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A Conflict-Coordination Framework for Constructing Living Shorelines: A Case Study of Ecological Seawalls

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Abstract

While coastal zones support economic and social development, they also face prominent contradictions between shoreline utilization and ecological protection. This study proposed an innovative conflict-coordination framework for constructing living shorelines, aiming to identify and mitigate multi-dimensional conflicts in coastal engineering. The framework introduced a four-dimensional conflict analysis structure encompassing policy, social environment, ecological environment, and technical capacity, thereby extending beyond traditional single-dimensional or ecological-only assessments. Furthermore, it integrated the Comprehensive Conflict Index (CCI) with a multi-objective coordination model that couples three core indicators (e.g., whole-life-cycle carbon emissions, comprehensive impact intensity, and the living shoreline index) to achieve synergistic optimization among lower carbon emission, less human intervention, and higher ecological function objectives. Applied to an ecological restoration and seawall ecologization project in Zhenhai District, Ningbo, the results demonstrated that the framework helped constructing living shorelines by effectively reducing comprehensive conflict intensity with 21.2%, decreasing total carbon emissions with 60.2%, and significantly improving both the living shoreline index and multi-objective coordination level. Compared to traditional coastal zone assessment methods, these findings highlighted the differentiated advantages of the proposed framework in quantifying conflict sources, enhancing coordination among multi-objectives, and providing scientific support for living shoreline construction and sustainable coastal management.

Keywords: living shorelines; conflict-coordination framework; ecological seawalls; whole-life-cycle carbon emission; coastal restoration

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1. Introduction

Coastal zones are major hubs for human activities. In China, they cover roughly 13.5% of the national land area but accommodate 43.3% of the population and generate 57.7% of GDP [1]. Dense population concentration is typically accompanied by intensive development and extensive shoreline use. China's mainland coastline now extends about 18,000 km, of which roughly 11,682 km (≈64.9%) has been developed [2]. As development intensifies, tensions between shoreline utilization and ecological protection have become increasingly apparent, most notably through rapid shoreline artificialization [3]. To protect lives and property from marine hazards, conventional coastal defense has relied on rigid

seawalls of masonry or concrete [4]. These hard structures sever the land–sea connection, alter hydrodynamics and sedimentation processes, damage habitats for coastal flora and fauna, and impair essential coastal ecosystem functions [5]. In some areas, they can even exacerbate problems such as coastal erosion [6].

In recent years, ecological awareness and concern for environmental protection have grown, prompting a shift in coastal defense priorities from solely hazard resistance to the restoration and conservation of coastal ecosystems [7]. Against this background, traditional hard-engineering solutions have gradually been replaced by green and nature-based measures [8]. Currin et al. proposed the concept of "living shorelines", emphasizing that such interventions can restore sediment dynamics, vegetation structure, and fisheries productivity in tidal marshes [9,10]. Since then, research on living shorelines as a nature-based solution has expanded [11–13], and extensive implementation in U.S. states such as North Carolina, Alabama, and Washington has produced notable ecological recovery [14–16]. In China, the concept of living shorelines has also gained increasing attention [17]. For example, salt marsh plantation in Chongming Dongtan serves as a nature-based flood defense for wave attenuation [18].

Synthesizing the literature and practice, living shorelines can be characterized in three aspects: (1) as naturally functioning coasts constructed from natural materials or combinations of natural and engineered materials—by deploying native vegetation, rock, sand, logs, coconut fiber, and ecological structures such as revetments and artificial reefs (e.g., oyster reefs) to create resilient, self-sustaining coastal systems [19]; (2) as ecological protection schemes that effectively mitigate erosion and improve geomorphic stability by restoring nature processes through vegetation, wetlands, and permeable structures [20]; and (3) as coastal management practices that ensure multiple ecosystem services and socioeconomic gains—by protecting and restoring coastal habitats, they support ecosystem functions while generating employment, fostering public participation, and improving local quality of life [21–23].

In light of national initiatives such as the construction of a marine ecological civilization, integrated protection and utilization of coastal zones, and the "dual-carbon" targets (carbon peaking and carbon neutrality), reconciling shoreline use with ecological protection has become a strategic priority [24,25]. However, current coastal restoration approaches are often one-dimensional, insufficiently tailored to local conditions, and prone to superficial greening that overlooks the need to coordinate shoreline utilization, low-carbon development, and ecological conservation [26]. Furthermore, existing studies and assessment frameworks generally focus on single objectives, such as ecological restoration effectiveness or economic benefits, while lacking an integrated mechanism for quantifying multi-dimensional conflicts and assessing the coordination among multiple goals [27,28].

To address these gaps, this study develops a conflict-coordination framework to systematically quantify the intensity of coastal utilization conflicts and to elucidate the synergies and trade-offs among shoreline utilization, low-carbon development, and ecological protection. Building on this analysis, we propose the ecological seawalls—a living shoreline construction mode with innovative technical measures aimed at optimizing multi-objective outcomes. The proposed framework offers a scientific basis for evidence-based decision-making and supports the sustainable management of coastal zones.

2. Materials and Methods

2.1. Study Area

The Coastal Ecological Restoration and Seawall Safety Enhancement Project in Zhenhai District is situated in Xiepu Town, Ningbo City, Zhejiang Province, China, and encompasses the reclaimed area north of Niluo Mountain and the Xinhongkou reclamation area. Zhenhai

District is located at the estuarine transition zone between the Yongjiang River and the East China Sea, characterized by a typical irregular semidiurnal tide, with mean tidal range of 1.76 m. Following large-scale reclamation, the original natural shoreline was completely transformed into artificial seawalls. The reclaimed zone is now dominated by chemical industrial parks and associated port facilities, exerting continuous anthropogenic pressure on the local coastal environment.

The Coastal Ecological Restoration and Seawall Safety Enhancement Project covers 12.6 km of shoreline and comprises: 241.2 ha of ecological improvement within the reclaimed area; 440.0 ha of tidal-flat ecological restoration outside the reclamation area; upgrade and ecological retrofitting of 12.6 km of seawalls; construction of 11.15 km of new water-system works within the reclaimed area; and 23 ha of site foundation treatment (Figure 1).

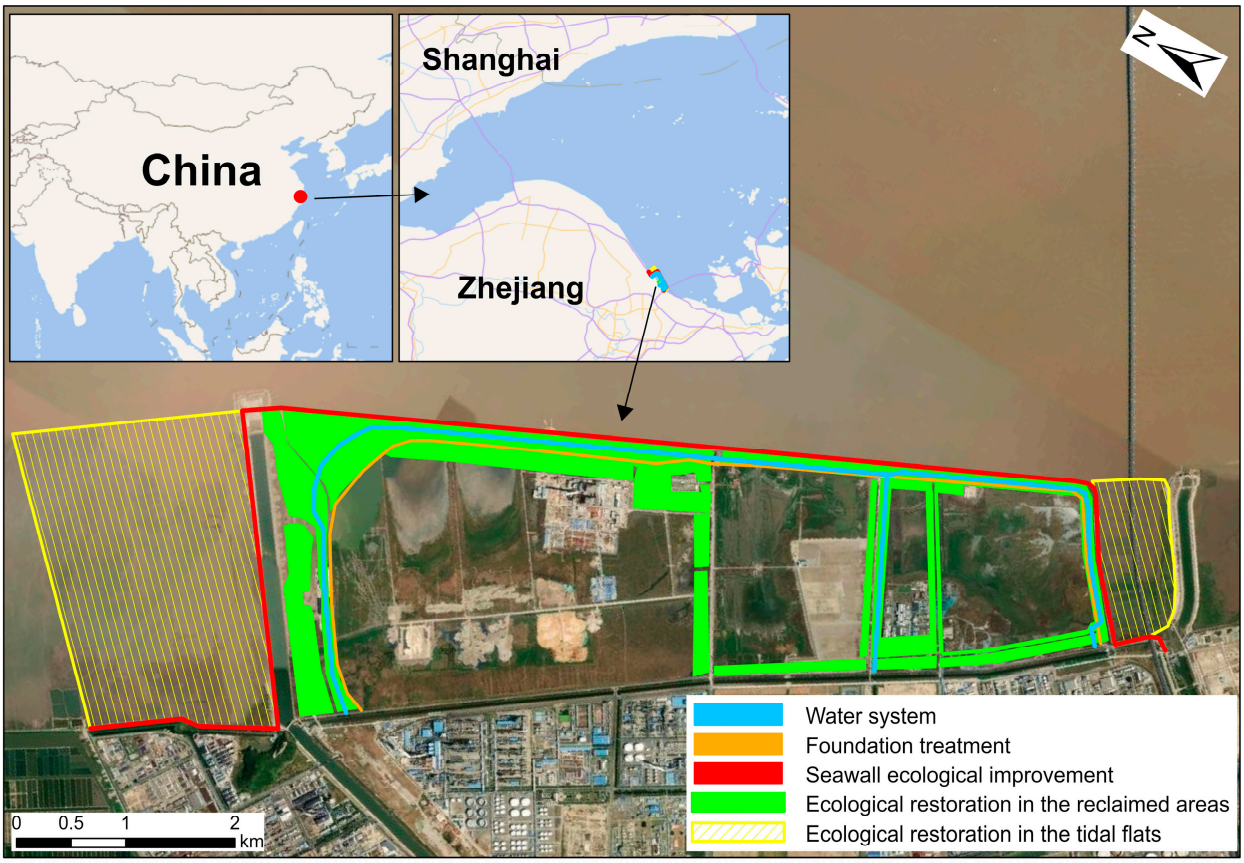


Figure 1. The design of Coastal Ecological Restoration and Seawall Safety Enhancement project in Zhenhai, Zhejiang.

Ecological measures within the reclaimed area included planting mixed forests, aquatic vegetation, grasslands, and shrub communities. Tidal-flat restoration employed diversified salt-tolerant assemblages (e.g., *Tamarix chinensis*, *Phragmites australis*, *Suaeda salsa*, *Scirpus triqueter*), supplemented by tree species such as *Hibiscus hamabo* and *Ilex integra*, and benthic habitat enhancement by razor-clam seeding. Seawall ecological measures comprised oyster placement at the seaward toe and soil capping with *Suaeda salsa* planting on the seaward platform of the outer seawall layer. The project commenced in March 2021 and passed final acceptance in December 2023.

2.2. Conflict-Coordination Framework

Existing approaches for analyzing coastal use conflicts often rely on coupled human and natural systems (CHANS) frameworks or ecosystem-based management (EBM) paradigms, both of which emphasize the dynamic feedback between human activities and ecosystem responses. The CHANS framework provides a theoretical foundation for understanding the bidirectional coupling and feedback processes that link human decisions and ecological consequence [29,30]. Meanwhile, EBM manages human interactions with ecosystems across a range of organizational, spatial and temporal scales [31,32].

However, these frameworks primarily address system feedback and adaptive management, with less emphasis on quantifying the spatial conflict intensity and the coordination among multiple coastal objectives. In contrast, the conflict–coordination framework proposed in this study extends beyond the traditional CHANS or EBM perspectives by explicitly coupling conflict intensity assessment (representing human–ecological–technical tensions) with multi-objective coordination modeling (representing the synergistic evolution of low-carbon, ecological, and social subsystems). This integration enables quantitative identification of the "pressure–response–coordination" dynamics within coastal development, thereby offering a more precise analytical tool for balancing utilization and protection under limited spatial and ecological constraints. The following is the detailed description of conflict–coordination framework.

2.2.1. Coastal Comprehensive Conflict

In the utilization and protection of coastal space, conflicts typically arise across four interrelated aspects: policy, social environment, ecological environment, and technical capacity [33]. Among them, policy conflicts occur when coastal activities contravene laws and regulations—such as marine environmental protection, ecological redlines, and marine functional zoning—or when sea-use approvals are granted or executed improperly. Social-environment conflicts stem from development that prioritizes rapid economic growth over ecological protection, often accompanied by inadequate investment in conservation. Ecological–environment conflicts emerge when coastal development exceeds the capacity of local ecosystems, causing negative ecological impacts. In some cases, projects undertaken under the guise of "restoration" further harm the environment. Conflicts related to technical capacity arise from deficiencies in ecological optimization within coastal spatial planning, material selection, and types of marine utilization. These conflict types are not mutually exclusive; many coastal interventions involve multi-dimensional tensions (e.g., Hainan's Haihua Island project produced both social conflict and substantial ecological degradation) [34]. Accordingly, assessing coastal conflict requires an integrated, multi-dimensional evaluation that identifies predominant conflict manifestations and targets them for mitigation to better reconcile utilization with protection.

The coastal conflict was quantified using the Comprehensive Conflict Index (CCI), which integrated the conflict manifestations from four dimensions: policy, social environment, ecological environment, and technical capacity [33]. The calculation method was as follows:

$$\begin{cases} CCI = 1, \ if \ P = 1 \\ CCI = P + 0.25 \times S + 0.25 \times E + 0.5 \times T, \ if \ P \neq 1 \end{cases}$$

where P, S, N, and T were the conflict intensity values of policy, social environment, natural environment, and technical capacity, respectively. The conflict value of each dimension was averaged from all indicators under that dimension. The four-dimensional conflict index system was shown in Table 1. The weights of dimensions were determined by expert scoring method. The detailed calculation methods and data sources referred to [33].

Table 1. Four-dimensional conflict indicator system.

Dimension	Index	Level	Value
P. Policy	P1. Marine Ecological Redline	Within, except permitted marine use types	1
		Outside	0
S. Social environment	S1. GDP per Capita (10^4 CNY)	>15	1
		10~15	0.7
		5~10	0.4
		<5	0.1
	S2. Coastal economic density (GDP/Coastline length) (10^8 CNY/km)	>15	1
		10~15	0.7
		5~10	0.4
		<5	0.1
	S3. Pollution emission intensity (wastewater emission/GDP) (10^4 tons/10^8 CNY)	>3	1
		2~3	0.7
		1~2	0.4
		<1	0.1
	S4. Expenditure for environmental protection (10^8 CNY)	<5	1
		5~10	0.7
		10~15	0.4
		>15	0.1
	S5. Ocean governance capacity	Low	1
		Moderate	0.6
		High	0.2
E. Ecological environment	E1. Water quality [a]	Worse than Grade IV	1
		Grade IV	0.8
		Grade III	0.6
		Grade II	0.4
		Grade I	0.2
	E2. Sediment quality [a]	Grade III	1
		Grade II	0.6
		Grade I	0.2
	E3. Biodiversity index [a]	<1	1
		1~2	0.8
		2~3	0.6
		3~4	0.4
		>4	0.2
	E4. Net primary productivity [a] (mg C/m^2·d)	<50	1
		50~60	0.8
		60~70	0.6
		70~80	0.4
		>80	0.2

Table 1. *Cont.*

Dimension	Index	Level	Value
T. Technical capacity	T1. Mode of marine use [b]	Entire change in ocean attributes	1
		Partial change in ocean attributes	0.6
		No change in ocean attributes	0.2
	T2. Time period of marine space use	Permanent	1
		Non-permanent	0.5
	T3. Areal proportion of constructed entity	Area of constructed entity/area of project	0~1
	T4. Areal proportion of impact zone	Area of 5%–flow velocity change/double area of project	0~1
	T5. Materials of constructed entity	Low ecofriendly	1
		Moderate ecofriendly	0.6
		High ecofriendly	0.2
	T6. Ecological Improvement	1-ecological investment/total project investment	0~1

[a] The value should multiply the coefficient based on marine space use to obtain conflict value. [b] The value should multiply modified coefficients based on marine space use to obtain the conflict value. The modified coefficients refer to [33].

2.2.2. Multi-Objective Coordination Degree

To construct living shorelines, low-carbon development and ecological protection must be prioritized during the development and utilization of coastal areas—thereby achieving the coordinated development of three core objectives: optimized low-carbon benefits, minimized human impact intensity, and maximized ecological protection benefits. In this study, a whole-life-cycle carbon emission model was used to quantify low-carbon benefits, a comprehensive impact intensity model to quantify human impact intensity, and a living shoreline index to quantify ecological protection benefits. A coordination degree model was further constructed to characterize the coordination degree among these three objectives. The specific details of these models are provided below:

(1) Whole-life-cycle carbon emissions

The whole-life-cycle carbon emission model can estimate the total cumulative carbon emissions of a project, spanning the construction, operation, and decommissioning phases. Carbon emission quantification is divided into two categories: one is the carbon-traceable category, quantified using the process analysis method; the other is the carbon-untraceable category, quantified using the input–output method [35]. By integrating the carbon emission calculation formulas for these two categories, the total whole-life-cycle carbon emissions of the project can be determined—specifically, through the accumulation of emissions across all phases and categories. The formula is as follows:

$$E(t) = \sum_{i=1} Q_i \times R_i \times t + \frac{P_n \times I_n \times t}{CPI_n} \times 138$$

where $E(t)$ represents the total carbon emissions over the whole life cycle (ton CO_2 eq). Q_i represents the quantity of the ith material used (ton, m^3 or kWh). R_i represents the

carbon emission factor of the *i*th material (ton CO_2 eq per unit). P_n represents the static investment in the base year (10^4 CNY). CPI_n represents the consumer price index (CPI) for year n (dimensionless). I_n represents China's carbon emission intensity for year n (ton CO_2 eq per million CNY). t represents the duration of the construction, operation, and decommissioning phases (year). The constant 138 is a normalization coefficient derived from the 2002 purchasing power parity (PPP) index between China and the United States, and the U.S. carbon emission intensity of the same year [35].

(2) Comprehensive impact intensity

Human impact intensity on coastal ecosystems is characterized using a comprehensive impact intensity model. For marine and coastal environments, human activities exert dual impacts. Development and utilization activities such as port construction, fisheries, oil and gas development, and coastal tourism reduce environmental carrying capacity by degrading ecosystem integrity. Oppositely, marine protection measures and environmental protection policies enhance environmental carrying capacity by mitigating anthropogenic degradation and restoring ecological function.

Based on these dual impacts of human activities on coastal environment, this study proposed a generalized time-varying model of comprehensive impact intensity:

$$I(t) = A(t) \times \left(1 - \frac{M(t) \times P(t)}{C(t)}\right)$$

where $I(t)$ represents the comprehensive impact of human activities on coastal utilization and protection at time t. The higher this value, the greater the comprehensive impact intensity. For the human activity intensity factor $A(t)$, the annual average thickness (in cm) of sediment erosion and deposition under flow velocity deviations exceeding 5% is selected as a representative indicator. For the protection measure effectiveness factor $M(t)$, the cumulative erosion improvement rate (in %) is selected as a representative indicator. For the policy intervention factor $P(t)$, normalized environmental protection investment (in 10,000 yuan) is selected as a representative factor. For the environmental carrying capacity factor $C(t)$, water quality, sediment quality, biodiversity, and net primary productivity serve as representative indicators.

(3) Living shoreline index

The ecological protection benefits are assessed by developing a living shoreline index model. The evaluation indicators are derived from the group standard Index System for Living Shoreline Evaluation (T/CSES 173-2024, [36]). The weights of the evaluation indicators were determined using the analytic hierarchy process, incorporating questionnaire responses from 20 experts. Table 2 presents the resulting weights of the living shorelines evaluation indicators for different coastline types. The living shoreline index is calculated as the sum of the products of each indicator's comprehensive impact weight and its corresponding status value. The formula is expressed as:

$$E(t) = \sum_{i=1}^{n} w_i \times e_i(t) \quad (1)$$

where w_i denotes the comprehensive impact weight of each indicator, and e_i represents the time-varying status value of the evaluation indicator.

Table 2. Weights of living shorelines indicators for different coastline types.

Indicators	Comprehensive Impact Weight		
	Production Coastline	**Living Coastline**	**Ecological Coastline**
Soil type	0.0511	0.0701	0.0685
Coastal erosion	0.0511	0.0701	0.0685
Areal proportion of ecological redline	0.1209	0.1600	0.1277
Seawater quality	0.0468	0.1035	0.0889
Marine debris in coastal waters	0.0468	0.1035	0.0889
Total length of coastline	0.0699	0.0647	0.0522
Natural coastline retention rate	0.0699	0.0647	0.0522
Backshore vegetation coverage	0.0595	0.0745	0.1209
Intertidal biodiversity	0.0595	0.0745	0.1209
Carbon sink capacity of coastal wetlands	0.0790	0.0620	0.1116
Population density	0.0969	0.0838	0.0596
Total output value of marine fisheries	0.1239	0.0340	0.0198
Output value of coastal tourism	0.1239	0.0340	0.0198

(4) Multi-objective coordination degree

The coordination among the three objectives—optimized low-carbon benefits, minimized human impact intensity, and maximized ecological protection benefits—can be quantified by calculating the coordination degree across the three corresponding models: whole-life-cycle carbon emissions, comprehensive impact intensity, and living shoreline index. The coordination degree refers to the extent of benign coupling among interacting subsystems, reflecting the quality of their coordinated state and indicating whether the system functions are mutually reinforcing at a high level or mutually constraining at a low level. The formula for calculating coordination degree is as follows:

$$T = \sum \beta_i U_i$$

where T represents the coordination degree, β_i represents the weight of each subsystem, and U_i represents the subsystem function. Specifically, U_1 corresponds to the whole-life-cycle carbon emissions $E(t)$, U_2 to the comprehensive impact intensity $I(t)$, and U_3 to the living shoreline index $L(t)$. Since a higher value of T indicates better coordination, the reciprocals of $E(t)$ and $I(t)$ are used in the calculation to align with the premise that lower emissions and lower impact intensity contribute positively to coordination degree.

2.2.3. Conflict-Coordination Model

Referring to the coupling coordination degree model [37], a conflict-coordination model is constructed by coupling the coastal comprehensive conflict intensity and the multi-objective coordination degree model. To quantify the balance between conflict and coordination, the formula of D is defined as follows:

$$D = \sqrt{CCI/T}$$

where D represents the conflict-coordination value, CCI denotes the comprehensive conflict intensity value, and T refers to the multi-objective coordination degree value. A lower value of D indicates a more optimal utilization mode.

3. Results

3.1. Coastal Comprehensive Conflict Intensity

The project was situated within a historical reclamation area originally designated as an industrial base in Zhenhai District, Ningbo, intended for the construction of ash storage

facilities for the Zhenhai and Beilun Power Plants. As the project site was beyond the marine ecological protection redline, no policy-related conflict was identified. Zhenhai, being both a national demonstration base for new industrialization and one of China's seven major petrochemical industrial bases, exhibits a strong economic reliance on industrial activities. This resulted in a relatively high social environment conflict intensity (0.860) in terms of shoreline utilization (Table 3).

Table 3. Coastal conflict results of the Zhenhai Project.

	Policy	Social Environment	Ecological Environment	Technical Capacity	Comprehensive Conflict Intensity (CCI)
Reclamation	0	0.860	0.700	0.832	0.806
Ecological restoration and seawall ecologization	0	0.860	0.650	0.514	0.635

The ecological environmental conflict intensity of the project was 0.700. This elevated value was mainly attributed to substantial marine environmental degradation caused by both construction and operational activities. During construction, the building of seawalls blocked land–sea connectivity, leading to a decline in seawater quality. Moreover, the reclamation activities fundamentally altered the natural attributes of the coastal intertidal zone, causing significant loss of marine organisms—such as nekton, benthos, phytoplankton, and zooplankton—within the reclaimed area. These impacts resulted in a reduced biodiversity and severe impairment of marine ecosystem functioning. In addition, the operation of industrial facilities such as power plants inevitably introduced ongoing adverse impacts on the marine environment, including pollutant discharge.

From a technical perspective, the reclamation of sea areas has completely transformed their natural attributes, resulting in the permanent loss of the intertidal zone. The entire reclaimed area was converted into terrestrial land, leading to poor ecological performance. These factors collectively contributed to a high technical conflict intensity (0.832). Overall, if the project proceeded with reclamation for industrial construction, its comprehensive conflict intensity would reach 0.806.

Due to the severe adverse impacts of reclamation on the marine ecological environment, China has progressively tightened its approval for reclamation projects since 2008, mandating the implementation of corresponding ecological restoration measures. In this project, ecological restoration and seawall ecologization reduced the comprehensive conflict intensity to 0.635, representing a decrease of approximately 21.2%. This reduction was primarily observed in the ecological environment and technical aspects. The diverse plant configuration and benthic organism seeding both inside and outside the reclaimed area contributed to a notable improvement in the ecological environment. The reintroduction of halophytic vegetation (e.g., *Spartina alterniflora* removal followed by native *Suaeda salsa* and *Phragmites australis* planting) significantly enhanced shoreline stability and primary productivity. Simultaneously, benthic fauna seeding accelerated sediment remediation and nutrient cycling, thereby improving water quality and benthic habitat conditions. These measures collectively reduced ecological stress and restored partial biological functionality within the intertidal zone. Compared to industrial construction, the ecological restoration and seawall ecologization had a lower conflict impact coefficient related to the ecological environment, reducing the ecological environment conflict intensity to 0.650.

From a technical perspective, the ecological restoration reflected the replacement of rigid engineering with eco-technical designs, including the use of permeable structures, natural revetment slopes, and bio-substrate materials. Such designs enhanced hydrological connectivity, minimized direct occupation of the intertidal zone, and improved habitat

heterogeneity. The incorporation of vegetation and habitat modules on the seawall surface further promoted ecological resilience. Consequently, alterations to the original natural attributes of the sea area were relatively moderate. In contrast to traditional hard-engineered seawalls, the ecological transformation of seawalls employed eco-friendly materials and increased investment in ecological aspects, significantly improving habitat quality in the seawall area. These eco-technical measures reduced the technical conflict intensity to 0.514 (Table 3), a decrease of approximately 38.2%.

Figure 2 presented a visual comparison of the Zhenhai seawall area before and after the implementation of ecological restoration and seawall ecologization. Before intervention (Figure 2, left), the shoreline exhibited typical characteristics of a hard-engineered coast, including steep artificial revetments, limited intertidal zones, and the absence of vegetation coverage. The seawall structure consisted mainly of concrete blocks and masonry, which provided flood protection but disrupted land–sea connectivity and offered minimal ecological value. After ecologization (Figure 2, right), the shoreline morphology and surface cover underwent significant transformation. Vegetation was established in front of and behind the seawalls. The gentle slope created by the regraded intertidal zone restored hydrodynamic exchange, enhanced sediment retention, and provided habitats for benthic organisms. These physical and ecological modifications collectively improved biodiversity, increased carbon sequestration capacity, and contributed to the observed reduction in ecological conflict intensity (from 0.700 to 0.650) and technical conflict intensity (from 0.832 to 0.514).

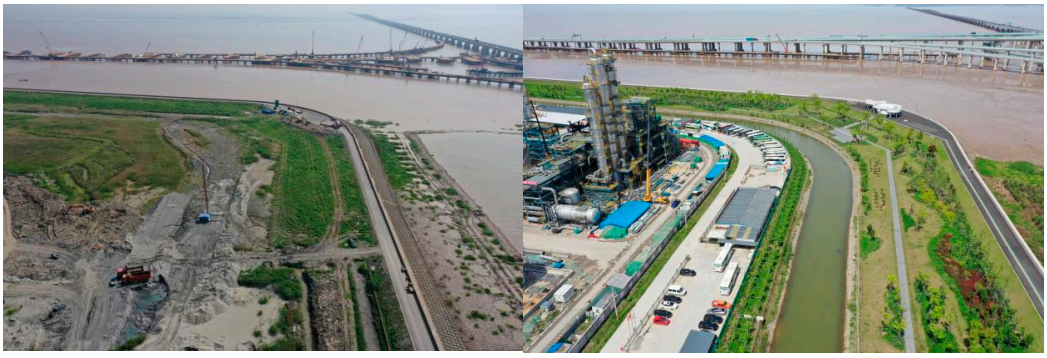


Figure 2. Seawall ecologization and ecological restoration in Zhenhai (**Left**: before implementation; **right**: after implementation. The photos were provided by Miao Hu).

3.2. Conflicts and Multi-Objective Coordination

If the project had adopted the original reclamation approach, the associated construction materials and investments would have generated approximately 83,169 tons of carbon dioxide emissions. In contrast, the ecological restoration and seawall ecologization strategy resulted in significantly lower emissions, 33,116 tons of carbon dioxide, representing a reduction of nearly 60.2%. The carbon emission boundary covered both the construction and operation stages, including raw material production and consumption, equipment and energy use, and the transportation of major construction materials. All activity data were derived from engineering design records and verified through on-site monitoring, ensuring the reliability of the results. Normalizing the carbon emissions from the reclamation method to 1, the emission intensity of the ecological measures is 0.398.

The comprehensive impact assessment in this study focuses primarily on the effects of construction on the adjacent sea area. The tidal flat within the project zone is relatively elevated, largely above 2 m, with seawater inflow occurring only during spring tides. Both the reclamation work and ecological restoration activities inside and outside the reclaimed

area induced negligible change in flow velocity (exceeding 5% variation), resulting in minimal marine impact per the applied comprehensive impact model.

Under the reclamation scenario, the living shoreline index of the project coastline was 0.425. Following ecological restoration and seawall ecologization, intertidal biodiversity and the carbon sequestration capacity of coastal wetlands improved, raising the living shoreline index to 0.491.

Considering the three objectives—optimized whole-life-cycle carbon emissions, minimized comprehensive human impact, and maximized ecological protection benefits—with equal weighting assigned to each, the multi-objective coordination value was 1.118 for the reclamation method and 1.516 for the ecological restoration strategy. The higher value associated with the ecological approach reflects stronger synergy among the three objectives. Incorporating the coastal conflict analysis, the conflict-coordination was 0.849 for reclamation and 0.647 for ecological restoration and seawall ecologization, confirming that the ecological strategy offers not only improved coordination across sustainability objectives but also a reduced level of conflict.

4. Discussion

To resist marine dynamic disasters and protect the lives and property of coastal residents, extensive seawalls have been constructed along China's coastline. The National Seawall Construction Plan (2017) set objectives to further improve the coastal flood prevention and disaster mitigation system over the next decade, aiming to extend the total length of national seawalls to 15,000 km and increase the compliance rate of existing seawalls to 57.1%. However, traditional hard seawalls have primarily focused on engineering-based flood control. Relying on the extensive use of natural stones and concrete blocks, these hard defense methods frequently result in the occupation of intertidal zones and severe degradation of marine ecosystems. With growing awareness of ecological conservation, Nature-based Solutions (NbS) have gained consensus as a sustainable approach to enhancing coastal resilience [38]. Such strategies emphasize the use of natural features, such as coastal salt marshes and mangroves, to dissipate wave energy, thereby not only strengthening disaster preparedness but also supporting co-benefits including carbon sequestration, biodiversity enhancement, and water purification [39]. For already-constructed traditional seawalls, ecological retrofitting represents a practical form of NbS. This approach combines artificial restoration with natural recovery processes to transform conventional hard structures into multifunctional ecological seawalls, integrating flood prevention, wave attenuation, ecological functions, and landscape values [40]. The transformation toward ecological seawalls reflects a broader shift in coastal management—one that aligns engineering goals with environmental sustainability and ecosystem service restoration.

Using the conflict-coordination method, this study systematically evaluated the spatial conflict characteristics and multi-objective coordination levels associated with different coastal engineering approaches, including traditional reclamation, ecological restoration and seawall ecologization, against the three objectives of optimized whole-life-cycle carbon emissions, minimized comprehensive human impact, and maximized ecological protection benefits. The results demonstrated that this method could effectively quantify multi-dimensional conflicts arising from coastal space utilization. While policy-related and social-environmental conflict intensities remained largely unchanged, ecological seawalls contributed to a reduced ecological environmental conflict intensity. Specifically, through the establishment of coastal wetland vegetation in front of the seawalls, ecological engineering on the structure itself, and terrestrial vegetative buffer zones behind it, ecological seawalls improved local seawater quality, sediment conditions, biodiversity, and net primary productivity [41]. In the case study of the Zhenhai project, traditional reclamation

and seawall construction would directly destroy the original intertidal habitats, resulting in high ecological environment conflict intensity. On the contrary, the implemented ecological restoration and seawall ecologization measures, such as vegetation planting and benthic organism seeding, preserved partial intertidal habitats and provided additional ecosystem services including water purification and biodiversity improvement, thereby lowering the ecological environmental conflict intensity. Furthermore, the technical conflict intensity of the reclamation method was also relatively high. Ecological measures mitigated technical conflicts by minimizing direct sea occupation, retaining partial natural maritime attributes, employing eco-friendly materials, and increasing investments in environmental protection. These approaches collectively contributed to a more sustainable and coordinated coastal utilization mode.

Building on the quantitative identification of coastal conflicts, targeted optimization measures can be developed to reduce conflict intensity. The conflict-coordination method further reveals changes in the synergistic relationships among multiple objectives, thereby offering a new technical pathway for the scientifically informed construction of living shoreline models. Compared to conventional approaches that rely on conflict indicators or purely ecological evaluation, the conflict-coordination method offers distinct advantages in integrating multiple objectives and quantifying coordination levels. It is applicable to conflict diagnosis across a variety of coastal projects, including seawall construction and ecological restoration, as well as to the optimization of living shoreline designs. In terms of multi-objective coordination, this study demonstrates that traditional reclamation and hard seawall construction perform poorly in both carbon emissions and ecological impacts. The production and transportation of construction materials involved in reclamation emit substantial amounts of CO_2, while the physical occupation and degradation of intertidal ecosystems lead to poor ecological outcomes and a low living shoreline index. In contrast, ecological restoration and seawall ecologization, through measures such as vegetation restoration and benthic organism seeding, reduced the use of high-carbon footprint materials, lowered overall project emissions, and minimized anthropogenic disturbance to coastal ecology. Furthermore, these measures enhanced long-term carbon sequestration capacity, improved biodiversity, elevated ecological benefits, and increased the living shoreline index. The case study presented here confirmed that the ecological seawalls model outperformed the traditional approaches, exhibiting lower coastal conflict intensity and higher multi-objective coordination. Ecological seawalls better align with the multifunctional requirements of living shorelines and exemplify a positive feedback mechanism characterized by low conflict and high coordination.

From a practical standpoint, the findings of this study offer significant implications for the design and management of seawalls. First, among various engineering alternatives, priority should be given to integrated approaches that balance disaster prevention with ecological benefits. This can be achieved by optimizing flood and wave dissipation structures, selecting eco-friendly materials, and creating natural habitats, all of which contribute to reduced coastal conflict and enhanced multi-objective coordination. For instance, constructing a graded wave-dissipation system ranging from offshore oyster reefs through wetland vegetation to onshore ecological seawalls can simultaneously improve disaster resilience and increase the ecological functionality of coastal zones. Second, in terms of project management, it is essential to establish a comprehensive evaluation framework that incorporates carbon accounting and ecological performance assessment. Low-carbon and ecologically oriented solutions should be prioritized to promote efficient utilization of shoreline resources and long-term ecosystem sustainability. In cases where low-carbon and ecological goals cannot be simultaneously fully achieved, ecological outcomes should be favored. Although ecological strategies may entail higher initial investments and slightly

elevated carbon emissions during construction, they offer substantial long-term benefits, including enhanced carbon sequestration, that compensate for initial emissions and provide greater sustainability over the full project lifecycle.

Beyond project-level applications, the results of this study also provide policy-oriented insights for integrated coastal management. First, the conflict–coordination analytical framework could be incorporated into national shoreline zoning and management plans to enable early identification and mitigation of spatial and ecological conflicts during project approval and design. The framework can inform site selection, design trade-offs and prioritization for NbS deployments where ecological, social and technical constraints differ. Second, the development of unified carbon-accounting guidelines for ecological seawalls and restoration projects would help standardize emission assessment and promote the adoption of low-carbon engineering practices. Third, the effective implementation of ecological seawalls requires stronger multi-agency collaboration among departments of water resources, ecology and environment, and urban and rural planning. Establishing a cross-sectoral coordination mechanism could enhance policy coherence and ensure that disaster prevention, ecological protection, and spatial planning objectives are mutually supportive. These recommendations can help translate the conflict–coordination framework into practical governance tools, supporting the broader transition toward nature-based and sustainable shoreline management in China.

Although this study focuses on China's coastal regions, the proposed conflict–coordination framework can be extended to international contexts. However, due to the limited availability of standardized ecological and socio-technical datasets from other countries, cross-regional quantitative comparison was not feasible at this stage. Future work will aim to validate the framework through international case applications.

5. Conclusions

This study developed a conflict-coordination model to systematically evaluate the conflict characteristics and multi-objective coordination levels associated with different coastal engineering modes. The results indicated that the traditional reclamation model exhibited high conflict intensity in both ecological environmental and technical dimensions, accompanied by substantial carbon emissions and limited ecological benefits. In contrast, the ecological restoration and seawall ecologization model demonstrated significant advantages in reducing conflict intensity, optimizing carbon emission structures, and enhancing biodiversity and carbon sequestration capacity, reflecting a positive feedback mechanism characterized by low conflict and high coordination. The study confirmed the applicability and scientific validity of the conflict-coordination method in balancing multiple objectives, including low-carbon development, ecological restoration, and disaster prevention and mitigation.

At a practical level, the findings suggested that seawall construction and shoreline utilization should prioritize integrated models that synergize protective functions with ecological benefits. Implementation of measures such as establishing coastal wetland vegetation, utilizing eco-friendly materials, improving hydrological connectivity, and restoring benthic organisms can effectively reduce spatial conflicts and enhance coordinative benefits. Furthermore, coastal management should establish a comprehensive evaluation system incorporating carbon emission accounting and ecological performance assessment, with ecological solutions being prioritized to facilitate a shift from single-objective engineering approaches to multi-functional ecological strategies. Future research should incorporate multi-scale and multi-type coastline case studies to further refine the theoretical framework and practical application of the living shorelines model, thereby supporting ecological civilization construction and promoting sustainable coastal development.

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