Impacts of Large-scale Reclamation on Coastal Wetlands and Countermeasures: Postprint

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Abstract

With the rapid economic development of coastal regions and mounting pressure from population growth, coastal reclamation activities have become a critical approach to alleviate the shortage of coastal land and promote development in coastal areas. While generating economic benefits, such activities also impose significant impacts on nearshore resources and coastal wetland ecosystems. Coastal wetlands constitute transitional zones of land-sea interaction, playing a vital role in maintaining biodiversity and dynamic land-sea balance. Therefore, based on an analysis of the characteristics of large-scale coastal reclamation in China, this study examines and discusses the comprehensive impacts of reclamation activities on the structure, function, and processes of coastal wetland ecosystems from the perspectives of coastal wetland patterns, maintenance of coastal wetland biodiversity, and biological distribution structures. The restoration strategies of "networks instead of points," "gradual approaches instead of urgent measures," "intensive measures instead of light ones," and "multiple approaches instead of few" are proposed to deepen the mechanisms of coastal wetland restoration and strengthen ecological restoration practices. An ecological compensation model of "two major categories, three hierarchical levels" is proposed to address the critical national needs for coastal wetland ecological compensation. By balancing economic gains and ecological losses, rationally allocating reclamation space, promoting sustainable utilization of coastal wetland resources and biodiversity conservation, and achieving harmonious development among various stakeholder groups.

Full Text

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Abstract

Driven by rapid economic development and population growth in coastal regions, large-scale reclamation has become a critical approach to alleviating land scarcity and promoting regional development. While generating substantial economic benefits, these activities have also inflicted severe impacts on nearshore resources and coastal wetland ecosystems. Coastal wetlands serve as transitional zones between marine and terrestrial systems, playing a vital role in maintaining biodiversity and the dynamic balance between land and sea. This study analyzes the comprehensive effects of reclamation on coastal wetland ecosystem structure, function, and processes by examining wetland patterns, biodiversity maintenance, and biological distribution structures, based on an investigation of large-scale reclamation characteristics in China. We propose restoration strategies summarized as "network-based instead of point-based," "long-term instead of short-term," "large-scale instead of small-scale," and "function-oriented instead of species-oriented" to deepen understanding of restoration mechanisms and strengthen ecological restoration practices. Additionally, we introduce an ecological compensation framework featuring "two major categories and three levels" to advance national priorities in coastal wetland compensation. By balancing economic gains against ecological losses and optimizing spatial layouts for reclamation, we provide a robust foundation for sustainable utilization of coastal wetland resources and biodiversity conservation, fostering harmonious development among diverse stakeholder groups.

Keywords: coastal wetlands, coastal reclamation, impact, ecological restoration, ecological compensation, trade-off

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China' s total coastline exceeds 1.8×10 km, encompassing rich coastal wetland resources. These wetlands play indispensable roles in environmental purification, coastal erosion prevention, flood control, habitat provision, biodiversity maintenance, and energy storage. However, as coastal economies expand, populations swell, and urbanization accelerates, the conflict between human needs and land availability has intensified, prompting extensive reclamation to create new space for development. Since the founding of the People' s Republic, China has experienced four major reclamation campaigns. Over the past four decades, large-scale reclamation has caused cumulative losses of approximately 2.19×10 km^2 of coastal tidal flats—equivalent to 50% of China' s total coastal wetland area. Conservative estimates project that by 2020, China will face reclamation demands exceeding 5,780 km^2, occupying 1.1×10^3–3.0×10^3 km of coastline. Data from the China Ocean Information Center' s "Marine Area Use Management Bulletin" indicate that while China' s reclamation management began relatively late and the growth rate has slowed, the total area of reclaimed land has never decreased. These large-scale projects, while economically beneficial, have triggered severe ecological consequences including wetland area shrinkage, habitat loss and fragmentation, hydrodynamic disruption, and dramatic biodiversity decline. To strengthen effective management of reclamation activities and achieve sustainable utilization of coastal wetland resources, it is essential to clearly identify these impacts through scientific assessment. Determining how to scientifically protect and restore coastal wetlands under intensive reclamation pressure represents a critical challenge for advancing sustainable development and biodiversity conservation, making the formulation of appropriate countermeasures crucial for fully implementing ecological civilization and green development principles.

To clarify the impacts of reclamation on China' s coastal wetlands, we must first analyze reclamation characteristics to develop targeted strategies. Based on four decades of data regarding wetland occupation, China's reclamation development demonstrates four key features: large area, rapid growth, extensive scope, and diverse types.

2. Impact of Reclamation on Coastal Wetlands

Coastal wetlands are both sensitive to climate change and ecologically fragile, playing crucial roles in water conservation, climate regulation, and biodiversity protection. While large-scale reclamation generates economic benefits, it negatively affects wetland ecosystem structure, function, and processes, specifically impacting coastal wetland patterns, biodiversity maintenance, and biological distribution structures.

2.1 Altering Coastal Wetland Patterns and Causing Wetland Loss

Reclamation occupies vast areas of natural coastal wetlands, drastically reducing the proportion of natural coastline and altering wetland patterns. Over the past 40 years, China' s natural coastline proportion has declined from 76% in 1980 to 44% in 2014, while artificial coastline increased from 24% to 56%. The four major delta regions face particularly severe threats. Since 2000, the Pearl River Delta has experienced significant declines in beach wetlands, salt marshes, and mangroves, with reclaimed areas exceeding 75% of total coastal wetland area by 2015, resulting in massive natural wetland loss. Since the 1970s, the Yellow River Delta has witnessed substantial changes across all wetland types, particularly after 2000, with large-scale losses of tidal flats and salt marshes. Although wetland restoration projects have increased freshwater reed marshes, making them a major wetland type in the delta, the Yangtze River Delta has seen notable decreases in beach and freshwater marsh wetlands. By 2015, remaining beach wetlands in the Liao River Delta accounted for only about one-third of the reclaimed area [Figure 1: see original paper].

2.2 Destroying Wetland Resources and Reducing Biodiversity Biological resources are living organisms that self-renew through reproduction and growth, providing materials for human production and life, supporting ecosystem continuity, maintaining ecological balance, and representing crucial ecological safeguards for sustainable development. Large-scale reclamation occupies existing biological habitats, destroys original populations, and exacerbates overexploitation through excessive fishing, hunting, and harvesting, breaking food chains and destabilizing ecosystems, thereby directly threatening biological security and sustainable development. Coastal wetlands serve as critical habitats for aquatic organisms, and large-scale reclamation projects alter hydrological characteristics, disrupt fish migration patterns, and destroy spawning grounds, causing critical habitat loss and sharp declines in fishery resources. Reclamation structures such as breakwaters and dikes also alter the vertical structure of biological habitats, concentrating previously separated species in single areas, increasing population densities, intensifying interspecific competition, and significantly reducing macrobenthic biodiversity and biomass in heavily reclaimed areas. Furthermore, reclamation blocks normal material transport between land and sea, preventing terrestrial nutrients from reaching coastal waters, thereby affecting food chains and fishery production while threatening beach vegetation growth. Consequently, biodiversity declines substantially due to disrupted biological interactions.

2.3 Fragmenting Habitats and Destroying Biological Distribution Structures Large-scale reclamation squeezes biological habitats, causing community collapse and sharp population declines. Simultaneously, activities such as embankment construction, shoreline hardening, development, and aquaculture ponds increase patch isolation, leading to habitat fragmentation, disrupted distribution structures, and community degradation or extinction. Our research in the Yellow River Delta reveals that from 1984 to 2014, *Suaeda salsa* salt marsh area shrank by approximately 78%, with obvious fragmentation trends. By 2014, the number of *S. salsa* patches had increased tenfold compared to 1984, while patch size and density decreased dramatically, with extremely low patch density in reclaimed areas. The distribution structure of *S. salsa* communities has also been disturbed, shifting toward aggregated patterns.

This fragmentation primarily occurs because aquaculture ponds, dikes, and embankments block tidal action, interfering with seed dispersal. Tides serve as the main dispersal mechanism for *S. salsa* seeds (wind alone cannot enable long-distance dispersal). In natural coastal wetlands, tidal action facilitates seed flow between patches, maintaining connectivity and enabling large community formation. However, reclamation completely blocks tides, causing most seeds to remain beneath parent plants and eliminating seed flow connectivity. This transforms distribution patterns from extensive continuous patches to numerous small, aggregated patches. Additionally, blocked hydrological processes destroy the gradual gradient of soil physicochemical properties from sea to land. Combined with the loss of ecological flows such as seed dispersal, the ecological boundaries of *S. salsa* communities exhibit shortening, narrowing, and structural simplification, pushing the community into an overly open state with reduced resistance to external disturbances.

3. Countermeasures and Recommendations

The "Opinions on Accelerating Ecological Civilization Construction" issued by the CPC Central Committee and State Council explicitly stipulates maintaining China's wetland area above 800 million mu, expanding ecological space and area, launching wetland ecological benefit compensation and "returning farmland to wetland" programs, and implementing strict total volume control systems for reclamation and natural coastline protection. These policies also require establishing marine ecological protection and restoration mechanisms with integrated land-sea coordination and regional 联动. Therefore, comprehensive deepening of research on coastal wetland restoration mechanisms under reclamation impacts is essential to advance practical restoration efforts.

3.1 Deepening Restoration Mechanism Research and Advancing Restoration Practices Coastal wetlands are vulnerable and scarce, making their ecological restoration a globally recognized strategy. As one of the countries most severely affected by coastal wetland degradation, China has increasingly recognized the necessity of restoration. In recent years, Chinese governments at all levels have invested substantial funds in hundreds of annual restoration projects. To further strengthen restoration efforts for degraded coastal wetlands, we propose multi-level ecological restoration solutions and explore a "four substitutions" restoration model tailored to reclamation impacts.

(1) "Network instead of point" : Construct ecological networks to achieve integrated multi-regional restoration. Isolated "point-based" restoration of single locations, components, or ecosystem types cannot fundamentally address the extensive negative impacts of reclamation. By building ecological networks that prioritize hotspot restoration and connect biological and hydrological processes, we can achieve integrated joint restoration across multiple components, types, and regions. Network construction rebuilds biological connectivity, enhances ecosystem stability, and enables simultaneous restoration of multiple ecological components. This approach links diverse ecosystem types and regions, creating cross-regional 联动 models that distribute ecological risks, decompose adverse effects, and increase overall ecosystem stability.

(2) "Long-term instead of short-term": Employ long time-series restoration to ensure stable post-restoration ecosystem maintenance. One-time restoration based on single time-point impacts cannot guarantee effectiveness or sustainability. Long time-series restoration incorporates phased approaches including pilot restoration, continuous mid-term restoration, and supplementary consolidation restoration. This approach considers the full life cycles of important biological components to eliminate impacts comprehensively while ensuring continuous supplementary restoration to offset reclamation effects.

(3) "Large-scale instead of small-scale" : Expand restoration scope to eliminate externalities and expansion effects of ecological impacts. Restoration limited to reclamation project boundaries cannot completely eliminate regional ecological damage. We must emphasize the externalities and expansion effects of reclamation impacts, expanding restoration boundaries to include adjacent ecosystems and adopting whole-region integrated restoration. Research should examine how reclamation affects surrounding ecosystems through pollution discharge, altered hydrological patterns, and blocked biological connectivity, then implement simultaneous joint restoration of both project areas and expanded zones to achieve comprehensive regional impact elimination.

(4) "Function-oriented instead of species-oriented" : Target ecosystem functions to ensure complete ecological processes and biodiversity conservation. Reclamation impacts typically involve multiple biological components, with direct consequences including functional disorder. Restoration focused on single species cannot guarantee functional recovery at the ecosystem level, limiting practical effectiveness. We propose a function-oriented restoration model that constructs multi-objective restoration frameworks targeting important ecological components, key processes, and abiotic environments—three levels directly affecting ecological function—to achieve joint restoration of process integrity and component diversity.

3.2 Strengthening Material Compensation Mechanisms and Exploring Multi-level Compensation Models Central and local governments have explicitly required establishing ecological compensation mechanisms as crucial environmental protection components, making advanced compensation for coastal wetlands a major national priority. Developing coastal wetland compensation mechanisms coordinates natural and socioeconomic systems, enables sustainable wetland ecosystem development, and ensures biodiversity and service function maintenance. We propose a "two major categories, three levels" compensation model for reclamation-induced wetland damage. The two categories are material quantity compensation and value-based compensation; the three levels are in-situ compensation, off-site substitution, and economic payment.

For habitat loss areas, we propose off-site substitution compensation scales and areas; for area-reduced regions, we calculate in-situ compensation rates and adjustment models; for biodiversity-impaired and function-degraded areas, we propose off-site substitution compensation approaches for improvement. For substitution and adjustment zones, suitable locations must be selected for functional comparison and area accounting. When in-situ compensation and off-site substitution are insufficient, losses and compensation values should be assessed, with remaining losses addressed through economic payments.

For material quantity compensation, key aspects include accounting for off-site compensation areas and researching habitat substitution mechanisms and methods based on substitute habitat similarity, substitution justification, and no-net-loss principles. For value-based compensation, comprehensive analysis of wetland ecosystem characteristics is needed, considering wetland types, regional ecological status, compensation scope, subjects and objects, methods and approaches, and standards while balancing ecological, economic, and social benefits with social acceptability and implementation feasibility. This ultimately forms a multi-objective, multi-scenario, multi-scale comprehensive regulation model for wetland ecosystems under uncertainty, providing quantitative compensation solutions for complex conditions.

3.3 Balancing Economic Benefits and Ecological Losses, Promoting Equilibrium and Sustainable Development While reclamation generates enormous economic benefits, it also causes ecological losses through direct ecosystem occupation and intensive exploitation of ecological service functions. Balancing these economic gains against ecological losses is crucial for reclamation planning and management. Optimizing reclamation scale and intensity to maximize economic benefits within acceptable ecological loss ranges represents the core of trade-off analysis. By estimating ecological losses from various reclamation development models and rationally allocating construction scales and configurations across different intensities, we can achieve optimal balance.

We identify three modes of ecological service function utilization in reclamation: (1) **Enhancing original functions**—for example, aquaculture strengthens the production service function of coastal wetlands for aquatic products; (2) **Generating new functions**—for instance, converting wetlands to farmland or salt fields restructures ecosystem components to produce previously non-existent outputs like crops or salt, while partially or completely replacing original supply services; and (3) **Providing production materials or space**—such as using water bodies as transportation carriers in port construction, or completely eliminating original ecological components to provide space for urban and industrial development.

The first mode, which retains core ecosystem components with relatively minor structural changes, represents light to moderate development. The second mode, which significantly alters ecosystem components and structure, constitutes moderate development. The third mode, which completely eliminates original ecosystem structure and components, represents heavy development.

Identifying these utilization modes forms the basis for balancing economic benefits and ecological losses. Trade-off analysis can be structured across four levels to construct a "quadrilateral" framework: (1) analyzing the benefit relationship between reclamation economic gains and direct ecological losses; (2) considering whether ecological losses can be compensated through restoration measures, further balancing loss magnitude against restoration potential; (3) determining that restoration costs, which depend on restoration quantity, also constitute reclamation costs for the socioeconomic system, thus requiring benefit analysis between direct economic gains and restoration costs; and (4) comprehensively considering restoration technology and success rates to balance financial investment against actual restoration outcomes.

Trade-off analysis must fully account for the complexity and nonlinearity of reclamation activities. Reclamation scale, type, and location are key factors determining ecological loss magnitude. Meanwhile, coastal wetland ecological functions exhibit nonlinear changes with critical positions or structures where impacts increase nonlinearly with reclamation scale. Therefore, estimating ecological losses by type, region, and scale is essential for scientifically optimizing reclamation and strengthening coastal wetland management to achieve coordinated development between resource exploitation and ecosystem protection.

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Note: Figure translations are in progress. See original paper for figures.