Cumulative ecological impacts of river sand mining under weak environmental governance in Indonesia

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ARTICLE INFO	ABSTRACT
	River sand and gravel extraction is a significant pressure on tropical rivers, yet links between governance and ecological outcomes are under-measured. We assessed East Lombok, Indonesia (2019–2025) with a Before-After/Control-Impact approach, combining field water quality and macroinvertebrates with Sentinel-2 land- cover change, RUSLE erosion modeling, and a site-level Governance Intensity Index (permits, inspections, sanctions/closures, revegetation). Turbidity (30–80 NTU compared with 10–30 NTU) and TSS (20–60 mg/L compared with 5–20 mg/L) were elevated in mined reaches relative to upstream/control reaches, and dissolved oxygen was 2–3 mg/L lower during monsoon flows. Remote sensing revealed 10–20% riparian vegetation loss and 15–30% bar expansion; RUSLE predicted a 10–25% increase in erosion risk at the catchment scale. Biotic responses were consistent: Shannon diversity decreased from ~2.0–2.5 to ~1.0–1.5, and EPT richness from 8–12 to 3–5 taxa downstream of extraction. More robust governance (higher index scores) mitigated—although not entirely—the magnitude of effect sizes for turbidity/TSS and loss of biodiversity. These results demonstrate cumulative seasonal effects that are conditioned by local governance implementation capacity, particularly enforcement consistency and post-extraction management. Existing policy instruments (licensing, riparian buffers, and post-extraction restoration) can ameliorate degradation when uniformly applied. We offer practical monitoring and management advice to help bring local governance in tropical sand-mining rivers in line with ecological protection.

1. Introduction

Sand and gravel mining in river channels, mainly small- to medium-scale, now ranks among the most pervasive human impacts on tropical river systems. While the sector supports livelihoods and local construction supply chains, the repeated extraction of bed material, together with the removal of riparian vegetation, alters sediment transport, encourages sediment deposition, and fragments habitats utilized by aquatic biota (Dennis et al., 2025; Kashvi & Dar, 2025; Khaustov & Amini, 2025). These effects cascade through various processes including increasing total suspended solids (TSS) and turbidity, which limits light availability and availability to the base of the aquatic food web changing aquatic communities to more tolerant taxa as DO, pH and conductivity vary; enhancing bar formation and bank erosion via excess sediment delivery; and destabilizing banks through riparian cover loss, a significant source of organic matter and a provider of thermal buffering (Allan et al., 2021).

Even though the mechanisms have been well articulated, empirical studies grounded in such evidence are rare in many developing countries where discourses of governance and ecological realities continue to be structurally misaligned. For this reason, Indonesia is an especially instructive case for such a synthesis. Indonesia's national mining law differentiates between minerals and rocks and—at least on paper— attempts to strike a balance between the exploitation of resources and protection of the environment and welfare of the community (Nasir et al., 2023; Apritania & Saputri, 2025). The capacity to control river sand mining at the local level is limited, and the activities of extraction are dispersed in the space involving a

large number of small producers working in several reaches of the river, which hinders monitoring, oversight, and control of their combined ecological effects.

Sediment delivery, water quality, and riparian structure may be affected from the reach to the catchment scale, even if the operations are those that would be considered trivial. In this regard, governance intensity is an important intervening factor determining the outcomes of mining pressures, and in turn, whether or not it results in manifest ecological disturbance, and not just a passive institutional background variable. Despite extensive reports on the biophysical consequences of river sand mining, many empirical studies continue to give relatively "benign" conclusions as a result of limitations in observational design and causal inference. Global reviews reveal that the sand crisis is not an environmental problem but a governance issue, characterized by weak regulation, sporadic enforcement, and widespread illegal extraction that systematically evades official statistics. In this case, ecological pressures may continue to be statistically underdetected, not because there are no impacts, but because they are institutionally obscured (Filho et al., 2021; UNEP, 2022).

Local authorities and administration data confirm this pattern. In East Lombok (NTB Province), 37 actors, individuals, and forms of partnerships and companies operate on the rivers and on the floodplains. None of these permit-holding actors were full permit holders as of the 2024 record, suggesting that environmental pressures are escalating unchecked by means of restoration, monitoring, or enforcement (Saputra et al., 2023). Among the hydrologic and ecological consequences: Turbidity spikes with monsoon flows, bars grow and are stripped of vegetation, riparian vegetation retreats, and all these factors combine to harm aquatic life. These ecological reactions suggest to us that they are a product not only of hydrological forcing but also of the limits of governance to stem sediment mobilization and habitat disruption. A host of studies have documented that sand and gravel extraction, predominantly from tropical rivers, leads to geomorphic and ecological degradation through bed-material extraction, by removing vegetation, and by incising channels (Koehnken et al., 2020).

Several studies have reported that downstream ecological impacts of sand mining are not consistently detectable. Nonetheless, such conclusions are often drawn on the basis of short-term monitoring that does not allow for the consideration of accumulated geomorphic change and sediment transfer over hydrological cycles. In monsoonal rivers, total suspended solids (TSS) and turbidity exhibit highly seasonal and interannual patterns due to extreme precipitation and flood events. Therefore, designs that cover only one season or that are of short duration may risk interpreting natural hydrological fluctuations as a lack of human-induced influence, and thereby weakening inferential power (Bittner et al., 2021; Kumar et al., 2023; Stevenson et al., 2024).

Mineral sand mining, reclamation, and spatial protection are regulated in Indonesia under the Law No. 3/2020; GR No. 96/2021 and its 2024 revision; Ministerial Regulation PUPR No. 28/2015 concerning riparian buffers; and NTB Provincial Regulation No. 34/2019. However, local authorities are frequently powerless to enforce, and formal legal requirements overly burden local capacity, which leads to governance voids where ecological strain can continue to exist and undermines the capacity to control the rate of extraction, spatial placement, and temporal scheduling.

In an effort to separate the effects of mining from natural hydrological variation, studies are more frequently employing Before–After/Control–Impact (BACI) or Upstream–Impact–Downstream designs (Smokorowski & Randall, 2017). Although these methods work well to separate the biophysical signals, in most applications, the physical and biological responses are considered without explicitly questioning how the term of governance affects the size and persistence of the detected impacts. In situ parameters (TSS/turbidity, DO/pH/EC/BOD/ COD, concentrations of Fe and Mn) combined with macroinvertebrates (H′, J′, EPT richness) and remote sensing (Sentinel-2 land-cover change) provide the possibility to evaluate river health at multiple scales and, coupled with governance indicators, to investigate governance-driven ecological results. The Revised Universal Soil Loss Equation (RUSLE) integrates an estimation of erosion risk at the catchment scale by factors of rainfall erosivity (R), soil erodibility (K), slope (LS), cover (C), and support practice (P). These technical approaches are compatible with national reclamation and riparian protection requirements and may open the way for adaptive governance (Boeing et al., 2022; Wang et al., 2023).

Although the Before–After Control–Impact (BACI) design is often considered a powerful standard in environmental impact assessment science, methodological literature warns that its strength of inference is highly dependent on the representativeness of control sites, the amount of pre-impact data, and that temporal replication should be consistent. When these conditions are not met, BACI frameworks may collapse into quasi before–and-after comparisons that yield biased estimates of impact magnitude and persistence (Smokorowski & Randall, 2017).

Global research shows that ecological effects are shaped by the strength and stability of governance. Routine monitoring and enforcement of buffers and revegetation after mining correlates with less steep increases in suspended sediment/turbidity and greater macroinvertebrate community resilience. In monsoonal systems, timing mining activities with hydrologic regimes—ceasing extraction during high flows and/or sensitive life history stages—is commonly cited as a way to lessen impacts. Yet to date, no studies have empirically examined whether such governance leads to discernible ecological moderation in Indonesia. The majority of studies are still qualitative or single-season, limiting the ability to draw causal inferences. This disconnect is even more clear in tropical riverine ecosystems, where incremental-scaled extraction and disjunct governance make it difficult to draw causal inferences between governance capacity and ecological outcomes.

Consequently, this research integrates multi-year (2019–2025) BACI data—combining water-quality, biodiversity, land-cover, and governance indicators— to examine how variations in governance intensity are associated with differences in ecological degradation in East Lombok's sand-mining rivers.

Such constraints are especially severe in the case of river sand mining, where administratively designated "control" sites are frequently subjected to illegal mining or disturbances indirectly related to them in the upstream areas. Officially permitted extraction volumes and lar scientific estimates of sediment removal in the Mekong Delta provide evidence for a massive mismatch, suggesting that administrative control status is not a reliable indicator of ecologically undisturbed conditions. Under such circumstances, BACI-based contrasts may underestimate governance-mediated impacts rather than reflect genuine ecological stability (Millimet & Alix-Garcia, 2020; Yuen et al., 2024).

This is a study of four fundamental questions:(RQ1) What are the differences in water-quality parameters (TSS, turbidity, DO, pH, EC, BOD/COD, Fe–Mn) among upstream, impact, and downstream sites relative to independent controls during 2019–2025? (RQ2) Do riparian-cover reduction and erosion-risk modeling (RUSLE) show a trend of increase near mined reaches compared to controls? (RQ3) Do metrics of macroinvertebrates (Shannon diversity (H′), evenness (J′), and EPT richness) decrease downstream of extraction? (RQ4) Does the level of governance (a composite based on permits, inspections, reclamation, and adaptive enforcement) moderate the impact on ecology?

Correspondingly, we expect that: (H1) TSS and turbidity will be elevated and DO depressed in the impacted/downstream reaches, more so during monsoons; (H2) Loss of riparian vegetation and bar expansion will be concentrated near mining access points, augmenting erosion hazards; (H3) Diversity of macroinvertebrates and EPT richness will decrease in impact/downstream reaches; and (H4) We expect that the ecological effects will be somewhat but not completely mitigated in regions of greater governance strength.

These predictions are consolidated in the conceptual model shown in Figure 1, which describes that sediment dynamics, water-quality responses, and-biotic integrity in river sand-mining systems are influenced by policy and governance. Figure 1. Conceptual model depicting the tradeoff between policy instruments and governance intensity at the level of ecological outcomes in river sand mining systems. The model combines licensing, inspection, and reclamation processes with sediment dynamics, water quality responses, and biotic integrity, and directs the BACI-based empirical investigation carried out in this study.
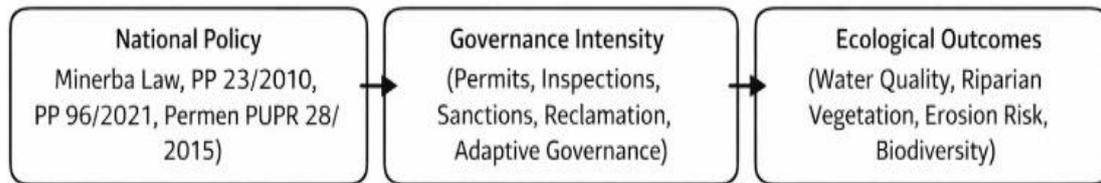

Fig1. Policy – Governance – Ecology interaction in River sand mining.

Source: Authors' own elaboration based on Law No. 3/2020 and GR No. 96/2021.

Figure 1. Conceptual framework illustrating the interaction between policy instruments, governance intensity, and ecological responses in river sand-mining systems. The framework combines the licensing, inspection, and remediation processes with sediment transport, water quality responses, and biotic integrity, and serves as a roadmap for the BACI-based empirical assessment presented in this study

2. Methods

2.1 Study area and designs

This study was conducted in East Lombok, West Nusa Tenggara Province (NTB), Indonesia, a semi-humid tropical area within the monsoonal hydrological system and subject to 1,600–2,000 mm mean annual precipitation. The relief is a volcanic highland, which is dissected by the Rinjani and Labuhan rivers to the lowlands to the east and west, respectively, with steep river headwaters and low-gradient alluvial plains subjected progressively to small-scale sand and gravel mining. Seasonal variation in flow: wet season (Nov–Apr) and dry season (May–Oct), which restricts the sediment processes and turbidity levels (Li et al., 2024). Sand and gravel mining takes place mainly in the floodplain stretches by mechanical excavation and dredging. For the year 2024, a total of 37 operators were found in the administrative data; these were mostly small-scale and semi-licensed. These environments constitute accumulative-stressor scenarios in which governance-ecology relationships can be tested.

Field studies and remote sensing analyses employed a Before–After/Control–Impact (BACI) design during 2019–2025. The sites were established at Upstream (U), Impact (I), Downstream (D), and Control (C) locations; the latter comprised two sites (the two control sites were very similar in terms of physiography and land use). Sampling was performed in campaigns in the dry and wet seasons. This quasi-experimental design separates the mining signal from background hydrologic variability and accounts for spatial autocorrelation (Zhang et al., 2023).

The present study uses a multi-method approach that enables us to analyze complex interactions at a biophysical and institutional level among the impacts of river sand mining. The integration of field-based water quality data, biological metrics, remote sensing, erosion modeling, and governance evaluation was intentional to prevent over-dependence upon one line of evidence. Such triangulation is required in monsoonal tropical rivers where short-term hydrologic variability may mask cumulative anthropogenic signals if they are interpreted with a single method or temporal snapshot. By combining infrastructure monitoring and management based on BACI design with governance indicators and spatial analysis, this design brings more power to causal inference in terms of intensity of regulation functioning as a moderator of observed ecological outcomes, rather than simply characterizing the biophysical degradation.

2.2 Data collection and analysis

Water-quality monitoring provided turbidity by in-situ measurement, TSS, DO, pH, EC, BOD, and COD were determined by using calibrated YSI ProDSS meters, and by laboratory analyses, including gravimetric and titrimetric methods, as per APHA (Abida et al., 2022). Levels of Fe and Mn were determined by atomic absorption spectrophotometry to assess possible geogenic mobilization. Two samples per reach were paired to allow BACI comparisons across years.

Benthic macroinvertebrates were sampled biologically with a standardized 500 μm Surber sampler in riffle habitats. Organisms were identified to the genus or family and summarized by Shannon diversity (H′), evenness (J′), and EPT richness - indicators that are sensitive to sediment and oxygen stress. These metrics provided biological evidence complementing physicochemical shifts. Riparian vegetation was assessed using 20 × 20 m transects to quantify canopy cover, disturbance, and composition. Hemispherical photography was used to estimate canopy closure.

Remote-sensing processing was performed on a multi-temporal (2019–2025) dataset composed of 10 m Sentinel-2 (L2A) images. Atmospheric correction was done using Sen2Cor, and a supervised classification was used to distinguish forest/shrub, agriculture, bare bar, and water bodies. The Normalized Difference Water Index (NDWI) was used to detect water bodies, while red–NIR ratios were applied to derive surface turbidity (Zhang et al., 2023). Loss of riparian cover and bar expansion adjacent to extraction sites were quantified by means of change-detection analysis. Erosion modeling: The modeling of A was based on the Universal Soil Loss Equation (USLE) model as modified in the revised model (RUSLE) as follows: $A = R \times K \times LS \times C \times P$. Rainfall erosivity (R) was calculated based on precipitation data from CHIRPS; soil erodibility (K) was based on data from SoilGrids; slope length (LS) was derived from SRTM DEM (30 m); cover (C) was based on land use/land cover classification of Sentinel-2 data; and support-practice (P) was obtained from field observations of reclamation or erosion-control structures (Schultz & West, 2020). Outputs were resampled to 30 m resolution to identify sub-catchments with elevated sediment risk. A Governance Intensity Index (GII) quantified local compliance with national laws (permits, inspections, penalties, remediation). The indicators were normalized to a 0–1 scale and averaged using equal weights to derive the Governance Intensity Index (GII). The equal weighting was not to convey that all the governance dimensions should be considered equally, but instead because there is no empirically defensible way to assign different weights to the components of enforcement in this regard (Medhioub et al., 2018). Adding penal weights in the absence of strong empirical evidence would be tantamount to introducing researcher discretion for the sake of researcher discretion, particularly in governance arenas where the administrative records are incomplete and uneven.

The Governance Intensity Index (GII) was built to measure local enforcement capacity, not just the existence of formal rules. Four facets were considered: (1) permit compliance, (2) inspection frequency, (3) sanctioning and closure actions, and (4) post-extraction remediation and revegetation. These dimensions were chosen based on the governance literature that highlights enforcement, monitoring, and adaptive responses as the primary influencers of environmental outcomes, especially in the context of resource extraction.

The choice of water quality parameters (TSS, turbidity, dissolved oxygen, pH, EC, BOD/COD, Fe–Mn) and metrics for macroinvertebrates (Shannon diversity, evenness, and EPT richness) represents a conscious selection of parameters that were ecologically sensitive to sediment disturbance and operational feasible in weak monitoring regimes. Other metrics (such as nutrient speciation or fish assemblages) may offer alternative views, but the omission of these is not an analytical oversight, and indeed is a purposeful consideration of indicators that have repeatedly been demonstrated to be responsive to sediment-driven stress and governance-driven variation in tropical river systems (Cineas & Dolédec, 2024).

Normalization and straightforward averaging were chosen over more elaborate aggregation methods (e.g., principal component analysis, or weighted indices) because the goal of the GII is to foster interpretability and transparency and not to maximize statistical efficiency. Since the index serves as a moderating variable rather than a predictive or latent variable, this method facilitates a more explicit connection between specific governance actions and ecological responses. Yet, the authors acknowledge that some subjectivity and potential bias linked to the availability of data and the qualitative nature of enforcement records may still exist in GII. It is a limitation that is explicitly taken into account in the interpretation of results, and the results are presented as suggestive moderation effects and not as definitive causes of attribution.

The Governance Intensity Index (GII) reflects the ability of enforcement to translate into concrete administrative actions (permits, inspections, sanctions, and post-extraction remediation) and not the latent quality of institutions. Although this process does increase transparency and makes the study more replicable, it is at the expense of informal practices, political negotiation, and discretionary tolerance that shape enforcement results on the ground. Therefore, the GII scores are best viewed as a measure of relative enforcement effort, rather than a complete measure of governance effectiveness, in line with previous governance-monitoring models (Armitage et al., 2007; Schultz & West, 2020).

Turbidity and land-cover measures from remote sensing are influenced by the atmosphere, sensor saturation with very high sediment loads, and spectral confusion in shallow waters or waters mixed with vegetation. Therefore, Sentinel-2 results were not considered as absolute values of sediment concentration but as indicators of relative spatial variation. Hence, they serve exclusively as complementary rather than determinative analyses, corroborating the field-based observations through spatial consistency rather than replacing in-situ measurement (Caballero et al., 2018).

2.3 Integration and validation

All data were processed with ArcGIS 10.8 and R 4.3. Generalized linear mixed-effects models (GLMMs) were used for each indicator to assess ecological responses to period (early 2019–2021 vs. late 2022–2025) and impact status (control vs. mined) as fixed factors, with site included as a

random factor. The interaction term (period × Impact) described the size of the BACI effect. (Li et al., 2024). Model assumptions were tested for homoscedasticity and normally distributed residuals. Pearson correlations were used to test the relationships between GII and ecological deltas (ΔTSS, ΔDO, ΔH′, Δ EPT). Spatial intersections were used to identify overlaps between high erosion risk (RUSLE > 75th percentile) and riparian loss > 15 %.

The triangulation of data from the field, remote sensing, and governance helped to enhance internal validity. Repeating patterns of elevated TSS/turbidity, depressed DO, increased erosion, and reduced biodiversity were taken as strong evidence of mining impacts. In contrast, there was divergence in effect size (ΔTSS, H′) among the high-governance sites (moderating effect of regulatory enforcement), with such smaller effect sizes (lower ΔTSS, higher H′) also suggesting the presence of moderating factors.

The geospatial products were validated using 20 ground control points per year, yielding a total accuracy of > 88% (Kappa ≥ 0.82). Such a co-evolutionary multi-line of evidence method allows for biophysical and river-ecosystem institutional drivers to be quantified and provides a template that can be adapted in other high sediment-yielding tropical catchments under surrounding aggregate-mining pressures.

The temporal partitioning of observations into early (2019–2021) and late (2022–2025) stages in time is an analytically required simplification and does not imply a strict separation in conditions of pre-impact and impact-intensive extraction. Pressure on mining and governance enforcement steadily developed, while hydrological extremes fluctuated intra-annually. Therefore, the period contrasts can smooth out momentary enforcement fluctuations and episodic sediment pulses. This pooling does give up some granularity of event attribution for the sake of better interpretability and statistical robustness, a tradeoff common to those working in establishment river monitoring studies. (Wang et al., 2023).

This temporal partitioning allows the BACI interaction term (Period × Impact) to reflect not only biophysical change over the course of time but also changes associated with changing governance intensity. Without this separation, interpreting the effects of BACI would risk confounding hydrological variability with changes in governance. The authors therefore emphasize that interaction effects should be interpreted cautiously as indicative of governance-mediated moderation rather than strict causality.

Despite the strengths of the multi-year Before–After Control–Impact (BACI) framework applied in this study, its inferential capacity remains conditional. Although control sites were chosen to reduce the direct influence of mining, full ecological isolation is not possible in river systems impacted by matrix sediment transport, upstream disturbance, and sporadic illegal extraction. As has been noted in methodological critiques of BACI, partial exposure of control sites can diminish estimated effect sizes and bias results toward a conservative interpretation. Therefore, the BACI interaction effects presented here should be considered as "minimum" estimates of cumulative ecological impact and not absolute levels of degradation.

3. Results and Discussion

3.1. Water quality and sediment dynamics

For all four rivers, turbidity and total suspended solids (TSS) were consistently higher at Impact (I) and Downstream (D) reaches than at Upstream (U) and Control (C) reaches (Fig. 1). In the wet season in the mined reaches, turbidity reached a maximum of 30–80 NTU and TSS a maximum of 20–60 mg L^{-1}, whereas in the control reaches it was 10–30 NTU and 5–20 mg L^{-1}. Dissolved oxygen (DO), in contrast, dropped from 6.0–7.5 mg L^{-1} (Control) to 3.5–6.0 mg L^{-1} (Impact). Results from GLMMs indicated significant BACI (before-after-control-impact) interactions for TSS, turbidity, and DO ($p <$ 0.05), evidencing that the mining-driven ecological signals were strongest in early high-flow monsoonal conditions (2019–2020) and could still be observed, though weakened, until 2025. EC and pH increased slightly in Impact sites while BOD$_5$ and COD varied more between years (Caballero et al., 2018). These seasonal differences imply that hydrological forcing during monsoonal high flow conditions enhances sediment entrainment from mined reaches, which elevates turbidity and oxygen loss above background variability.

Trace metals (Fe, Mn) sporadically exceeded freshwater standards during monsoon high flows—indicative of geogenic release mobilization from the riverbanks. These findings reaffirm H1 and suggest that the impact of sand mining on water quality is more severe during the monsoon peak due to sediment resuspension, reduced light penetration, and increased oxygen consumption. Likewise, in India and Malaysia, weak regulations have permitted sedimentation and oxygen deprivation in mining zones for years (Ahmed et al., 2023; Shah et al., 2025).

Since monsoonal high-flows promote sediment resuspension and mobilization within mining reaches, these seasonal pulses also lead to reductions in dissolved oxygen and the formation of physicochemical stressors. These stressors have been documented to disproportionately impact sediment-sensitive benthic taxa, notably EPT taxa, which are evaluated in the following subsection for their ecological responses. This seasonal synchronization of hydrology and sediment processes thus lends a mechanistic basis for turbidity responses and downstream biotic sensitivity.

3.2 Land cover and erosion risk

Analysis from remote sensing (Sentinel-2, 2019–2025) revealed substantial decline of riparian vegetation (10–20%) and bar expansion (15–30%) within 250 m around the active extraction sites, while the control reaches showed ≤ 5% changes (Fig. 2). The RUSLE simulations predicted higher LS × C factor values (i.e. catchments influenced by mining had an increase of +10–25% in LS × C, as compared to the controls with an increase of ≤ +10%). Hotspot analysis associated these changes with mid-catchment slopes that funnel sediment to extraction sites, particularly where clearing met cultivation frontiers.

In effect, these physical changes alter channel-side shading, thermal buffering, and inputs of organic matter, all factors that contribute to sediment pulses during peak flows. These results

are consistent with H2: that unmitigated extraction would increase erosion and geomorphic instability. Similar results across tropical systems suggest that channel incision, bar widening, and bank erosion are common consequences of in-channel aggregate mining (Chevalier et al., 2019).

Although the obligation of management has been regulated in the Government Regulation No. 96/2021 and Ministerial Decree No. 28/2015 of the Minister of Public Works and Public Housing, the post-mining rehabilitation and protection of the buffer zone in East Lombok is de facto non-existent (Park, 2024). The gap between legal standards and situational realities indicates a lack of enforcement and points to the need for a device for adaptively monitoring. This enforcement gap is empirically reflected in the spatial and temporal patterns of water-quality degradation observed across the study sites, as illustrated in Figure 2.
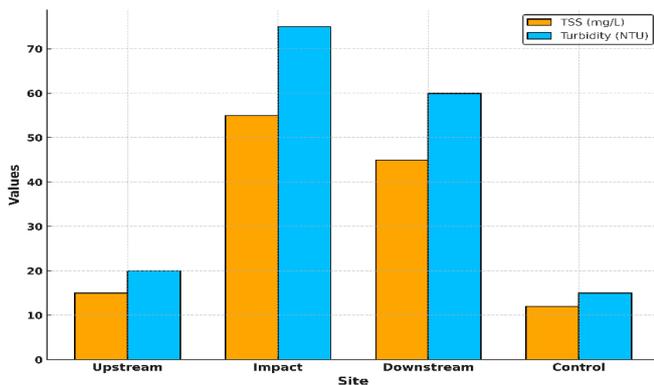

Fig 2. Water quality: TSS and turbidity across sites

Source: Processed from the BACI sampling conducted in East Lombok (2019–2025).

3.3. Biotic response and integrity of the ecosystem

The response of macroinvertebrate communities to perturbations in the physical and chemical environment was progressive. Shannon diversity (H′) for controls was 2.0–2.5, and for reach of impacts was 1.0–1.5, and evenness (J′) was 0.7 for controls and 0.4–0.5. EPT richness decreased from 8–12 taxa to 3–5 taxa, and Plecoptera was nearly absent at the severely mined sites (Cineas & Dolédec, 2024; Jam et al., 2018; Shamsuddin et al., 2025). These were the most severe declines in turbidity during moist-season missions. H3 was supported by significant Impact × Period interactions for H′ and EPT richness ($p < 0.05$) in GLMM analyses, which predicted a reduction of macroinvertebrate diversity as a function of cumulative extraction. Results are consistent with global reports from the Philippines and Southeast Asia, where EPT is regarded as a sediment and nutrient load-sensitive taxa (Igloria et al., 2024; Gulzar et al., 2025). Biological impairment parallels elevated TSS and loss of riparia exhibiting ecological sense among physicochemical, geomorphic, and living indicators (Baxa et al., 2020; Godspower et al., 2024). As biodiversity decreases, ecosystem processes such as nutrient retention, oxygen cycling, and habitat complexity are undermined, putting long-term river resilience at risk.

Macroinvertebrates are not considered here as comprehensive indicators of ecosystem condition, but rather as integrative indicators of combined physicochemical and habitat disturbance. Their value is rather in their sensitivity to sediment loading, oxygen deprivation, and habitat simplification - all of which are stressors related to sand-mining impacts. Although fish and top predators may have different responses, macroinvertebrate metrics provide a conservative and governance-relevant signal of ecological degradation that is less confounded by mobility and stocking effects.

3.4 Intensity of governance and moderation effects

The GII scores varied between 0.2 and 0.7, and thus the strength of enforcement was too heterogeneous to allow generalization. Extraction was partially permitted in high-governance areas (GII ≥ 0.6), where surveillance and periodic inspections of post-extraction revegetation were consistently implemented. These adjustments reduced the BACI response magnitudes for TSS and turbidity by 15–20%, and the decline in EPT richness was lessened to around 30%. By contrast, the low-governance (GII ≤0.3) region suffered an utter collapse: TSS/turbidity rose 50–60%, EPT richness dropped by more than 60%, and Plecoptera were almost completely extirpated downstream. These results confirm H4, that strong governance buffers ecological impacts—although it does not entirely prevent them. Gaps in enforcement, inadequate systems for inspections, and occasional reclamation lead to persistent sediment stresses. A comparative analysis of India and Malaysia confirms that the balkanization of institutions muddies the line between wanted and unwanted behaviors, and in the case of the Philippines, the domestication of bioassessment at the local level holds potential as an enforcement tool.

Although greater governance intensity is correlated with smaller magnitudes of ecological impact, these relationships should be interpreted as moderation effects, rather than as direct control. Governance is said to co-evolve with other contextual elements and cannot be boiled down to a single factor determining ecological outcomes. Other factors, such as site accessibility, size of mining operations, and local geomorphic conditions, may have an effect on the impact gradients reported, and this design does not allow for complete isolation of these effects.

3.5 Indicator concordance and causal inference

While BACI modeling, remote sensing, erosion estimates, and governance indicators combined enhance inference via triangulation, this study does not assert a proximate causal linkage between the intensity of governance and the ecological results. Governance is treated as a moderating system variable that conditions the visibility, persistence, and magnitude of ecological degradation rather than as a direct causal driver. Any interpretation of governance as a deterministic cause would exceed the inferential capacity of the present design.

Across datasets, the indicators were highly consistent. TSS and turbidity increases were also highly correlated with decreasing DO ($r = -0.73$, $p < 0.01$) and were spatially coincident with riparian loss > 10% and bar expansion > 25%.

RUSLE and remote-sensing results supported these findings: high-turbidity sections were associated with areas of land degradation and vegetation loss (ΔRUSLE > 20%). A similar pattern was apparent in biotic indices—sites with the most severe riparian loss also had the lowest H′ and EPT richness (Jam et al., 2025). This triangulation bolsters a single explanatory mechanism: mining releases sediment, alters water chemistry, induces geomorphic instability, and disrupts biotic integrity. Such corroboration enhances the reliability of inference in the context of changing tropical hydrology (Koehnken et al., 2020; Hassnain et al., 2022). Although statistically significant associations were observed between governance intensity and ecological indicators, these relationships should not be interpreted as strict causal effects. The BACI design balances out variability over time and space to improve inferences; however, attribution of causality is contingent on factors in the context that are not measured.

3.6 Policy and management implications

East Lombok is not presented as an exceptional case but as a representative manifestation of tropical river sand mining under fragmented governance, where formal regulatory frameworks coexist with limited enforcement capacity—a configuration common across Southeast Asia and other developing regions.

On the whole, the findings point to the persistence of the regulatory and enforcement gap. Background Indonesia possesses sufficient instruments domestically, such as the Mining Law 3/2020, Government Regulation 96/2021, and the Ministerial Regulation PUPR 28/ 2015; yet, there are still gaps in the application of these instruments on the ground in East Lombok. Adaptive governance must thus integrate seasonal moratoria, buffer-zone enforcement, mandatory reclamation, and integrated biomonitoring involving macroinvertebrates and remote sensing. Environmental progress, they show, has much more to do with steady enforcement on the ground – and the participation of local communities – than with new legislation (Armitage et al., 2017; Benjar et al., 2023). Including bioassessment in permit inspection cycles and releasing the data openly could create a synergy of administrative and ecological oversight (Aldabaibeh et al., 2026; Asif et al., 2023). To situate these findings within broader tropical estuarine systems, Table 1 provides comparative data from Indonesia, India, Malaysia, and the Philippines. The contrast shows how differences in enforcement of governance, inspection intensity, and ecological monitoring shape outcomes in the river sand-mining sector across regions. Thus, the East Lombok case is situated in a wider Southeast Asian pattern of strong legal regimes but uneven implementation at the ground level.

Table 1. Comparative ecological and governance outcomes of tropical river sand mining

Country/Region	System/ Reference	Water-quality signal	Biotic response	Governance features	Key takeaway
East Lombok, Indonesia (2019–2025)	This study	TSS 20–60 mg/L; Turbidity 30–80 NTU; DO reduced by 2–3 mg/L at Impact sites	Shannon diversity 1.0–1.5 (vs 2.0–2.5 control); EPT 3–5 taxa (vs 8–12)	GII 0.2–0.7; inspections and partial revegetation	Impacts are substantial in the wet season; higher governance moderates but does not prevent
India (Meghalaya, South Bengal)	(Padmalal & Maya, 2014)	Sharp increase in turbidity, Fe/Mn, and BOD/COD near extraction	Loss of sensitive taxa reported	Described as "unscientific mining," fragmented enforcement	Intense seasonal sediment pulses, weak governance
Malaysia (Langat River Basin)	(Ahmed et al., 2023)	Very high TSS and turbidity; stressful conditions for biota	Declines in diversity, tolerant taxa dominate	Regulations exist, but over-extraction persists	Example of severe ecological stress under weak enforcement
Philippines (Tambis River, Palompon, Leyte)	(Igloria et al., 2024)	Water-quality gradients detected by bioassessment	Biotic indices sensitive to BOD/nutrients	Emerging bioassessment protocols; governance integration ongoing	Demonstrates the value of linking biomonitoring to governance

Source: Padmalal & Maya (2014); Ahmed et al. (2023); Igloria et al. (2024)

4. Conclusion

This research reveals that small-scale river sand and gravel mining in East Lombok has resulted in measurable environmental damage to water, sediment, and biotic parameters. At Impact reaches, turbidity and TSS increased two- to three-fold, accompanied by lower dissolved oxygen and the loss of riparian vegetation and macroinvertebrate diversity. RUSLE analysis and Sentinel-2 images showed high erosion risk and bar growth close to the areas of extraction. The effects were dampened but not abolished by the intensity of regulation, as measured by permitting, inspection, and reclamation. Zones with intensified enforcement exhibited reduced BACI effect sizes for TSS and

higher Shannon diversity. These results reveal that ecological recovery depends not only on hydrological cycles but also on consistent governance and adaptive monitoring. Enhancing the enforcement of river-buffer regulations (PUPR 28/2015), institutionalizing bioassessment of macroinvertebrates, and requiring revegetation after extraction are key measures that will contribute to sustainable river-aggregate management in the monsoonal systems of Indonesia.

Statements and Declarations

Ethical considerations

The authors buried all ethical requirements in this work, including no plagiarism, no data fabrication or falsification, no

dual submission, and no preaching to the choir. The authors declare that all data and analyses presented, and all figures included in this manuscript, are original and have been created by the authors in accordance with the standards of research integrity.

Acknowledgments

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of interest

The authors declare no known financial or personal conflicts of interest that could have influenced the work reported in this paper.

Author contributions

Sam'an Abdul Madjid: Conceptualization, Funding acquisition, Field investigation.

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Evi Satispi: Validation, Writing – Technical editing.

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AI use declaration

During the preparation of this manuscript, AI-assisted language tools were used for linguistic refinement. All results were critically assessed and edited by the authors, and they are solely responsible for the content and the conclusions of this paper.

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