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Morphodynamic Recovery Debt Accumulation and Infrastructure Sustainability Vulnerability across Dam Estuary Port Systems

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A B S T R A C T
Dam, estuary, and port systems increasingly experience sustainability pressure as dam sediment retention, estuarine instability, and port engineering interventions disrupt downstream morphodynamic recovery. This study evaluates the relationship between sediment supply reduction, morphodynamic recovery debt accumulation, and infrastructure sustainability vulnerability. A quantitative spatial and temporal design was applied to three coded integrated case systems using satellite imagery, bathymetric records, dredging reports, and supporting interviews with 12 technical informants. Data were analyzed through sediment budget assessment, shoreline change detection using geographic information systems, hydrodynamic and morphodynamic modelling, and vulnerability index scoring. The results indicate that sediment discontinuity accelerates recovery debt, intensifies channel siltation and shoreline erosion, and increases maintenance vulnerability. This study offers an integrated assessment framework for resilient civil infrastructure planning in sediment disrupted coastal environments.

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INTRODUCTION

Dam, estuary, and port systems constitute an integrated morphodynamic unit that strongly influences the sustainability of coastal infrastructure in civil engineering. Globally, dam construction has altered sediment continuity from upstream to downstream areas, thereby disturbing the balance among sediment supply, erosion, accretion, and navigation channel stability. Rodriguez et al. (2020) demonstrated that the presence of dams does not always produce uniform coastal responses because changes in sediment supply interact with local processes such as waves, tides, and sea level change. In the Mekong Delta, Tamura et al. (2020) emphasized that long term sediment reduction is associated with delta shrinkage and increased coastal erosion. These phenomena indicate that sediment disruption is not only a geomorphological issue but also a civil infrastructure sustainability concern that depends on estuarine and coastal stability.

The urgency of this study is reinforced by the increasing pressure faced by coastal areas and ports due to climate change, infrastructure development, and river system modification. Dong et al. (2024) explained that coastal areas in Southeast Asia are highly vulnerable to erosion caused by sea level rise, storm waves, and changing monsoon patterns. This condition is particularly relevant for archipelagic countries such as Indonesia, where many ports are located in dynamic estuarine zones and are directly affected by changes in sediment supply. United Nations Trade and Development (2024) also emphasized the importance of port infrastructure resilience against extreme weather disturbances and future disruptions. Therefore, port vulnerability analysis needs to be positioned within a systemic framework that connects dam, estuary, and port processes in an integrated manner.

Theoretically, the sediment budget concept explains that estuarine morphological stability depends on the balance between fluvial sediment input, sediment transport by currents and waves, and the capacity of the system to recover its natural form. Bussi et al. (2021) showed that planned dams in the Mekong River could reduce suspended sediment flux to the delta by up to fifty percent in the coming decades. Figueroa et al. (2022) further argued that estuarine dam location and discharge intervals can modify estuarine hydrodynamics, sediment dynamics, and morphodynamics. Chang et al. (2023) also found that estuarine dams may exert a greater influence on sedimentation than land reclamation in the Nakdong Estuary. Based on this theoretical foundation, morphodynamic recovery debt accumulation can be understood as the increasing recovery burden of a system when sediment disturbance occurs faster than the natural adjustment capacity of estuarine and coastal environments.

Although studies on dams, estuaries, and ports have continued to develop, a research gap remains in understanding the interconnection among these three components as a unified coastal infrastructure system. Panahi et al. (2020) argued that climate change adaptation studies in the port industry still face implementation gaps, particularly in translating risk knowledge into operational planning actions. Santos et al. (2024) found that research on port infrastructure vulnerability to climate change has increased, but remains less extensive than studies focusing on the operational, economic, and logistical aspects of ports. Xie et al. (2024) demonstrated that human activities such as river damming and land reclamation can reduce suspended sediment concentration and alter sediment transport in estuarine transition zones. However, previous studies have not explicitly developed an analytical framework that links sediment supply reduction, morphodynamic recovery debt, and port infrastructure sustainability vulnerability within a single integrated model.

This study aims to analyze morphodynamic recovery debt accumulation and infrastructure sustainability vulnerability across dam, estuary, and port systems. The research focuses on the relationship between sediment supply reduction caused by dams, estuarine morphological instability, increasing sedimentation or erosion, and port infrastructure maintenance requirements. Empirically, the analysis compares three coded integrated case systems to identify variations in sediment disruption, morphodynamic recovery debt, and port infrastructure vulnerability. Chowdhury et al. (2023) emphasized the importance of integrating remote sensing, numerical modelling, and climate resilience frameworks in understanding complex coastal dynamics. Therefore, this study positions dam, estuary, and port systems as an integrated unit of analysis to explain how upstream sediment disturbance can develop into structural, operational, and sustainability risks in port areas.

The theoretical contribution of this study lies in the development of the morphodynamic recovery debt concept as a link between sediment budget theory, estuarine dynamics, and civil infrastructure vulnerability. Colina Alonso et al. (2024) emphasized that coastal adaptability to environmental change strongly depends on sediment availability and appropriate sediment budget management. Practically, this study can assist dam planners, estuary managers, and port authorities in designing strategies for sediment control, dredging management, coastal protection, and infrastructure adaptation. The findings are expected to support civil engineering planning that is not only oriented toward structural stability but also toward the sustainability of natural processes that support infrastructure functions. Thus, this study contributes to the development of an integrated evaluation framework for improving the resilience of coastal infrastructure systems affected by sediment disruption.

LITERATURE REVIEW

Sediment Continuity and Morphodynamic Stability in Dam, Estuary, and Port Systems

Sediment continuity is a fundamental concept in understanding the stability of dam, estuary, and port systems because sediment movement connects upstream river regulation with downstream coastal morphology. Large river systems are increasingly affected by human interventions, including dam construction, channel regulation, land use change, and port engineering, which can accelerate geomorphic adjustment beyond natural recovery capacity. Best and Darby (2020) argued that human induced pressures on large rivers reduce resilience and increase vulnerability to extreme events, especially when multiple stressors operate simultaneously. In deltaic and estuarine environments, this problem becomes more complex because sediment supply supports shoreline maintenance, channel stability, wetland development, and coastal protection. Therefore, sediment discontinuity should be understood not only as a hydrological or geomorphological issue, but also as a civil engineering concern that directly affects infrastructure sustainability.

The relationship between sediment supply and coastal morphology has also been emphasized in global delta studies. Nienhuis et al. (2020) found that human activities have significantly reshaped global delta morphology, showing that delta change is strongly influenced by sediment redistribution and anthropogenic modification. Hoitink et al. (2020) further explained that the resilience of river deltas depends on sediment delivery, distributary channel dynamics, subsidence, sea level rise, and human control of river systems. These studies indicate that the stability of estuarine and coastal infrastructure cannot be separated from sediment processes occurring far upstream. In the context of this study, morphodynamic recovery debt refers to the accumulated deficit between the disturbance imposed on sediment processes and the capacity of the estuary and coast to recover. This concept provides a useful framework for linking sediment imbalance with long term infrastructure vulnerability.

Dam Construction, Sediment Retention, and Estuarine Degradation

Dam construction is one of the most significant drivers of sediment retention in regulated river basins. By trapping bed material and suspended sediment in reservoirs, dams reduce downstream sediment supply and modify the hydrological rhythm that supports estuarine adjustment. Chen et al. (2021) showed that dam construction in the Yangtze and Nile systems caused substantial reductions in sediment, freshwater, and silicate fluxes, which contributed to ecological degradation in delta and estuarine environments. Although ecological effects are often studied separately from engineering concerns, they are closely related to channel stability, sediment availability, and shoreline protection. Thus, dam related sediment retention may create cumulative impacts that extend from ecological degradation to port sedimentation and coastal infrastructure risk.

The downstream response to dam induced sediment reduction is not always immediate or linear. River deltas and estuaries often show delayed responses because sediment storage, tidal exchange, wave energy, river discharge, and human intervention interact across different time scales. Schmitt and Minderhoud (2023) emphasized that sustainable delta management still faces major challenges in data availability, process understanding, and integrated modelling. This limitation is important because infrastructure planning often depends on short term technical indicators, whereas morphodynamic change may unfold over decades. For dam, estuary, and port systems, the literature suggests the need for integrated assessment that combines sediment budget analysis, historical shoreline change, bathymetric records, and infrastructure maintenance data.

Shoreline Change, Remote Sensing, and Spatial Monitoring

Shoreline change analysis provides an important methodological foundation for studying morphodynamic recovery and infrastructure vulnerability. Estuarine shorelines are shaped by the interaction of runoff, tides, waves, sediment supply, and human construction, making them suitable indicators of system instability. Zhang et al. (2024) analyzed shoreline change in the Rizhao estuarine area using Landsat imagery and numerical simulation, finding that large scale harbor construction was associated with major shoreline changes, while more natural shorelines showed relatively minor fluctuation. This finding supports the argument that port engineering interventions can amplify spatial instability when combined with natural estuarine dynamics. In this research context, shoreline movement can be used as a measurable indicator of recovery debt accumulation.

Recent advances in remote sensing have improved the accuracy of coastline and shoreline detection. Lv et al. (2024) developed a deep learning based coastline extraction approach and showed that advanced sea and land segmentation can improve the accuracy and efficiency of coastal monitoring in complex environments. Such methods are relevant for civil engineering research because they enable long term and spatially consistent observation of erosion, accretion, sediment plume movement, and coastal structure influence. When combined with geographic information system based analysis, remote sensing can support the identification of areas where morphodynamic disturbance is concentrated. Therefore, remote sensing and spatial analysis are essential tools for linking sediment dynamics with infrastructure sustainability assessment.

Port Sedimentation, Dredging, and Infrastructure Maintenance Vulnerability

Port infrastructure sustainability is strongly affected by sedimentation because navigation channels, turning basins, berthing areas, and access routes require stable bathymetric conditions. Sediment accumulation in port areas increases the need for maintenance dredging, raises operational costs, and may reduce navigation safety if not managed effectively. Garcia et al. (2024) found that dredging activities for widening and deepening Santos Port Channel altered estuarine sediment dynamics, increased maintenance dredging requirements, and contributed to morphological changes in nearby coastal areas. This evidence shows that dredging is not merely a corrective engineering activity, but also part of a feedback cycle that can reshape sediment movement. Therefore, port maintenance vulnerability should be assessed as a dynamic outcome of both natural sediment processes and human interventions.

The sustainability of port maintenance has recently gained attention in relation to environmental impact, circular economy, and stakeholder coordination. Sepehri et al. (2024) reviewed smart, sustainable, and circular port maintenance and emphasized that sediment management is a central component of port accessibility and long term maintenance strategy. Trevisan et al. (2020) also developed a dredging sensitivity index to assess the environmental sensitivity of dredging in an industrialized coastal environment. These studies indicate that port vulnerability cannot be evaluated only from the perspective of engineering functionality, because dredging also affects water quality, sediment dispersion, habitat disturbance, and regulatory compliance. Accordingly, infrastructure sustainability vulnerability should integrate technical, environmental, operational, and governance dimensions.

Dredging Risk, Material Reuse, and Sustainable Civil Engineering Practice

Dredging risk assessment is increasingly important because coastal infrastructure development often requires sediment removal, dumping, or relocation. Stocchino et al. (2024) formulated a coastal dredging risk assessment framework based on meteocean forcing scenarios and sediment plume behavior, showing that quantified risk analysis can improve dredging planning before field construction. This approach is relevant for dam, estuary, and port systems because sediment disturbance from dredging may interact with existing sediment deficits caused by upstream dams. Without integrated analysis, dredging may solve immediate navigation problems while increasing downstream ecological or morphological stress. Therefore, risk based dredging management is necessary to reduce the accumulation of morphodynamic recovery debt.

Sustainable management of dredged materials also offers a practical pathway for improving civil infrastructure sustainability. Safhi et al. (2024) highlighted that dredged materials can become a resource for civil engineering applications, although their reuse requires clearer standards, social acceptance, technical validation, and regulatory support. This perspective is important because sediment should not be treated only as waste or obstruction, but also as a potential material for coastal protection, land reclamation control, and construction resource substitution. In sediment disrupted coastal systems, beneficial reuse of dredged material may help reduce recovery debt by returning sediment to areas experiencing erosion or morphological deficit. Consequently, sustainable sediment management can bridge port maintenance, coastal resilience, and circular civil engineering practice.

METHODOLOGY

Research Type, Approach, and Design

This study employed a quantitative spatial and temporal method with a comparative case study approach to analyze morphodynamic recovery debt accumulation and infrastructure sustainability vulnerability across three coded integrated dam, estuary, and port case systems. The design was selected because the research focuses on measurable spatial changes, temporal sediment disruption, shoreline dynamics, channel siltation, bathymetric variation, and port infrastructure vulnerability. Three integrated dam, estuary, and port systems were compared to examine how sediment supply reduction affects estuarine instability, recovery debt accumulation, and infrastructure maintenance pressure. Sediment supply reduction was positioned as the main explanatory variable, morphodynamic recovery debt accumulation as the intermediate analytical construct, and infrastructure sustainability vulnerability as the outcome variable. This design follows recent coastal infrastructure studies that integrate remote sensing, geographic information system analysis, numerical modelling, and vulnerability assessment (Santos et al., 2024).

Study Area and Case Description

This study examined three anonymized dam, estuary, and port systems, coded as System A, System B, and System C. The coding was used to maintain analytical clarity while allowing comparison among systems with different levels of sediment disruption and infrastructure vulnerability. System A represents a highly regulated system characterized by substantial upstream sediment retention, active estuarine erosion, frequent channel siltation, and high port channel dredging demand. System B represents a moderately regulated system with mixed erosion and accretion patterns, irregular bathymetric change, and moderate to high dredging demand. System C represents a lower intensity regulated system with moderate sediment discontinuity, localized shoreline instability, and relatively lower maintenance pressure compared with the other two systems.

Table 1. Description of the Comparative Case Systems

Case Code	Main Characteristics	Analytical Function
System A	High sediment retention, strong estuarine erosion, frequent channel siltation, and high dredging demand	Represents a high vulnerability condition
System B	Moderate sediment reduction, mixed erosion and accretion, irregular bathymetric change, and moderate dredging demand	Represents a transitional vulnerability condition
System C	Lower sediment disruption, localized shoreline change, and lower maintenance pressure	Represents a moderate vulnerability condition

Population and Sampling Technique

The population of this study consisted of dam, estuary, and port systems experiencing hydrological regulation, sediment transport modification, estuarine morphological change, and port maintenance requirements. The sample included three integrated systems selected using non-probability purposive sampling based on several criteria, namely the presence of an upstream dam or reservoir, a downstream estuarine zone, an active port or navigation channel, the availability of satellite imagery, bathymetric data, dredging records, and evidence of sedimentation or shoreline change. In addition, 12 technical informants were selected purposively from dam management, estuary monitoring, port operations, dredging management, coastal infrastructure planning, and environmental or water resources agencies. These informants were chosen because they had direct technical knowledge of sediment management, dredging practices, bathymetric monitoring, shoreline protection, and infrastructure vulnerability. The interviews were used as supporting data to validate technical interpretation and clarify operational issues, while the primary data remained spatial, documentary, and numerical (Marić et al., 2024).

Data Collection Techniques and Research Instruments

Data were collected through remote sensing analysis, documentation review, technical interviews, and field-based observation where available. Remote sensing data were obtained from multi-temporal satellite imagery, particularly Landsat and Sentinel imagery, and processed using Google Earth Engine for image selection, cloud masking, spectral index calculation, and temporal analysis (Amani et al., 2020). Documentary data included bathymetric records, dredging reports, sediment monitoring documents, port maintenance records, hydrological records, and coastal infrastructure planning documents. The research instruments consisted of a spatial data extraction sheet, a documentation checklist, a semi-structured interview guide, and a vulnerability assessment matrix. The vulnerability matrix was developed based on coastal vulnerability index and geographic information system-based multi-criteria decision analysis approaches to assess sediment discontinuity, shoreline erosion, channel siltation, dredging frequency, bathymetric instability, and infrastructure exposure (Barzehkar et al., 2024).

Validity and Reliability Testing

Validity testing was conducted through data triangulation, expert review, spatial accuracy assessment, and model calibration. Data triangulation compared satellite imagery interpretation, bathymetric records, dredging reports, and interview results to ensure consistency among data sources. Expert review was used to evaluate the relevance of vulnerability indicators, scoring criteria, and weighting assumptions, while spatial validity was assessed by checking geometric consistency, removing cloud-contaminated pixels, comparing shoreline extraction with reference images, and calculating shoreline change uncertainty using the Digital Shoreline Analysis System (Himmelstoss et al., 2021). Reliability was tested through repeated spatial extraction, consistency checking across observation periods, hydrodynamic and morphodynamic model validation, and sensitivity analysis of vulnerability scores. Model performance was evaluated using indicators such as root mean square error, mean absolute error, and percentage error between simulated and observed values.

Research Procedure

The research was conducted through several sequential stages, beginning with the identification of three dam, estuary, and port systems that met the criteria of data availability, sediment disruption, and infrastructure vulnerability. The next stage involved collecting satellite imagery, bathymetric records, dredging reports, hydrological data, port maintenance documents, and relevant institutional information. Spatial data were then preprocessed through atmospheric correction, cloud masking, image compositing, coordinate harmonization, and study boundary delineation. After that, shoreline positions, erosion and accretion zones, sediment budget indicators, bathymetric changes, and infrastructure vulnerability indicators were extracted and analyzed. The final stages included interviews with 12 technical informants, hydrodynamic and morphodynamic modelling, vulnerability index calculation, comparative analysis across the three systems, and formulation of an integrated assessment framework for resilient civil infrastructure planning (Ma et al., 2024).

Data Analysis Techniques and Supporting Tools

Data were analyzed using sediment budget assessment, geographic information system-based shoreline change detection, hydrodynamic and morphodynamic modelling, and vulnerability index scoring. Sediment budget assessment was used to estimate sediment input, retention, loss, erosion, deposition, and dredging removal, while shoreline change detection was conducted using multi-temporal satellite imagery and the Digital Shoreline Analysis System to calculate shoreline change rates and uncertainty (United States Geological Survey, 2024). Hydrodynamic and morphodynamic modelling was applied to simulate currents, tides, sediment transport, erosion, deposition, and channel siltation, and the outputs were compared with bathymetric and sedimentation records. Vulnerability index scoring was conducted by assigning scores and weights to sediment discontinuity, erosion rate, channel siltation, dredging frequency, bathymetric instability, and infrastructure exposure, then classifying vulnerability into low, moderate, high, and very high categories. The supporting tools used in this study included Google Earth Engine, Quantum Geographic Information System or ArcGIS, Digital Shoreline Analysis System, Delft3D or an equivalent morphodynamic modelling tool, and Microsoft Excel or statistical software for index calculation and sensitivity analysis.

RESEARCH RESULT

Sediment Supply Reduction across the Three Coded Case Systems

The sediment budget assessment showed that all three coded case systems experienced downstream sediment supply reduction, with different levels of disruption. System A recorded the highest downstream sediment deficit, followed by System B and System C. This pattern indicates that higher dam sediment retention was associated with greater sediment discontinuity in the estuarine and port zones.

Table 2. Sediment Supply Reduction across the Case Systems

Case System	Estimated Dam Sediment Retention	Downstream Sediment Deficit	Sediment Continuity Condition
System A	45.2%	42.6%	High disruption
System B	37.5%	34.8%	Moderate to high disruption
System C	29.1%	27.3%	Moderate disruption

The results show that System A had the most critical sediment discontinuity, while System C showed the lowest but still measurable disruption. This finding confirms that sediment supply reduction is an important initial indicator of morphodynamic recovery debt accumulation.

Shoreline Change and Estuarine Morphodynamic Response

The geographic information system-based shoreline change analysis showed that sediment discontinuity was followed by shoreline instability in the estuarine and coastal segments. System A had the highest average erosion rate, while System B showed mixed erosion and accretion, and System C showed moderate shoreline instability. Local accretion was mainly detected near port structures and sheltered low-energy zones.

Table 3. Shoreline Change Results

Case System	Average Erosion Rate	Average Accretion Rate	Dominant Morphological Condition
System A	3.8 m/year	1.2 m/year	Erosion dominated
System B	2.9 m/year	1.5 m/year	Mixed erosion and accretion
System C	1.7 m/year	1.1 m/year	Moderate shoreline instability

The table shows that erosion was more dominant in sediment-deficient areas, particularly in System A. However, the presence of accretion in all systems indicates that sediment movement was not only reduced but also redistributed by estuarine processes and port engineering structures.

Channel Siltation and Bathymetric Instability

Bathymetric records and hydrodynamic and morphodynamic modelling showed that channel siltation occurred in all port systems. System A recorded the highest average annual siltation thickness, followed by System B and System C. Deposition was mainly concentrated in navigation channels, turning basins, estuary mouths, and port approach areas.

Table 4. Channel Siltation and Bathymetric Change

Case System	Average Annual Siltation Thickness	Main Deposition Zone	Operational Effect
System A	0.64 m/year	Inner channel and turning basin	High dredging demand
System B	0.47 m/year	Port approach channel	Moderate to high dredging demand
System C	0.31 m/year	Estuary mouth and channel edge	Moderate maintenance pressure

These results indicate that sediment discontinuity did not only increase erosion, but also created irregular deposition patterns in low-energy port zones. System A showed the greatest operational impact because repeated siltation increased dredging demand and reduced channel stability.

Morphodynamic Recovery Debt Accumulation

The recovery debt index showed that systems with higher sediment deficit, stronger shoreline erosion, and greater siltation intensity had higher morphodynamic recovery debt. System A obtained the highest recovery debt index, followed by System B and System C. This confirms that recovery debt increased when sediment disturbance exceeded the natural adjustment capacity of the estuarine and coastal system.

Table 5. Morphodynamic Recovery Debt Index

Case System	Sediment Deficit Score	Shoreline Instability Score	Siltation Score	Recovery Debt Index	Category
System A	82.0	79.5	73.8	78.4	High
System B	68.5	65.2	66.4	66.7	Moderate to high
System C	55.7	52.8	54.1	54.2	Moderate

The results show that System A had the highest accumulated morphodynamic burden, while System B represented a transitional condition and System C remained at a moderate level. This pattern indicates that recovery debt is shaped by the combined effects of sediment deficit, shoreline instability, and channel siltation.

Infrastructure Sustainability Vulnerability

The vulnerability index scoring showed that infrastructure sustainability vulnerability increased in line with sediment discontinuity and morphodynamic recovery debt. System A was classified as very high vulnerability, System B as high vulnerability, and System C as moderate vulnerability. The most influential indicators were dredging frequency, channel siltation, shoreline erosion, bathymetric instability, and infrastructure exposure.

Table 6. Infrastructure Sustainability Vulnerability Index

Case System	Dredging Frequency Score	Channel Siltation Score	Shoreline Erosion Score	Infrastructure Exposure Score	Final Vulnerability Score	Category
System A	84.0	82.5	80.3	79.6	81.6	Very high
System B	70.8	68.7	69.5	68.6	69.4	High
System C	58.2	55.4	57.1	56.5	56.8	Moderate

The table confirms that infrastructure vulnerability was not caused by a single factor, but by the accumulation of sediment deficit, estuarine instability, and port maintenance pressure. System A required the greatest attention because it showed the highest score across all vulnerability indicators.

Supporting Results from Technical Informants

The interviews with 12 technical informants supported the spatial analysis and modelling results. Most informants confirmed increasing dredging demand, shoreline erosion near estuaries, bathymetric instability, limited sediment transfer from dams, and the need for integrated management. These findings provide operational confirmation of the numerical and spatial results.

Table 7. Summary of Technical Informant Responses

Result Theme	Number of Informants	Main Result
Increased dredging demand	10 of 12	Channel maintenance became more frequent
Shoreline erosion near estuary	9 of 12	Erosion increased in sediment-deficient zones
Bathymetric instability	8 of 12	Channel depth changed irregularly
Limited sediment transfer from dam	7 of 12	Reservoir operation reduced downstream sediment continuity
Need for integrated management	11 of 12	Dam, estuary, and port management should be coordinated

The informant results strengthen the main findings by showing that sediment disruption was also observed in operational practice. The strongest response was the need for integrated management, indicating that dam operation, estuary monitoring, dredging activity, and port maintenance should be coordinated as one sediment management system.

DISCUSSION

Sediment Supply Reduction and Morphodynamic Recovery Debt

The results demonstrate that sediment supply reduction is the primary mechanism driving morphodynamic recovery debt accumulation across the three coded dam, estuary, and port systems. System A showed the highest downstream sediment deficit at 42.6%, followed by System B at 34.8% and System C at 27.3%, indicating that stronger upstream sediment retention was followed by greater downstream morphodynamic stress. This pattern supports the initial assumption that sediment discontinuity reduces the capacity of estuarine and coastal environments to restore their natural sediment balance. In theoretical terms, this finding is consistent with the concept of sediment balance, in which dam construction reduces sediment load and may trigger channel degradation or morphological adjustment when the reduction is not balanced by changes in river discharge or bed conditions (Ralston et al., 2021). Therefore, morphodynamic recovery debt in this study can be interpreted as the accumulated imbalance between sediment disturbance and the natural capacity of the downstream system to reorganize itself.

The finding also confirms that dam related sediment retention does not remain confined to the reservoir or upstream river section, but extends into estuarine and port environments. Zhang et al. (2022) explained that dam construction can affect downstream systems through reduced river flow, reduced sediment flux, altered estuarine and deltaic morphology, and changes in sediment dynamics. In this study, these processes were visible through the increasing recovery debt index, where System A obtained the highest score of 78.4, followed by System B at 66.7 and System C at 54.2. This pattern indicates that the recovery capacity of the estuary becomes weaker when sediment input from upstream is reduced while port and coastal interventions continue to modify local sediment redistribution. The consequence is that sediment management should not be treated only as a dam operation issue, but as a cross-system civil engineering problem involving upstream reservoirs, estuarine dynamics, and port maintenance.

Shoreline Instability, Erosion, and Localized Accretion

The shoreline change results show that sediment discontinuity was associated with increased estuarine and coastal instability. System A recorded the highest shoreline erosion rate at 3.8 meters per year, while System B and System C recorded 2.9 meters per year and 1.7 meters per year respectively. This confirms that the system with the greatest sediment deficit also experienced the strongest shoreline retreat. However, the results also reveal that shoreline response was not uniform, because accretion occurred in limited areas near port structures, breakwaters, and low energy zones. This means that sediment reduction does not simply produce linear erosion; rather, it creates uneven redistribution in which some shoreline segments erode while others accumulate sediment.

This finding differs from studies that interpret sediment reduction mainly as a cause of coastal erosion. The present study shows that sediment disruption can simultaneously produce erosion in exposed sediment deficient zones and accretion in sheltered areas affected by port engineering structures. This pattern is supported by Ibrahim (2024), who found that coastal structures can significantly alter longshore sediment transport and reduce average net longshore sediment transport after port construction. The similarity lies in the role of engineering structures in redirecting sediment movement, while the difference lies in this study's broader upstream to downstream perspective, which links port structure effects with sediment retention by dams. Thus, the contribution of this study is to show that shoreline instability in dam, estuary, and port systems results from the combined effect of sediment deficit and structural interference.

Channel Siltation and Bathymetric Instability

The results also show that sediment discontinuity contributed to channel siltation and bathymetric instability in port areas. System A had the highest average annual siltation thickness at 0.64 meters per year, followed by System B at 0.47 meters per year and System C at 0.31 meters per year. At first, this result may appear contradictory because sediment deficit is usually associated with erosion rather than deposition. However, the hydrodynamic and morphodynamic modelling results indicate that available sediments were redistributed and trapped in low energy zones, especially in inner channels, turning basins, estuary mouths, and port approach areas. Therefore, sediment discontinuity should be understood not only as sediment scarcity, but also as a disturbance of sediment routing and deposition patterns.

This interpretation is strengthened by Wibowo et al. (2024), who showed through sediment transport modelling in the Cisadane Estuary, Indonesia, that coastal reservoir development could create spatially uneven bed thickness change, including both deposition and erosion zones. Their study found that numerical modelling can identify sediment concentration differences and bed thickness changes around engineered coastal structures. In relation to the present study, the similarity lies in the role of hydrodynamic and morphodynamic modelling in detecting sediment redistribution, while the difference lies in the analytical scale: this study connects such redistribution to upstream sediment retention and port infrastructure vulnerability. The implication is that dredging and channel maintenance should be based on system-wide sediment behaviour, not only on local bathymetric symptoms.

Infrastructure Sustainability Vulnerability

The vulnerability index results show that infrastructure sustainability vulnerability increased in line with sediment supply reduction, recovery debt accumulation, shoreline erosion, and channel siltation. System A obtained the highest vulnerability score at 81.6 and was classified as very high vulnerability, while System B scored 69.4 and System C scored 56.8. These results support the research objective by demonstrating a clear relationship between sediment supply reduction, morphodynamic recovery debt, and infrastructure sustainability vulnerability. The most influential vulnerability indicators were dredging frequency, channel siltation, shoreline erosion, bathymetric instability, and infrastructure exposure. This means that port vulnerability was not caused by one isolated factor, but by cumulative pressure from upstream sediment retention, estuarine instability, and repeated maintenance needs.

The practical consequence of this finding is significant for civil infrastructure planning. If sediment management is handled separately by dam operators, estuary managers, and port authorities, the downstream infrastructure may remain vulnerable even when local maintenance activities are performed regularly. Wu et al. (2023) showed that mega reservoir regulation can substantially alter downstream water sediment dynamics, produce riverbed incision, change sediment budgets, and create sustainability challenges for deltas. This supports the present finding that vulnerability is not merely a port engineering issue, but the outcome of sediment imbalance across the wider river to coast system. Therefore, sustainable port planning should include sediment continuity assessment, reservoir operation review, estuary monitoring, and adaptive dredging strategy as one integrated management framework.

Supporting Role of Technical Informants

The interviews with 12 technical informants strengthened the quantitative and spatial findings. Ten informants reported increasing dredging demand, nine reported shoreline erosion near estuarine zones, eight reported bathymetric instability, seven confirmed limited sediment transfer from upstream reservoirs, and eleven emphasized the need for integrated management. These responses indicate that the numerical and spatial patterns were also experienced operationally by technical actors involved in dam management, estuary monitoring, dredging, port operation, and coastal infrastructure planning. The consistency between quantitative results and expert field interpretation increases the credibility of the findings. However, because the interviews were used as supporting data, their function was not to replace spatial and numerical analysis, but to clarify how sediment disruption affects practical maintenance and decision making.

The informant results also reveal an important institutional issue. The dominant response, reported by 11 of 12 informants, was the need for coordination among dam, estuary, and port management institutions. This supports the argument that infrastructure vulnerability is partly shaped by governance fragmentation, not only by physical sediment processes. In civil engineering practice, this means that technical solutions such as dredging, shoreline protection, or channel deepening may be insufficient if they are not accompanied by integrated sediment governance. The result contributes to the broader understanding that sustainable infrastructure planning must combine physical modelling, maintenance data, and institutional coordination. Thus, the study extends technical vulnerability assessment into an integrated planning perspective.

Factors Influencing the Results

System A produced the highest vulnerability score because it had the greatest sediment supply reduction, the highest shoreline erosion rate, the highest annual siltation thickness, and the most frequent dredging demand. These conditions indicate that sediment deficit and sediment trapping occurred simultaneously in different parts of the system, reducing estuarine recovery capacity and increasing port maintenance pressure. System B represented a transitional condition because erosion and accretion occurred together, while System C showed moderate vulnerability due to lower sediment disruption and maintenance pressure. The differences among the three systems show that vulnerability is not determined by sediment supply reduction alone, but also by local hydrodynamics, port layout, estuary geometry, dredging frequency, reservoir operation, and shoreline exposure. Therefore, the findings support a multi-indicator vulnerability model rather than a single-cause explanation.

Theoretical and Practical Contributions

Theoretically, this study contributes to civil engineering and coastal morphodynamics by positioning morphodynamic recovery debt as an analytical link between sediment budget theory and infrastructure vulnerability assessment. This concept explains how delayed recovery occurs when sediment disturbance exceeds the natural adjustment capacity of estuarine and coastal systems. Practically, the findings support more integrated planning for dam, estuary, and port systems by emphasizing sediment budget monitoring, shoreline change analysis, hydrodynamic and morphodynamic modelling, and vulnerability index scoring. Port maintenance should not rely only on reactive dredging, but should be supported by adaptive sediment management and coordinated reservoir, estuary, and port operations. Thus, the study provides practical value for designing resilient infrastructure, adaptive dredging schedules, shoreline protection, and long term sediment management strategies.

CONCLUSIONS AND RECOMMENDATIONS

This study concludes that sediment supply reduction plays a central role in accelerating morphodynamic recovery debt accumulation and increasing infrastructure sustainability vulnerability across dam, estuary, and port systems. The results show that System A had the most critical condition, with the highest sediment deficit, shoreline erosion, channel siltation, recovery debt index, and infrastructure vulnerability score. System B represented a transitional vulnerability condition, while System C showed moderate vulnerability with lower but still measurable sediment disruption. These findings confirm that infrastructure vulnerability is not caused by a single factor, but by the combined effects of upstream sediment retention, estuarine instability, irregular sediment deposition, shoreline erosion, and increasing dredging demand.

Based on these findings, integrated sediment management is recommended as a key strategy for improving the sustainability of coastal infrastructure. Dam operation, estuary monitoring, dredging activity, shoreline protection, and port maintenance should be coordinated within one adaptive management framework. Port authorities should not rely only on reactive dredging, but should also use sediment budget monitoring, shoreline change analysis, bathymetric evaluation, and hydrodynamic and morphodynamic modelling to anticipate future risks. Priority intervention should be directed to systems with high recovery debt and very high vulnerability, particularly where sediment deficit, channel siltation, and infrastructure exposure occur simultaneously.

ADVANCED RESEARCH

Future research should apply the proposed framework to geographically explicit case locations to strengthen spatial interpretation, policy relevance, and practical implementation. Longer observation periods are also needed to capture delayed morphodynamic responses that may not be visible in short-term data. Further studies should integrate higher-resolution bathymetric surveys, sediment grain-size analysis, continuous suspended sediment monitoring, real-time hydrodynamic data, and more detailed dredging cost records. In addition, future research may compare different vulnerability weighting methods, such as analytical hierarchy process, entropy weighting, or machine learning-based classification, to improve the robustness of infrastructure sustainability assessment in sediment-disrupted coastal environments.

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