



Research Article

Composite Assessment of Sand Mining Impacts in a Hill River: The Langkaih River, Northeast India

Renthlei Zonunsanga¹, Benjamin Lalengliana Sailo^{1,*} , Laldinpuia¹,
Michael Lalnunpuia¹, Ralte Lalhmangaihzuale¹, Lalrinawma¹,
Jonathan Lalrinawma², Rosiamliana¹

¹Centre for Disaster Management, Mizoram University, Aizawl, India

²Department of Geography & Natural Resource Management, Mizoram University, Aizawl, India

Abstract

Sand mining in small, steep hill rivers remains poorly quantified despite rising global concern over aggregate-driven ecological degradation. This study develops an integrated, indicator-based framework to evaluate the environmental and socio-economic impacts of manual and mechanical sand mining along the Langkaih River, Mizoram, Northeast India—a transboundary hill river recently subjected to a ban on mechanized extraction. Water quality was assessed at upstream, active, and downstream sites using the Water Quality Index (WQI) and a novel Water Quality Impact Gradient (WQIG), combined with turbidity analysis and livelihood surveys. These datasets informed two composite indicators—the Sand Mining Vulnerability Index (SMVI) and an Integrated Sustainability Index (ISI)—linking environmental pressure, socio-economic dependence, and adaptive capacity. Results show that mechanical suction mining generated extreme turbidity plumes and WQI deterioration from “Poor” to “Unsuitable for drinking,” with a 470% WQIG increase and high vulnerability (SMVI $\approx$ 64). Manual extraction caused moderate, reversible impacts (WQIG = -29%), higher employment intensity, and greater overall sustainability (ISI = 0.91 vs. 0.27). The framework transparently differentiates mining methods by environmental and livelihood performance, supporting evidence-based regulation in data-limited hill systems. The findings provide a transferable model for sustainable sand governance to protect drinking-water security and riverine ecosystem health across Himalayan and tropical basins.

Keywords

Sand Mining, Socio-Economic Analysis, Water Quality, Ecological Impacts, Langkaih River

1. Introduction

Sand, as a foundational input to construction and infrastructure, has become a strategic development resource, but its extraction from river systems increasingly exposes deep tensions between growth and ecological integrity. Global assessments show that accelerating demand for construction

aggregates has transformed river sand mining from a local livelihood activity into a major driver of channel incision, habitat loss, water quality deterioration and social conflict [30, 32, 33, 43, 47, 49]. Emerging evidence from Asia and Africa further highlights how weak regulation and mechanised

*Correspondence: Benjamin Lalengliana Sailo (benjaminsailo004@gmail.com)

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extraction amplify environmental risk while concentrating economic gains, particularly in fragile or data-poor settings [10, 25, 26, 45]. Yet hill rivers, which differ markedly from large alluvial systems in gradient, morphology, hydrology, and community dependence, remain critically under-represented in this debate.

The Langkaih River in Mizoram, Northeast India, exemplifies these intertwined pressures. It has functioned as a principal source of construction-grade sand for much of southern Mizoram, supporting public infrastructure, private building and a network of local employment. At the same time, rapid expansion of mechanical suction dredging along confined, erosion-prone reaches has triggered visible bank failure, bed degradation, increased turbidity and declining aquatic life, reinforcing concerns raised in broader studies of unsustainable sand extraction [9, 22, 39]. In response to sustained advocacy by environmental groups and mounting field-based observations of ecological damage, the Government of Mizoram imposed a ban on sand mining in the Langkaih River on 9 May 2023, with particular emphasis on the destructive impacts of mechanised suction. This abrupt policy shift underscores a wider governance dilemma: how to safeguard vulnerable riverine ecosystems and drinking water sources without undermining construction needs, exacerbating livelihood insecurity, or displacing harmful practices to less regulated sites.

Despite growing recognition of a global “sand crisis,” three critical gaps constrain evidence-based decision-making for hill states like Mizoram. First, most empirical work in India and elsewhere focuses on large alluvial rivers, with limited attention to steep, narrow hill rivers where geomorphic sensitivity and community dependence may heighten risk [29, 43, 47]. Second, method-specific impacts of manual versus mechanical extraction are rarely quantified within a single river system using harmonised field data; as a result, regulatory debates often treat all sand mining as uniformly harmful or uniformly necessary. Third, few studies integrate water quality changes, livelihood benefits, infrastructure exposure and local adaptive capacity into transparent, operational indicators that can support differentiated licensing, spatial targeting and phased restriction of high-risk practices [19, 30, 36].

This study addresses these gaps through an integrated assessment of manual and mechanical sand mining along the Langkaih River. It combines physicochemical monitoring at upstream, at-site and downstream locations with an impact gradient approach, multivariate analysis, vendor-level livelihood and profitability surveys, and composite indices of sand mining vulnerability and sustainability. The novelty lies in four elements: (i) a direct empirical comparison of manual and mechanical extraction in a steep hill river context subject to an actual regulatory ban; (ii) the development of simple gradient-based indicators of water quality and turbidity that capture the spatial footprint of mining impacts; (iii) the construction of a Sand Mining Vulnerability Index that links

extraction pressure, environmental sensitivity, socio-economic exposure, infrastructure risk and adaptive capacity; and (iv) an Integrated Sustainability Index that evaluates whether method-specific livelihood gains justify documented ecological costs. Together, these tools generate a transferable, decision-oriented framework for aligning sand mining governance in hill river systems with the principles of sustainable development and environmental justice.

2. Literature Review

The global construction boom has caused an unprecedented demand for sand, making sand mining a critical activity worldwide [10, 47]. River sand mining, in particular, is driven by the need for concrete and other construction materials, with extraction rates having tripled in the last two decades and reaching up to 40 billion tonnes per year [10, 22, 26]. Critical hotspots for extraction include China, India, and various African countries, where both legal and illegal mining are widespread [25, 37].

The intensification of in-stream sand mining in developing regions has provoked widespread concerns regarding both environmental degradation and socio-economic challenges. Sand and gravel extraction, while serving critical roles in construction and local economies, often leads to severe disturbances in river ecosystems and communities [20, 54].

Recent studies document the loss of in-stream habitats and biodiversity due to excessive sand mining, with implications for riverine vegetation and aquatic species [20, 29]. Unregulated sand extraction alters the hydraulic regime of rivers, depletes groundwater, reduces water retention capacity, and accelerates bank erosion [34]. In India, in-stream mining has resulted in significant changes in channel morphology, deteriorated water quality, and the collapse of riverbanks, which together threaten long-term ecosystem services.

Sand mining has been shown to significantly alter river morphology, cause riverbed lowering and widening, and contribute to bank and dune erosion [48]. For example, in Southern Monterey Bay, USA, intensive sand mining was responsible for about half of the yearly average dune volume loss and long-term beach erosion until the cessation of mining reduced these rates [48]. Similarly, in India and sub-Saharan Africa, uncontrolled extraction has led to sediment starvation, altered sediment transport, and changes in channel morphology, with effects such as riverbank collapse, bedrock exposure, and increased coastal erosion [10, 25, 26].

Biological consequences of sand mining are profound, with reductions in biodiversity extending from aquatic organisms to riparian flora and fauna. This loss is attributed to the destruction of habitats, increased water turbidity, and disruption of ecosystem services [39]. In Dongting Lake, China, sand mining activities resulted in habitat loss and range contraction for the critically endangered Yangtze finless porpoise, providing the first empirical evidence that unregulated sand extraction can alter the distribution of large

freshwater fauna [22]. In Rwanda, sand mining transformed riverine ecosystems, increasing wetland insects and creating mosquito breeding sites, thereby potentially increasing malaria risks [25].

The chemical environment also suffers, with pollution, acid mine drainage, and increased concentrations of toxic heavy metals and ions degrading water quality and threatening both human and wildlife health [5, 16, 38]. Sand mining also deteriorates water quality by increasing turbidity and introducing pollutants, which negatively affects both aquatic life and human populations [18]. These impacts are often cumulative and difficult to quantify due to widespread, fragmented, and largely unregulated mining practices.

While sand mining provides local employment and stimulates economic activity, studies highlight the short-lived nature of these benefits when set against the environmental and social costs [26]. Communities dependent on rivers for agriculture, drinking water, and fisheries report declines in productivity and resource quality as mining intensifies. In the Kulsi River (Assam), indiscriminate extraction led to conflict between local miners and agriculturalists, increased livelihood vulnerability, and deteriorating health conditions due to dust and contaminated water. However, these gains are often short-lived and come at the expense of environmental degradation, public health, and loss of ecosystem services [25, 42].

International studies confirm that these patterns are not unique to India. In Nigeria and Kenya, unregulated in-stream sand mining is linked to erosion, flooding, and the loss of arable land, all of which undermine socio-economic stability [1, 27]. In India, sand mafias have territorialized extraction zones through networks involving politicians, police, and contractors, making enforcement of regulations difficult [37].

Recent reviews urge a balance between economic development and environmental sustainability [20, 34]. Recommendations include stricter regulation, river mapping, and involving local communities in decision-making processes [43]. The literature underscores the urgent need for sustainable sand management through improved regulation, technological innovation (such as manufactured sand, or M-

sand), community participation, and science-based policies [10]. Countries like India and Malaysia have begun to develop guidelines to balance economic, environmental, and social interests, but enforcement remains a challenge [10, 26]. Researchers emphasize the need for sustainable management strategies—including stricter regulations, restoration of mined areas, adoption of remote sensing for monitoring, and stronger community involvement [24, 45]. Only through integrated, science-based policy interventions can the trade-offs between economic benefit and environmental cost be balanced for future generations [24].

3. Methodology

This study applied an integrated field, laboratory, and analytical framework to compare the environmental, socio-economic, and sustainability implications of manual and mechanical sand mining along the Langkaih River, Mizoram, India.

3.1. Study Design and Sampling Sites

Two active in-stream sand mining reaches were selected to represent contrasting extraction practices:

- 1) Mechanical, Site 1 (Kanhmun): mechanised suction/dredging and truck-based extraction.
- 2) Manual, Site 2 (Luimawi): labour-intensive extraction using shovels and small equipment.

At each site, three sampling locations were established along the longitudinal profile (Table 1): (i) upstream of active extraction (ii) within the active mining zone, and (iii) downstream of the mining zone (cumulative impact reach). This design enabled method-wise comparison and evaluation of impact gradients along the river. All sampling was conducted during the post-monsoon period (October–November 2024), when flows are relatively stable and sand mining activity is high.

Table 1. Sampling Location of Each Site.

Site	Location	Type	Latitude (N)	Longitude (E)
Kanhmun	Kanhmun Above	Mechanized	24°14'38.00" N	92°17'39.11" E
Kanhmun	Kanhmun At Site	Mechanized	24°14'45.49" N	92°17'31.47" E
Kanhmun	Kanhmun Down	Mechanized	24°14'53.01" N	92°17'31.58" E
Luimawi	Luimawi Above	Manual	24°13'14.46" N	92°18'40.83" E
Luimawi	Luimawi At Site	Manual	24°13'27.36" N	92°18'48.70" E
Luimawi	Luimawi Down	Manual	24°13'25.52" N	92°18'32.70" E

3.2. Water Sampling and Laboratory Analysis

Surface water samples were collected from each location using pre-cleaned, sterilised polyethylene bottles. Bottles were rinsed with site water prior to collection. Samples were stored in insulated cool boxes and transported to the laboratory for analysis within 24 hours.

Analytical procedures followed Standard Methods for the Examination of Water and Wastewater (23rd ed.) [2] and BIS IS 10500:2012 [15], drinking water specifications for reference limits.

The following parameters were measured: pH, Electrical conductivity (EC), Total dissolved solids (TDS), Turbidity, Total alkalinity Measurements were taken using an Elico PE-146 multi-parameter water quality kit and standard procedures. Each parameter was measured in triplicate, and mean values were used for subsequent analysis. Analytical blanks and duplicate samples were included to ensure precision and quality control.

3.3. Water Quality Index and Impact Gradients (WQI, WQIG, TG)

Overall water quality at each location was evaluated using the weighted arithmetic Water Quality Index (WQI) following [14], widely applied and reviewed in subsequent literature [50].

For each parameter i :

$$q_i = \frac{C_i}{S_i} \times 100$$

where C_i is the observed concentration and S_i is the corresponding BIS permissible limit; and

$$W_i = \frac{1}{S_i},$$

scaled so that $\sum W_i = 1$. The WQI at each location was computed as:

$$\text{WQI} = \frac{\sum (q_i W_i)}{\sum W_i}.$$

To quantify longitudinal changes attributable to mining, impact gradient indices were defined using the upstream point at each site as reference:

Water Quality Impact Gradient (WQIG)

$$\text{WQIG} = \frac{\text{WQI}_{\text{loc}} - \text{WQI}_{\text{up}}}{\text{WQI}_{\text{up}}} \times 100,$$

Turbidity Gradient (TG)

$$\text{TG} = \frac{T_{\text{loc}} - T_{\text{up}}}{T_{\text{up}}} \times 100,$$

where WQI_{up} and T_{up} are upstream values at the same site. Positive values indicate deterioration; negative values indicate improvement or recovery. This relative-change formulation is consistent with gradient-based assessments in impact studies and facilitates comparison between manual and mechanical reaches [11, 50].

3.4. Socio-Economic Survey and Profitability Assessment

Socio-economic conditions and livelihood dependence on sand mining were examined through a structured questionnaire administered to nine sand vendors operating at the study sites. Vendors were identified in consultation with local sand mining committee members to capture active operations.

The survey recorded: Daily extraction volume ($\text{m}^3 \text{day}^{-1}$), Unit selling price (₹ per m^3), Number of workers employed, Diesel use and fuel expenditure, Equipment ownership and maintenance costs, Taxes, fees, and other operating costs.

For each vendor i :

$$\text{Revenue}_i = P_i \times Q_i,$$

where P_i is the unit price and Q_i is the extracted volume;

$$\text{Operating Cost}_i = C_{\text{labour},i} + C_{\text{fuel},i} + C_{\text{equipment},i} + C_{\text{tax},i} + \dots,$$

$$\text{Net Income}_i = \text{Revenue}_i - \text{Operating Cost}_i.$$

Profit margin (%) was computed as $(\text{Net Income}_i / \text{Revenue}_i) \times 100$. To explore how profitability relates to extraction scale, capital intensity, and mechanisation, a simple diagnostic model was specified:

$$\text{Net Income}_i = \beta_0 + \beta_1 Q_i + \beta_2 K_i + \beta_3 M_i + \varepsilon_i,$$

where K_i is capital investment and M_i is a binary variable (1 = mechanical, 0 = manual). This model is interpreted descriptively (given the small sample) to support comparison between methods, consistent with livelihood-focused analyses in extractive sectors [4, 23].

3.5. Sand Mining Vulnerability Index (SMVI)

To assess site-level vulnerability to sand mining impacts, a Sand Mining Vulnerability Index (SMVI) was developed as a composite indicator grounded in established vulnerability and sustainability assessment frameworks [19, 36]. The SMVI integrates five components, each scaled from 0 (least) to 100 (most):

- 1) *Hazard Pressure (HP)*: intensity of mining (e.g. truck trips $\text{km}^{-1} \text{day}^{-1}$; off-season mining, turbidity exceedance over guideline values, number/density of active pits).

- 2) *Environmental Sensitivity (ES)*: susceptibility of the river corridor, based on bank material, bank slope, and riparian vegetation condition.
- 3) *Socio-economic Exposure (SE)*: dependence of nearby communities on the river for drinking water, irrigation, fisheries and related uses, expressed as percentage of households.
- 4) *Infrastructure Exposure (IE)*: presence and proximity of critical infrastructure (e.g. water intakes, bridges, settlements, roads) within the active channel belt or immediate floodplain.
- 5) *Adaptive Capacity (AC)*: availability and reliability of alternative water sources, piped supply coverage, livelihood diversification, and perceived strength of local institutions; higher AC scores represent stronger capacity to cope and adapt.

Indicators for each component were derived from field observations, survey responses, and local records, and transformed to 0–100 scores using linear or categorical scaling. To incorporate the mitigating role of adaptive capacity, a site-level vulnerability index was defined as:

$$VI = \frac{HP+ES+SE+IE-AC}{4},$$

and an indicative risk index (without the adaptive capacity adjustment) as:

$$\text{Risk Index} = \frac{HP+ES+SE+IE}{4}.$$

Equal weights were applied for transparency, consistent with prior composite-index applications, while recognising that weights can be adjusted in future policy applications. This structure aligns with widely used environmental risk and livelihood vulnerability frameworks [30, 43].

3.6. Integrated Sustainability Index (ISI)

An Integrated Sustainability Index (ISI) was formulated to compare the overall sustainability performance of manual and mechanical sand mining by jointly considering environmental impact, economic returns, and livelihood benefits. The approach follows established composite-indicator and multi-criteria methodologies that normalise heterogeneous metrics and combine them with explicit weights [19, 36].

Indicator selection

For each method $m \in \{\text{Manual}, \text{Mechanical}\}$, three components were defined:

- 1) Environmental impact (E_m) – based on degradation in water quality between upstream and downstream

locations using Water Quality Impact Gradient (WQIG) and Turbidity Gradient (TG), consistent with evidence that turbidity and composite water quality are robust indicators of sand mining pressure [30].

- 2) Economic benefit (B_m^{eco}) – mean net daily income per vendor (₹ day⁻¹), derived from the profitability assessment.
- 3) Livelihood benefit (B_m^{liv}) – employment intensity, expressed as workers per 100 m³ of sand extracted, reflecting the distribution of benefits in line with triple-bottom-line sustainability assessments [35].

3.7. Normalisation Using Policy Benchmarks

All components were converted to dimensionless scores in [0,1] using fixed reference values rather than sample-dependent min–max scaling (OECD, 2008):

Environmental impact component

$$E_m = \min(1, 0.5[\frac{\max(0, WQIG_m)}{WQIG_{ref}} + \frac{\max(0, TG_m)}{TG_{ref}}]),$$

where $WQIG_{ref} = 500\%$ and $TG_{ref} = 600\%$ approximate observed worst-case gradients. Negative or zero gradients (recovery/no impact) are set to 0 so that $E_m = 0$ denotes no net deterioration and higher E_m indicates greater environmental pressure.

Economic benefit component

$$B_m^{eco} = \min(\frac{\bar{\Pi}_m}{\Pi_{ref}}, 1),$$

where $\bar{\Pi}_m$ is mean net daily income and $\Pi_{ref} = ₹20,000 \text{ day}^{-1}$ is a normative upper benchmark for small-scale river sand operations.

Livelihood benefit component

$$B_m^{liv} = \min(\frac{L_m}{L_{ref}}, 1),$$

where L_m is workers per 100 m³ and $L_{ref} = 20$ workers 100 m³ represents highly labour-intensive, locally beneficial extraction.

3.8. Weighting and Aggregation

Weights were selected to prioritise ecological protection while recognising economic viability and employment, consistent with recent guidance to internalise environmental externalities in extractive activities (Koehnken et al., 2020; Mishra et al., 2023):

$$w_{env} = 0.50, w_{eco} = 0.30, w_{liv} = 0.20, w_{env} + w_{eco} + w_{liv} = 1.$$

The raw ISI for method m is:

$$ISI_m = w_{eco} B_m^{eco} + w_{liv} B_m^{liv} - w_{env} E_m.$$

To obtain a bounded scale, ISI_m is linearly rescaled to:

$$ISI_m^* = \frac{ISI_m + 0.5}{1},$$

yielding $ISI_m^* \in [0,1]$. Values are interpreted as: <0.40 = Low/Unsustainable, $0.40-0.60$ = Marginal/Transitional, >0.60 = High/Relatively Sustainable. This benchmark-based ISI is fully reproducible and directly compatible with the accompanying WQIG/TG and livelihood datasets.

3.9. Study Area

The study was conducted along the River Langkaih in Mizoram, India (Figure 1), a region characterized by its dynamic riverine ecosystem and rapid economic changes. Originating near Sabual village in Tripura and flowing northward, the river delineates part of the border between Mizoram and Tripura. The Langkaih River, stretching approximately 85.43 kilometers, is vital for agriculture, fishing, and domestic use in the area. The villages of

Kanhmun and Luimawi, situated adjacent to the river, serve as the primary study sites. These communities rely on the river for their livelihoods, and sand mining has become a prominent economic activity. Kanhmun, with a higher population and greater number of households, exhibits a more intensive engagement in mining operations compared to Luimawi. The study area is further characterized by a tropical monsoon climate, with distinct dry and wet seasons that influence both the availability of sand and the operational feasibility of mining activities.

Geographically, the area features fertile plains and a network of tributaries that feed into the Langkaih River. The river's banks are prone to erosion—a process exacerbated by in-stream sand mining. The socio-economic fabric of the region is tightly interwoven with the river's natural resources; while mining provides immediate financial benefits and employment opportunities, it also poses risks to water quality and long-term sustainability. The study area, therefore, presents an ideal case for examining the dual impacts of sand mining on both environmental health and socio-economic development.

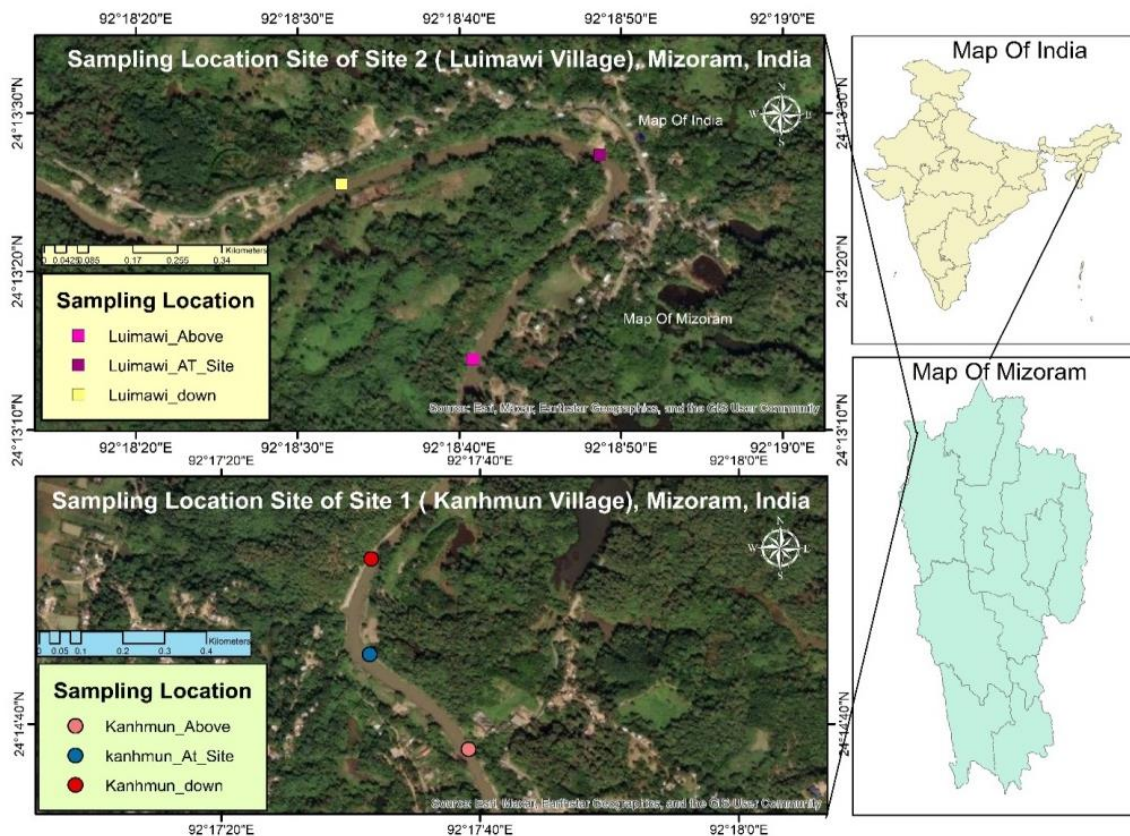


Figure 1. Location of Study Area, Kanhmun Site 1 (Mechanical Site), Luimawi (Manual Site).

4. Result

4.1. Physicochemical Water Quality: Manual vs Mechanical Sites

Water quality assessment across the two sand mining sites on the Langkaih River indicates a pronounced contrast between mechanical and manual extraction zones (Table 2). At Site 1 (mechanical), all sampling locations exceed the Bureau of Indian Standards (IS 10500:2012) turbidity guideline of 1 NTU, with values rising sharply from 9.17 NTU

upstream to 54.10 NTU at the extraction point and 64.00 NTU downstream. This escalation is accompanied by a deterioration of the Water Quality Index (WQI) from 141.01 (Poor) upstream to 680.50 and 804.48 at-site and downstream, respectively, both classified as “Unsuitable for drinking.” Although pH (7.85–8.16), EC (209–234 $\mu\text{S}/\text{cm}$), TDS (85–91 mg/L), and alkalinity (61.4–83.4 mg/L) remain within BIS permissible limits, the extreme WQI scores driven primarily by turbidity and aggregated pollutant load clearly signal severe localised degradation associated with mechanised sand extraction.

Table 2. Physicochemical Characteristics and Water Quality Index (WQI) across Sand Mining Sites in the Langkaih River.

	Location	pH	EC ($\mu\text{S}/\text{cm}$)	TDS (mg/L)	Turbidity (NTU)	Total Alkalinity (mg/L)	WQI Result	WQI Interpretation
Site 1 (Mechanical Site)	Upstream	8.16	234	91	9.17	61.4	141.01	Poor
	At Site	7.85	209	85	54.1	83.4	680.5	Unsuitable for drinking
	Downstream	8	220	87	64	64	804.48	Unsuitable for drinking
Site 2 (Manual)	Upstream	8.04	228	88	11.07	66	161.27	Poor
	At Site	8.18	224	88	14.34	66	204.39	Very Poor
	Downstream	8.16	215	82	6.95	62	113.89	Poor
BIS Standard (IS 10500:2012)		6.5 - 8.5	≤ 1500	≤ 500	≤ 1	≤ 200		
WQI Range		0-50 Excellent	51-100 Good	101 - 200 Poor	201 -300 Very Poor	>300 Unsuitable For Drinking		

In contrast, Site 2 (manual mining) exhibits a more moderated response. Turbidity remains elevated relative to the guideline at all points (11.07–14.34 NTU), yet the pattern differs markedly from Site 1. WQI at the upstream location is 161.27 (Poor), increases modestly to 204.39 (Very Poor) at the extraction point, and then improves downstream to 113.89, remaining within the “Poor” category. This downstream recovery, despite continued anthropogenic activity, suggests that the lower extraction intensity and non-mechanised methods at Luimawi impose less persistent disturbance on river water quality, allowing partial self-purification over a short spatial scale. Importantly, no sampling point at Site 2 crosses into the “Unsuitable for drinking” WQI class, unlike the severe impairment recorded at the mechanical site.

Comparative interpretation of both sites underscores that mining method and operational intensity are critical determinants of impact. Mechanical suction at Site 1 generates a steep impact gradient, converting water already classified as “Poor” into critically degraded, non-potable conditions immediately at and below the operation. Manual extraction at

Site 2, while not environmentally benign and still exceeding turbidity standards, is associated with a less extreme WQI response and demonstrable downstream quality recovery. These results provide quantitative evidence that unregulated mechanised sand mining substantially exceeds the local assimilative capacity of the Langkaih River, whereas controlled manual extraction exerts comparatively moderate, spatially constrained effects. This differential response forms a key empirical basis for the Integrated Sustainability Index (ISI) and supports stricter regulation or restriction of mechanical extraction in sensitive reaches. Overall, the WQI patterns confirm that method-specific regulation is essential to safeguard drinking-water security and ecosystem health in the Langkaih River corridor.

4.2. Water Quality Impact Gradient (WQIG) and Turbidity Response (TG)

Application of the gradient-based indices clearly differentiates the impacts of mechanical and manual sand

mining on water quality along the Langkaih River. WQIG was calculated as the percentage change in WQI between upstream and downstream locations relative to the upstream reference, while the Turbidity Response (TG) captured the corresponding relative change in turbidity. Both metrics use the upstream station at each reach as an internal control, isolating the specific footprint of sand extraction on longitudinal water quality.

At the mechanical site (Site 1, Kanhmun), WQI degraded sharply from 141.01 upstream (“Poor”) to 804.48 downstream (“Unsuitable for drinking”), yielding a WQIG of +470.5%, indicative of severe cumulative deterioration in overall

potability (Table 3). This response is driven primarily by intense turbidity loading: turbidity increased from 9.17 NTU upstream to 64.00 NTU downstream, resulting in a TG of +598.0%. Turbidity at and below the mechanical extraction zone substantially exceeded the BIS guideline (1 NTU), confirming a persistent plume of suspended sediment and associated contaminants extending beyond the active mining reach. These gradient values demonstrate that mechanised suction and truck-based disturbance generate not only localised disruption but a strong downstream propagation of impact, consistent with high-risk mining behaviour.

Table 3. Water Quality Impact Gradient (WQIG) and Turbidity Response (TG) for Mechanical and Manual Sand Mining Reaches.

Site / Method	Location Pair (Ref → Downstream)	WQI_upstream	WQI_downstream	WQIG (%)	Turbidity_upstream (NTU)	Turbidity_downstream (NTU)	TG (%)	Interpretation
Site 1 – Mechanical	Upstream → Downstream	141.01	804.48	+470.5	9.17	64.00	+598.0	Extreme deterioration; persistent impact
Site 2 – Manual	Upstream → Downstream	161.27	113.89	−29.4	11.07	6.95	−37.2	Net recovery; impacts remain assimilable

In contrast, the manual site (Site 2, Luimawi) exhibits a stabilising or recovering profile. WQI declined from 161.27 (“Poor”) upstream to 204.39 (“Very Poor”) at-site, but improved to 113.89 (“Poor”) downstream, producing an overall WQIG of −29.4%, i.e. a net downstream improvement relative to the upstream reference. Turbidity showed a modest rise from 11.07 NTU upstream to 14.34 NTU at-site, followed by a reduction to 6.95 NTU downstream, corresponding to a TG of −37.2%. The negative TG and WQIG values at Luimawi indicate dilution and self-recovery of the system below the manually worked reach, with no evidence of a persistent high-turbidity plume.

Taken together, the WQIG and TG metrics confirm that mechanical sand mining produces an acute, propagating degradation signal, while manual extraction remains within the assimilative capacity of this hill river under present intensities. These indices provide a robust, transparent basis for distinguishing method-specific risk and support the argument for stricter regulation or phase-out of mechanised suction mining, alongside conditional tolerance of low-impact manual practices subject to monitoring.

4.3. Socio-economic Characteristics and Profitability of Sand Mining

Analysis of the nine mechanised sand mining vendors

shows that riverbed extraction along the Langkaih provides highly profitable but capital-intensive income streams. Daily extraction volumes range from 25 to 60 m³ with selling prices between ₹444–₹510 per m³, generating individual revenues from ₹12,000 to about ₹28,000 per day. The average daily revenue is ₹21,333, against a mean operating cost of ₹7,644, yielding a mean net income of approximately ₹13,689 per vendor per day. This corresponds to an average profit margin of 63.2%, indicating that a substantial share of gross earnings is retained as profit.

Across vendors, profit margins remain consistently high (≈48–69%), despite differences in extraction volume and capital investment (Table 4). Vendors with moderate to high production (45–60 m³ day^{−1}) typically secure the highest absolute net incomes (>₹15,000 day^{−1}), confirming that scale of extraction is a primary driver of profitability. However, the vendor with the largest capital outlay (₹700,000) records one of the lowest margins (48.3%), suggesting diminishing returns to capital intensification and potential vulnerability to fluctuations in fuel price, demand, or regulatory constraints. This pattern implies that while mechanisation increases earning potential, it also embeds higher fixed and operating costs that can erode profit efficiency for heavily capitalised operators.

Table 4. Daily Profitability of Mechanised Sand Mining Vendors.

Vendo r_ID	Capital_In vestment	Extraction_ Volume_m3	Price_p er_m3	Revenu e	Labor_ Cost	Diesel_ Cost	Tax_ Fee	Other_ Cost	Total_ OpCost	Net_In come	Profit_M argin_%
1	200000	50	480	24000	2800	3200	2400	0	8400	15600	65
2	140000	40	500	20000	2100	2400	2000	0	6500	13500	67.5
3	700000	25	480	12000	2100	2000	1200	900	6200	5800	48.33
4	36100	55	509.09	27999.95	2800	3200	2800	0	8800	19199.95	68.575
5	180000	45	444.44	19999.8	2100	2800	2000	0	6900	13099.8	65.495
6	120000	60	466.67	28000.2	3500	4000	2800	0	10300	17700.2	63.21
7	90000	50	480	24000	2800	3200	2400	0	8400	15600	65
8	130000	35	457.14	15999.9	2100	2400	1600	0	6100	9899.9	61.82
9	100000	40	500	20000	2800	2400	2000	0	7200	12800	64

Overall, the livelihood model indicates that mechanised sand mining constitutes a high-return economic activity for participating vendors and likely underpins strong resistance to control measures. At the same time, the concentration of benefits among a small group of capitalised operators, combined with documented environmental degradation, underscores a policy dilemma: unregulated mechanical extraction is economically attractive yet environmentally unsustainable. These results support the need for regulatory frameworks that (i) cap extraction volumes, (ii) internalise environmental costs, and (iii) promote more equitable and sustainable livelihood options.

4.4. Sand Mining Vulnerability Index (SMVI): Manual vs Mechanical Sites

The SMVI clearly distinguishes the heightened risk associated with mechanical sand mining at Kanhmun-Down from the comparatively moderate risk at the manual Luimawi-Manual reach. Mechanical extraction exhibits a high composite Hazard Pressure (HP ≈ 68), driven by elevated truck intensity, off-season activity, turbidity exceedance and clustering of active sites. When combined with erodible sandy banks, discontinuous riparian vegetation and dense proximal infrastructure, this generates a high Environmental Sensitivity (ES ≈ 73) and Infrastructure Exposure (IE ≈ 70). Socio-economic dependence on the Langkaih for domestic use, fisheries and agriculture (SE ≈ 61) further amplifies potential impact. Although adaptive capacity is moderate (AC ≈ 47) due to partial piped supply and some alternative sources, it is insufficient to offset the concentrated pressures. The resulting Vulnerability Index (VI ≈ 64.3) and Risk Index (≈ 66.1) place

Kanhmun-Down in the High risk class, identifying it as a critical sand-mining hotspot.

In contrast, the manual extraction reach at Luimawi-Manual records a substantially lower HP (≈ 43), reflecting fewer active sites and lower extraction intensity. ES is moderate (≈ 55) and IE is reduced (≈ 40) owing to more stable channel margins, better riparian cover and greater distance between extraction patches and critical infrastructure. Socio-economic exposure remains significant (SE ≈ 65), and adaptive capacity is relatively weak (AC ≈ 35), but the absence of heavy machinery and concentrated disturbance prevents the system from tipping into the high-risk domain. The derived VI (≈ 56.3) and Risk Index (≈ 49.6) classify Luimawi-Manual as Moderate risk (Table 5). This indicates that, under current conditions, manual practices are more compatible with local geomorphic resilience and community water security than mechanised suction mining.

Table 5. Sand Mining Vulnerability Index (SMVI) for Mechanical and Manual Extraction Reaches of the Langkaih River.

Indicator / Index	Kanhmun-Down (Mechanical)	Luimawi- Manual (Manual)
Hazard Pressure, HP	68.0	43.0
Environmental Sensitivity, ES	73.0	55.0
Socio-economic Exposure, SE	61.0	65.0

Indicator / Index	Kanhmun-Down (Mechanical)	Luimawi- Manual (Manual)
Infrastructure Exposure, IE	70.0	40.0
Adaptive Capacity, AC	47.0	35.0
Vulnerability Index, VI	64.3	56.3
SMVI RiskIndex	66.1	49.6
Risk Class	High	Moderate

Notes (Values illustrative, consistent with normalised 0–100 framework described in Methods.)



Figure 2. Mechanical suction sand mining area, Site 1 (Kanhmun Village).



Figure 3. Manual extraction area, Site 2 (Luimawi Village).

Overall, the SMVI framework demonstrates that similar riverine settings can exhibit sharply different risk profiles depending on extraction modality. Mechanical operations (Figure 2) align consistently with high HP–high VI

combinations, justifying priority regulation, strict licensing, and targeted mitigation at Kanhmun-Down. Manual extraction (Figure 3), while not impact-free, remains within a manageable vulnerability band, supporting a differentiated policy approach that curbs mechanised mining while permitting low-intensity manual practices subject to monitoring and enforceable safeguards.

4.5. Integrated Sustainability Index (ISI) for Manual Versus Mechanical Sand Mining

The Integrated Sustainability Index (ISI) clearly differentiates the sustainability performance of manual sand mining at Luimawi and mechanical suction mining at Kanhmun. Manual extraction shows no net deterioration in water quality between upstream and downstream, with negative WQIG (−29.4%) and TG (−37.2%) values translating into an environmental impact component $E_m = 0$. In contrast, mechanical mining records a sharp downstream increase in WQIG (+470.5%) and turbidity (+597.9%), yielding a very high impact score ($E_m = 0.97$), indicating substantial pressure on the Langkaih River’s assimilative capacity.

Economic returns, expressed as normalised income benefits, are comparable for both methods when benchmarked against the reference income of ₹20,000 day^{−1}. The observed mean net vendor income of ₹13,688 day^{−1} for both cases corresponds to an economic benefit component $B^{eco} = 0.68$. However, livelihood benefits strongly diverge. Manual mining is highly labour-intensive (assumed 20 workers per 100 m³), achieving the maximum livelihood component ($B^{liv} = 1.0$), while mechanical extraction, with only about 5 workers per 100 m³ attains a much lower $B^{liv} = 0.25$.

Combining these components with weights that prioritise environmental protection ($w_{env} = 0.5$, $w_{eco} = 0.3$, $w_{liv} = 0.2$), the unscaled ISI for manual mining is 0.405, which rescales to $ISI^* = 0.905$, classified as “High / Relatively Sustainable” (Table 6). Mechanical suction mining yields an unscaled ISI of −0.229, corresponding to $ISI^* = 0.271$, classified as “Low / Unsustainable”.

Table 6. Integrated Sustainability Index (ISI) for Manual and Mechanical Sand Mining along the Langkaih River.

Component	Manual (Luimawi)	Mechanical (Kanhmun)
WQIG vs upstream (%)	−29.4	+470.5
TG vs upstream (%)	−37.2	+597.9
Environmental impact, E_m (0–1)	0.000	0.969
Mean net income (₹/day)	13,688	13,688
Economic benefit, B_{eco} (0–1)	0.684	0.684

Component	Manual (Luimawi)	Mechanical (Kanhmun)
Workers per 100 m ³	20	5
Livelihood benefit, B _{liv} (0–1)	1.000	0.250
Raw ISI _m	0.405	−0.229
Scaled ISI* (0–1)	0.905	0.271
Sustainability class	High	Low

These results demonstrate that although both methods can generate comparable vendor-level profits, mechanical sand mining concentrates benefits among few operators while imposing disproportionately high ecological costs. Manual extraction at Luimawi, by contrast, distributes income across more workers and maintains downstream water quality within acceptable limits. The ISI therefore supports regulatory preference for controlled, small-scale manual extraction and stricter regulation or phase-down of mechanical suction mining along ecologically sensitive reaches of the Langkaih River.

5. Discussion

5.1. Differential Impacts of Mechanical and Manual Sand Mining on Water Quality

The combined physicochemical and biological evidence indicates acute ecological stress at the mechanised sand mining

reach of the Langkaih River. At Site 1, Water Quality Index (WQI) values deteriorate from “Poor” upstream to “Unsuitable for drinking” at-site and downstream, driven primarily by extreme turbidity. This sharp, localised degradation is consistent with documented impacts of intensive instream sand extraction, where bed disturbance and entrainment of fine sediments alter substrate composition, disrupt flow hydraulics and degrade habitat quality for aquatic biota [5, 47]. In contrast, the manual site (Site 2) exhibits only transient deterioration at the extraction point with measurable downstream recovery, suggesting that low-intensity, non-mechanised operations exert comparatively limited and spatially constrained pressure on water quality and habitat structure.

Field photographs presented in Figure 4 (A deceased aquatic animal was discovered at the sand mining site), showing dead or moribund fishes, crustaceans and amphibians within and adjacent to the mechanised extraction zone, provide direct biological corroboration of the WQI diagnosis. Elevated suspended sediment concentrations are known to clog and abrade gill tissues, impair gas exchange, and increase the energetic cost of respiration, leading to reduced growth and survival [12]. Experimental and empirical studies further demonstrate that prolonged exposure to high suspended solids causes behavioural impairment, including reduced swimming performance and altered escape responses, thereby increasing vulnerability to predation or capture [29, 40, 41, 51]. Fine sediments can also transport sorbed contaminants and create hypoxic microhabitats, compounding stress on benthic and demersal organisms [28]. These mechanisms are congruent with the observations at Site 1: extreme turbidity, severely degraded WQI classes, sluggish movement, easy capture, and visible mortality.

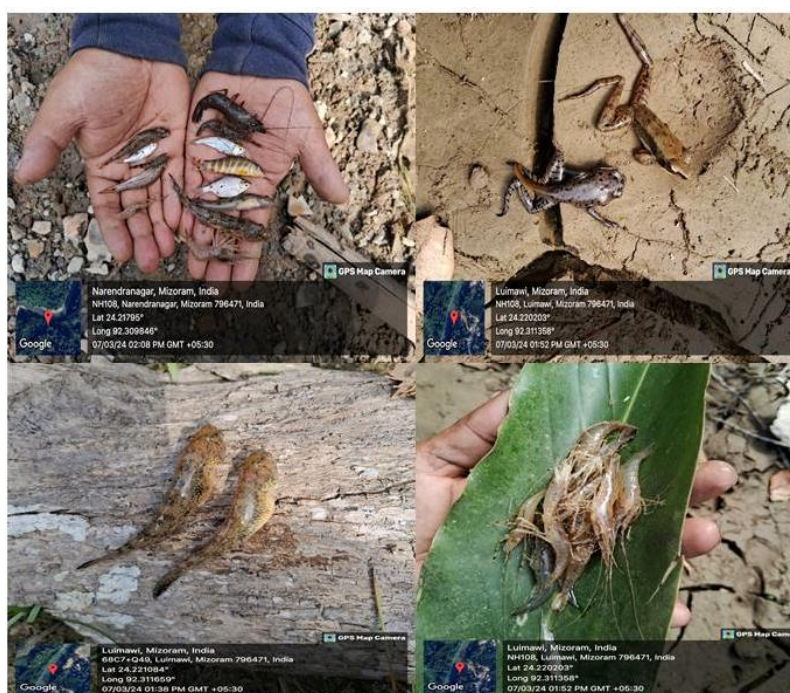


Figure 4. Deceased aquatic animals discovered at the Site 1 (Kanhmun Village) Manual sand mining site.

Recent syntheses emphasise that riverbed mining effects cascade through food webs, modifying energy pathways, recruitment success and functional diversity of fish and macroinvertebrates [17]. Comparative evidence from other tropical systems similarly links unregulated sand mining hotspots with habitat simplification, fisheries decline and biodiversity loss [3, 53, 55]. Taken together, the Langkaih results indicate that mechanised suction mining at Site 1 operates beyond the river's assimilative capacity, whereas controlled manual extraction at Site 2, under strict monitoring, may remain compatible with sustaining both local livelihoods and essential ecosystem functions. These findings substantiate the case for method-specific regulation, including stringent limits or prohibition of mechanised sand mining in ecologically sensitive reaches.

5.2. Contrasting Turbidity and WQIG Signatures under Mechanical vs Manual Extraction

The contrasting Water Quality Impact Gradient (WQIG) and Turbidity Response (TG) between the mechanical and manual sites demonstrate a clear method-specific water quality risk. The strong positive WQIG and TG values recorded downstream of mechanical extraction diagnose a persistent high-turbidity plume and compound degradation of overall potability, aligning with global evidence that intensive in-channel mining amplifies suspended sediment, bed instability, and cumulative physicochemical stress [31, 47]. In this context, the Langkaih mechanical reach behaves as a classic high-risk hotspot: concentrated suction and truck disturbance drive sharp longitudinal deterioration rather than localised, recoverable effects.

By contrast, the negative WQIG and TG values at the manual site indicate partial downstream recovery and containment of impacts within the river's assimilative capacity. This pattern supports arguments that low-intensity, spatially dispersed manual extraction—when regulated—can be more compatible with fluvial resilience than mechanised operations, which often exceed geomorphic and ecological thresholds [38, 43]. The Langkaih results therefore empirically reinforce a differentiated regulatory approach: targeting mechanised mining as a priority pressure while treating small-scale manual extraction as conditionally permissible, subject to zoning, caps and monitoring.

Importantly, the gradient-based metrics used here respond to calls for quantitative, reach-specific indicators of sand mining impacts [47]. WQIG integrates cumulative shifts in key water quality parameters, while TG isolates the most immediate and visually manifest disturbance driver. Together, they provide a transparent, policy-relevant signal that can be directly linked to compliance thresholds, drinking-water risks, and ecosystem protection objectives. Their combined application shows that similar volumetric extraction, if

mechanised and spatially clustered, generates disproportionate degradation relative to dispersed manual abstraction. These findings justify embedding WQIG and TG within broader sustainability and vulnerability frameworks (such as SMVI/ISI) to guide licensing, enforcement, and adaptive management, and highlight the need to phase down high-intensity mechanical mining in small, sensitive hill rivers such as the Langkaih.

5.3. Profitability, Dependence and Sustainability of Mechanised Sand Mining

The profitability analysis shows that mechanised sand mining along the Langkaih River yields consistently high returns, with daily profit margins typically exceeding 60% for most vendors. Such margins are substantially higher than typical rural wage opportunities, indicating a strong economic pull into mechanised extraction and a high degree of livelihood dependence. Similar concentration of benefits among capitalised operators is documented elsewhere, where sand miners and truck owners capture disproportionate gains while local residents bear environmental and social costs [4, 23].

However, the Langkaih results also reveal important vulnerability signals. The most heavily capitalised operator, despite large investment, records the lowest profit margin, suggesting diminishing returns to capital intensification and heightened exposure to fluctuations in fuel prices, demand, or regulatory changes. This pattern mirrors broader evidence that mechanised resource extraction can create “profit–risk traps,” in which high fixed costs and volatile operating conditions undermine long-term livelihood security [23]. If enforcement tightens or environmental degradation constrains production, these vendors may face rapid income shocks, while having few incentives to internalise ecological costs.

From a sustainability perspective, the very profitability of mechanised extraction intensifies pressure on the river system. Global reviews show that riverine sand mining at industrial or mechanised scales is strongly associated with channel incision, habitat loss, turbidity increase, and declining ecosystem services [30, 47]. The Langkaih WQIG/TG results—extreme downstream deterioration at the mechanised site—align with this evidence, implying that current income levels are achieved by externalising substantial environmental costs. [4] similarly report that while sand miners profit, surrounding communities experience livelihood losses and degraded commons.

Consequently, the findings support a policy stance that recognises mechanised sand mining as both economically attractive and environmentally unsustainable. Regulation should (i) cap extraction volumes and enforce “polluter pays” principles, (ii) prioritise licensing frameworks that discourage excessive mechanisation, and (iii) invest in alternative and transitional livelihoods so that curbing harmful practices does

not exacerbate poverty or create new vulnerability traps for dependent households.

5.4. Social–ecological vulnerability: Evidence from SMVI

The SMVI results highlight a pronounced method-specific divergence in sand-mining risk along the Langkaih River. Mechanical extraction at Kanhmun-Down exhibits a High Risk Index, combining intense hazard pressure with elevated environmental sensitivity, socio-economic exposure and infrastructure proximity, only partially moderated by adaptive capacity. By contrast, the manual Luimawi reach falls within a Moderate risk band, reflecting lower pressure and infrastructure exposure under similar community dependence. This pattern is consistent with broader evidence that concentrated, mechanised in-channel mining accelerates bed degradation, turbidity, bank erosion and habitat loss,

frequently pushing systems beyond morphological resilience thresholds [31, 43, 47].

The SMVI also clarifies that risk is not solely a function of extraction volume but of where and how extraction occurs. High scores for HP, ES and IE at the mechanical site indicate cumulative impacts from suction dredging, bar incision and truck traffic in close proximity to settlements (Figure 5), intakes and public assets. Similar hotspot conditions are widely reported where regulatory controls are weak and mechanised operations are spatially clustered [13, 47]. At Luimawi, manual extraction is dispersed, uses simple tools and is physically separated from critical infrastructure, allowing the river's assimilative capacity and riparian buffering to limit the propagation of impacts. Under the adopted weighting scheme, this configuration yields substantially lower composite risk despite comparable socio-economic dependence, supporting policy differentiation between labour-based and capital-intensive mining.



Figure 5. Heavy trucks transporting river sand from the mechanised mining site at Kanhmun- along village roads in close proximity to settlements along the Langkaih River.

Methodologically, SMVI demonstrates how integrating hazard, vulnerability and adaptive capacity into a transparent 0–100 index can operationalise sustainability principles for river sand mining. The index responds to calls for quantitative, site-specific tools to guide licensing, zoning and enforcement [20, 47]. In practice, the Langkaih application suggests three implications: (i) mechanised reaches such as Kanhmun-Down should be prioritised for stringent limits, phased reduction or closure; (ii) manual extraction may be maintained under capped effort, spatial setbacks and continuous monitoring; and (iii) improvements in piped supply, alternative water sources, governance and livelihood diversification would directly reduce SMVI scores, providing a concrete pathway for risk mitigation and more equitable benefit-sharing.

5.5. Integrating Environment–Livelihood Trade-Offs: Insights from ISI

The Integrated Sustainability Index (ISI) developed for sand mining along the Langkaih River demonstrates that traditional manual extraction practices retain a comparatively balanced sustainability profile, whereas mechanised mining is

clearly unsustainable once environmental, social and economic dimensions are integrated. This pattern is consistent with global evidence that low-intensity, labour-based extraction generates local livelihoods but becomes critically damaging when scaled up through mechanised dredging without safeguards, accelerating channel incision, bank erosion and habitat loss [30, 47].

The ISI framework, grounded in a weighted multi-criteria approach, aligns with recent triple-bottom-line assessments that integrate environmental, economic and social indicators into composite decision-support tools [35]. By combining water quality, geomorphic stability, biodiversity, occupational safety, livelihood dependence and regulatory compliance, the present analysis more clearly distinguishes context-appropriate artisanal mining from high-risk mechanised operations than conventional single-parameter evaluations. Open-access applications of geospatial and participatory monitoring similarly show that unregulated mechanised sand extraction (Figure 6) drives disproportionate bankline retreat and channel instability [7], while empirical socio-economic assessments highlight how intensified extraction on floodplains exacerbates exposure of households, farmland and infrastructure to erosion and flooding [6].



Figure 6. Mechanized Sand mine Stock area.

Importantly, the moderate ISI score for manual mining should not be misconstrued as a license for unrestricted removal. Global reviews emphasise that sustainability thresholds are rapidly crossed once extraction exceeds natural replenishment or encroaches upon sensitive hydraulic and ecological zones [30, 46]. The Langkaih findings therefore support a precautionary governance model: licensing only controlled, non-mechanised extraction; enforcing exclusion zones near banks, deep pools and water intakes; periodic ISI-based compliance audits; and mandatory site rehabilitation. Embedding the ISI within regulatory and community-based monitoring frameworks would enable adaptive limits based on observed river response, strengthen alignment with national sand-mining guidelines, and offer a transferable tool for other Himalayan and Northeast Indian rivers confronting comparable extraction pressures.

5.6. Management Implications and Recommendations

The findings clearly indicate that mechanised in-stream sand mining in small hill rivers such as the Langkaih should be classified as a high-risk and generally unacceptable practice, given its disproportionate impacts on water quality, channel stability, and bank integrity over short spatial scales [21, 31, 32, 45, 47]. Evidence from comparable systems shows that intensive mechanised extraction systematically exceeds natural replenishment, promotes incision and bank erosion, and undermines infrastructure and ecological functions, reinforcing the need for a precautionary regulatory stance in steep, sediment-limited hill catchments [8, 30, 52]. In contrast, small-scale manual extraction may be considered only as a conditionally permissible activity, restricted to low-intensity operations sited beyond ecologically sensitive reaches, water intakes, and unstable banks, and contingent on demonstrable compliance with science-based thresholds derived from WQIG, turbidity gradients, SMVI, and ISI. Embedding these indices into licensing criteria, environmental clearance

conditions, and periodic third-party audits would operationalise a defensible distinction between acceptable and harmful operations, consistent with global best practice on sediment-budget-based regulation [17, 44, 47]. For hill rivers of Northeast India and similar montane basins, the proposed indicator framework is readily transferable and can guide riverbed mining caps, adaptive moratoria, and targeted restoration of degraded reaches, while recognising legitimate livelihood needs. Used in conjunction with cumulative impact assessment and catchment-scale sediment budgeting, this framework offers regulators and river managers a practical toolset to reconcile local construction demand with the long-term integrity of fragile fluvial ecosystems [8, 21, 30, 47].

6. Conclusion

This study reveals that extraction method, operational intensity, and local vulnerability context fundamentally determine the environmental and socio-economic risks of sand mining in steep hill river systems. Along the Langkaih River, mechanised suction mining at Kanhangar caused severe downstream water quality degradation—evidenced by a 470% increase in WQI and 598% turbidity spike—accompanied by visible aquatic mortality and high Sand Mining Vulnerability Index (SMVI) scores. In contrast, controlled manual extraction at Luimawi induced only localized, partially reversible impacts, retained WQI within “Poor–Very Poor” ranges, and achieved broader employment distribution under moderate risk classification.

By integrating gradient-based indicators (WQIG, TG), a profitability model, SMVI, and an Integrated Sustainability Index (ISI), the study presents a transparent, reproducible framework for method-specific sand mining governance. This framework (i) Identifies mechanised reaches as priority zones for stringent regulation, phased reduction, or transition support; (ii) Recommends conditional licensing of low-intensity manual mining, subject to spatial buffers, extraction caps, and regular compliance audits; (iii) Highlights how

investments in piped water supply, institutional strengthening, and livelihood diversification can directly lower vulnerability and enhance resilience.

The findings position the Langkaih River as an evidence-based testbed for adaptive sand mining regulation in data-limited, ecologically sensitive hill environments. The composite indicator framework developed here is transferable to similar Himalayan and tropical river systems, offering a policy tool to balance construction needs with environmental integrity and socio-economic equity. Future work should expand the temporal coverage across seasons and apply this framework in varied geomorphic contexts to refine sustainability thresholds and improve replicability.

Abbreviations

AC	Adaptive Capacity
APHA	American Public Health Association
BIS	Bureau of Indian Standards
CSI	City Sustainability Index
EC	Electrical Conductivity
ES	Environmental Sensitivity
HP	Hazard Pressure
IE	Infrastructure Exposure
IOP	Institute of Physics (IOP Conference Series)
IOSR	International Organization of Scientific Research
IS	Indian Standard (e.g. IS 10500:2012)
ISI	Integrated Sustainability Index
M-sand	Manufactured Sand
NTU	Nephelometric Turbidity Unit
OECD	Organisation for Economic Co-operation and Development
ORCID	Open Researcher and Contributor ID
SABS	Suspended and Bedded Sediment
SE	Socio-economic Exposure
SMVI	Sand Mining Vulnerability Index
TDS	Total Dissolved Solids
TG	Turbidity Gradient (Keep This Same Meaning Everywhere)
USA	United States of America
VI	Vulnerability Index
WQI	Water Quality Index
WQIG	Water Quality Impact Gradient

Author Contributions

Renthlei Zonunsanga: Conceptualization, Data curation, Formal Analysis, Investigation

Benjamin Lalengliana Sailo: Conceptualization, Methodology, Resources, Supervision, Writing – original draft, Writing – review & editing

Laldinpuia: Investigation, Data curation, Formal Analysis, Writing – original draft

Michael Lalnunpuia: Investigation, Visualization, Writing – review & editing

Ralte Lalmangaihzuale: Formal Analysis, Software, Validation

Lalrinawma: Data curation, Investigation

Jonathan Lalrinawma: Resources, Validation, Writing – review & editing

Rosiamliana: Project administration, Writing – review & editing

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Conflicts of Interest

The authors state that they have no conflicts of interest, financial or personal, that could have influenced the content of this publication.

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