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Multidisciplinary Evaluation of the Impact of Sand and Stone Mining on Water Quality and the Kampar River Ecosystem

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Abstract

The Kampar River serves as a vital, important freshwater system that sustains ecological processes and provides essential resources for surrounding communities. However, intensive sand and stone mining activities have created increasing pressures on this ecosystem, raising concerns about long-term sustainability. Although mining generates substantial economic returns, its adverse impacts extend beyond ecological degradation, encompassing hydromorphological alterations, reduced biodiversity, and social conflicts. This study employs a multidisciplinary framework to evaluate the impacts of riverbed mining on water quality and ecosystem health, integrating ecological, socioeconomic, and institutional dimensions. Field research was conducted between May and August 2024 across four villages in Tambang District, Kampar Regency, combining water quality monitoring, field observations, and community interviews with secondary datasets such as satellite imagery and official reports. Analytical techniques included physicochemical testing, descriptive assessments, and SWOT analysis to formulate management strategies. The findings indicate a significant decline in water quality, with recorded temperatures of 30.6–34°C, acidic pH levels around 5.2–5.6, and turbidity slightly above national Class II standards. These changes, coupled with continuous dredging, accelerate riverbed deepening, increase the risk of bank collapse, and contribute to declining fish populations and catches. Socially, uncontrolled extraction generates community tensions and heightens socioeconomic disparities, threatening local resilience. SWOT analysis emphasizes strategies such as strengthening regulations, fostering cross-sectoral collaboration, and empowering community-based stewardship. This research provides a comprehensive evidence base to inform sustainable watershed governance, supporting evidence-based and locally grounded decision-making, ensuring ecological integrity, social well-being, and economic development are effectively balanced in managing the Kampar River.

Keywords: Sand and stone mining, Water quality, River ecosystem, Multidisciplinary impacts, Kampar River

1. Introduction

Freshwater ecosystems across the globe face growing threats from human exploitation, particularly through sand and stone mining. Such activities alter river morphology, degrade water quality, and reduce biodiversity, thereby undermining critical ecosystem services and community resilience. Increased turbidity reduces light penetration and suppresses primary productivity, while dredging disrupts sediment transport, destroys benthic habitats, and diminishes fish spawning grounds. These issues have become a global concern, with UNEP (2019, 2022) framing sand extraction as an emerging resource governance challenge and calling for sustainable sand governance as an essential component of achieving the Sustainable Development Goals (SDGs).

The Kampar River in Riau Province, Indonesia, exemplifies these challenges. Extending more than 400 kilometers, the river provides freshwater for household consumption, agriculture, capture fisheries, and transportation. However, intensive sand and stone mining—particularly in Tambang District—has significantly reshaped the river's physical and ecological conditions (Hadi et al., 2025). Recent studies have shown that several water quality parameters, including turbidity, total suspended solids (TSS), and nutrient levels, have reached or exceeded national thresholds, signaling declining ecological resilience (Harjoyudanto et al., 2023; Yuliati et al., 2024). These findings highlight a deteriorating trajectory that threatens both biodiversity and human livelihoods.

Ecological consequences are evident in declining biodiversity and disrupted fish populations, driven by habitat destruction and sediment overload (Asiah et al., 2021). For local communities, reduced fish catches undermine traditional livelihoods, exacerbating poverty and generating conflict between fishers and mining operators. Economic valuation studies further show that these ecological changes translate into tangible losses for capture fisheries along the Kampar River (Rahmadita et al., 2023). At the same time, weak law enforcement, fragmented institutional responsibilities, and the persistence of unlicensed operations exacerbate these pressures, reflecting broader governance challenges in Indonesia's mining sector (Yuliati et al., 2024; Rohman et al., 2024).

Although research on the Kampar River has documented various physicochemical indicators of water quality and aspects of hydromorphological change (Harjoyudanto et al., 2023; Hadi et al., 2025), most studies have remained sectoral and limited in scope. Few have applied a multidisciplinary framework that integrates ecological, socioeconomic, and institutional perspectives, despite the interconnected nature of these impacts. This gap limits the capacity to design holistic policies that simultaneously address environmental degradation and community well-being.

This study addresses that gap through a multidisciplinary evaluation of the impacts of sand and stone mining on the Kampar River, combining water quality monitoring, ecological assessment of aquatic biodiversity, socioeconomic surveys, and institutional analysis within a single analytical framework. By integrating these approaches, the study shows how extraction practices jointly transform hydromorphology, ecosystem services, and local livelihoods, and provides concrete evidence to help provincial and district authorities refine extraction quotas, spatial zoning, and monitoring procedures in support of more transparent, accountable, and sustainable river basin governance.

2. Methods

2.1 Time and Location of the Study

This research was conducted from May to August 2024 in the Kampar River, covering four villages within the administrative area of Tambang District, Kampar Regency: Padang Luas, Terantang, Parit Baru, and Kualu. This location was chosen due to its intensive mining activities and its reflection of the ecological and social conditions of the river's coastal communities, as shown in Figure 1.

This study directly addresses this gap through a multidisciplinary assessment of the impacts of sand and stone mining on the Kampar River. The approach combines water quality monitoring, assessments of aquatic biodiversity, socioeconomic surveys, and institutional analysis within a single analytical framework. By synthesizing these findings, the study clarifies and advances scientific understanding of how mining practices drive hydromorphological change, degrade ecosystem services, and increase social vulnerability, and provides practical evidence for provincial and district governments to adjust extraction quotas, tighten mining zonation, and strengthen monitoring and compensation schemes, thereby steering river basin governance towards more transparent, accountable, and sustainable practice.

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2.2 Water Quality Assessment

Water quality assessment in the Kampar River was conducted by combining physical, chemical, and nutrient parameters to obtain a comprehensive picture of river health. Physical parameters (temperature, TDS, depth, current velocity, turbidity, DHL) and chemical parameters (pH, DO, BOD, NO_3^-, PO_4^{3-}) were analyzed following procedures standardized by the American Public Health Association (APHA, 2017). These indicators were selected because they represent key ecological processes, anthropogenic influences, and compliance with national water quality regulations.

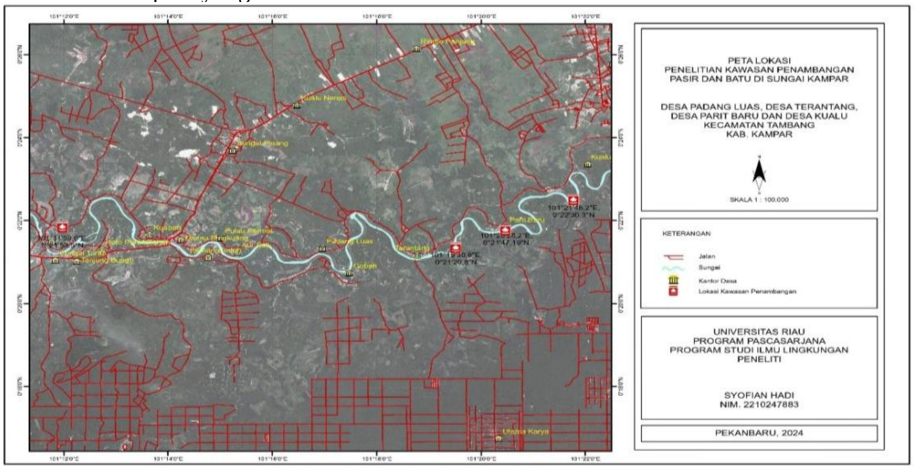

Figure 1. Study Location Map

Table 1. Parameters and Methods Used in Water Quality Assessment

Category	Parameter	Method / Reference Standard (APHA, 2017)
Physical	Temperature (°C)	Thermometric Method (APHA 2550 B)
	Depth (m)	Depth Sounding / Graduated Rod (APHA 1060 B)
	Flow Velocity (m/s)	Current Meter Method (APHA 1060 B)
	Transparency (Clarity) (cm)	Secchi Disk Method (APHA 1060 B)
	Turbidity (NTU)	Nephelometric Method (APHA 2130 B)
	TDS (mg/L)	Gravimetric / Conductivity Method (APHA 2540 C)
	TSS ((mg/L))	Gravimetric Method (APHA 2540 D)
	EC (µS/cm)	Conductivity Meter (APHA 2510 B)
Chemical	pH	Electrometric Method (APHA 4500-H^+ B)
	DO (mg/L)	Winkler Method (APHA 4500-O C)

	BOD_5 (mg/L)	5-Day Incubation (APHA 5210 B)
	COD (mg/L)	Dichromate Reflux (APHA 5220 C)
	NO_3^- (mg/L)	UV Spectrophotometric Method (APHA 4500-NO_3^- B)
	PO_4^{3-} (mg/L)	Ascorbic Acid Method (APHA 4500-P E)

2.3 Ecological Assessment

Ecological assessment focused on documenting fish species identified through local ecological knowledge of fishers, which reflects biodiversity shifts in the Kampar River. Habitat observations included measurements of substrate, flow velocity, and turbidity to understand their influence on aquatic communities. This combined approach integrates community insights with scientific observation for a comprehensive ecological perspective.

2.4 Social and Economic Survey

A total of 96 respondents from the fisherfolk, mining workers, and village officials clusters were surveyed using questionnaires and semi-structured interviews. The data were analyzed using descriptive statistics and thematic analysis to capture livelihood impacts and social conflict. This approach ensured a deep understanding of the socioeconomic dynamics in mining-affected communities.

2.5 Policy and Institutional Analysis

This analysis examined regulatory frameworks, including the Mineral and Coal Mining Law, Environmental Protection Law, and Riau regional by laws. Institutional arrangements for water resource governance were assessed to evaluate coordination, monitoring, and enforcement capacities. The findings aimed to identify gaps between regulatory provisions and practical implementation.

2.6 Data Analysis

Data analysis used a mixed-methods approach to integrate physicochemical, ecological, socioeconomic, and institutional information. Water-quality data from the four villages were summarised with descriptive statistics and graphs to compare sites and sampling periods and to assess compliance with national standards (APHA, 2017; Government of Indonesia Regulation No. 22/2021). Changes in river width along mined reaches were quantified by digitising multi-temporal satellite images and field measurements (2015–2025). Information on fish taxa from community interviews and habitat observations was tabulated and interpreted qualitatively in relation to these physical and chemical changes. Socioeconomic and institutional survey data were processed using frequency tables and simple cross-tabulations, while open-ended responses were coded into themes capturing perceptions, conflicts, and local responses. The primary objective of the analysis is to characterize environmental gradients and governance conditions in a data-limited context, rather than to test formal statistical hypotheses; therefore, the analysis is focused on descriptive statistics rather than inferential statistics. Quantitative indicators and qualitative insights were then synthesised within a SWOT framework; scores and weights were used to build IFAS and EFAS matrices, locate the sand-mining system in the strategic quadrant, and derive environmental management strategies for the four sand-mining villages in Tambang Subdistrict, Kampar Regency.

3. Results and Discussion

3.1 Ecological Impact

The ecological impact of sand and stone mining activities in the Kampar River can be seen in the condition of water quality (Figure 2).

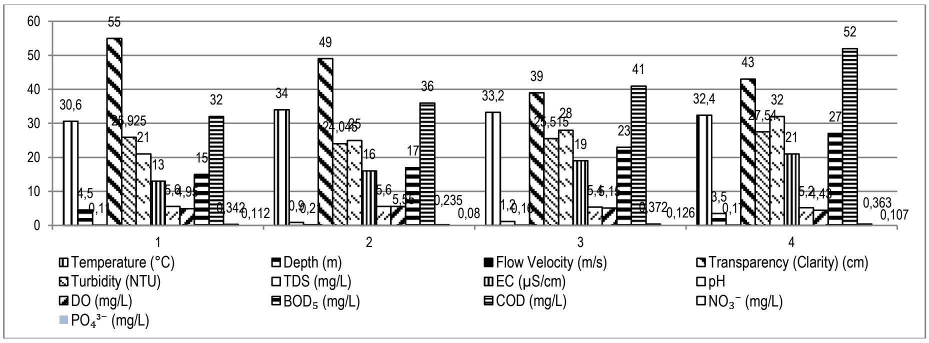

Figure 2. Water Quality Conditions of the Kampar River in the Sand and Stone Mining Area

Recorded surface temperatures ranged from approximately 30.6–34 °C, pH values were acidic (around 5.2–5.6), and turbidity frequently exceeded the national Class II thresholds, in line with elevated TSS, TDS, and electrical conductivity. Dissolved oxygen tended to be low, while BOD and COD were relatively high compared with reference values in Government of Indonesia Regulation No. 22/2021 and APHA (2017), indicating organic enrichment and reduced assimilative capacity. These measurements point to marked hydrochemical alteration in reaches affected by intensive extraction. Geomorphological observations and multi-temporal analysis of channel width between 2015 and 2025 further document substantial physical modification of the river corridor at mining sites (Figure 3).

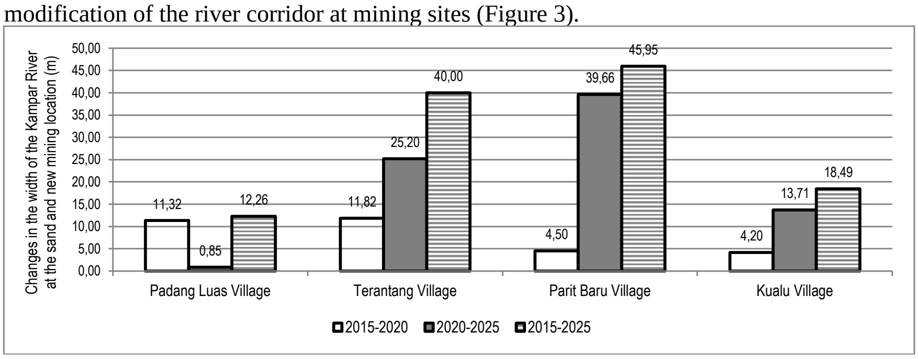

Figure 3. Dynamics of Changes in the Width of the Kampar River at Sand and Stone Mining Locations in Four Villages (2015–2025)

Along the mined reaches in Padang Luas, Terantang, Parit Baru, and Kualu, the channel widened by several tens of metres over the decade, with the largest cumulative expansion observed at Parit Baru and Terantang. This widening reflects progressive bank retreat and bed reworking associated with repeated dredging, creating a more open and unstable channel cross-section compared with less disturbed segments upstream and downstream.

Ecological information obtained through community interviews and habitat observations complements these physical measurements. Local fishers identified approximately 20 fish taxa in the mining area (Table 2), including *Mystus* spp., *Pangasius*, *Belodontichthys*, *Puntius*, and *Rasbora*, indicating a community that historically supported diverse trophic and habitat guilds. At the same time, respondents consistently reported declining catches over the last decade, a perceived shift of fish towards less disturbed stretches of the river, and increasing difficulty in maintaining household income from capture fisheries.

Table 2. Types of Fish in the Sand and Stone Mining Area from the results of interviews with local residents

Number	Local Name	scientific name	Genus	Family
1	Geso	*Hemibagrus wyckii*	Mystus	Bagridae
2	Baung	*Hemibagrus nemurus*	Mystus	
3	Nila	*Oreochromis niloticus*	Oreochromis	Cichlidae
4	Motan	*Thynnichthys thynnoides*	Thynnichthys	Cyprinidae
5	Pantau	*Rasbora argyrotaenia*	Rasbora	
6	Kopiek	*Barbodes schwanefeldi*	Barbodes	
7	Tobionggalan	*Puntioplites bulu*	Puntioplites	
8	Lomak	*Leptobarbus hoevenii*	Leptobarbus	
9	Kelabau	*Osteochilus kelabau*	Osteochilus	
10	Sepimping	*Oxygaster anomalura*	Oxygaster	
11	Barau	*Hampala macrolepidota*	Hampala	
12	Tilan	*Mastacambelus unicolor*	Mastacambelus	Mastacembelidae
13	Kapituk	*Trichogaster trichopterus*	Trichogaster	Osphronemidae
14	Silinca	*Belontia hasselti*	Belontia	
15	Juaro	*Pangasius polyuranodon*	Pangasius	Pangasiidae
16	Patin	*Pangasius pangasius*	Pangasius	
17	Tapah	*Wallago leeri*	Wallago	Siluridae
18	Singaghek	*Belodontichthys dinema*	Belodontichthys	
19	Silais	*Kryptopterus* sp.	Kryptopterus	

Taken together, the measured decline in water quality, the documented channel widening, and the reported changes in catches and fish distribution suggest that intensified sand and stone mining is driving hydrochemical stress and habitat simplification that heighten the vulnerability of fish assemblages to sediment disturbance and hypoxia. These patterns are consistent with evidence from other tropical river systems, where increased turbidity, reduced dissolved oxygen, and altered channel morphology have been linked to reduced fish abundance, shifts in species composition, and medium-term stock declines (Asiah et al., 2021; Yuliati et al., 2024). In line with recommendations from the river sand-mining management literature, the ecological signals observed in the Kampar River underline the need for targeted mitigation, including multi-temporal monitoring of water quality and channel geometry, restrictions on extraction zones and intensity, and riparian rehabilitation using bioengineering techniques as part of an integrated strategy to restore habitat quality and safeguard aquatic biodiversity (UNEP, 2022).

3.2 Social and Economic Impact

The economic conditions of communities in the four villages affected by sand and stone mining in the Kampar River are presented in Figure 4. Figure 4 shows that sand demand and prices are predominantly high, which directly drives the expansion of extraction activities in the four study villages. However, the market remains unstable and dominated by intermediaries, so local miners gain only limited profits, while household income data indicate that most families remain in the low-income group. Although advanced technology adoption has boosted production, it has also accelerated environmental degradation and increased external costs, thereby pressuring traditional livelihoods such as fishing (Arsyad et al., 2020; Rentier & Cammeraat, 2022). Similar global patterns show that high demand often results in short-term economic gains but unequal benefit distribution and ecological-economic risks, highlighting the need for policy interventions such as permit formalization, fair benefit-sharing, supply chain stabilization, and livelihood diversification to ensure sustainable local development (Rentier & Cammeraat, 2022; UNEP, 2019; Rahmadita et al., 2023). These economic dynamics are closely related to the social conditions of the community in the four villages affected by sand and stone mining, as shown in Figure 5.

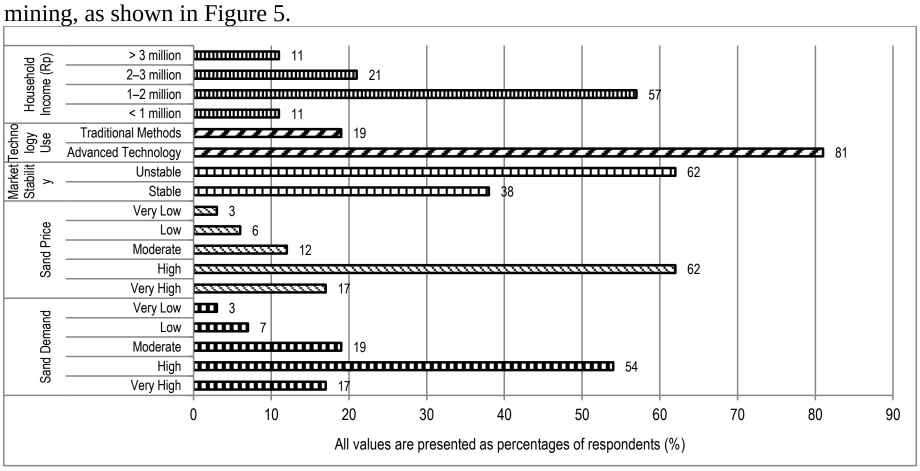

Figure 4. Economic Conditions of Sand and Stone Mining in Four Villages on the Kampar River

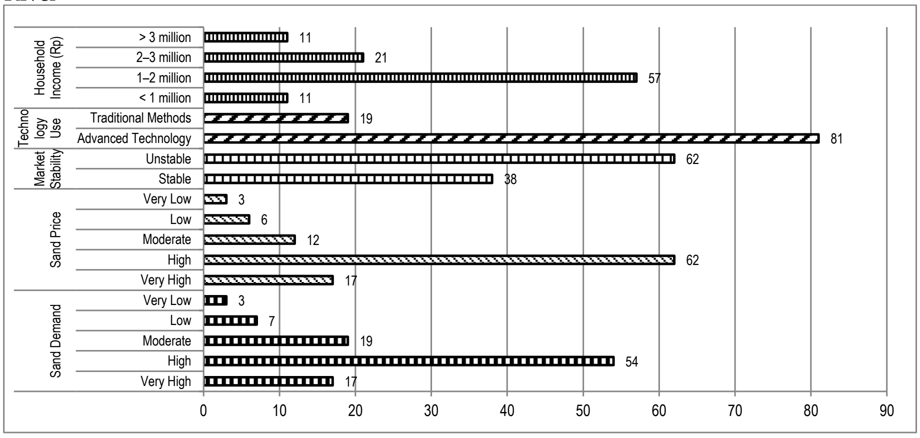

Figure 5. Social conditions of the community in four villages affected by sand and stone mining along the Kampar River

Figure 5 presents the social conditions of communities in four villages affected by sand and stone mining along the Kampar River, highlighting aspects of local wisdom, education, environmental knowledge, participation, and conflict. The percentages in Figure 5 show that although communities retain cultural values and moderate educational attainment, limited environmental knowledge, low participation, and reported conflicts highlight increasing social vulnerability (UNEP, 2022). Weak community engagement enables external actors and intermediaries to dominate, producing unequal benefit distribution and raising the risk of conflict, consistent with patterns in river sand mining studies (Rentier & Cammeraat, 2022; Rahmadita et al., 2023). These pressures generate social externalities, including infrastructure damage, health concerns, and declining traditional livelihoods, underscoring the urgency of interventions through environmental literacy, participatory mechanisms, and transparent benefit-sharing (Yuliati et al., 2024; UNEP, 2022).

3.3 Law and Institutions

The analysis of legal and institutional aspects presented in Figure 6 reveals that about 86.95% of mining sites operate without proper permits, while 70% of respondents view law enforcement as reactive and weak, echoing wider concerns that existing mining legislation and fragmented enforcement in Indonesia fail to safeguard against illegal extraction (Hasibuan & Japri, 2024; Rohman et al., 2024). Limited inter-agency coordination (60%), insufficient monitoring capacity (55%), and low community participation (29%) illustrate fragile governance that enables illegal practices and benefits intermediaries at the expense of local communities (Rentier & Cammeraat, 2022). Patterns in Figure 6 are consistent with what recent sand-governance scholarship describes as multi-level governance gaps, where formal rules exist on paper but are undermined by fragmented responsibilities, weak enforcement capacities, and minimal public oversight. These governance failures are increasingly recognised as a key driver of unsustainable sand extraction globally, implying that institutional reform and clear allocation of mandates are as critical as technical limits on extraction volumes (UNEP, 2019, 2022; Marschke & Rousseau, 2022; Yasmin, 2024; Rahman, 2025).

These governance weaknesses translate into tangible economic externalities, such as infrastructure damage and declining fish catches, consistent with findings from other riverine systems in Asia (UNEP, 2022). The resulting economic pressures, including reduced fisher incomes and higher recovery costs, highlight how legal and institutional failures directly shape livelihood outcomes and reinforce the need for integrated policies that strengthen enforcement, enhance monitoring through technology, and ensure equitable benefit-sharing (Wijayanti et al., 2023; Haq et al., 2023; Hasibuan & Japri, 2024).

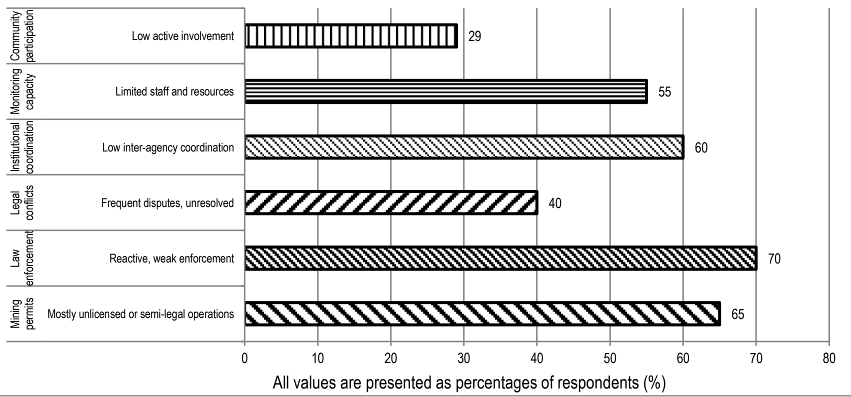

Figure 6. Law and Institutional Conditions of Sand and Stone Mining in Four Villages along the Kampar River

3.4 Tecnology

Sand and gravel mining in the Kampar River initially employed traditional methods using shovels, baskets, and small pumps, which, despite limited scale, gradually impacted spawning habitats and benthic communities. Rising demand has driven a shift to mechanized suction dredging and floating excavators, enabling rapid, large-scale sediment removal, often unlicensed and supported by on-site workshops (Jaiswal, 2022; Hadi et al., 2025). These activities have caused riverbed incision, channel widening, increased turbidity, and loss of fish habitats, as documented in field observations and global studies (Koehnken et al., 2020; Rentier & Cammeraat, 2022), while also elevating total suspended solids and reducing dissolved oxygen, threatening aquatic biota (Jaiswal, 2022).

Socio-economically, mechanization temporarily benefits capitalized miners but imposes significant costs on local communities through declining fisheries, damaged infrastructure, and livelihood losses, a pattern also reported in other sand-mining regions (UNEP, 2019; Yuliati et al., 2024; Asare et al., 2024; Hadi et al., 2025). Despite police interventions in February 2025, mechanized extraction persists, reflecting weak licensing and monitoring. To ensure sustainability, integrated strategies including extraction quotas, zoning, satellite and UAV-based monitoring, web-based GIS platforms, and social compensation schemes are recommended to harmonize ecological protection with socio-economic resilience (Koehnken et al., 2020; UNEP, 2022; Diaconu et al., 2023; Bayazidy et al., 2024).

3.5 SWOT Analysis

The Internal Factor Analysis Summary (IFAS) of sand mining in the Kampar River indicates a total score of 3.04, suggesting that internal strengths outweigh weaknesses, with sand availability and fish diversity as key factors requiring careful management (Source: IFAS–EFAS Analysis Document). The External Factor Analysis Summary (EFAS) shows a total score of 3.48, meaning that external opportunities such as market demand and accessibility are stronger than threats, while the coordinates (x = 0.26; y = 0.28) place the strategy in Quadrant I (Strength–Opportunity), emphasizing the use of strengths to exploit opportunities (Source: IFAS–EFAS Analysis Document).

Nevertheless, ecological pressures are significant because excessive extraction has been shown to cause riverbed incision, channel widening, turbidity increase, and aquatic habitat loss, as documented by Rentier and Cammeraat (2022; UNEP, 2019). Field evidence, including images of suction pumps, material stockpiles, and dredged pits, reinforces local findings of morphological change and river widening as reported by Hadi et al. (2025).

From a socio-economic perspective, although mining generates short-term benefits for miners, it creates distributive conflicts because local fishers and riverside farmers suffer long-term losses, consistent with the study of Yuliati et al. (2024) and global evidence on the social costs of sand extraction (UNEP, 2019). Institutional and regulatory frameworks remain weak due to unlicensed operations and limited spatial oversight, requiring evidence-based policy interventions such as extraction quotas, zoning, and social compensation mechanisms (UNEP, 2022).

Mitigation strategies recommended in the literature include sediment audits, quantitative restrictions based on sediment budgets, and multi-temporal monitoring using satellite imagery and hydromorphodynamic modeling (Koehnken et al., 2020; UNEP, 2022). Therefore, although the position falls within the Strength–Opportunity quadrant, the sustainability of sand mining in the Kampar River will depend on integrating advanced monitoring technologies, governance reforms, and ecosystem rehabilitation (UNEP, 2019, 2022; Koehnken et al., 2020; Diaconu et al., 2023; Bayazidy et al., 2024) with the management action plan presented in Table 3.

Table 3. Action Plan for Sustainable Management of Sand and Gravel Mining in the Kampar River

Timeline	Action Plan	Responsible Stakeholders	Key Performance Indicators (KPI)
Short-Term (0–1 year)	- Conduct a **sediment audit** to determine extraction quotas. - Enforce licensing compliance and impose a moratorium on illegal sites.	Local Government, Environmental Agency, Ministry of Energy and Mineral Resources, River Basin Authority	- Sediment budget report available.- ≥80% of miners licensed.- Illegal mining sites closed.

Medium-Term (1–3 years)	- Establish **zoning and extraction quotas** based on sediment audit. - Develop a **real-time monitoring system** (satellite, drones, water quality sensors). - Form a **multi-stakeholder forum** (government, communities, academia, miners).	Local Government, Ministry of Spatial Planning, Environmental Agency, Universities, NGOs	- Zoning map and quota system legalized.- Monitoring system operational (monthly reports).- Multi-stakeholder forum meets at least 4 times per year.
Long-Term (3–5 years)	- Implement **riverbank rehabilitation** with riparian vegetation. - Introduce **social–economic compensation mechanisms** (CSR, redistribution funds for fishers/farmers). - Integrate sustainable mining into **spatial and development plans (RTRW/RPJMD)**.	Local Government, Ministry of Environment and Forestry, Mining Companies, Regional Planning Agency (Bappeda)	- ≥70% of mined areas rehabilitated.- Compensation schemes implemented transparently.- Local regulations incorporate sustainable sand mining governance.

4. Conclusion

This multidisciplinary evaluation reveals that sand and stone mining in the Kampar River has caused severe multidimensional degradation across ecological, socioeconomic, nstitutional, and technological aspects. Ecologically, water quality deterioration (pH 5,6, temperature 30.6–34°C, elevated turbidity) combined with progressive channel widening (2015–2025) and mechanized dredging has disrupted aquatic habitats, resulting in declining fish populations among 19 identified taxa and reduced catch rates for local fishers. Socio-economically, asymmetric benefit distribution perpetuates community vulnerability, where intermediary dominated supply chains extract profits while traditional livelihoods suffer from environmental externalities, compounded by limited environmental awareness and low participatory engagement (29%). Institutionally and technologically, critical governance failures 87% unlicensed operations, weak enforcement (70% perceive as inadequate), and fragmented coordination (60%) enable continued illegal extraction using advanced mechanized equipment, necessitating urgent integrated interventions including permit formalization, technology-based monitoring, spatial zoning, riparian restoration, and equitable benefit-sharing mechanisms to ensure sustainable watershed management that balances ecological integrity, social welfare, and economic development.

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