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Impacts of nickel mining activities on coastal ecosystems: An analysis of interactions between human activities and geological systems

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ABSTRACT
Background: Rising nickel demand has accelerated nickel mining expansion in Indonesia, a major lateritic nickel supplier. Upland disturbance can intensify erosion and sediment delivery, stressing coastal ecosystems and communities dependent on coastal resources. Existing assessments commonly treat erosion–sedimentation processes and downstream socio-ecological impacts separately, leaving the mechanism linking upland disturbance to coastal consequences insufficiently integrated. **Methods:** This study developed a mechanistic conceptual model within a Social–Ecological Systems (SES) framework using a conceptual–analytical, literature-based design. A PRISMA-informed workflow selected 30 documents, which were analysed through thematic coding, causal mapping, and SES mapping. **Findings:** Six recurring process themes emerged: land disturbance; geomorphic mediation (runoff → erosion → sediment transport); sediment connectivity; changes in resource units (turbidity, total suspended solids [TSS], and water quality); decline in coastal resource-system functions; and social consequences moderated by governance. In tropical archipelagic settings, short upstream–downstream distances and high rainfall can shorten ecosystem response times. Where mining mobilises fine lateritic sediment fractions, the reviewed literature suggests that they may contribute to prolonged turbidity and stored sediment that can later be resuspended, potentially delaying ecological recovery. **Conclusion:** These mechanisms are indicative patterns requiring site-specific field validation. The model supports integrated watershed–coastal management, using turbidity/TSS as an analytical-threshold early-warning indicator supported by monitoring, enforcement, rehabilitation, and governance response capacity. **Novelty/Originality of this article:** This study explicitly embeds erosion, sediment transport, and sediment connectivity as the mechanistic bridge linking nickel-mining disturbance to coastal ecological and livelihood risks within a single SES-based pathway.

KEYWORDS: coastal ecosystems; legacy sediment; nickel mining; sediment connectivity; social-ecological systems; total suspended solids (TSS).

1. Introduction

In recent years, nickel has increasingly become a strategic global commodity, mainly because of its role in the stainless-steel industry and electric-vehicle batteries as part of the energy transition (IEA, 2021). This demand surge has accelerated nickel exploration and exploitation in countries with large reserves, including Indonesia (USGS, 2023). Consequently, mining expansion is reflected not only in increased production but also in wider mining footprints and supporting infrastructure in landscapes that were previously relatively less disturbed (USGS, 2023).

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Physically, many Indonesian nickel mining activities occur in hilly landscapes relatively close to the coastline and influenced by high rainfall. These conditions create strong upstream–downstream connectivity through drainage networks and rivers. When mining opening alters land cover and surface morphology, surface runoff and erosion can increase. As topsoil and vegetation are removed, surface stability declines, and material becomes more readily transported into waterways and then toward coastal zones. This indicates that mining impacts do not necessarily stop at the mine site but may propagate along geomorphic and hydrologic pathways linking land and coast (Syvitski et al., 2005).

In coastal zones, increased sediment load and turbidity can disturb sensitive ecosystems such as coral reefs and mangroves, which play key roles in supporting biodiversity and ecosystem services (Alongi, 2015). These ecological impacts can translate into social impacts for coastal communities, including capture fisheries and aquaculture, through declining water quality and habitat condition (Climate Rights International, 2024; Jaida et al., 2023; Syarifuddin, 2022). On the other hand, the economic contribution of the nickel sector—investment, state revenue, and employment—often serves as the primary justification for industrial expansion. However, evaluations of environmental and social impacts are still frequently conducted separately: some studies focus on ecological change without explaining the geomorphic mechanisms that generate sediment stressors, while others emphasize mining technical aspects without systematically linking them to downstream coastal disturbance. This creates a need for a more integrated approach to understand nickel mining as a complex interaction among human needs, surface-geologic dynamics, and coastal ecosystem responses that can shape coastal vulnerability and unsustainability.

This study adopts the Social–Ecological Systems (SES) perspective as formulated by Ostrom (2009), which divides a system into a resource system, resource units, actors, and a governance system. In this manuscript, the mine–watershed–coast continuum is positioned as the resource system; sediment/turbidity and water quality as resource units; mining companies and coastal communities as actors; and mining regulation, monitoring, and oversight as the governance system. SES is not only a conceptual foundation but is used analytically to trace a disturbance pathway: pressure from actors (mining activities) triggers bio-physical change through geomorphic processes; these changes increase resource units (sediment/turbidity and water quality change) and reduce resource system function (coastal ecosystems), while the governance system determines whether the pathway is moderated through monitoring, enforcement, and rehabilitation or is allowed to develop.

In Indonesia, the governance pathway described in this study is embedded in a national regulatory architecture that applies to nickel operations in the Sulawesi and Maluku Nickel Belt (Pemerintah Republik Indonesia, 2021a, 2021b). Environmental approval is governed through the national environmental protection and management framework, while the screening of activities requiring AMDAL, UKL-UPL, or SPPL is specified through implementing environmental regulations (Kementerian Lingkungan Hidup dan Kehutanan Republik Indonesia, 2021; Pemerintah Republik Indonesia, 2021b). Mineral-mining operations are further governed through the national mineral and coal mining framework, which regulates business licensing, work-plan and reporting requirements, community development and empowerment, and administrative sanctions (Pemerintah Republik Indonesia, 2021a, 2025). Within this institutional setting, the governance component of the SES model is not limited to the existence of formal rules; it also denotes the capacity to identify erosion–sediment pathways during environmental assessment, translate them into monitoring and management commitments, and enforce or adapt those commitments across the mine–watershed–coast continuum (Pemerintah Republik Indonesia, 2021b, 2021a). The proposed model therefore complements, rather than replaces, site-specific environmental assessment by making the upstream–downstream sediment pathway explicit within the governance process (Kementerian Lingkungan Hidup dan Kehutanan Republik Indonesia, 2021; Pemerintah Republik Indonesia, 2021a).

From an environmental geology perspective, nickel mining can accelerate geomorphic change mediated by erosion and sediment transport. Land clearing, removal of vegetation cover, and surface reshaping increase erosion susceptibility, which can be explained using the Universal Soil Loss Equation (USLE), especially the land cover factor (C) and slope length–steepness factor (LS) (Renard et al., 1997; Wischmeier & Smith, 1978). Syvitski et al. (2005) emphasizes that human activities increase sediment flux to the ocean through land-use change, including mining. However, the magnitude of sediment reaching coastal waters is not determined solely by upstream erosion volume, but also by geomorphic connectivity (e.g., distance to the coast, river transport capacity, and sediment delivery ratio). Thus, the geologic system acts as a mediator transmitting anthropogenic pressure from land to coastal zones. Within SES, these geomorphic mechanisms bridge pressure from actors into changes in resource units (increased sediment load/turbidity), which then influence the resource system (coastal ecosystem functions).

Coastal impacts primarily occur through increased sedimentation and turbidity that reduces light penetration and disturbs sensitive ecological functions. In coral reefs and shallow-water systems, reduced light can suppress primary productivity; in mangroves, increased sediment can alter substrate conditions and filtering/shoreline protection functions (Alongi, 2015). Therefore, this study also draws on the concepts of carrying capacity and ecosystem resilience. Carrying capacity refers to the tolerance limit of a system to absorb pressure without permanent degradation, while resilience refers to the capacity of a system to recover after disturbance. When sediment pressures recur and exceed ecological tolerance, recovery capacity declines and the system may shift toward a less productive and more vulnerable state. In this context, unsustainability is not treated as a single direct consequence of mining, but as the outcome of interactions among disturbance intensity, upstream–downstream connectivity, and limited coastal carrying capacity and resilience.

In recent years, studies have examined mining impacts on coastal environmental quality and social conditions, including erosion, sedimentation, and stress on shallow marine ecosystems (Borrelli et al., 2017; Friess et al., 2019). Geomorphology literature shows that surface disturbance and land-cover change can increase runoff and sediment yield, especially in steep landscapes with intense rainfall (Borrelli et al., 2017). Here, sediment connectivity becomes crucial because it explains how upland disturbances are effectively transmitted downstream through hydrologic networks and geomorphic processes, so impacts may accumulate in coastal systems (Heckmann et al., 2018). Land–sea connectivity further emphasizes that land and sea are a single bio-physical continuum: land-derived sedimentation not only increases turbidity but may also alter coastal habitats such as coral reefs and mangroves with important ecological and social functions (UNEP, 2021). Coastal sustainability literature highlights that carrying capacity and resilience determine whether anthropogenic pressures are absorbed and recovered or gradually reduce ecosystem function (IPBES, 2019).

In tropical contexts such as Indonesia, sediment transport is strongly influenced by rainfall intensity, catchment characteristics, and local geological material properties. In lateritic nickel landscapes, fine particle fractions and iron-oxide-rich materials may be mobilised during rainfall-driven runoff events. Under suitable hydrodynamic and geochemical conditions, these materials may remain suspended for longer than coarser sediment fractions and can contribute to prolonged turbidity in receiving waters. During the wet season, mobilisation of fine particles may strengthen upstream–downstream connectivity and increase the frequency of coastal disturbance. However, the magnitude and persistence of these effects depend on sediment grain size, mineralogy, flocculation processes, river and coastal hydrodynamics, distance to the coast, and the effectiveness of sediment-control measures. The proposed relationship should therefore be understood as a context-dependent mechanism rather than a universally verified characteristic of all Indonesian lateritic nickel mining settings.

Although SES studies stress the importance of understanding interactions between bio-physical and social components in sustainability (Partelow, 2018; Rocha et al., 2018), geomorphology/sedimentation literature and SES literature often develop separately: sediment studies emphasize physical mechanisms without explicitly embedding them into SES structure, while SES studies rarely place sediment transport and upstream–downstream connectivity as the main mediation mechanism connecting human activity to coastal system change. Therefore, the main research gap is the limited number of studies that integrate geomorphic processes as a mechanistic bridge between mining activity (actors), changes in resource units (sediment/turbidity), and declines in coastal resource system function within an SES framework, including spatial determinants such as disturbance extent, distance to the coast, and intensity of geomorphic disruption.

Based on this gap, the novelty of this study lies in developing an integrative conceptual model that positions erosion and sediment transport as the primary intermediate mechanism, while mapping how disturbance intensity, landscape connectivity, coastal carrying capacity/resilience, and governance interact to form coastal unsustainability. This paper aims to: synthesize recent literature on nickel mining, sedimentation dynamics, and coastal SES in tropical settings; develop a conceptual model explaining how anthropogenic pressure is mediated by geomorphic processes into ecological change and social response; and identify conceptually when sediment loads exceed coastal tolerance and recovery capacity toward a critical threshold, while formulating conceptual implications for connectivity-based watershed–coastal management.

As a broader macro-context, the Anthropocene concept is used briefly to situate lateritic nickel mining as a form of anthropogenic pressure capable of accelerating sediment-cycle processes and reshaping landscapes over relatively short time scales. However, the analytical focus of this paper remains on the upstream–downstream sediment pathway and its implications for coastal social–ecological systems, rather than on Anthropocene debates per se. Accordingly, the following sections develop a literature-based, mechanistic explanation that links upland disturbance, geomorphic mediation, sediment connectivity, and coastal socio-ecological response within a single integrated analytical framework.

2. Methods

This study used a conceptual–analytical approach based on literature synthesis to develop a mechanistic conceptual model of coastal unsustainability driven by nickel mining. The PRISMA-informed workflow in Section 2.1 is used to transparently document source identification and screening, but the study is not a systematic review aimed at effect-size estimation or exhaustive evidence appraisal. Because no primary data were collected, the design focused on three steps: mapping system components in the SES framework, tracing the mechanistic chain from upstream disturbance to coastal response, and constructing the conceptual model through cross-study synthesis. Model development followed a literature-based conceptual framework development approach built iteratively from recurring patterns across sources (Luft et al., 2022; Naeem et al., 2023).

2.1 Literature search and selection (PRISMA-informed workflow)

A targeted literature search was conducted through scientific databases/search engines and public repositories. Keywords were organized into three clusters: lateritic nickel mining and land disturbance; erosion–sediment transport; and coastal impacts plus socio-ecological and governance dimensions. The search and selection process were documented through identification–screening–inclusion stages, adapting common review reporting guidance (Page et al., 2021; Pantic & Hamilton, 2024). Selected sources included peer-reviewed articles and credible institutional reports for coastal sustainability contexts (IPBES, 2019; UNEP, 2021), emphasizing the last 10 years with limited exceptions for foundational references.

Figure 1 presents the PRISMA flow diagram. Briefly, identification included n = 120 records from database/search-engine queries and n = 5 additional records from repositories and institutional reports. After screening and eligibility assessment, the final synthesis included 30 documents (17 peer-reviewed journal articles, 9 institutional/government/organization reports or handbooks, and 4 supporting documents). After duplicate removal, n = 100 records were screened; n = 60 were excluded at screening, and n = 10 full-text articles were excluded for the reasons summarised in Figure 1.

Table 1. Thematic coverage of the included documents (n=30)

Process theme	Operational focus (extraction variables)	No. of documents informing theme*	Indicative key sources (examples)
Disturbance	Land clearing, vegetation removal, surface morphology change	8	Borrelli et al (2017) Panagos et al (2023) USGS (2023)
Geomorphic mediation	Runoff → erosion → sediment transport; sediment delivery ratio	6	Panagos et al (2023) Renard et al (1997) Wischmeier & Smith (1978)
Sediment connectivity	Upstream–downstream connectivity; drainage/river transport capacity	6	Heckmann et al (2018) Syvitski et al (2005) James (2013)
Resource-unit change	Turbidity / total suspended solids (TSS); water-quality change	8	Babin & Stramski (2004) Petus et al (2016); Macdonald (2015)
Resource-system response	Coastal ecosystem function (mangrove/coral/seagrass)	8	Alongi (2015); Friess et al (2019); Tuttle & Donahue (2022)
Social & governance implications	Livelihood risk; governance response capacity (monitoring, enforcement, rehabilitation)	11	Ostrom (2009); UNEP (2021); IPBES (2019); Climate Rights International (2024); Jaida et al (2023)

Note. Documents may inform more than one theme; counts therefore represent thematic coverage rather than mutually exclusive categories. The table was developed by the authors from the final synthesis dataset (n = 30).

Evidence-base adequacy was assessed for conceptual model development (rather than effect-size estimation) through thematic saturation during coding—additional documents no longer introduced new process themes and primarily refined context variation—and evidence coverage, tabulated by recording which themes each document informed (Table 1). In the final dataset (n = 30), theme coverage ranged from 6 to 11 documents, and each theme was supported by multiple document types (peer-reviewed studies and institutional reports), reducing reliance on single-source claims.

2.2 Unit of analysis and operational extraction variables

Documents were treated as units of analysis. Each included source was extracted using a structured sheet with operational variables: disturbance type (e.g., land clearing, overburden stripping, haul road development); geomorphic mechanisms (e.g., increased runoff, sheet/rill erosion, sediment delivery ratio); sediment indicators (e.g., turbidity, TSS, sediment yield, or equivalent qualitative indicators); coastal ecosystem responses (e.g., reduced light penetration, habitat change in coral/seagrass/mangrove); social impacts (e.g., fisheries/aquaculture disruption, shifting fishing grounds, household risks/costs); and governance elements (regulation, monitoring, enforcement, rehabilitation). These extracted data supported thematic synthesis and SES mapping and anchored the upstream–downstream mechanism explanation (Heckmann et al., 2018; Nagel & Partelow, 2022; Syvitski et al., 2005).

2.3 Unit of analysis and operational extraction variables

Analysis focused on transforming the literature dataset into a mechanistic conceptual model of the upstream–downstream pathway from nickel mining to coastal impact. This technique was chosen to bridge a methodological gap between upland bio-physical processes (erosion–sediment transport) and downstream socio-ecological impacts that are often discussed separately. Because no field data were produced, the analysis aimed to build consistent cross-study causal relationships rather than test statistical hypotheses, consistent with conceptual framework development (Luft et al., 2022).

First, thematic synthesis was conducted through structured coding and data condensation. Extracted findings were initially assigned to the predefined extraction domains: disturbance forms, geomorphic processes, sediment indicators, coastal ecosystem responses, social implications, and governance elements. A mechanistic relationship was retained as a core pathway theme when it was supported by at least two included sources or when one mechanism-focused source provided a clear causal explanation that was directly relevant to the mine–watershed–coast continuum. "Key sources" were defined as reputable peer-reviewed studies with an explicit process explanation, case studies closely matching tropical archipelagic or lateritic contexts, or credible institutional technical reports used for governance and management practice.

When findings differed across sources, they were not averaged or treated as mutually cancelling evidence. Instead, the source context was compared to identify conditions that could explain variation, including rainfall regime, slope, catchment size, distance to the coast, sediment characteristics, river discharge, estuarine or coastal hydrodynamics, and sediment-control practices. Findings were then coded as context-dependent where the direction or magnitude of the response varied but the underlying mechanism remained plausible. A general pathway theme was retained only when a consistent mechanistic link could still be identified across the contextual variation. Claims supported only by isolated evidence or by unresolved contradictory findings were not used as central causal links in the conceptual model, but were retained only as qualifying examples where relevant. This procedure strengthened the traceability of the model while preserving context variation rather than forcing artificial agreement among sources (Naeem et al., 2023).

Second, themes were mapped into the SES framework to make relationships explicit: actors, resource system, resource units, and governance system (Nagel & Partelow, 2022). Mapping structured the pathway: mining activities by actors act as pressure; geomorphic processes (erosion–sediment transport) function as upstream–downstream mediation; sediment/turbidity changes represent changes in resource units; and the governance system moderates or amplifies the pathway through monitoring, enforcement, and rehabilitation. Sediment connectivity literature was used to justify why upland disturbances can remain connected to downstream systems (Heckmann et al., 2018; Syvitski et al., 2005). Finally, the conceptual model was constructed and refined by: drafting the initial pathway; checking logical consistency of each linkage across themes and sources; and revising to accommodate context variation (tropical conditions, dominance of fine lateritic particles, governance role).

2.4 Data collection: search channels, time window, and eligibility criteria

In this study, data were collected in the form of literature documents and treated as the unit of analysis. Because the study aims to build a conceptual model, the primary sources consisted of scientific articles and institutional reports relevant to explaining a single overarching mechanism: how lateritic nickel mining disturbance on land triggers geomorphic processes (runoff–erosion–sediment transport) that subsequently affect coastal ecosystem conditions and coastal communities dependent on those ecosystems. In other words, prior studies were used not merely to summarize "impacts," but to extract mechanistic evidence that can be assembled into a coherent upstream–downstream pathway (Luft et al., 2022; Naeem et al., 2023).

The literature search was conducted through several main channels: Google Scholar and the University of Indonesia Library as broad entry points for cross-publisher discovery; publisher journal pages (to access open-access articles or accepted manuscripts when available); and institutional repositories (e.g., university repositories and open repositories) and credible organizational portals for reports and handbooks. The search window was primarily limited to publications from 2015–2025 to maintain recency, with limited exceptions for foundational references required as conceptual anchors (e.g., SES framework or global sediment-flux framing).

Keyword strategies used Boolean operators (AND/OR) across three clusters: lateritic nickel mining and land disturbance (e.g., nickel laterite, nickel mining, open pit, land clearing, deforestation, overburden, haul road); erosion and sediment processes (e.g., runoff, erosion, sediment yield, sediment delivery ratio, sediment connectivity, suspended sediment, turbidity, TSS); and coastal impacts and socio-ecological governance (e.g., coastal turbidity, mangrove/coral/seagrass, fisheries, livelihood, governance). To ensure relevance for Indonesia as a tropical archipelagic setting, additional contextual keywords were used such as Indonesia, tropical island, archipelago, and ridge-to-reef.

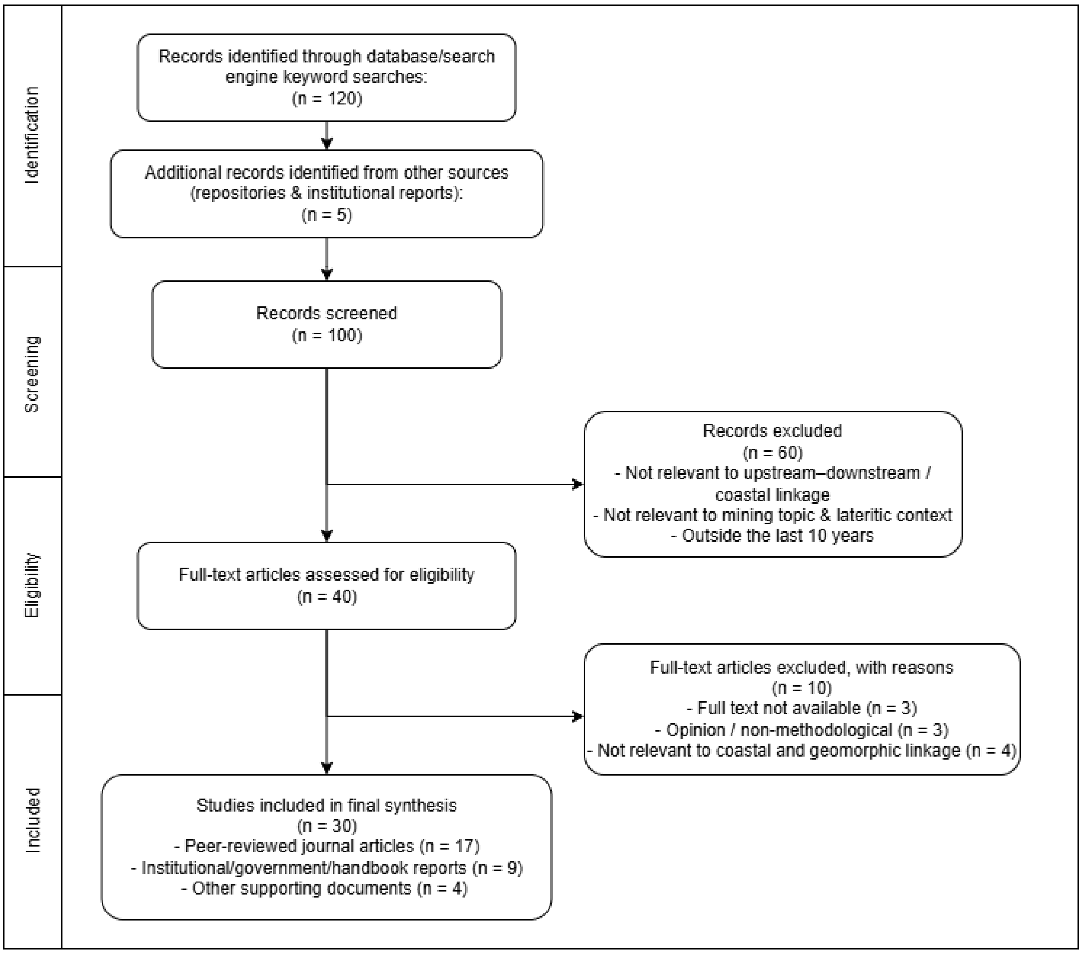

Fig. 1. PRISMA-informed literature selection workflow

Eligibility criteria were defined as follows. Inclusion criteria: studies that explain erosion or sediment-transport mechanisms resulting from land disturbance or extractive activities; studies that link sediment/turbidity to coastal ecosystem change; studies that discuss relevant socio-ecological implications or governance responses; and credible institutional reports for coastal sustainability contexts. Exclusion criteria: sources without accessible full text; opinion pieces without clear methodological basis; duplicates; and studies unrelated to an upstream–downstream/coastal linkage framing. Based on this process, the final synthesis included 30 documents: 17 peer-reviewed journal articles, 9 institutional/government/organizational reports or handbooks, and 4 supporting documents (books, organizational web pages, and investigative media reports). Each included source was extracted using a structured extraction sheet capturing: disturbance type; geomorphic mechanism; sediment indicators; coastal ecosystem response; social impacts; and governance elements (Heckmann et al., 2018; Nagel & Partelow, 2022; Syvitski et al., 2005).

3. Results and Discussion

The initial results stage produced two main outputs: an integrated summary of thematic patterns from the literature synthesis and a mapping of process themes and system components forming the basis for conceptual model construction. Operationally, these outputs were produced through thematic coding of extracted evidence and then organized into an SES-based mapping matrix to connect upstream and downstream processes consistently. Because selection details, dataset composition, and inclusion numbers have been presented earlier (including the PRISMA flow diagram), this section focuses on thematic patterns and the mechanistic structure emerging from the analysed literature.

Overall, the analyzed literature provides complementary coverage of bio-physical processes and socio-ecological dimensions. Land-use change and erosion studies explain why surface disturbance can increase runoff and sediment yield across various landscapes (Borrelli et al., 2017; Panagos et al., 2023). Sediment connectivity studies clarify that impacts do not stop at the disturbance site but can be transmitted through drainage networks and rivers to downstream coastal zones (Heckmann et al., 2018; Syvitski et al., 2005). Coastal ecosystem studies—especially mangroves and tropical coastal systems—show that physical change such as sedimentation and turbidity can disrupt habitat function and ecosystem services (Alongi, 2015; Friess et al., 2019). Methodological and analytical framework literature supports the consistency and traceability of synthesis and system mapping (Naeem et al., 2023; Nagel & Partelow, 2022; Ostrom, 2009). The key pattern from this integration is that upstream change is translated into downstream pressure primarily through sediment delivery mechanisms, so coastal ecological and social impacts can be interpreted as part of a connected process chain.

3.1 Six process themes

Thematic synthesis shows that findings cluster into six process themes forming the upstream–downstream mechanistic pathway (Table 2). These themes are results of coding and grouping from the literature (not an a priori assumption) and serve as the basis for pathway construction:

Table 2. Six process themes derived from thematic coding and causal mapping

Theme	Synthesised meaning (mechanism)	Operational indicators/evidence	SES linkage
Disturbance	Upstream land disturbance initiates the pathway by reducing surface stability and increasing erosion susceptibility.	Land clearing/vegetation removal; surface reshaping; mine infrastructure (Borrelli et al., 2017; Panagos et al., 2023).	Actors' pressure → upstream change
Geomorphic mediation	Runoff → erosion → sediment transport translates disturbance into sediment supply and delivery potential.	Runoff increase; erosion intensity; sediment delivery mechanisms (Renard et al., 1997; Wischmeier & Smith, 1978).	Physical mediation linking actors to resource units
Sediment connectivity	Connectivity controls how efficiently sediment moves	Distance to coast; drainage density; river transport	Amplifies upstream–

	through drainage networks to the coast; high connectivity accelerates downstream response.	capacity; rainfall regime (Heckmann et al., 2018; Syvitski et al., 2005).	downstream coupling
Resource-unit change (turbidity/TSS)	Sediment reaching the coast manifests first as changes in *resource units*, especially turbidity and TSS.	Turbidity/TSS; optical/light attenuation change (Babin & Stramski, 2004; Macdonald, 2015; Petus et al., 2016).	Resource units provide early operational signal
Resource-system response	Persistent sediment stress reduces coastal ecosystem function and services, potentially lowering resilience and carrying capacity.	Coral light limitation, altered Symbiodiniaceae photophysiology, sediment deposition and clearance stress; mangrove root-zone oxygen limitation, pneumatophore exposure or burial, and habitat-service decline (Al-Khayat & Alatalo, 2021; Alongi, 2015; Bessell-Browne et al., 2017; Friess et al., 2019; Tuttle & Donahue, 2022).	Resource system function declines
Social & governance implications	Ecological degradation translates into livelihood risks and triggers governance responses; response capacity moderates whether pressure becomes chronic.	Fisheries/aquaculture disruption; monitoring/enforcement/rehabilitation capacity (Climate Rights International, 2024; IPBES, 2019; Jaida et al., 2023; Ostrom, 2009; Syarifuddin, 2022; UNEP, 2021).	Governance system as moderator; feedback to actors

Note. The six themes were generated through structured extraction, thematic coding, and causal mapping of the included documents. SES = social–ecological systems.

Across studies, the most consistent cross-study pattern is a repeating causal chain: (i) land-cover disturbance and surface morphology change increase runoff and erosion, especially under high rainfall (Borrelli et al., 2017; Panagos et al., 2023); (ii) sediment produced upstream becomes downstream pressure when sediment connectivity is high—e.g., short upstream–downstream distance, dense drainage networks, and sufficient river transport capacity—so suspended sediment/turbidity can be transmitted efficiently to coastal zones (Heckmann et al., 2018; Syvitski et al., 2005); and (iii) repeated turbidity pressures reduce water quality and stress sensitive coastal habitats, which can later generate social impacts on fisheries/aquaculture and trigger governance response needs (Alongi, 2015; Friess et al., 2019; IPBES, 2019; UNEP, 2021). This pattern supports the analytical contribution of the study: it does not only state that "impacts occur," but identifies where the pathway is amplified (connectivity) and which operational indicator is most stable for detection across system components (turbidity/TSS).

Operationally, these themes were assembled from the extraction variables defined in the methods section (disturbance type, geomorphic mechanism, sediment indicators, coastal ecological responses, social impacts, and governance elements). This extraction-to-theme workflow provides a transparent link between the literature dataset and the conceptual model: themes are not narrative labels, but represent recurring "modules" of the same upstream–downstream chain across multiple studies (Luft et al., 2022; Naeem et al., 2023). The six-theme structure also helps position where management can intervene—either at the source of disturbance, along the transmission pathway (connectivity), or at the point of early detection (turbidity/TSS)—before ecological and social consequences become chronic (IPBES, 2019; UNEP, 2021).

3.2 SES mapping and summary pathway

The themes were mapped into SES to build a consistent analytical structure. In this mapping, mining activities and affected groups are positioned as actors; the connected land–watershed–coast as the resource system; sediment/turbidity and water quality as resource units; and regulation, monitoring, and rehabilitation as the governance system (Ostrom, 2009). The pathway presented is derived from mapping literature into the SES matrix rather than an initial assumption. The causal flow is summarized as: land disturbance triggers increased runoff/erosion and sediment transport; geomorphic processes increase resource units (sediment/turbidity and water quality change); resource-unit change reduces resource-system function (coastal ecosystems); declining ecosystem function then leads to social consequences.

Along this pathway, governance is positioned as a factor that can moderate (through monitoring, enforcement, rehabilitation) or fail to intervene, allowing impacts to continue. In Indonesia's tropical archipelagic context, the thematic pattern is strengthened by short upstream–downstream distances, high rainfall, and fine lateritic sediments. Spatial proximity shortens response time because sediment travel distance and time are relatively brief and landscape buffering capacity can be limited, so coastal responses may appear faster and recur. Conceptually, these conditions increase the likelihood of persistent suspension and prolonged turbidity, so pressure on shallow-water habitats and coastal community activities can last longer than in systems with faster-settling sediments. These findings do not provide quantitative impact magnitudes because no field measurement was performed; rather, they provide a mechanistic and traceable analytical foundation for subsequent analysis, including consistency checks across links and conceptual identification of critical thresholds.

In practical terms, the SES mapping clarifies the differentiation between resource units and the resource system. In this paper, turbidity/TSS and coastal water quality are treated as resource units because they are measurable "units" that change first and provide operational evidence of upstream pressure reaching the coast. By contrast, the coastal ecosystem (e.g., mangrove and coral-reef functions) is treated as the resource system because it represents the broader ecological structure and function that is affected after resource units deteriorate. This distinction is important because governance interventions can be triggered at the resource-unit level (e.g., early warning from turbidity/TSS) before the resource system experiences longer-term functional decline.

3.3 Analysis of results based on criteria/variables (SES-based)

This section analyzes the thematic synthesis using variables defined and mapped in the SES framework. Analysis is conceptual to assess how each variable shapes the upstream–downstream pathway from mining disturbance to coastal socio-ecological response. The mechanistic pathway below is derived from literature synthesis through thematic coding and causal mapping to the SES matrix; relationships therefore follow recurring cross-source patterns rather than generalization from a single case (Naeem et al., 2023; Nagel & Partelow, 2022; Ostrom, 2009). Tables 3 and 4 summarize the SES-based variables, their mechanistic roles, operational indicators, downstream implications, and governance responses along the upstream–downstream sediment pathway**.**

Table 3. SES-based variables, mechanistic roles, operational indicators, and downstream implications

SES criteria/variable	Mechanistic role in the upstream–downstream pathway	Operational indicators extracted from the literature	Main ecological–social implication
Disturbance (trigger)	Initiates the pathway by exposing soil and surficial material, reducing land	Land clearing or vegetation loss; surface morphology	Greater likelihood that sediment enters flow networks and generates

	stability, and increasing runoff–erosion potential (Borrelli et al., 2017).	modification; haul roads and other mining infrastructure; disturbed-area extent and intensity.	downstream turbidity pulses, particularly where mediation and connectivity are high.
Geomorphic mediation: runoff → erosion → sediment transport	Translates anthropogenic disturbance into biophysical change and determines whether sediment remains local or becomes downstream pressure (Panagos et al., 2023).	Runoff intensity; sheet or rill erosion; sediment supply to rivers; seasonal rainfall and erosivity signals.	Efficient transport converts upland sediment into recurring coastal stress; disrupted transport pathways reduce downstream exposure.
Sediment connectivity (pathway amplifier)	Governs delivery efficiency from upland disturbance to coastal waters, determining how much available sediment reaches downstream environments (Heckmann et al., 2018).	Upstream–downstream distance; drainage-network structure; river transport capacity; hydrometeorological conditions; connectivity breaks or buffers.	Explains why similar mining disturbance can produce different coastal outcomes; where fine iron-oxide-rich lateritic fractions are mobilised, they may remain suspended longer and contribute to prolonged turbidity under site-specific hydrodynamic conditions.
Resource units: turbidity, suspended sediment, and water quality	Provides the most stable operational marker that the land-to-coast pathway is active and bridges upstream processes with downstream ecological response (Babin & Stramski, 2004; Syvitski et al., 2005)	Turbidity/TSS; suspended sediment; water-quality proxies; optical or light-attenuation change.	Signals stress in shallow coastal waters; prolonged turbidity may reduce benthic light availability and increase pressure on sensitive habitats.
Resource-system response: coastal ecosystem function and analytical threshold	Represents functional decline when repeated resource-unit pressure exceeds recovery capacity; frames the ecological threshold analytically rather than as a single measured value (IPBES, 2019).	Reduced benthic light; coral symbiont and photochemical stress; sediment deposition on coral tissue; mangrove root-zone oxygen limitation and pneumatophore exposure; substrate change and habitat-function disturbance.	Declining coral and mangrove function, reduced ecosystem services, increased vulnerability, and greater transformation risk as resilience declines (Berkes & Folke, 1998; Rocha et al., 2018).
Social consequences	Connects ecological degradation to livelihood impacts among coastal users and households dependent on ecosystem functions.	Fisheries or aquaculture disruption; changing fishing grounds; household risks and costs; social vulnerability and unequal access to coastal resources.	Socio-economic pressure and environmental-justice risks may emerge when downstream households disproportionately bear the costs of ecological decline (IPBES, 2019; UNEP, 2021).
Feedback feature (system dynamics)	Explains how downstream degradation feeds back to actors and governance,	Public complaints; conflict; demands for monitoring or zoning;	Demonstrates that impacts are not endpoints: social pressure

	reshaping behaviour and institutional response over time (Ostrom, 2009; UNEP, 2021)	audit pressure; social-license and reputational costs.	can alter mining practices, increase oversight, and intensify adaptive governance.

Note. This table presents a literature-synthesis-based interpretation of mechanistic roles, indicators, and downstream implications within the proposed SES framework. It does not report site-specific measured effect sizes. SES = social–ecological systems; TSS = total suspended solids.

Table 3 demonstrates that the upstream–downstream pathway is shaped not by a single factor, but by interactions among disturbance intensity, geomorphic mediation, sediment connectivity, changes in turbidity/TSS, ecosystem sensitivity, and social feedback. This diagnostic structure also clarifies that governance interventions should not be concentrated only at the mine site or only at the coast. Instead, responses need to be aligned with the specific pathway segment where sediment generation, transport, delivery, ecological exposure, or social consequences are most critical. Table 4 therefore translates the SES-based analysis into governance responses that can be applied across the mine–watershed–coast continuum.

Table 4. Governance responses along the upstream–downstream sediment pathway

Critical pathway segment	Main governance response	Intended function
Disturbance source: mine footprint and disturbed surfaces	Limit and stage clearing; maintain vegetation buffers; plan drainage; stabilize exposed surfaces; implement erosion-control measures; conduct rapid revegetation and maintenance.	Reduce sediment availability and runoff generation before material enters drainage networks.
Geomorphic mediation: slopes, drainage, and channels	Apply runoff interception and routing; install and maintain sediment traps or check dams where appropriate; manage slopes; protect channels; undertake wet-season preparedness and inspection.	Interrupt or weaken the runoff–erosion–transport sequence that converts mine-site disturbance into sediment delivery.
Sediment connectivity: critical tributaries, river corridors, and outlets	Identify critical links; protect river corridors; establish retention and buffer areas; reduce direct connectivity where feasible; apply event-based controls during high rainfall.	Reduce delivery efficiency from uplands to estuaries and nearshore waters.
Resource units: river outlets, estuaries, and shallow nearshore waters	Conduct routine and event-based turbidity/TSS monitoring at key nodes; define analytical thresholds and response triggers; investigate repeated exceedance or worsening trends.	Detect active sediment pressure early and activate intervention before ecosystem-level degradation becomes chronic.
Resource-system response: coral, mangrove, and other sensitive habitats	Protect sensitive habitats; strengthen buffers; conduct targeted restoration; use turbidity/TSS trends to trigger early ecological assessment and management action.	Maintain ecological function and recovery capacity before repeated exposure produces more persistent decline.
Social consequences and feedback	Provide reporting and grievance mechanisms; strengthen compliance enforcement and environmental audits; coordinate watershed–coast institutions; incorporate community concerns into adaptive management.	Address livelihood and environmental-justice risks while converting downstream feedback into improved oversight and response capacity.

Legacy sediment within flow networks and land–sea transition zones	Include stored sediments in rehabilitation planning; assess sediment storage areas in rivers, floodplains, estuaries, and nearshore zones; prioritize management where resuspension may sustain turbidity.	Reduce reliance on mine-site revegetation alone when previously mobilised sediments may continue to affect coastal waters.

Note. Governance is interpreted as response capacity rather than solely as the presence of formal rules. Responses should be adapted to site-specific hydrology, geomorphic connectivity, sediment characteristics, ecosystem sensitivity, and institutional capacity.

In addition, the SES-based analysis highlights a critical feedback feature of the system. Once coastal resource-system functions decline and livelihoods are disrupted, social pressure and conflict can feed back to actors and governance through public complaints, increased scrutiny, and demands for stronger coastal zoning, stricter monitoring requirements, or environmental audits for mining companies. These feedbacks demonstrate that downstream impacts are not merely endpoints; they can reshape actor behaviour, increase operational and reputational pressures, and stimulate more adaptive governance responses over time (Ostrom, 2009; UNEP, 2021). In this regard, the governance responses outlined in Table 4 should be understood not only as preventive measures, but also as mechanisms for responding to ecological and social signals that emerge along the mine–watershed–coast continuum.

Overall, the analysis indicates that coastal unsustainability does not arise from mining presence alone. Rather, it emerges through systemic interactions among disturbance intensity, geomorphic mediation, sediment connectivity, changes in turbidity/TSS and water quality, coastal ecosystem sensitivity, social consequences, and the capacity of governance systems to intervene at critical points along the pathway. Tables 3 and 4 therefore show that effective management requires both an understanding of the mechanisms that generate downstream sediment pressure and governance responses tailored to the specific segments where that pressure can be prevented, interrupted, detected, or mitigated.

3.4 Comparison with previous studies

This section compares the conceptual model developed in this study with prior literature to clarify the study's contribution: not adding new empirical field measurements, but integrating cross-disciplinary findings into a traceable upstream–downstream pathway within an SES framing (Nagel & Partelow, 2022; Ostrom, 2009). In many bodies of work, erosion/sedimentation studies and coastal socio-ecological studies have developed within different disciplinary spaces, so upstream mechanisms are not always explicitly linked to downstream socio-ecological consequences. The comparison below highlights where this study aligns with prior findings and where it adds value by making the "missing link" explicit—particularly the role of geomorphic mediation and sediment connectivity as the bridge from upland disturbance to coastal socio-ecological pressure.

Overall, this study synthesizes the key findings of previous literature into a single mechanistic conceptual model that connects upstream disturbance, sediment delivery pathways, coastal ecosystem degradation, and social consequences under the SES framework. Overall, the comparison indicates that this study is consistent with core findings in prior literature—disturbance increases erosion, hydroclimate amplifies mobilization, connectivity governs delivery, and turbidity/sedimentation can degrade coastal ecosystems (Alongi, 2015; Borrelli et al., 2017; Friess et al., 2019; Heckmann et al., 2018; Panagos et al., 2023). The key added value is the explicit integration of these elements into a single SES-based mechanistic chain, making the upstream–downstream linkage traceable and analytically coherent rather than implicitly assumed.

Table 5. Comparison matrix: prior literature clusters and the contribution of this study

Literature cluster	What prior literature establishes and commonly leaves implicit	Contribution of this study
Land-use change and erosion	Land disturbance increases runoff and erosion, raising the potential for downstream sediment pressure (Borrelli et al., 2017). Studies often remain at a general cause–effect level without embedding the pathway within a socio-ecological structure.	Positions disturbance as the pathway trigger and explicitly links it to downstream ecological and social outcomes through geomorphic mediation and sediment connectivity within SES.
Rainfall erosivity and hydroclimate	Tropical rainfall regimes amplify runoff and erosion and are commonly treated as stand-alone environmental drivers (Panagos et al., 2023).	Treats rainfall as a pathway intensifier operating within geomorphic mediation and connectivity, clarifying how hydroclimate accelerates downstream exposure.
Sediment connectivity	River networks, distance to the coast, and transport capacity determine whether erosion becomes a coastal impact (Heckmann et al., 2018). Connectivity is often treated primarily as a natural landscape property.	Reframes connectivity as a mechanism shaped by disturbance and management, linking actors' pressure to changes in resource units, especially turbidity/TSS, and downstream socio-ecological effects (Syvitski et al., 2005).
Coastal ecosystem response	Sedimentation and turbidity can degrade habitat functions and ecosystem services in mangroves and tropical coastal ecosystems, but upstream sediment-generation processes are often not fully traced (Alongi, 2015; Friess et al., 2019).	Connects upland disturbance → sediment delivery → turbidity/TSS → coastal ecosystem-function decline, making upstream drivers and downstream responses traceable within SES.
SES applications and governance	SES identifies actors, resource systems, resource units, and governance systems, but physical mediation may remain implicit or purely categorical (Ostrom, 2009; Partelow, 2018).	Provides process-based content for SES: erosion, sediment transport, and connectivity operate as the explicit bridge between actors' pressure, resource-unit change, resource-system decline, and governance response capacity.
Resilience, thresholds, and transformation	Repeated pressures can reduce resilience and contribute to system shifts, but empirical thresholds are usually site-specific and may not be directly operational in data-limited contexts (Berkes & Folke, 1998; Rocha et al., 2018).	Uses an analytical-threshold framing linked to turbidity/TSS as an early-warning indicator while maintaining that quantitative thresholds require local validation.
Institutional and global assessments	Broad assessments highlight environmental degradation, vulnerability, and unequal access to resources, but frequently do not specify how upland disturbance becomes downstream socio-ecological pressure (IPBES, 2019; UNEP, 2021).	Adds a mechanistic land-to-coast pathway that operationalises environmental-justice concerns and identifies where governance can interrupt, moderate, or respond to sediment-driven pressure.

Note. This comparison synthesises representative literature clusters and their typical analytical emphasis; it is not intended as an exhaustive systematic comparison of all studies in each field. SES = social–ecological systems; TSS = total suspended solids.

From an institutional perspective, global assessments and policy-oriented reports emphasize that ecosystem degradation interacts with social vulnerability and unequal access to resources; therefore, downstream sediment pressures can also be interpreted as an environmental-justice issue when costs are disproportionately borne by coastal households (IPBES, 2019; UNEP, 2021). Compared with such broad framing, this study contributes a process-based pathway that makes the missing link explicit: how upland disturbance becomes downstream socio-ecological pressure through geomorphic mediation and connectivity, and where governance capacity can interrupt or moderate that pathway (Nagel & Partelow, 2022; Ostrom, 2009).

3.5 Implications and in-depth discussion

The findings imply that environmental risk should not be assessed solely at the mine footprint but across the coupled land–watershed–coast system (Heckmann et al., 2018; Syvitski et al., 2005). A central implication is conceptual: coastal turbidity should be interpreted as an accumulated outcome of upstream processes rather than as an isolated "pollution" indicator. When land disturbance increases runoff and erosion, and when sediment connectivity is high, turbidity becomes the operational marker that the upstream–downstream pathway is active. These reframing matters because it shifts attention from a single location (the mine site) to a process pathway that spans the catchment and coastal zone.

The study also strengthens the SES framework by giving mechanistic content to relationships among components. SES is often used to classify actors, resource units, resource systems, and governance. Here, those components are linked through a traceable causal chain: actors (mining operations, and downstream users such as coastal households) generate disturbance; geomorphic processes mediate transmission (runoff → erosion → sediment transport); resource units change (turbidity/TSS and water quality); the coastal resource system experiences functional decline; social consequences emerge; and governance moderates the pathway through response capacity (Nagel & Partelow, 2022; Ostrom, 2009; Partelow, 2018). Importantly, coastal degradation is not an endpoint. As fisheries and aquaculture are disrupted and coastal households face higher costs and risks, negative feedback may arise through social pressure, conflict over coastal space, and reputational or operational risks for mining companies, affecting social license to operate and prompting stronger governance responses (Ostrom, 2009; UNEP, 2021).

Bio-physically, the implications are sharpened in tropical archipelagic settings such as Indonesia. High rainfall and short upstream–downstream distances shorten response time and can increase the frequency of turbidity pulses during the wet season (Panagos et al., 2023). Where fine lateritic particle fractions are mobilised, their mineralogical and optical properties may contribute to prolonged turbidity through slower settling, light scattering, and attenuation. The extent of this effect is context-dependent and may vary with grain-size distribution, flocculation, salinity, discharge intensity, and local coastal hydrodynamics. The reviewed literature also suggests that sediment delivered from disturbed uplands can be stored temporarily within river networks, floodplains, estuaries, or shallow coastal zones and may later be resuspended during high-flow events or wave action. Such legacy sediment can sustain turbidity pressure after upstream disturbance has declined, although the magnitude and duration of this process require site-specific field verification (James, 2013; Syvitski et al., 2005). Practically, this implies that recovery strategies cannot rely solely on revegetation of disturbed surfaces; they also need to consider sediment already stored within the delivery system.

At the level of water-column optics, suspended mineral matter affects light availability through both scattering and absorption. Where mining disturbance mobilises, fine lateritic fractions containing iron-oxide-rich particles, their influence may extend beyond a simple increase in visual turbidity. Iron-bearing mineral assemblages can modify spectral light absorption, while the magnitude of scattering and attenuation depends on particle-size distribution, concentration, mineralogical composition, aggregation or flocculation, and water chemistry. In coastal receiving waters, the combined effects of scattering and absorption can reduce both the quantity and spectral quality of downwelling light reaching benthic habitats. Consequently, similar turbidity or TSS values may not represent the same ecological exposure at different sites when suspended-material composition, river discharge, salinity, or coastal hydrodynamics differ. In this study, turbidity/TSS should therefore be interpreted as an operational indicator of a broader optical exposure regime rather than as a direct one-to-one measure of ecological damage (Babin & Stramski, 2004; Macdonald, 2015; Stramski et al., 2007).

For coral reefs, reduced benthic irradiance can constrain photosynthesis by symbiotic dinoflagellates of the family Symbiodiniaceae and may thereby affect energy acquisition for tissue maintenance, growth, calcification, and recovery. Corals may show short-term photoacclimation under reduced light, but prolonged or repeated light limitation can reduce physiological performance depending on coral taxon, depth, prior adaptation to naturally turbid conditions, and the duration and intensity of exposure. Suspended sediment also creates a stress pathway distinct from light attenuation: particles settling on coral tissue may require mucus production and ciliary transport for removal, increasing energy expenditure and reducing energy available for growth and recovery. Fine sediment can also constrain larval settlement even where adult colonies tolerate brief exposure. In mangroves, excessive deposition may alter sediment porosity and oxygen availability; where aerial roots are present, burial or obstruction of pneumatophores can constrain gas exchange and intensify root-zone stress. Thus, ecological response is shaped by multiple linked processes rather than turbidity alone (Al-Khayat & Alatalo, 2021; Bessell-Browne et al., 2017; Tuttle & Donahue, 2022).

Accordingly, this study does not treat coral-stress thresholds as a universal numerical TSS or turbidity value. Ecological thresholds are context-dependent because they vary with exposure intensity, duration, recurrence, sediment deposition rate, grain size, water movement, reef depth, species composition, life stage, and the background light environment. The analytical-threshold approach proposed here should therefore be understood as a management trigger based on repeated exceedance, worsening trends, or deviations from locally established background conditions, followed by field investigation and intervention. This approach is more suitable for a conceptual model than prescribing a single threshold value for all Indonesian coastal settings. Site-based monitoring should subsequently integrate turbidity/TSS, light attenuation, sediment deposition, coral condition, and local hydrodynamic conditions to derive thresholds that are ecologically meaningful and operationally applicable (Bessell-Browne et al., 2017; Petus et al., 2016; Tuttle & Donahue, 2022).

Within a carrying capacity and resilience framing, sustained or repeated pressures can reduce recovery capacity and increase the risk of transformation to a less functional state (Berkes & Folke, 1998; IPBES, 2019; Rocha et al., 2018). This reinforces the need to interpret turbidity/TSS trends together with locally measured light attenuation, sediment deposition, habitat condition, and hydrodynamic setting when evaluating whether ecological recovery capacity is being compromised. From a governance and management perspective, the most operational pathway suggested by the synthesis is to use turbidity/TSS as an analytical-threshold early-warning indicator. Turbidity is relatively feasible to monitor routinely and is directly connected to upstream erosion–transport–connectivity processes; it therefore provides a practical trigger for response before pressures become chronic and ecosystem resilience declines (IPBES, 2019; UNEP, 2021). Governance should be understood as response capacity rather than rules alone: routine and event-based monitoring, compliance enforcement, resources for erosion/sediment controls, and effective rehabilitation across the watershed–coast continuum. In short-response systems, delayed detection increases the likelihood that intervention occurs only after ecosystem-level degradation is well advanced. Therefore, integrated watershed–coastal governance, supported by early-warning monitoring and coordinated interventions along the sediment pathway, is the most practical implication of the model (Ostrom, 2009; UNEP, 2021).

3.6 Synthesis of discussion and research limitations

This study synthesizes nickel mining impacts on coastal systems as an upstream–downstream mechanistic pathway within SES: disturbance → geomorphic mediation (runoff → erosion → sediment transport) → sediment connectivity → turbidity/TSS and water-quality change → coastal ecosystem function decline → social consequences, moderated by governance response capacity (Nagel & Partelow, 2022; Ostrom, 2009). The thematic synthesis indicates that the pathway is not a single linear "impact statement" but a connected process chain that can be traced across recurring patterns in the literature. In this sense, the main contribution is analytical: it provides a coherent structure that bridges physical-process studies and socio-ecological studies that are often discussed separately (Heckmann et al., 2018; Partelow, 2018; Syvitski et al., 2005).

A key synthesis point is that geomorphic processes function as the bridge that transmits upstream pressure into downstream change. Land disturbance and land-cover change can increase runoff and erosion, especially under high rainfall (Borrelli et al., 2017; Panagos et al., 2023). However, downstream impact depends on whether the landscape efficiently delivers sediment; sediment connectivity therefore becomes the pathway amplifier, shaping when and how coastal waters experience turbidity pulses (Heckmann et al., 2018). In tropical archipelagic settings, spatial proximity and intense rainfall can shorten response times and increase event frequency, making repeated pressures more likely. Where fine lateritic sediment fractions are mobilised, they may contribute to prolonged turbidity and the temporary storage of sediment that can later be resuspended. This context-dependent mechanism may help explain why recovery can lag behind reductions in upstream disturbance, but its magnitude and duration require site-specific validation (Babin & Stramski, 2004; James, 2013; Macdonald, 2015).

Another synthesis point is that the pathway does not end at ecological change. As resource-system function declines, socio-economic consequences emerge through fisheries and aquaculture disruption, shifts in fishing grounds, and increased household risks and costs. These effects can be unevenly distributed and may raise environmental-justice concerns, as emphasized in institutional assessments (IPBES, 2019; UNEP, 2021). Moreover, downstream impacts can feed back to actors and governance through social pressure and higher operational/reputational costs, potentially prompting stricter oversight or coordinated management responses (Ostrom, 2009; UNEP, 2021). This feedback framing reinforces the logic of using SES: it connects biophysical processes, social consequences, and governance capacity in a single system.

Because the study relies on secondary literature and does not collect field data, findings are conceptual and do not quantify numeric thresholds. This is not only a limitation but also a design-efficiency choice: a literature-based model is appropriate for building an initial analytical framework where site measurements are not yet available (Luft et al., 2022; Naeem et al., 2023). Nonetheless, several limitations should be acknowledged. First, publication bias may exist: studies reporting impacts may be easier to identify than "low/no impact" studies. Second, heterogeneity across contexts (rainfall regimes, catchment geomorphology, distance to the coast, and management practices) limits overly specific generalization. Third, thematic synthesis and SES mapping involve interpretive elements even when decision rules are applied; therefore, transparency in coding and causal mapping is essential for traceability (Naeem et al., 2023). Fourth, coding and causal mapping were conducted by a single researcher; an independent inter-coder reliability assessment was not performed. Although the coding protocol, decision rules, thematic coverage matrix, and documentation of context variation were used to strengthen transparency and traceability, single-coder interpretation remains a potential source of analytical bias. Future applications of the framework could use independent dual coding or peer debriefing to assess coding consistency and further strengthen the robustness of the conceptual model.

A further limitation concerns the interpretation of lateritic fine-particle behaviour and legacy-sediment resuspension. Because the study synthesises evidence across different environmental settings and does not include direct sedimentological, hydrodynamic, or water-quality measurements from a specific nickel-mining catchment, these relationships are presented as indicative mechanistic patterns rather than field-verified empirical proofs. Their magnitude and persistence are likely to vary according to particle-size distribution, mineralogy, rainfall regime, river discharge, estuarine mixing, coastal hydrodynamics, and local sediment-control practices. Future site-based research should therefore test these mechanisms through seasonal turbidity/TSS monitoring, sediment-characterisation analysis, and mapping of sediment storage and resuspension zones.

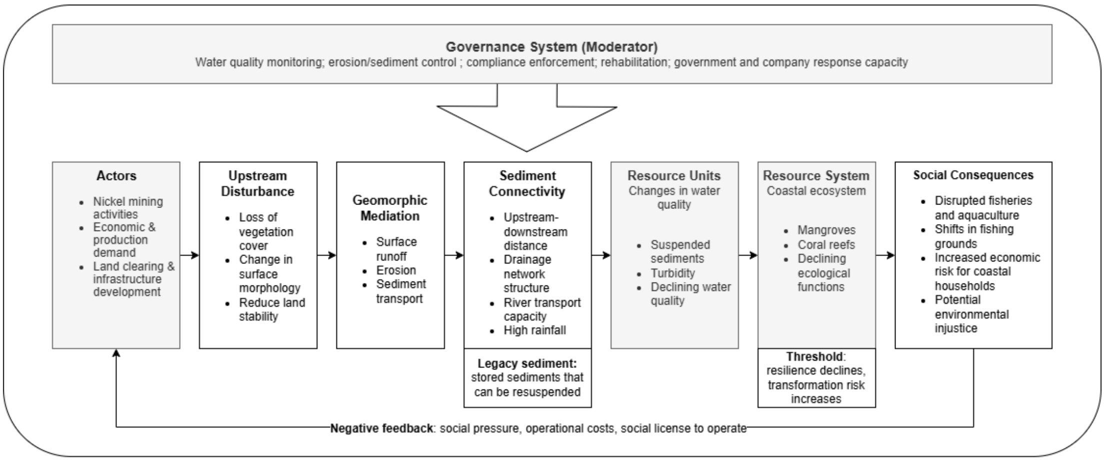

Fig. 2. Mechanistic upstream–downstream conceptual model of nickel mining impacts on coastal ecosystems within an SES framework

These limitations define a clear agenda for future research. The next logical step is to test the conceptual model at specific sites using seasonal turbidity/TSS monitoring, sediment-connectivity mapping, and indicators of coastal ecosystem and livelihood response. Such testing would help refine context-specific analytical thresholds and evaluate intervention effectiveness. Importantly, because legacy sediment can sustain turbidity pressures, monitoring and management should include not only mine-site revegetation but also sediment stored within river networks and nearshore deposits (James, 2013; Syvitski et al., 2005). The full synthesis is summarized in the conceptual model and mechanistic pathway diagram (Figure 2), which serves as the primary visual reference for the upstream–downstream linkage described in this paper.

4. Conclusions

This paper concludes that nickel mining impacts on coastal ecosystems should not be treated as isolated local phenomena, but as an upstream–downstream process pathway operating within a Social–Ecological Systems (SES) framework. In this system, pressure from upstream actors is functionally connected to downstream ecosystems through common bio-physical mechanisms; therefore, analysis should not separate upland processes from coastal responses (Heckmann et al., 2018; Ostrom, 2009). The literature synthesis indicates a consistent mechanistic chain: upland disturbance triggers geomorphic processes (runoff → erosion → sediment transport), strengthened by sediment connectivity, which drives resource-unit change (turbidity/TSS and water quality) and reduces coastal resource-system function. This decline then generates social consequences, while governance determines whether the pathway is moderated or develops into chronic pressure (Heckmann et al., 2018; Ostrom, 2009; Syvitski et al., 2005).

In tropical archipelagic settings such as Indonesia, short upstream–downstream distances and high rainfall shorten response time and raise the risk of repeated pressure events. Where fine lateritic sediment fractions are mobilised, they may contribute to prolonged turbidity and the formation of stored sediment that can later be resuspended, potentially delaying recovery even after upstream disturbance decreases. The magnitude of this process is context-dependent and should be tested through site-specific monitoring and sediment-characterisation studies (Babin & Stramski, 2004; James, 2013; Macdonald, 2015). Therefore, environmental recovery should not focus only on revegetation of mined surfaces, but should also address stored sediments within river networks and land–sea transition zones to reduce long-term coastal impacts (James, 2013; Syvitski et al., 2005).

Three operational recommendations follow from this synthesis. First, management should shift from a mine-site focus to integrated watershed–coastal management that explicitly addresses sediment transmission pathways, including main channels, critical tributaries, estuaries, and shallow nearshore habitats adjacent to sensitive ecosystems. These locations are particularly important because they provide the most direct evidence that the upstream–downstream pathway is active and that sediment pressures may be accumulating (Heckmann et al., 2018; Syvitski et al., 2005).

Second, turbidity/TSS should be used as an analytical-threshold early-warning indicator through routine and event-based monitoring at upstream outlets, estuaries, and shallow nearshore waters. Repeated exceedance or worsening trends should trigger investigation and response before ecosystem-level degradation becomes chronic. Without timely detection of turbidity pressure, intervention may occur only after ecological recovery capacity has already declined (IPBES, 2019; UNEP, 2021).

Third, governance should be strengthened as response capacity rather than understood solely as the presence of formal rules. This includes monitoring resources, compliance enforcement, rehabilitation effectiveness, cross-scale coordination across the watershed–coast continuum, and management of stored or legacy sediments within flow networks and land–sea transition zones. Such measures are necessary because recovery cannot rely on revegetation of mined surfaces alone when previously mobilized sediments continue to affect coastal waters (Ostrom, 2009; UNEP, 2021). Finally, future work should empirically test this model at specific locations through seasonal turbidity/TSS measurement, sediment-connectivity mapping, and monitoring of coastal ecosystem and livelihood responses to refine context-specific thresholds and evaluate intervention effectiveness.

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References

Al-Khayat, J. A., & Alatalo, J. M. (2021). Relationship between tree size, sediment mud content, oxygen levels, and pneumatophore abundance in the mangrove tree species avicennia marina (Forssk.) Vierh. *Journal of Marine Science and Engineering*, *9*. https://doi.org/10.3390/jmse9010100

Alongi, D. M. (2015). The impact of climate change on mangrove forests. *Current Climate Change Reports*, *1*(1), 30–39. https://doi.org/10.1007/s40641-015-0002-x

Babin, M., & Stramski, D. (2004). Variations in the mass-specific absorption coefficient of mineral particles suspended in water. *Limnology and Oceanography*, *49*(3), 756–767. https://doi.org/10.4319/lo.2004.49.3.0756

Berkes, F., & Folke, C. (1998). *Linking social and ecological systems: Management practices and social mechanisms for building resilience*. Cambridge University Press. https://doi.org/10.5751/ES-00202-040205

Bessell-Browne, P., Negri, A. P., Fisher, R., Clode, P. L., & Jones, R. (2017). Impacts of light limitation on corals and crustose coralline algae. *Scientific Reports*, *7:11553*(August), 1–12. https://doi.org/10.1038/s41598-017-11783-z

Borrelli, P., Robinson, D. A., Fleischer, L. R., Lugato, E., Ballabio, C., Alewell, C., Meusburger, K., Modugno, S., Schütt, B., Ferro, V., Bagarello, V., Oost, K. Van, Montanarella, L., & Panagos, P. (2017). An assessment of the global impact of 21st century land use change on soil erosion. *Nature Communications*, *8*(1). https://doi.org/10.1038/s41467-017-02142-7

Climate Rights International. (2024). *Nickel unearthed: The human and climate costs of Indonesia's nickel industry*. https://cri.org/reports/nickel-unearthed/

Friess, D. A., Rogers, K., Lovelock, C. E., Krauss, K. W., Hamilton, S. E., Lee, S. Y., Lucas, R., Primavera, J., Rajkaran, A., & Shi, S. (2019). The state of the world's mangrove forests: Past, present, and future. *Annual Review of Environment and Resources*, *44*, 89–115. https://doi.org/10.1146/annurev-environ-101718-033302

Heckmann, T., Cavalli, M., Cerdan, O., Foerster, S., Javaux, M., Lode, E., Smetanová, A., Vericat, D., & Brardinoni, F. (2018). Indices of sediment connectivity: Opportunities, challenges and limitations. *Earth-Science Reviews*, *187*, 77–108. https://doi.org/10.1016/j.earscirev.2018.08.004

IEA. (2021). *The role of critical minerals in clean energy transitions*. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

IPBES. (2019). *Global assessment report on biodiversity and ecosystem services*. https://doi.org/10.5281/zenodo.3831673

Jaida, I., Sahadi, A. A., & Ginting, P. (2023). *Kebijakan, risiko, dan pencegahan dampak pertambangan nikel pada laut di Indonesia: Dengan hasil penelitian studi lapangan di* *kawasan Indonesia Morowali Industrial Park*. Aksi Ekologi dan Emansipasi Rakyat (AEER). https://www.aeer.or.id/wp-content/uploads/2023/08/Kertas-Kebijakan_Kebijakan-Risiko-dan-Pencegahan-Dampak-Pertambangan-Nikel-Pada-Laut-di-Indonesia-.pdf

James, L. A. (2013). Legacy sediment: Definitions and processes of episodically produced anthropogenic sediment. *Anthropocene*, *2*, 16–26. https://doi.org/10.1016/j.ancene.2013.04.001

Kementerian Lingkungan Hidup dan Kehutanan Republik Indonesia. (2021). *Peraturan menteri lingkungan hidup dan kehutanan republik Indonesia no. 4 tahun 2021*. *3*, 1–319. https://peraturan.bpk.go.id/Details/210998/permen-lhk-no-4-tahun-2021

Luft, J. A., Jeong, S., Idsardi, R., & Gardner, G. (2022). Literature reviews, theoretical frameworks, and conceptual frameworks: an introduction for new biology education researchers. *CBE Life Sciences Education*, *21*(3), rm33. https://doi.org/10.1187/cbe.21-05-0134

Macdonald, R. K. (2015). Turbidity and light attenuation in coastal waters of the Great Barrier Reef. *James Cook University*, 232. https://www.researchgate.net/publication/293518378_Turbidity_and_Light_Attenuation_in_Coastal_Waters_of_the_Great_Barrier_Reef_Submitted_2015

Naeem, M., Ozuem, W., Howell, K., & Ranfagni, S. (2023). A step-by-step process of thematic analysis to develop a conceptual model in qualitative research. *International Journal of Qualitative Methods*, *22*, 1–18. https://doi.org/10.1177/16094069231205789

Nagel, B., & Partelow, S. (2022). A methodological guide for applying the social-ecological system (SES) framework: A review of quantitative approaches. *Ecology and Society*, *27*(4). https://doi.org/10.5751/ES-13493-270439

Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. *Science*, *325*(July), 419–422. https://doi.org/10.1126/science.1172133

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *Bmj*, *372*. https://doi.org/10.1136/bmj.n71

Panagos, P., Hengl, T., Wheeler, I., Marcinkowski, P., Rukeza, M. B., Yu, B., Yang, J. E., Miao, C., Chattopadhyay, N., Sadeghi, S. H., Levi, Y., Erpul, G., Birkel, C., Hoyos, N., Oliveira, P. T. S., Bonilla, C. A., Nel, W., Al Dashti, H., Bezak, N., … Borrelli, P. (2023). Global rainfall erosivity database (GloREDa) and monthly R-factor data at 1 km spatial resolution. *Data in Brief*, *50*, 109482. https://doi.org/10.1016/j.dib.2023.109482

Pantic, K., & Hamilton, M. (2024). Conducting a systematic literature review in education: A basic approach for graduate students. *Brock Education Journal*, *33*(1), 49–65. https://doi.org/10.26522/brocked.v33i1.1121

Partelow, S. (2018). A review of the social-ecological systems framework: applications, methods, modifications, and challenges. *Ecology and Society*, *23*(4). https://doi.org/10.5751/ES-10594-230436

Pemerintah Republik Indonesia. (2021a). *Peraturan pemerintah republik Indonesia no. 96 tahun 2021*. https://jdih.esdm.go.id/dokumen/view?id=2449

Pemerintah Republik Indonesia. (2021b). Peraturan Pemerintah Republik Indonesia no 22 Tahun 2021. *Sekretariat Negara Republik Indonesia*, *1*(078487A), 1–483. https://peraturan.bpk.go.id/Details/161852/pp-no-22tahun-2021

Pemerintah Republik Indonesia. (2025). *Peraturan pemerintah republik Indonesia no. 39 tahun 2025*. https://peraturan.bpk.go.id/Details/331105/pp-no-39-tahun-2025

Petus, C., Devlin, M., Thompson, A., McKenzie, L., Da Silva, E. T., Collier, C., Tracey, D., & Martin, K. (2016). Estimating the exposure of coral reefs and seagrass meadows to land-sourced contaminants in river flood plumes of the great barrier reef: Validating a simple satellite risk framework with environmental data. *Remote Sensing*, *8*(3). https://doi.org/10.3390/rs8030210

Renard, K. G., Foster, G. R., Weesies, G. A., & McCool, D. K. (1997). Predicting soil erosion by water: A guide to conservation planning with the revised universal soil loss equation (RUSLE). In *US. Department of Agriculture, Agriculture Handbook* (Issue 703). https://bibliotecadigital.infor.cl/items/13ee1619-bb3c-4893-8026-2e53e8e0c02e

Rocha, J. C., Peterson, G., Bodin, Ö., & Levin, S. (2018). Cascading regime shifts within and across scales. *Science*, *362*(6421), 1379–1383. https://doi.org/10.1126/science.aat7850

Stramski, D., Babin, M., & Wozniak, S. B. (2007). Variations in the optical properties of terrigenous mineral-rich particulate matter suspended in seawater. *Limnology and Oceanography*, *52*(6), 2418–2433. https://doi.org/https://doi.org/10.4319/lo.2007.52.6.2418

Syarifuddin, N. (2022). Pengaruh industri pertambangan nikel terhadap kondisi lingkungan maritim di Kabupaten Morowali. *Jurnal Riset & Teknologi Terapan Kemaritiman*, *1*, 19–23. https://doi.org/10.25042/jrt2k.122022.03

Syvitski, J. P. M., Vörösmarty, C. J., Kettner, A. J., & Green, P. (2005). Impact of humans on the flux of terrestrial sediment to the global coastal ocean. *Science*, *308*(5720), 376–380. https://doi.org/10.1126/science.1109454

Tuttle, L. J., & Donahue, M. J. (2022). Effects of sediment exposure on corals: a systematic review of experimental studies. *Environmental Evidence*, *11*(1), 1–33. https://doi.org/10.1186/s13750-022-00256-0

UNEP. (2021). *Making peace with nature: A scientific blueprint to tackle the climate, biodiversity and pollution emergencies*. Making Peace with Nature. https://www.unep.org/resources/making-peace-nature

USGS. (2023). *Mineral commodity summaries 2023*. U.S. Geological Survey. https://pubs.usgs.gov/publication/mcs2023

Wischmeier, W. H., & Smith, D. D. (1978). Predicting rainfall erosion losses: A guide to conservation planning. *Agriculture Handbook No. 537*, *537*, 285–291. https://www.ars.usda.gov/ARSUserFiles/60600505/RUSLE/AH_537 Predicting Rainfall Soil Losses.pdf

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