doi.org/10.1007/s10661-023-11905-3>

- [18] Minella, J. P. G., Merten, G. H., Reichert, J. M., & Clarke, R. T. (2007). Estimating suspended sediment concentrations from turbidity measurements and the calibration problem. *Hydrological Processes*, 22(12), 1819–1830. <https://doi.org/10.1002/hyp.6763>
- [19] Morera, S., Condom, T., Crave, A., Steer, P., & Guyot, J. (2017). The impact of extreme El Niño events on modern sediment transport along the western Peruvian Andes (1968–2012). *Scientific Reports*, 7(1), 11947. <https://doi.org/10.1038/s41598-017-12220-x>
- [20] Nones, M., & Guo, C. (2025). Remote sensing as a support tool to map suspended sediment concentration over extended river reaches. *Acta Geophysica*, 73(5), 4655–4668. <https://doi.org/10.1007/s11600-025-01638-x>
- [21] Nord, G., Michielin, Y., Biron, R., Estèves, M., Freche, G., Geay, T., Hauet, A., Legouët, C., & Mercier, B. (2020). An autonomous low-power instrument platform for monitoring water and solid discharges in mesoscale rivers. *Geoscientific Instrumentation, Methods and Data Systems*, 9(1), 41–67. <https://doi.org/10.5194/gi-9-41-2020>
- [22] Paulista, R. S. D., Almeida, F. T. de, Souza, A. P. de, Hoshide, A. K., Abreu, D. C. de, Araújo, J. W. da S., & Martim, C. C. (2023). Estimating Suspended Sediment Concentration Using Remote Sensing for the Teles Pires River, Brazil. *Sustainability*, 15(9), 7049. <https://doi.org/10.3390/su15097049>
- [23] Perks, M., Warburton, J., Bracken, L. J., Reaney, S., Emery, S. B., & Hirst, S. (2017). Use of spatially distributed time-integrated sediment sampling networks and distributed fine sediment modelling to inform catchment management. *Journal of Environmental Management*, 202, 469–478. <https://doi.org/10.1016/j.jenvman.2017.01.045>
- [24] Rasmussen, T. J., Ziegler, A. C., Rasmussen, P. P., & Stiles, T. C. (2006). THE VALUE OF CONTINUOUS TURBIDITY MONITORING IN TMDL PROGRAMS. https://pubs.usgs.gov/misc/FISC_1947-2006/pdf/1st-7thFISCs-CD/8thFISC/Session%2011C-4_Rasmussen.pdf
- [25] Solano-Rivera, V., Geris, J., Granados-Bolaños, S., Brenes-Cambronero, L., Artavia-Rodríguez, G., Sánchez-Murillo, R., & Birkel, C. (2019). Exploring extreme rainfall impacts on flow and turbidity dynamics in a steep, pristine and tropical volcanic catchment. *CATENA*, 182, 104118. <https://doi.org/10.1016/j.catena.2019.104118>
- [26] Song, G., Jiang, Y., Lei, X., & Zhai, S. (2025). Measurement of Suspended Sediment Concentration at the Outlet of the Yellow River Canyon: Using Sentinel-2 Images and Machine Learning. *Remote Sensing*, 17(14), 2424. <https://doi.org/10.3390/rs17142424>
- [27] Tamás, E. A., Vas, L. T., & Tóth, P. (2025). Turbidity probes for surrogate suspended sediment monitoring on large rivers, Hungary (pp. 626–633). <https://doi.org/10.1201/9781003475378-91>
- [28] Villa, A., Fölster, J., & Kyllmar, K. (2019). Determining suspended solids and total phosphorus from turbidity: comparison of high-frequency sampling with conventional monitoring methods. *Environmental Monitoring and Assessment*, 191(10), 605. <https://doi.org/10.1007/s10661-019-7775-7>
- [29] Wang, J., Lu, X., Liew, S. C., & Zhou, Y. (2009). Retrieval of suspended sediment concentrations in large turbid rivers using Landsat ETM+: an example from the Yangtze River, China. *Earth Surface Processes and Landforms*, 34(8), 1082–1092. <https://doi.org/10.1002/esp.1795>
- [30] Wang, Y., Rajib, S. M. S. M., Collins, C. D., & Grieve, B. (2018). Low-Cost Turbidity Sensor for Low-Power Wireless Monitoring of Fresh-Water Courses. *IEEE Sensors Journal*, 18(11), 4689–4696. <https://doi.org/10.1109/jsen.2018.2826778>