Ecological Processes

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Identifying ecological risk and cost–benefit value for supporting habitat restoration: a case study from Sansha Bay, southeast China

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Abstract

Background Coastal wetlands with high biodiversity and productivity provide essential ecosystem services that have a significant positive socio-economic impact. However, coastal reclamation, pollution, and climate change are threatening coastal wetlands. Thus, it is critical to identify priority areas for restoration and improve habitat resilience to adapt to environmental changes. Here, we propose a general analysis framework integrating nature-based solutions (NbS) into habitat restoration to increase coastal resilience to multiple stressors in Sansha Bay, southeast China.

Results The total loss of value in ecosystem services due to reclamation in Sansha Bay was US$162.18 million from 2000 to 2015. The coastal habitats were at medium risk of degradation, with some high-risk areas concentrated in the northwest and along the west coasts, which were prioritized for restoration.

Conclusions Our proposed framework, which integrates hard and soft engineering such as mudflat renovation, mangrove afforestation, and an ecological seawall, can aid in the improvement of coastal resilience. The project cost was US$12.71 million and was estimated to generate US$36.75 million in environmental services. We recommend evaluating and monitoring shoreline changes, environmental factors, and marine biological resources using long-term sampling surveys and remote sensing methods. Our findings can serve as a guide for government decision-making in coastal restoration planning and management.

Keywords Reclamation, Ecological risk, Restoration, Nature-based solutions, Coastal resilience

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Background

With the expansion of the marine and coastal economy, coastal areas are becoming more densely populated. Due to the high demand for land in coastal areas, reclamation is commonly performed to increase the amount of land available for development (Hossain et al. 2019; Meng et al. 2017). Although reclamation promotes socio-economic development, it often results in a significant decline in wetland ecological services, sharp reductions in coastal wetland resources, and the destruction of wetland ecosystems. Coastal wetlands provide important ecosystem services, including flood prevention, climate regulation, water conservation, pollution control, and regional ecological balance (Duarte et al. 2013). At least 775 million people globally rely heavily on coastal ecosystems (Saunders et al. 2020). However, in recent decades, a large area of coastal wetland has been destroyed due to coastal reclamation, marine pollution, and climate change (e.g., marine heat waves, sea level rise (SLR), and drought). Coastal ecosystems are declining globally; the global coverage of salt marshes, mangroves, and seagrasses has declined by 35–85% (Lotze et al. 2006; Pendleton et al. 2012). Therefore, it is critical to reduce the ecological risk of coastal wetlands from the complex interaction of anthropogenic disturbance and climate change, implement innovative conservation solutions to increase coastal resilience, and ultimately reverse coastal ecological degradation and increase the socio-economic benefits derived from coastal wetlands.

Although land use change, pollution, and climate change all interact with ecosystem dynamics, risk forecasts from these stressors are typically reported independently (Halpern et al. 2008; Lu et al. 2018). Several studies have explored these interactive stressors by focusing on the cumulative ecological risk involved in the complex interaction between anthropogenic disturbance and climate change (Arkema et al. 2014). Van den Brink et al. (2019) developed a general framework for assessing the ecological impact of multiple urban stressors on aquatic ecosystems, understanding aquatic ecosystem responses to a multi-stressor environment, and informing appropriate urban ecosystem management strategies. Debecker et al. (2017) discovered the latitude-dependent synergism of threats to ecosystems caused by the interactive effects of metal exposure and warming. Lu et al. (2018) developed an integrated approach to investigate the cumulative threats to the environment caused by the co-occurrence of pollution and climate change. Although some researchers have tentatively explored the interactive effects of anthropogenic disturbance and climate change on regional ecological risk, their studies have primarily concentrated on terrestrial ecosystems. Few have studied coastal and marine ecosystems due to the relatively complex interactions between human disturbances and climate change. Therefore, more research on the interactions of coastal reclamation, marine pollution, and climate change on coastal and marine ecosystems is required. Priority areas for coastal ecosystem restoration should be identified to reduce the risk of coastal wetland damage and increase the net benefits derived from restored coastal wetlands for people.

After determining priority areas, conservation and restoration solutions may be planned and implemented. Nature-based solutions (NbS) are defined by the International Union for Conservation of Nature as innovative and sustainable conservation management solutions that are motivated by the self-regulation of natural systems to address various societal challenges (IUCN 2020; Maes and Jacobs 2017). NbS aim to protect, sustainably manage and restore nature, as well as improve ecosystems, to efficiently solve social problems related to climate change, food and water security, public health, natural disasters, and social and economic development, while also providing human well-being and ecosystem services. Active restoration refers to the deliberate human intervention in degraded or damaged ecosystems to help them recover and regain their ecological functions. Despite a growing body of research demonstrating that the restoration of coastal marine systems involving the use of natural processes and materials could be considered an NbS to improve coastal marine biodiversity and support human health and well-being (Rezek et al. 2019; Thorhaug et al. 2017; Wang et al. 2021a), there has been little restoration in coastal zones compared to restoration of terrestrial or freshwater environments, rendering the assessment of the effectiveness of coastal restoration as an NbS challenging. Moreover, project monitoring and evaluation are insufficient. A timely evaluation of ecological restoration outcomes can produce valuable insights for the future.

Overall, the lack of a general analysis framework incorporating cumulative risk assessment, evaluation, and monitoring of coastal habitat restoration costs and benefits has prevented ecological restoration coupling NbS from being fully implemented. Here, we proposed such a framework aimed at improving the resilience of coastal habitats to multiple stressors and considered Sansha Bay, southeast China, as a case study. The objectives of this study were to (1) investigate the cumulative risk to coastal wetlands caused by the interaction of anthropogenic disturbance and climate change; (2) evaluate the costs and benefits of coastal habitat restoration; and (3) propose an NbS for coastal habitat restoration. First, we assessed the historical and current status of coastal wetlands in Sansha Bay by analyzing the spatiotemporal dynamics of coastal reclamation using ecosystem service accounting. Second, we examined the cumulative risk of coastal reclamation, marine pollution, and extreme storm surges to coastal wetlands to identify priority areas for coastal restoration. Finally, we developed an NbS approach and conducted a cost–benefit analysis for a planned habitat restoration project, along with recommendations for post-restoration evaluation and monitoring.

Methods

Study area

Sansha Bay is a semi-enclosed bay in southeast Ningde City, Fujian Province, China. The prevailing climate is subtropical maritime monsoon, with an average annual rainfall of 2350 mm and average annual temperature of 17.5 °C. The average tidal range in this region is approximately 5.0 m, with an average wave height of 0.1 m. Our study focused on the inner part of the Bay, which, in 2015, included approximately 6354 ha of coastal wetlands (e.g., mangroves, mudflats, saltmarshes), and is surrounded by mountains of various elevations (Fig. 1). Due to land scarcity, many marine areas were reclaimed in the early 2000s to provide space for urban development and foster economic growth in the Sansha Bay area. In the course of reclamation, a sizeable portion of coastal wetlands was converted into construction land between 2000 and 2015. Notably, Sansha Bay is the site of a *Larimichthys crocea* mariculture operation, with 165 km^2 of fishing zones in the inner bay. The aquaculture industry in the area is a source of a large amount of pollution, thus posing a serious threat to the ecological health of coastal wetlands (Zhu et al. 2013).

Research framework and workflow

To guide this study, we proposed an NbS-based framework that would support NbS planning by including ecological risk assessment, habitat restoration design, and cost–benefit analysis (Fig. 2). NbS planning, which includes ecosystem protection and restoration, can significantly contribute to disaster risk reduction and sustainable ecosystem management (Anderson and Renaud 2021; Seddon 2022). In this workflow, we first obtained an open geospatial database and conducted a field survey based on the identified NbS planning goals, i.e., increasing the net benefits generated by ecosystem services (Maes and Jacobs 2017). Subsequently, we analyzed the historical structure and function change in

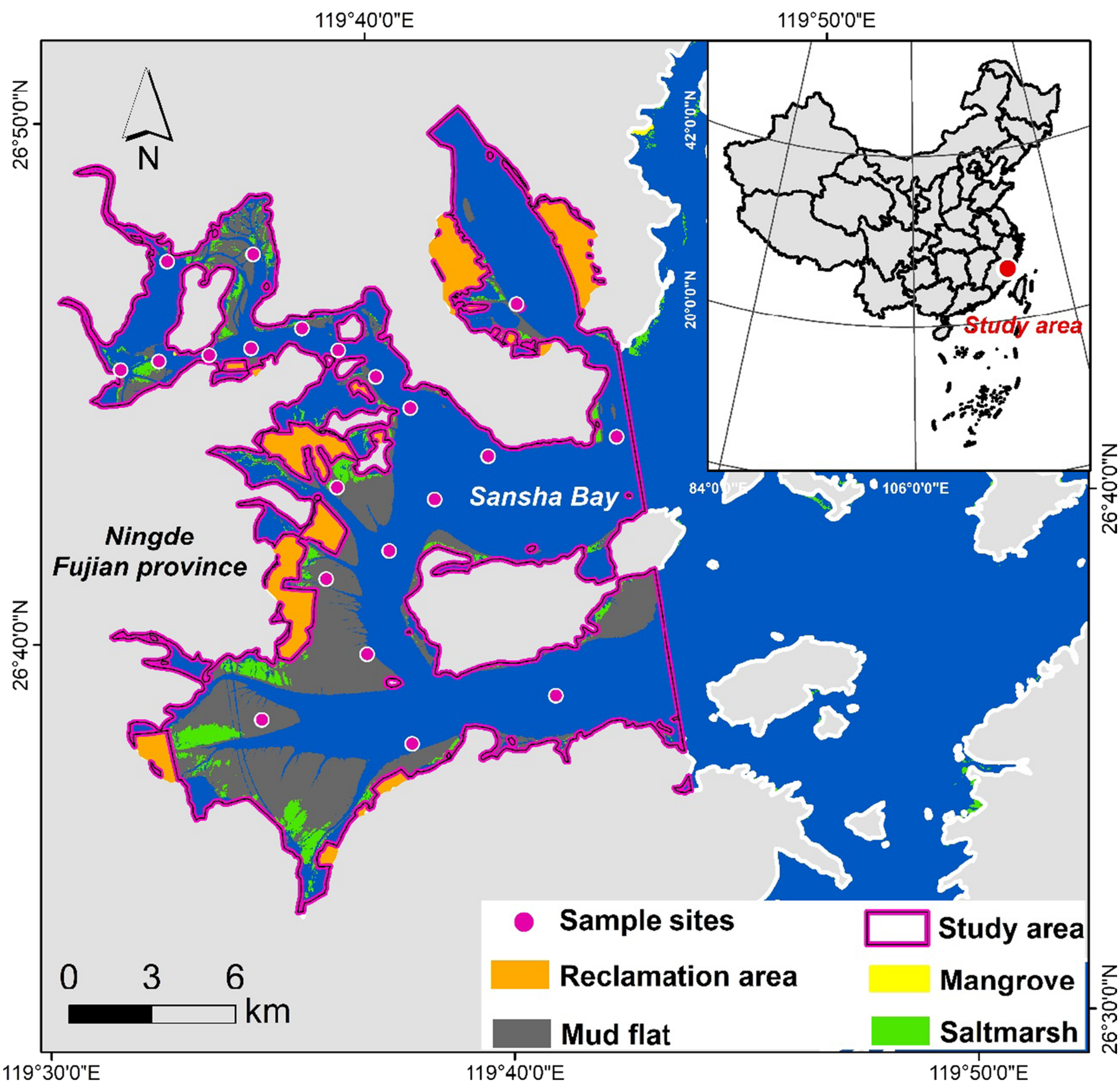

Fig. 1 Location of Sansha Bay and distribution of coastal habitats, reclamation areas, and sampling sites

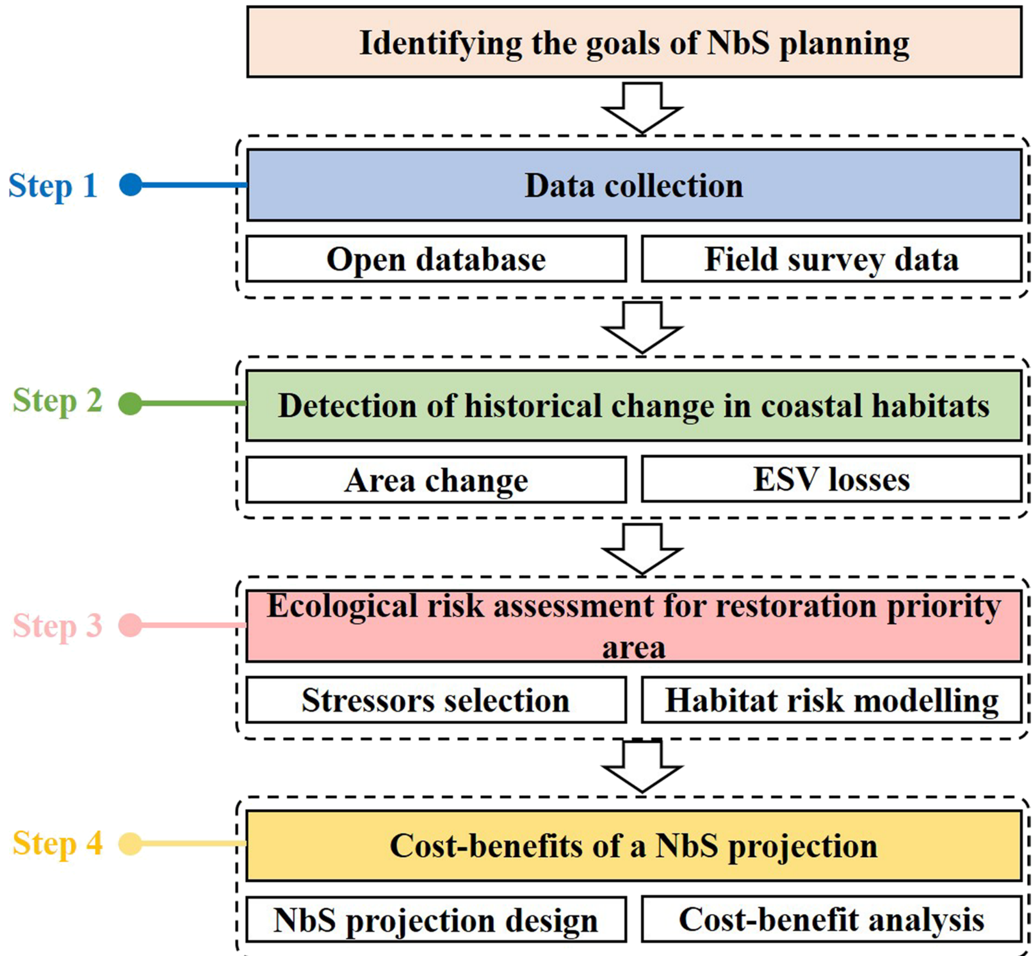

Fig. 2 Conceptual framework of the research methods. NbS: nature-based solution, ESV: ecosystem services value

coastal habitats, as represented by changes in the area and ecosystem services value (ESV), respectively. We then constructed a habitat risk assessment model based on reclamation, pollution, and ecological quality data to assess future ecological risks posed to coastal habitats and identify priority areas for NbS planning in high-risk areas. Finally, a projection for habitat restoration was created using nature-based use scenarios and technology and its cost and benefit were estimated using ESV accounting.

Data sources

Fieldwork was conducted in April and October of 2016 to investigate the pollution risk and ecological quality in Sansha Bay during two different seasons. A total of 21 sampling sites were selected, including 13 sites for assessing both seawater and ecological quality, and 8 sites for assessing only seawater quality (Fig. 1), in accordance with the sampling methods outlined in the Specifications for Oceanographic Survey (Liu et al. 2007). To assess the habitat risk of reclamation, historical reclamation areas were extracted by overlaying land use/cover data of 2000 and 2015 from the GlobeLand30 datasets obtained from the National Geomatics Center of China and produced using over 20,000 Landsat and Chinese HJ-1 satellite images with a resolution of 30 m (Chen et al. 2017). The ESV per unit area in each habitat and reclamation type was calculated using the Ecosystem Services Value Database (ESVD) and Costanza et al. (2014). To analyze the habitat risk to extreme SLR, the SLR rate along the coast of Sansha Bay was obtained from the Global Tide and Surge Reanalysis dataset and a digital elevation model (DEM) was obtained from the USGS NASA Shuttle Radar Topography Mission (SRTM). Table 1 shows the data sources and characteristics used in this study.

Detection of historical structure and function change in coastal wetlands

An understanding of the historical structure and function change in coastal wetlands is the basis of future ecological

Table 1 Data sources and characteristics used in this study

Data name	Data type	Data source	Data time
Pollution and ecological quality data	Excel	Field survey	2016
Coastal habitats	Raster with 10-m resolution	Zhang et al. (2022)	2015
Land use/cover types	Raster with 30-m resolution	GlobeLand30 datasets http://www.globallandcover.com	2000 and 2015
Ecosystem services value	Excel	Ecosystem Services Value Database https://www.esvd.net/	2007 and 2016
Extreme SLR	Shapefile	Global Tide and Surge Reanalysis dataset https://research.vu.nl/en/datasets/global-tide-and-surge-reanalysis-gtsr	2050 and 2100
Digital elevation model (DEM)	Raster with 30-m resolution	USGS NASA SRTM https://lpdaac.usgs.gov/products/srtmgl1v003	2015

risk assessments. Reductions in climate regulation, waste treatment, coastline protection, air quality regulation, biodiversity protection, and other ecological functions are the main cause of the decreases in ESV induced by the reclamation of coastal wetlands and changing ecological functions. The changes in coastal wetlands along Sansha Bay were extracted from the GlobeLand30 datasets for 2000 and 2015. The new area included within the coastline between 2000 and 2015 was identified as reclaimed land over this period, and the changed area of coastal wetland was determined by superimposing the coastal wetland and reclamation layers in ArcGIS® software (Esri, Redlands, CA). The loss of ESV caused by coastal reclamation was calculated by multiplying the lost area in each coastal wetland by the difference in ESV per unit area between each coastal wetland and reclamation type. The equation is as follows:

$$\mathrm{ESV}_{(\mathrm{loss},ij)} = A_{ij} \times \left(\mathrm{ESV}_i - \mathrm{ESV}_j\right), \tag{1}$$

where $\mathrm{ESV}_{(\mathrm{loss},ij)}$ is the ESV loss caused by converting i-type wetland to j-type reclaimed land, A_{ij} is the i-type wetland area lost to j-type reclaimed land, ESV_i is the ESV per unit area in i-type wetland, and ESV_j is the ESV per unit area in j-type reclamation. ESV_i and ESV_j represent the values of Ningde, China, in 2000 and 2015, respectively.

Ecological risk assessment for identifying the restoration priority areas

Analysis of anthropogenic stressors

Reclamation activities Previous studies have shown that the effects of reclamation activities on coastal ecosystems decrease with distance from artificial and aquaculture coastlines, implying that the greater distance from the coastline, the lower the negative influences of reclamation activities on coastal ecosystems (Sharp et al. 2018). We characterized the threat of reclamation activities to coastal wetlands in Sansha bay according to the type of coastline (e.g., artificial, aquaculture, and natural).

Pollution status and ecological quality Using field sampling, we measured 17 parameters (such as pH, dissolved oxygen, and chemical oxygen demand) to assess water quality, as well as diversity and evenness indices of phytoplankton and benthonic animals, to determine ecological quality. The measured parameters and methods are listed in Additional file 1: Table S1.

Water quality was evaluated based on the criteria of water quality assessment using the following equations:

$$\mathrm{PI}_{ij} = {}^{C_{ij}}/_{S_i}, \tag{2}$$

$$\mathrm{PI}_{\mathrm{DO},j} = \begin{cases} \left|\mathrm{DO}_j - \mathrm{DO}_f\right| / \left(\mathrm{DO}_f - \mathrm{DO}_s\right), \mathrm{DO}a\text{‰ ¥}\mathrm{DO}_s \\ 10 - 9\,\mathrm{DO}_j/\mathrm{DO}_s\,, \mathrm{DO} < \mathrm{DO}_s \end{cases}, \tag{3}$$

$$\mathrm{PI}_{\mathrm{pH},j} = \frac{\left|\mathrm{pH}_j - \mathrm{pH}_m\right|}{D_s}, \mathrm{pH}_m = \frac{\mathrm{pH}_u + \mathrm{pH}_l}{2}, D_s = \frac{\mathrm{pH}_u - \mathrm{pH}_l}{2}, \tag{4}$$

where PI_{ij} is the pollution index of pollutant i [excluding dissolved oxygen (DO) and pH] at sampling site j, C_{ij} is the measured concentration of pollutant i at sampling site j, S_i is the assessment criterion of pollutant i, $\mathrm{PI}_{\mathrm{DO},j}$ is the pollution index of DO at sampling site j, DO_j is the measured DO concentration at sampling site j, DO_f is the saturation concentration of DO, DO_s is the assessment criteria of DO, $PI_{\mathrm{pH},j}$ is the pollution index of pH at sampling site j, pH_j is the measured value of pH at sampling site j, pH_u is the upper limit value of the assessment criteria, and pH_l is the lower limit value of the assessment criteria. Following field sampling and analysis of seawater quality, the Kriging spatial interpolation method was used to calculate the pollution index for each spatial unit in Sansha Bay.

Ecological quality was evaluated using the following equations (Yang et al. 2017; Zhang et al. 2020):

$$\mathrm{DI}_j = -\sum_{i=1}^{S} p_{ij} \log_2 p_{ij}, \tag{5}$$

$$\mathrm{EI}_j = {}^{\mathrm{DI}_j}/_{\log_2 \mathrm{S}}, \tag{6}$$

where DI_j and EI_j are the diversity index and evenness index at sampling site *j*, respectively, p_{ij} is the ratio of the number of species *i* to the total number of samples from sampling site *j*, and *S* is the number of species in the samples.

Sea level rise Many areas in developing regions have abandoned natural coastlines in favor of impervious surfaces. The newly constructed impervious surfaces push coastal wetlands toward the ocean, impeding landward mitigation and increasing the flood risk of coastal wetlands due to SLR. Therefore, the SLR pressure in mangrove forests was determined by the rate of SLR, elevation at local mangroves, and adjacent coastline type. The SLR rate along the Sansha Bay coast and habitat DEM were used to indicate the threat of SLR to coastal habitat.

Cumulative ecological risk assessment modeling

The primary threats to coastal wetland resilience in Sansha Bay are land reclamation for development (Li and Wang 2020), anthropogenic pollution (Zhu et al. 2013), and extremely high sea levels (Ying et al. 2015). We constructed a habitat risk assessment (HRA) model using InVEST software (version 3.3.3) (Stanford University, Stanford, CA) to evaluate the ecological impact of these threats on the habitat. The HRA model is an exposure–consequence framework with three dimensions: exposure, sensitivity, and resilience. It allows users to assess the cumulative risk posed to habitats caused by stressors, i.e., anthropogenic activities, identify priority areas for habitat conservation and restoration, and investigate the resilience of ecosystems to multiple threats (Caro et al. 2020; Sharp et al. 2018). Data pre-processing was performed prior to HRA modeling and the stressor layers were reclamation, pollution, and SLR:

1. The stressor layer of reclamation activities included the artificial and aquaculture coastline layers, as well as their 400 m, 800 m, and 1200 m buffers. The intensity of reclamation stress decreased with increasing distance from the reclaimed coastline.
2. The pollution stressor layer was determined by the pollution index range with a threshold of 1. The regions with pollution indices greater than 1 were extracted using the ArcGIS 10.4 software to represent the exposure of coastal habitats to pollution.
3. Regions where the SLR rate along the Sansha Bay coast exceeded the global mean SLR rate and the habitat DEM was below the mean sea level were extracted to create the SLR stressor layer which represented the exposure of coastal habitats to SLR. A buffer analysis with 300 m, 600 m, and 900 m zones was conducted to create the coastal erosion stressor layer in ArcGIS® 10.4.

Next, the effects of stressors on habitats (e.g., mangrove, saltmarsh, and mudflat) were assessed by quantifying the biodiversity and ecosystem services provided by habitats and ecological governance (the number of protected areas was obtained from the Ningde Wetland Waterfowl Mangrove Nature Reserve Master Plan).

Table 2 Specific framework of habitat risk assessment

Attribute	Score criteria[a]		
	Low risk	**Medium risk**	**High risk**
Exposure			
Spatial overlay	Habitat and stressor overlay for 0–20%	Habitat and stressor overlay for 20–50%	Habitat and stressor overlay for 50–100%
Stress intensity	Low intensity	Medium intensity	High intensity
Consequence–sensitivity			
Loss in area	Low loss in area (0–20%)	Medium loss in area (20–50%)	High loss in area (50–100%)
Change in structure	Low loss in structure (0–20% loss, little to no structural damage)	Medium loss in structure (20–50% loss, partial structural damage)	High loss in structure (50–100% loss, total structural damage)
Consequence–resilience			
Biodiversity of plankton[b]	Diversity index for 2–3	Diversity index for 1–2	Diversity index for 0–1
Biodiversity of benthos[b]	Diversity index for 2–3	Diversity index for 1–2	Diversity index for 0–1
Management effectiveness	Very effective with the number of marine protection area (> 2)	Somewhat effective with the number of marine protection area (1–2)	Not effective, poorly managed with no marine protection area

[a] Indicates that the scoring criteria is in accordance with Sharp et al. (2018)

[b] Indicates that the scoring criteria is in accordance with the PRC National Standard (2008)

The specific HRA framework is shown in Table 2. The spatial overlap and intensity of coastal habitats and anthropogenic activities were selected as exposure indices in the HRA framework to reflect the location and intensity of the impact of anthropogenic activities on coastal wetlands, respectively. The area and structural changes in coastal habitats were selected as sensitivity indices reflecting the response of coastal habitats to the impact of anthropogenic activities; the greater the habitat area loss, the greater the sensitivity of coastal habitats to the impact of anthropogenic activities. Marine biodiversity and the number of wetland natural conservation zones were selected as resilience indices reflecting the recovery of coastal wetlands after disturbance from anthropogenic activity. Generally, coastal habitats with greater biodiversity have a stronger ability to recover from disasters; however, the resistance declines as biodiversity increases (Van Ruijven and Berendse 2010).

Post-manipulation of the data, the overall exposure (E) and consequence (C) scores were calculated using the following equations:

$$E_{ij} = \frac{\sum_{k=1}^{n} \frac{e_{ijk}}{d_{ijk} - w_{ijk}}}{\sum_{k=1}^{n} \frac{1}{d_{ijk} \times w_{ijk}}}, \tag{7}$$

$$C_{ij} = \frac{\sum_{k=1}^{n} \frac{c_{ijk}}{d_{ijk} - w_{ijk}}}{\sum_{k=1}^{n} \frac{1}{d_{ijk} \times w_{ijk}}}, \tag{8}$$

where e_{ijk} indicates the exposure rating of habitat i to stressor j in criterion k, c_{ijk} indicates the consequence rating, d_{ijk} is the data quality rating, w_{ijk} denotes the importance weighting, and n represents the number of criteria evaluated for each habitat. Due to the uncertainty in the grade evaluation of each index, the error caused by the classification of grade evaluation can be reduced through data quality rating and the index weight can be used to reduce the impact of secondary influences on habitat when calculating risk.

Finally, the cumulative risk (CR_{ij}) to each habitat from all stressors was calculated based on the Euclidean distance and the risk of coastal habitat damage was graded as high, medium, or low based on the maximum risk score (MRS). High risk corresponds to grid cells with scores greater than 66% of MRS; medium risk corresponds to grid cells with scores between 33 and 66% of MRS, and low risk corresponds to grid cells with scores between 0 and 33% of MRS (Sharp et al. 2018). The equation for CR_{ij} calculation is as follows (Arkema et al. 2014):

$$\mathrm{CR}_{ij} = \sum_{j=1}^{n} \sqrt{(E_{ij} - 1)^2 + (C_{ij} - 1)^2}, \tag{9}$$

where CR_{ij} is the sum of all risk scores of stressors to habitat i.

Cost–benefit estimation of habitat restoration

We identified priority areas for ecological conservation and restoration by conducting an ecological risk assessment, and we proposed an ecological restoration project as an NbS to recover ecological function and reduce risk in areas with significant anthropogenic impacts. Ecological restoration aims to restore ecosystem health and provide products and services for humans for a long time as quickly as possible while minimizing restoration costs and maximizing benefits. Therefore, it is critical to empirically evaluate the effectiveness of ecological restoration projects, including this study. We used a cost–benefit analysis to evaluate the effectiveness of the coastal ecological restoration project at our site along the western coast of Sansha Bay. A cost–benefit analysis is a systematic method for determining which economic decisions to make and which to avoid by quantifying and comparing all costs and benefits of the project (Stewart–Sinclair et al. 2021). Authorities use this method when planning investments in public services to obtain the maximum benefit at a minimum cost. The costs of a coastal ecological restoration project include project construction investment (e.g., mudflat renovation, vegetation planting, constructing a landscape plank road, constructing a seawall and water gate) as well as ongoing maintenance costs. The equation for calculating these costs is as follows:

$$C_O = (1 + \varepsilon) \sum_{i=1}^{n} C_i, \tag{10}$$

where C_o is the total cost of the coastal ecological restoration project; ε is the maintenance cost, accounting for 2% of the total cost (Bayraktarov et al. 2016); and C_i is the cost of each item in the project.

To calculate the economic benefits provided by coastal wetlands (e.g., mangroves and saltmarshes) after restoration, we calculated the multiple ESV of each wetland (e.g., climate regulation, waste treatment, coastline protection, air quality regulation, and biodiversity protection) using the ESVD based on the capital base price in Ningde in 2016. The equation is as follows:

$$B_e = \sum_{i=1}^{n} (\mathrm{ESV}_i \times A), \tag{11}$$

where B_e is the total benefit of the restored coastal wetland, ESV_i is the ESV of type i, and A is the area of the restored coastal wetland. Since the ESVD data were collected in different years and described in 2007 $/ha/yr, all ecosystem service values were converted into 2016 $/ha/yr, using the same units as the cost.

Results

ESV loss associated with coastal wetlands from 2000 to 2015

To better assess future ecological risks in Sansha Bay coastal habitats, it is necessary to elucidate historical changes in the ecological structure and function of coastal habitats. As shown in Fig. 3, most reclamation activities occurred on the western and northern coasts of inner Sansha Bay, resulting in a major loss of ESV (Fig. 3A). The total reclamation area between 2000 and 2015 was 2919.36 ha (Fig. 3B). Due to the rapid development of the aquaculture industry in Sansha Bay, approximately 2242.01 ha of coastal wetlands and mudflats were converted for aquaculture after 2000, which was 76.79% of the total reclamation area. Furthermore, 352.72, 164.23, and 141.01 ha of the wetland was converted into construction land, bare land, and cropland, accounting for 12.08%, 5.63%, and 4.83%, respectively, of the total area reclaimed (Fig. 3B). The ESV loss associated with coastal reclamation was $162.18 million (Fig. 3C). The conversion of coastal wetland to aquaculture and construction lands accounted for the greatest ESV loss of $116.97 million, which was 72.12% of total ESV loss. The ESV losses induced by the conversion of coastal wetland to bare land and cropland were $25.01 million and $17.12 million, respectively.

Status of pollution and ecological quality

Areas with high pollution indices were primarily concentrated in northwest Sansha Bay (the mouths of the Qidu and Huotong rivers surrounding sites S2–S7) and western Sansha Bay around sites S13, S16, and S19 (Fig. 4), indicating a greater pollution threat to coastal wetlands in these regions. The areas with high diversity indices were distributed near sites S2, S11, S13, and S19, suggesting higher ecological quality in these regions. Seawater and ecological quality were significantly negatively correlated, with high pollution and biodiversity indices at sites S2, S13, and S19 (Table 3).

Spatial hotspots of future ecological risk and threats

Due to the dense distribution of aquaculture ponds in western and northern Sansha Bay, the ecological threats posed by fish farming were mainly concentrated in these regions (Fig. 5A). Except for the area northeast of

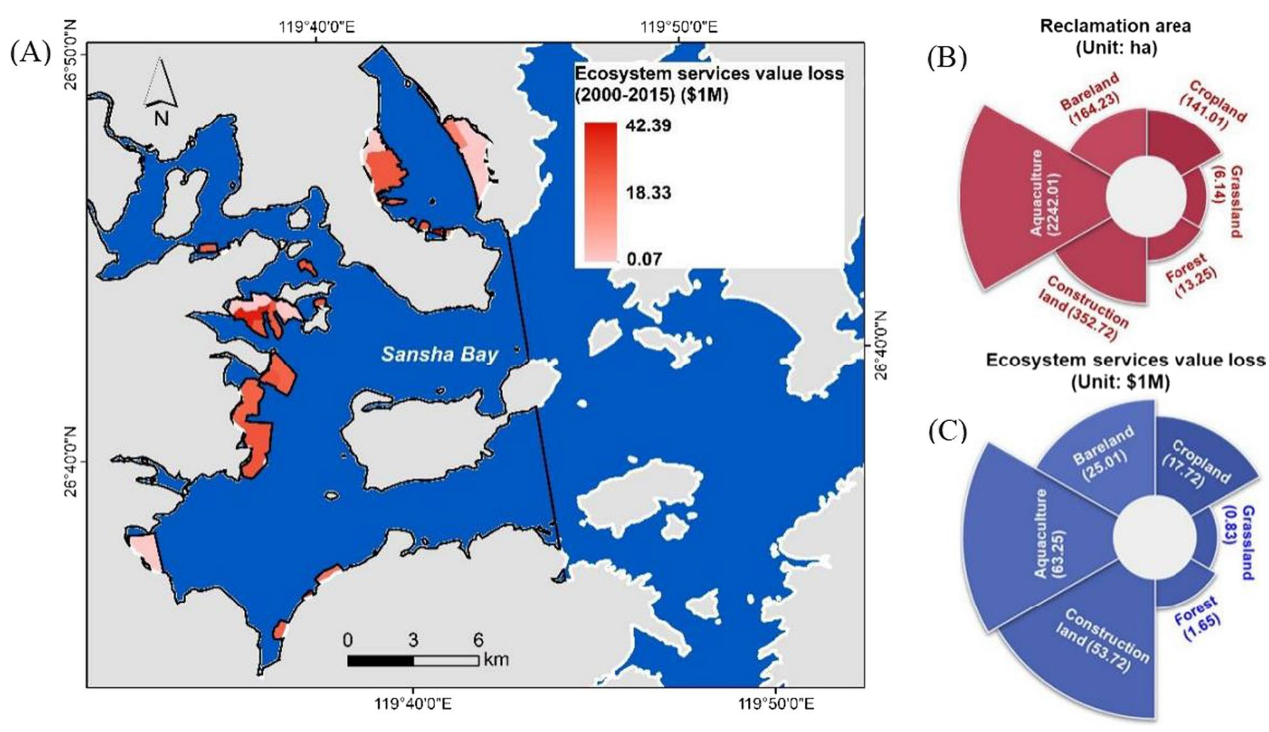

Fig. 3 **A** Ecosystem services value losses caused by reclamation in Sansha Bay from 2000 to 2015. **B** Types and area (ha) of different reclamation activities from 2000 to 2015. **C** Ecosystem services value loss caused by different reclamation activities

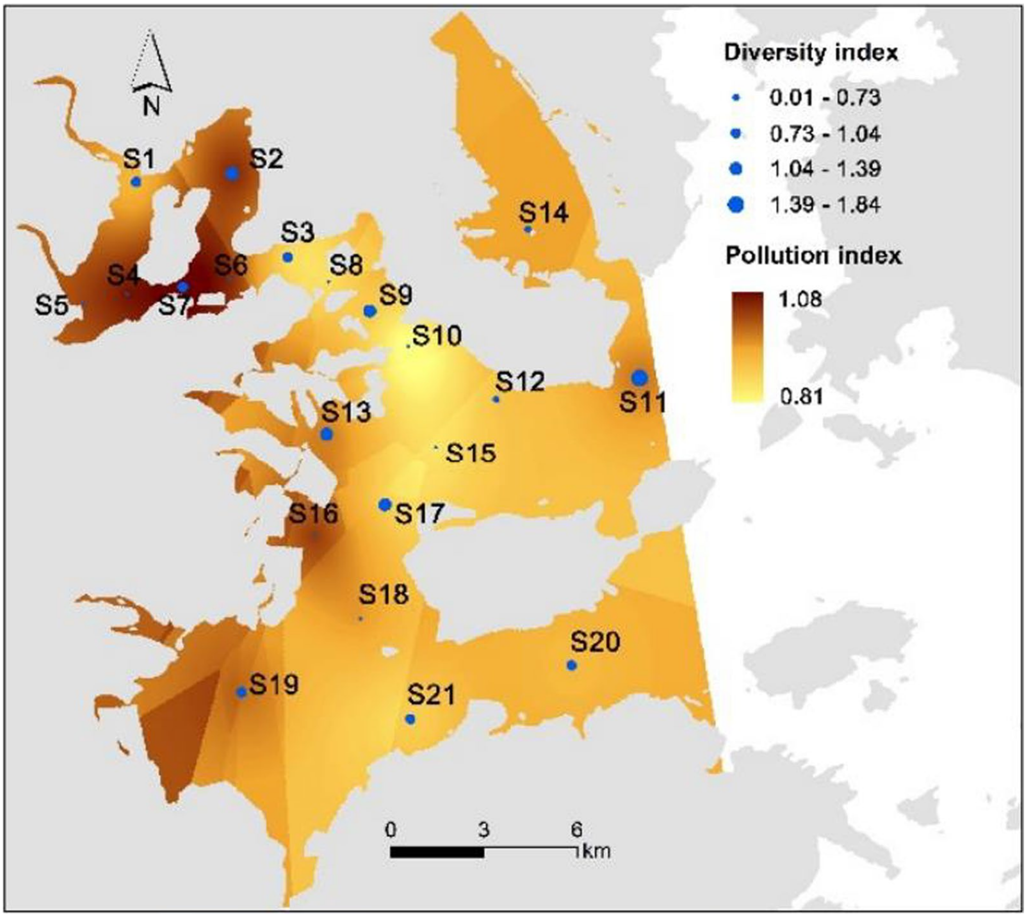

Fig. 4 Spatial distribution of biodiversity and pollution indices

Sansha Bay, the threat of urban development was minimal in all areas (Fig. 5B). The severely polluted areas of Sansha Bay were mainly concentrated in the northwest (the mouths of the Qidu and Huotong rivers) and west (Fig. 5C). The northwest and southwest coasts of Sansha Bay faced extreme SLR threats (Fig. 5D). The coastal wetlands in the northeast and south of Sansha Bay were more likely to be eroded by RSL because the migration of wetlands to land was hindered by artificial shorelines (Fig. 5E).

Overall, coastal wetlands were at medium risk of being damaged (Fig. 5B). Low-risk areas were mainly concentrated in southern Sansha Bay and around the central island. Due to the interactive and cumulative effects of fish farming, pollution, and extreme SLR, high-risk areas were primarily concentrated along the western coast of Sansha Bay and the mouth of the Qidu River (Fig. 5C and D), indicating that protection and restoration measures and projects should be prioritized in these regions.

Cost–benefit analysis of habitat restoration projects in ecological risk reduction

Based on an ecological risk assessment that identified priority areas for ecological restoration, a coastal wetland restoration project in western Sansha Bay was designed (Fig. 6A). Ecological conservation and restoration necessitate nature-based and ecological technology based on a systems engineering concept to rebuild human–ecosystem relationships for human well-being (Benayas et al. 2009; Bullock et al. 2011). Therefore, we designed a natural irregular shoreline to link the reclamation site to the surrounding marine ecosystem. The highest elevation of the ecological shoreline was set in accordance with the 50-year flood control standard. To promote the reconstruction of marine habitats, the revetment uses a graded slope structure with vegetation planted on an ecological grid. The outer revetment is equipped with a hydrophilic platform for public entertainment. This approach not only extends the artificial coastline, but also ensures

Table 3 Pollution index, biological diversity index, evenness index (for phytoplankton and benthic animals), and cumulative risk (CR) at each sampling site

Sampling site	Pollution index*	Diversity index	Evenness index	CR
S1	0.91	0.91	0.32	2.53
S2	1.08	1.36	0.55	1.53
S3	0.89	1.02	0.33	3.85
S4	1.04	–	–	5.08
S5	1.01	–	–	5.08
S6	1.04	–	–	5.65
S7	1.07	1.04	0.45	4.20
S8	0.90	–	–	4.01
S9	0.97	1.39	0.44	4.72
S10	0.81	–	–	4.75
S11	1.04	1.84	0.56	1.44
S12	0.96	0.63	0.39	0.63
S13	1.01	1.39	0.45	3.29
S14	0.94	–	–	0.78
S15	0.91	–	–	0.63
S16	1.07	–	–	6.38
S17	0.93	0.65	0.48	1.44
S18	1.00	–	–	1.88
S19	1.04	1.33	0.37	1.56
S20	0.95	0.99	0.63	1.53
S21	0.91	1.02	1.01	2.32

*Represents the mean values of the pollution index of inorganic nitrogen and active phosphate, because only the measured concentrations of inorganic nitrogen and active phosphate exceededthe 4th category seawater quality standard

ecosystem continuity and integrity by expanding the ecotone area between the coastline and coastal wetland (Fig. 6B).

Afterward, we calculated the costs and benefits of NbS-integrated habitat restoration. As the benefits of mangrove afforestation outweighed those of other ecological measures in this project, it was the sole action for which biological benefits were calculated. In 2016, the total cost of the NbS was \$11.55 million, with mudflat renovation accounting for the largest share (32.73%) of the total cost (Table 4). The total potential benefit of the NbS was \$7.35 million in 2016, less than the total cost during the same period (Table 5). However, the total potential benefit increased over time and was approximately three times the total cost by 2020, with the ecosystem service of coastline protection accounting for the largest share of the benefit (78.37%). Thus, coastal NbS can not only effectively offset project implementation costs, but can also provide a rapid gain in ecological value in a short period, particularly for the service of coastline protection.

Discussion

Identification of priority areas for habitat restoration using an improved framework

Unlike previously proposed frameworks, our framework incorporates a cumulative risk assessment to identify priority ecological restoration areas applicable to all ecological risk areas. It is more effective than general ecological assessment tools for precise planning and deployment of restoration projects. Furthermore, integrating ESV into a habitat restoration-NbS could result in synergies in ecosystem structure and function to maximize the benefits of habitat restoration, implying that the ecosystem structure and function can remain relatively stable through certain self-regulation methods. For example, through a cost–benefit analysis of ecological restoration schemes based on the ecosystem service accounting and the tradeoff method, ecological restoration measures that mimic nature (diverse and complete ecosystem structure) and have low costs and high efficiency (high ESV) can be selected. Our enhanced assessment framework is applicable to other regions affected by interactions between anthropogenic interference and climate change.

Coastal areas provide benefits such as habitats for fishery species and opportunities for tourism and recreation. However, anthropogenic activities in these areas reduce the resilience of coastal areas to future threats and undermine the ecosystem services provided by them. HRA, as implemented through the InVEST model, provides an effective framework for integrating the impacts of multiple stressors across habitats, as well as decision-making support for balancing anthropogenic demands and habitat health (Halpern et al. 2008; Wyatt et al. 2017). This method integrates expert opinion and the Euclidean distance approach to quantify and map the habitat-specific effects of various anthropogenic activities to generate the cumulative risk across habitats (Arkema et al. 2014). We focused on three major ecological challenges faced by Sansha Bay (reclamation, pollution, and SLR), introduced the HRA model to evaluate the ecological status of Sansha Bay, and identified the areas most in need of protection and restoration. Our findings provide scientific support to help inform marine habitat restoration projects.

According to the findings of this analysis, the coastal habitats of Sansha Bay are at medium risk overall. The two primary stressors in high-risk habitats are reclamation for aquaculture and pollution. Areas with high ecological quality are expected to be threatened by severe pollution in the future; thus, pollution control and biodiversity enhancement are required to reduce the risk posed to coastal wetlands in Sansha Bay. The high-risk areas were concentrated on the northwest and west

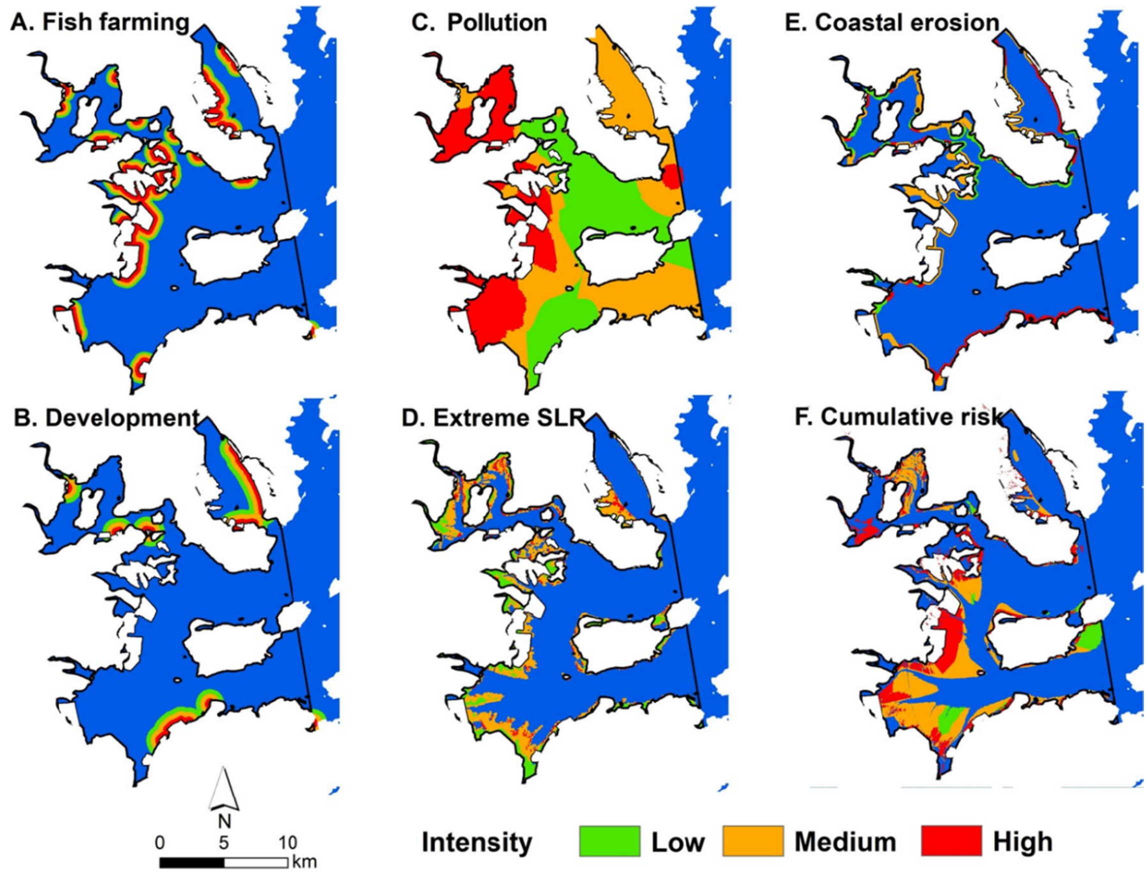

Fig. 5 Intensity and spatial distributions of five stressors in Sansha Bay: **A** fish farming (reclaimed by aquaculture ponds), **B** development (reclaimed by impervious surface), **C** pollution, **D** extreme SLR, **E** coastal erosion, and **F** cumulative risk

coasts of Sansha Bay and should be prioritized for restoration. In these regions, a multi-species symbiotic community dominated by mangroves could be constructed via vegetation restoration with mangrove afforestation to provide foraging and reproduction habitats for birds, insects, and marine organisms and restore the structure and function of damaged coastal wetlands. Ecological farming (e.g., artificial fish reefs and facilities for large algae cultivation) could be installed underwater to buffer the seawall from waves. These areas also provide habitat for fish and shellfish for reproduction, growth, foraging, and hiding, allowing marine species to inhabit and build a three-dimensional ecological protection system for the coastal zone.

To prevent further deterioration of coastal habitats, strengthening the protection and management of areas at low and medium risk of damage is also crucial. Anthropogenic activities on coastal wetlands should be limited to a reasonable area to avoid harmful impacts on ecosystem functions. We recommend educating residents about the importance of tidal flat and wetland protection, increasing their awareness of ecological protection, and reducing damage to coastal mudflats and wetlands caused by a lack of awareness about these issues.

Monitoring and management of coastal resilience post habitat restoration

Habitat restoration is critical for mitigating anthropogenic biodiversity loss and reducing threats to ecosystems. The effectiveness of ecological restoration projects should be evaluated to justify the importance of restoration in natural resource management and to improve practices (Rodríguez-Rodríguez et al. 2021; Wortley et al. 2013). In general, successful habitat restoration must improve ecosystem structures and functions while increasing the socio-economic benefits derived by society from restored ecosystems (Jessop et al. 2015; Palmer and Filoso 2009; Wu and Lin 2020). The initial costs of seawall renovation, mudflat desilting, and afforestation are relatively high and the benefits from improved ecosystem services, such as climate regulation, air and water quality improvement, biodiversity protection, and erosion control, take a long time to manifest (Cao et al. 2017). In the

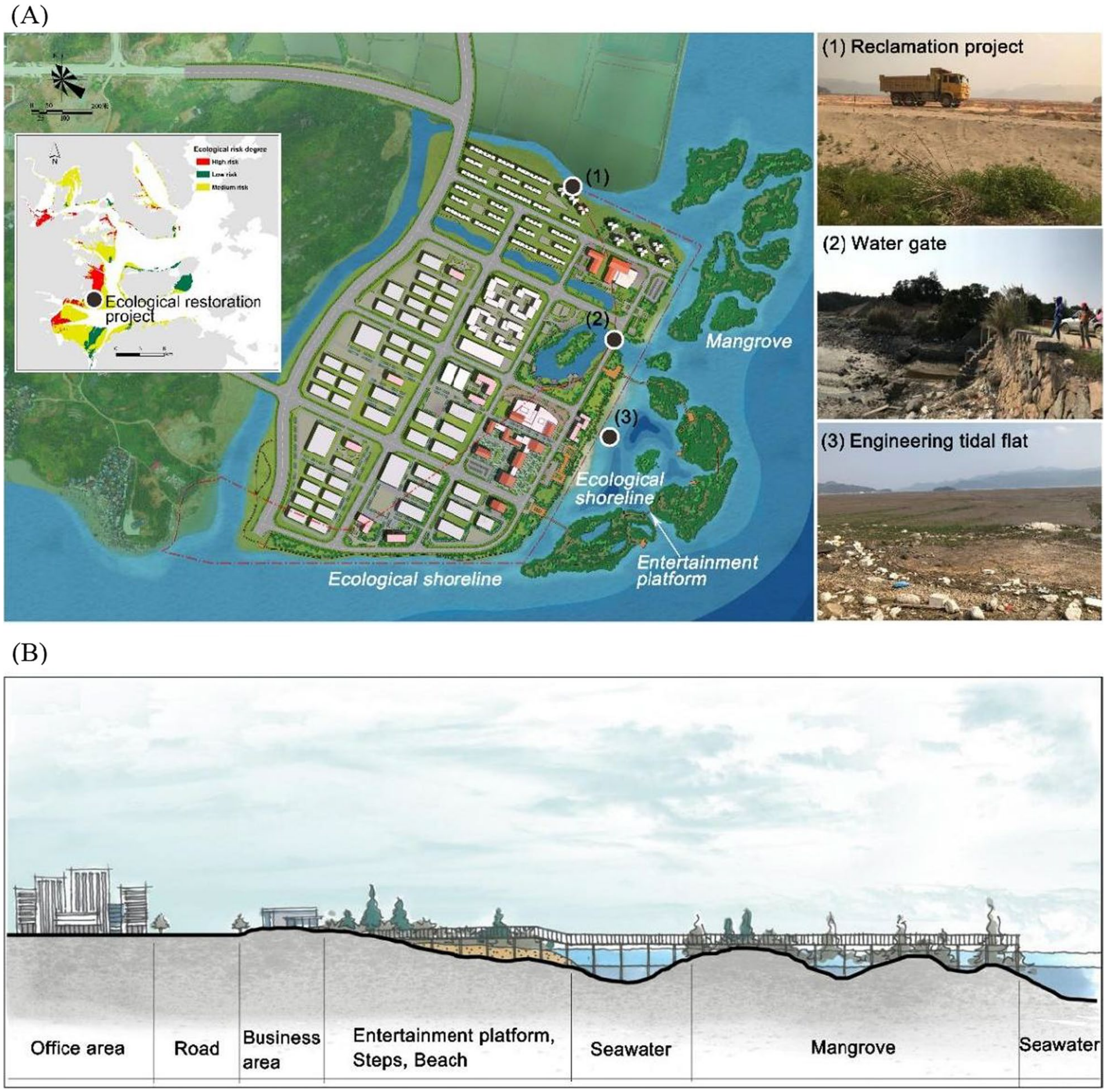

Fig. 6 **A** Ecological restoration project design. **B** Cross-section of the ecological restoration project on the western coast of Sansha Bay

Table 4 Costs of the proposed ecological restoration project

Project	Area (ha)	Earthwork (m^3)	Unit price ($/$m^3$)	Total cost (2016 $1 million)	Total cost (2020 $1 million)
Beach	3.07	92,070	32.11	2.96	3.26
Mudflat renovation	21.84	393,094	9.63	3.78	4.16
Mudflat vegetation	21.84		4.82	1.05	1.16
Landscape plank road	0.75		80.26	0.61	0.67
Seawall (m)	3200		481.54	1.54	1.69
Water gate				1.61	1.77
Total				11.55	12.71

Table 5 Potential benefits of the proposed ecological restoration project

Ecosystem services	Area (ha)	Unit value* ($/ha/yr)	Total value (2016 $1 million)	Total value (2020 $1 million)
Climate regulation	21.84	14,019.89	0.31	1.55
Waste treatment	21.84	20,827.36	0.45	2.25
Coastline protection	21.84	263,803.54	5.76	28.80
Air quality regulation	21.84	12,552.46	0.27	1.35
Biodiversity protection	21.84	25,579.76	0.56	2.80
Total			7.35	36.75

*Represents the mean value of each ecosystem service of mangroves in the Fujian Province, China

medium term, the benefits outweigh the costs because renewable resources have lower maintenance costs and longer lifetimes. Initial investments in NbS depreciate over longer periods than those in technical systems, although rapid depreciation is exacerbated by numerous taxation and accounting systems. Ultimately, the long-term benefits of ecological restoration are associated with improved ecological stability. Despite extensive discussion on how to measure successful restoration, monitoring or evaluating projects in practice is often inadequate or challenging. Therefore, it is crucial to evaluate both the direct consequences of habitat restoration on natural systems and environmental quality as well as the indirect effects on socio-economic and environmental benefits immediately following restoration.

To verify and assess the effectiveness of ecological restoration on a regional scale or continuously track and monitor the status of a restoration project, regional eco-environmental problems must be accurately identified and the changes in key metrics must be monitored using high-precision and wide-ranging remote sensing technology (del Río-Mena et al. 2020; Wang et al. 2021b). Unmanned aerial vehicle remote sensing technology is a rapid, accurate, and effective tool for small-scale evaluation and monitoring of restoration projects. It can be used for the protection and restoration of beaches, revetments, and coastal wetlands.

The ecological restoration project for Sansha Bay is a planned project that will soon be implemented. Here, we estimated the cost and potential benefits of the project. We plan to conduct field sampling and long-term unmanned aerial vehicle remote sensing monitoring of key natural attributes in the ecosystem to assess functional changes following the implementation of the restoration project. We propose that dynamic changes in shoreline attributes, mangrove and mudflat habitat elements, marine biological resources, and species be monitored (Additional file 1: Table S2). Vegetation, birds, invasive species, water depth, topography, seawater quality, and sediment quality are all important aspects of mangrove and mudflat habitats (Chu et al. 2021). Marine biological resources that must be monitored include phytoplankton, zooplankton, fish eggs and larvae, swimming organisms, benthos, and intertidal organisms. Additionally, socio-economic benefits derived from restored habitats must be evaluated using ESV accounting methods, including opportunities for livelihood, coastline protection, seafood supply, seawater purification, climate regulation, biodiversity protection, provision of cultural entertainment services, and carbon sequestration.

Conclusions

This study developed a general analytical framework that integrates cumulative risk assessment, NbS, and habitat restoration to increase the resilience of coastal habitats to multiple stressors. A cumulative risk assessment was used to identify priority areas for habitat restoration in Sansha Bay, China, and an NbS was designed to reduce the risk of coastal wetland degradation in the area. ESV was used in a cost–benefit analysis of the NbS proposal to quantify the socio-economic benefits of habitat restoration.

The results indicate that coastal habitats in Sansha Bay are at a medium risk from future pollution and SLR. In particular, the northwest and west coasts contain some high-risk areas that should be prioritized for restoration. The priority areas identified using the cumulative risk assessment are suitable for the implementation of restoration projects. A coastal NbS can effectively offset project implementation costs in addition to generating continuous long-term ecological benefits. Integrating habitat restoration, NbS, and ecosystem services could result in a synergy of ecosystem structure, function optimization, and socio-economic benefits.

This study had a limitation in that it only considered the cumulative effect (one of the interaction effects) of human and climate stressors on the structure and function of coastal habitats; thus, the cost–benefit analysis of the planned habitat restoration project produced a theoretical result that may not be representative of the actual result of project implementation. Therefore, we plan to measure additional interactive effects (such as synergistic effects) among various stressors in our future work to better support coastal habitat restoration. Furthermore, after restoration, the direct effects of habitat restoration on natural systems and environmental quality will be measured promptly using field surveys, and the indirect effects on socio-economic benefits will be evaluated using specific accounting methods in ESV based on socio-ecological survey data rather than empirical ESV values.

Abbreviations

NbS	Nature-based solutions
ESV	Ecosystem services value
SRTM	Shuttle Radar Topography Mission
SLR	Sea level rise
HRA	Habitat risk assessment
E	Exposure
C	Consequence
CR	Cumulative risk
MRS	Maximum risk score

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13717-023-00432-1.

Additional file 1: Supporting Information.

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Author contributions

Conceptualization, QC and YL; data curation, YL, FH, and YZ; formal analysis, YL and YZ; investigation, YL, QC, and FH; methodology, YL and QC; project administration, XX and FH; resources, XX and FH; software, YZ; writing—original draft, YL, and QC; writing—review and editing, QC, YL, FH, and XX. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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