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Application of coastal hazard index to advance nature based protection for coastal communities in the small islands

Martiwi Diah Setiawati[1,2] · Muhammad Rizki Nandika[2] · Udhi Eko Hernawan[2] · Herlambang Aulia Rachman[3] · Uday Chatterjee[4] · Novy Susetyo Adi[5] · La Ode Alifatri[2] · Tsuyoshi Eguchi[6] · Indarto Happy Supriyadi[2] · Nuraini Rahma Hanifa[7] · Bayu Prayudha[2] · Yudha Setiawan Djamil[8] · Aulia Oktaviani[7] · Sam Wouthuyzen[2] · Siti Sulha[9] · Jeverson Renyaan[2] · Aidy M. Muslim[10]

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Abstract

In the face of rising the seas, relying solely on seawalls and other reinforced coastlines is unsustainable due to the high costs associated with their construction and upkeep and unforeseen effects on habitats. Restoring and conserving coastal habitats can be more affordable, long-term solutions for protecting the coast. Yet, basic knowledge about where, how, and for whom habitats decrease the risk of coastal disasters is typically lacking from decision-makers. This study investigates how climate change may affect coastal areas and how natural coastal habitats may help protect them. We studied two small tropical islands, Bintan and Seribu Islands, Indonesia. The research applied the InVEST Coastal Vulnerability model to calculate the hazard index. To assess the effect on the vulnerable population, a grid system for the coastal population was created and overlaid with the hazard index. The comprehensive analysis indicates that if the coastal habitat is lost in the future, Bintan and Seribu Islands will face a severe threat from rising sea levels, with 96% and 63% of the inhabitants being highly exposed to climate hazards. Furthermore, the model shows that preserving natural coastal habitats by 2040 could help protect approximately 104 and 17 km of coastline areas in Bintan and Seribu Islands, respectively. Ecosystems offer safeguards to certain thinly inhabited, distant coastal villages, certain of those with a large, vulnerable population. Thus, this study highlights that natural coastal habitat is essential in climate change

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✉ Martiwi Diah Setiawati, martiwi1802@gmail.com; ✉ Uday Chatterjee, raj.chatterjee459@gmail.com; Muhammad Rizki Nandika, rizki.nandika@gmail.com; Udhi Eko Hernawan, udhi001@brin.go.id; Herlambang Aulia Rachman, herlambangauliarachman@gmail.com; Novy Susetyo Adi, novisusetyoadi@kkp.go.id; La Ode Alifatri, laodealifatrii@gmail.com; Tsuyoshi Eguchi, eguchi.t@yamaguchi-u.ac.jp; Indarto Happy Supriyadi, inda002@brin.go.id; Nuraini Rahma Hanifa, nuraini.rahma.hanifa@brin.go.id; Bayu Prayudha, bayu005@brin.go.id; Yudha Setiawan Djamil, yudh006@brin.go.id; Aulia Oktaviani, oktawulia@gmail.com; Sam Wouthuyzen, samwouthuyzen@yahoo.com; Siti Sulha, siti037@brin.go.id; Jeverson Renyaan, jeverson.renyaan@brin.go.id; Aidy M. Muslim, aidy@umt.edu.my | [1]Institute for the Advanced Study of Sustainability (UNU-IAS), United Nations University, Tokyo, Japan. [2]Research Center for Oceanography, National Research and Innovation Agency (BRIN), Jakarta, Indonesia. [3]Department of Marine Sciences, University of Trunojoyo Madura, Bangkalan, Indonesia. [4]Department of Geography, Bhatter College, Dantan, Kharagpur, West Bengal, India. [5]Directorate of Small Islands and Coastal Area Utilization, Ministry of Marine Affairs and Fisheries (MMAF), Jakarta, Indonesia. [6]Center for Research and Application of Satellite Remote Sensing (YUCARS), Yamaguchi University, Ube City, Japan. [7]Research Center for Geological Disaster, National Research and Innovation Agency (BRIN), Bandung, Indonesia. [8]Research Center for Climate and Atmosphere, National Research and Innovation Agency (BRIN), Bandung, Indonesia. [9]Bureau for Public Communication, National Research and Innovation Agency (BRIN), General Affairs, and Secretariat, Jakarta, Indonesia. [10]Institute of Oceanography and Environment (INOS), Universiti Malaysia Terengganu (UMT), 21030 Kuala Terengganu, Terengganu, Malaysia.

adaptation. Enhancing and safeguarding these natural habitats is crucial for mitigating climate-related hazards and ensuring community resilience.

Article Highlight

- The first semi-quantitative assessment in Indonesia showcasing the role of natural capital in reducing the risk of climate hazards in the small islands was conducted.
- Coastal habitats protect roughly one-third of the shoreline length in both study sites.
- The coastal habitat could save about one-third and two-thirds of the most vulnerable communities along the Bintan and Seribu Islands coastal areas.

Keywords Climate change adaptation · Nature-based solution · InVest model · Coastal vulnerability · Small Islands

1 Introduction

Vulnerability assessment involves a holistic approach to understanding complicated interactions between social, natural, and engineered systems; it can refer to persons, groups, systems, and locations where scalar differences and the capacity to communicate across spatial scales are crucial [1, 2]. It offers the foundation for risk [3, 4], hazard and disaster mitigation policies [1, 2, 4–6]and for vulnerable groups [7]. Coastal areas are vulnerable to risks, including those related to the climate. Climate-related hazards have affected over 5.2 billion people (96% of the world's population) from 1998 to 2017, with a total economic loss of 2,239 billion USD [8]. These risks are projected to increase globally [9].

Present Sea Level Rise (SLR) has a severe effect consisting of land loss and erosion of the coasts, raised tidal flooding, and elevated salinization of coastal aquifers, leading to habitat shrinkage, changes in the geographical distribution of aquatic species, decline in biodiversity, and drop in ecosystem services [10]. For instance, SLR could affect wetland salinization, which can alter the fundamental physical and chemical characteristics of the water and soil ecosystem and have considerable effects on the natural systems in the region [11]. Also, SLR could affect soil salinization, which may cause severe problems for food security and socio-economic activities [12]. Additionally, the SLR will impact residential zones within the Shared Socioeconomic Pathways (SSP) scenarios, necessitating the relocation of households to a safer region due to flood risk [12]. Further, there is evidence that SLR could lead to considerable global coral cover drops owing to increased turbidity caused by greater sediment resuspension [13]. These findings support theories that a rapid rise in global sea level could threaten coral survival.

Under RCP 4.5, SLR will reduce global GDP by 0.19% [14]. Countries like Vietnam, Thailand, and Bangladesh will experience more severe consequences, with expected GDP declines of 7.60%, 9.37%, and 5.37%, respectively [14]. Consequently, fostering resilient communities has become a pressing concern for coastal residents [15]. One of the most common actions is constructing barriers along the coast, such as seawalls and bulkheads. However, these conventional methods of coastal defence are now recognized as unsustainable [16]. Moreover, reinforced coastlines can be costly to construct and sustain while also posing risks such as coastal erosion, habitat loss, and deterioration, as well as negative effects on people who rely on resilience ecosystems for defence, sustenance, and livelihood [17].

The issues over hardened shorelines have generated interest in alternate coastal protection strategies that might be less harmful to the environment, more affordable to sustain over time, and capable of delivering essential co-benefits [18]. Coastal habitats like mangroves, seagrass beds, marshes, coral reefs, and coastal forests have shown the feasibility of mitigating storm-related waves, surges, floods, and erosion [19, 20]. Nature-based measures are often considered favorable coastal adaptation solutions since they do not hinder additional measures afterward (World Bank, 2021). In some circumstances, habitat restoration and conservation are more cost-effective than building infrastructure (e.g., mangrove restoration versus breakwater construction) [21]. A comprehensive study on the World's most catastrophic 2004 Indian Ocean tsunami in Banda Aceh, Indonesia, revealed that mangroves of different ages and areal coverages were proven to significantly reduce a tsunami's hydrodynamic force by up to 70% and to mitigate structural damage by up to 60% [22]. Coastal ecosystems can adjust to climate change and may even outperform hard infrastructure in the long term [23]. This is particularly positive for island states since they have natural coastal habitats that act as layers of protection against coastal hazards in their highly vulnerable coastal zones [24]. Yet, the effectiveness of ecosystems in safeguarding coastal areas varies depending on the specific circumstances [9, 25]. Therefore, it is essential to have a comprehensive knowledge of where natural habitats are of utmost significance for protecting coastlines, particularly with the risks posed by population growth and modernization.

Islands nations are extremely sensitive to environmental threats due to a combination of physical, ecological, and socio-economic characteristics, such as their severe climate hazard exposure, remoteness, small size, high reliance on natural resources, brittle infrastructure plans, and subpar building standards [26]. Thus, Island nations are highlighted due to the vast spectrum of damage caused by climate risks, and the speed of recovery following a disaster is challenging. Moreover, disaster response and recovery capabilities can vary greatly, and social risk factors that make specific populations more sensitive to hazards receive more significant consideration. There is broad agreement that socioeconomic level, age, gender, ethnicity, and education are quantitative markers of disparities in capacity and resource access, which increases the vulnerability in the social aspects [5, 27]. Yet, the association between vulnerable communities and their environments, which can potentially provide risk reduction, has received less attention than the growing use of demographic information metrics in research projects to assess the risk faced by vulnerable communities (Arkema et al. 2017).

Several approaches have been used to integrate parameters for coastal vulnerability analysis, including Principal Component Analysis (PCA) [5], Analytical Hierarchy Process (AHP) [28], Fuzzy method [6], and Coastal Vulnerability Index (CVI) analysis [29, 30]. However, those parameters did not include the framework of variation of coastal habitat and future projection under climate change scenarios. The InVEST Coastal Vulnerability Model (CVM) is the extension of the CVI concept with the additional value of the combination of natural habitat, which can be assessed with various scenarios. This method was applied in the United States of America [9, 31, 32], Oman [33], China [34] and India [35]. However, InVEST CVM approaches have not been applied in Southeast Asia (SE Asia), whereas this region is noted as a global hotspot for biodiversity and one of the most ecologically threatened [36]. Moreover, to the best of our knowledge, no study has been conducted in Indonesia to develop a coastal vulnerability index designed for national implementation by an authorized government agency acting as the national geospatial data custodian for vulnerability map (Ministry of Marine Affairs and Fisheries) using showcases comparison of small islands with different biophysics and socio-economic conditions. Therefore, a similar study that applied InVEST CVM is crucial to be conducted in Indonesia since it can promote the role of natural capital and be expanded on a larger scale.

Decision-makers need tools that provide spatial information (containing physical, socioeconomic, and ecological data) on where and how ecosystems best protect vulnerable coastal communities and evaluate options for nature-based coastal protection. Various methods have been used to quantify the benefits of coastal habitats for protection, for example, process-based model prediction as a tool in cost–benefit analyses of preventive measures [37], preference surveys to measure people's willingness to pay for coastal safeguarding [38] and simple analysis of regression to link coastal habitat existence to the decreased damage [39]. These methods can help decision-making, but they need much data and knowledge to execute, which may limit their use by organizations with low capacity and resources. In addition, the aforementioned studies have not been conducted by simultaneously comparing small islands with different biophysical and socio-economic conditions (e.g., islands with developed urbanization and tourism sector vs islands with less developed ones). Therefore, transparent, reproducible, and accessible tools and data determine the areas in which ecosystems are most important to humans, especially in countries with limited resources and capacity.

In this study, we analyzed the coastal hazard and social vulnerability of two small islands in Indonesia, i.e., Bintan and Seribu Islands, using the InVEST-CVM. We presented the analysis findings and discussed how they can be utilized in directing various planning initiatives to increase coastal resilience in the country. To the best of our knowledge, this is the first semi-quantitative assessment in Indonesia that showcases the role of natural capital in reducing the risk of climate hazards and how it will impact vulnerable communities along the coastal areas. Thus, the study addressed three main questions regarding the nature-based protection of coastlines: (1) Which areas are exposed to coastal hazards and have high social vulnerability? (2) How would the spatial distribution of risk change under SLR scenarios? (3) Where do coastal ecosystems currently provide protection services to the most socially vulnerable groups, and where could they do so in the future under SLR? What insights can be synthesized from applying the CVM to small islands with differences in biophysics and socio-economic conditions?

2 Materials and methods

2.1 Study area

As an archipelagic country, Indonesia is highly exposed to climate-related hazards, such as floods and extreme weather. There were an average of 2550 incidents yearly since 2008, and hydrometeorological disasters were dominant [40, 41].

These hazards cause huge losses and damages to the economy and infrastructure, nearly USD 3.5 trillion between 1990 and 2021 [42]. From 2014 to 2018, the central government spent around USD 90 million to USD 500 million annually, with an extra USD 250 million from regional governments, for disaster response and rehabilitation [43]. This valuation did not consider other costs, such as disaster displacement. Moreover, the recovery process varies across regions, depending on their social vulnerability and disaster readiness [44]. Thus, it is vital to understand the risk of coastal hazards and enhance the resilience of the coastline in Indonesia.In particular, small islands rely heavily on their marine and coastal ecosystems, which include mangrove forests, seagrass beds, coral reefs, and terrestrial plants, among many others.

This paper used two small islands as study sites: the Bintan and Seribu Islands (Fig. 1). We chose the islands to represent small islands with high climates and anthropogenic pressures in the tropical region. Bintan is home to approximately 166 thousand inhabitants dispersed throughout 272 islands, with a total land area of more than 1300 km^2 [45]. This region has a tropical environment with air temperatures ranging from 24.4 to 31.8 °C and a relative humidity of 84% [45]. The months with the most rainfall are April–May, November, December, and January, while February has the least rainfall [45]. These islands, situated close to Singapore and Malaysia, face various climate-related hazards, including flooding and forest fires. It also experiences pressure from human activities, such as rapid land cover change (i.e., the open land was expanded four times from 1995 to 2020) and oil spills [46, 47].

Seribu Islands has a population of 28 thousand people in 2021, covering an 8.7 km^2 land area and 11 islands [48]. These islands have a mean temperature ranging from 26.1 to 29.9 °C [49], with the average annual amount of rainfall being 1888.74 mm, while the wind speed was 4–10 m/s [48]. Seribu Islands, small islands part of Jakarta megacities, face serious issues related to climate-related hazards, self-land reclamation (i.e., one of the inhabitant islands expanded 120% of the land area from 1992 to 2022), and ecosystem destruction [49]. Additionally, these islands' GDP depended on natural resources, particularly from the production of natural components [45, 48]. The local government continues prioritizing the tourism sector as one of their main targets in increasing economic growth even though this sector is not the primary source of GDP [50, 51].

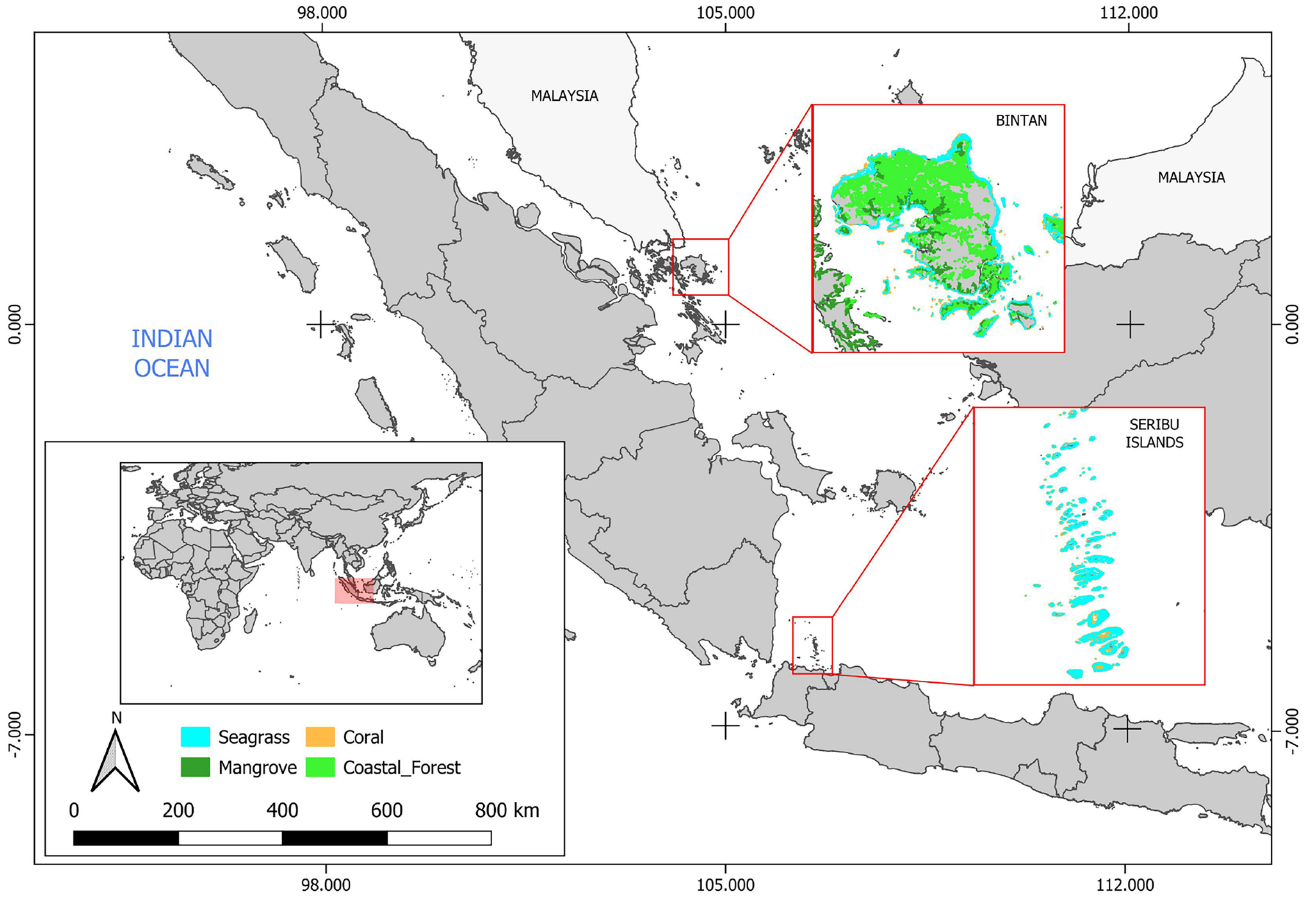


Fig. 1 The study area of two study sites (upper), Bintan Island (Lower) Seribu Islands

The soil type of Bintan Island was Orthic Podzols [52], while Seribu Islands were coral sand with a thick level of less than 1 m [53]. Orthic Podzols are physically and chemically deficient and experience moisture deprivation during dry periods due to significant drainage. They are also prone to soil erosion, and the potential for agriculture is limited [52]. Meanwhile, sand coral is often marginal ground with a low capacity to hold water and requires even more careful management due to its potential for water loss [53]. It readily evaporates or absorbs water, making it unsuitable for plant growth [53]. Therefore, those conditions make both pilot sites more vulnerable to climate-related hazards.

Both pilot sites are frequently hit by flooding and storms [46, 49–51]. The primary area in these sites is categorized as a low-lying island, particularly the Seribu Islands, with 41% of its land below an altitude of 3 m. While the Bintan Islands consist of 272 islands [46], we limited the study area to the main islands of Bintan due to some difficulties in the mapping validation. With regards to Seribu Islands, it consists of 114 islands [49], and we covered most of the islands except on the edge of the northern part of the archipelagos due to some data limitation (i.e., relief data set). Furthermore, the validation mapping was only conducted in the highest-risk areas with inhabitant populations.

2.2 Data

Table 1 shows several data used as input models to obtain the Hazard Index (HI) score. The HI was calculated based on Eq. 1 with reference to Table 2 and ranges from 1 to 5. Further details were explained in Sect. 2.2. Moreover, we used biophysical components such as shoreline type, relief, natural habitat, wind and wave exposure, storm surge, and SLR. These datasets were obtained from various sources, and the InVEST model provided some.

2.2.1 Shoreline type

The coastal type describes the shoreline's composition, significantly impacting its vulnerability to erosion/ abrasion. We combined various datasets to create a comprehensive coastal-type map covering the entire country. Determining coastal types began with visual classification using high-resolution satellite image mosaics from Google Earth. This classification also utilized mangrove distribution maps obtained from the Indonesia Geospatial Information Agency (BIG), assuming the presence of muddy coastlines where mangroves are dominant. Finally, field investigations were conducted to observe the shoreline types directly and use this in-situ data to improve previously created datasets.

2.2.2 Coastal habitat

We identified four main natural habitat types in the Bintan and Seribu Islands that offer coastal defence: mangrove forests, seagrass beds, coral reefs, and coastal forests. The presence and combination of these coastal habitats significantly influence the degree of protection against erosion and inundation by reducing wave energy, lessening the impact of storm surges, and stabilizing sediment [31].

Data sources from the Research Center for Oceanography, BRIN, under the Coremap initiative, were utilized to map the distribution of coral reefs and seagrass. Meanwhile, mangrove and coastal forest distribution was obtained from land cover data provided by BIG. Coral reefs in deep offshore areas that were not detectable by satellites were excluded from the analysis. All data are available in shapefile format.

2.2.3 Relief

The relief data, including the Digital Elevation Model (DEM) and bathymetry data, were collected from the Geospatial Information Agency (BIG). The National DEM (DEMNAS) was created by combining data from various sources, including IFSAR (Interferometric Synthetic Aperture Radar) with a 5-m resolution, TerraSAR-X at a 5-m resolution (after some adjustments), and ALOS (Advanced Land Observing Satellite) PALSAR (Phased Array type L-band Synthetic Aperture Radar) with an 11.25-m resolution. This dataset uses the EGM2008 vertical reference with a spatial resolution of 0.27 arcseconds. On the other hand, the National Bathymetric Data (BATNAS) was generated by analyzing gravitational anomaly data from altimetry. This dataset also includes sounding data collected by various institutions like BIG and the National Research and Innovation Agency (BRIN), previously known as the National Geophysical Data Center (NGDC), the Agency for the Assessment and Application of Technology (BPPT), the Indonesian Institute of Sciences (LIPI) and Center for Marine Geology Research and Development (P3GL), and others using both single and multibeam survey techniques. The spatial resolution of the BATNAS dataset is 6 arcseconds, and it is referenced to the Mean Sea Level (MSL).

Table 1 List of datasets

Data type		Year	Spatial resolution/scale	Source
Natural habitat	Seagrass	2016	30 m	Research Center for Oceanography BRIN—COREMAP-CTI Project
	Coral Reefs	2016	30 m	Research Center for Oceanography BRIN—COREMAP-CTI Project
	Mangrove	2020	6 m	Ministry of Environment and Forestry of Republic of Indonesia
	Terrestrial Land	2019	1: 50,000 (25 m)	Indonesia Geospatial Information Agency (BIG)
Wind exposure		2016	0.5 degree	Natural Capital Project releases.naturalcapitalproject.org
Wave exposure		2016	0.5 degree	Natural Capital Project releases.naturalcapitalproject.org
Surge potential (continental shelf)		2016	–	Natural Capital Project releases.naturalcapitalproject.org
Relief	Elevation	2018	0.27 arcseconds	Geospatial Information Agency https://tanahair.indonesia.go.id/demnas/#/demnas
	Bathymetry	2018	6 arcseconds	Geospatial Information Agency https://tanahair.indonesia.go.id/demnas/#/batnas
Shoreline type		2023	–	Visual Interpretation from Google Earth combined with field work survey in Bintan-June 2023 and in Seribu Islands- July 2023
Sea level rise (SLR)		1993–2022	0.25 degree	Regional Sea Level Trends AVISO https://www.aviso.altimetry.fr

Table 2 Variables and rankings of the coastal hazard index (Adopted from [9])

Variable	Exposure rank				
	1 (very low)	2 (Low)	3 (intermediate)	4 (High)	5 (very high)
Natural coastal habitat	Coral reefs, Coppice, Mangrove		Caribbean Pine	Seagrass	No natural habitat
Type of shoreline		Seawall	rock	mud	sand
Relief	Fifth quantile	Fourth quantile	Third quantile	Second quantile	First quantile
Winds	First quantile	Second quantile	Third quantile	Fourth quantile	Fifths quantile
Wave Exposure	First quantile	Second quantile	Third quantile	Fourth quantile	Fifths quantile
Surge Potential	First quantile	Second quantile	Third quantile	Fourth quantile	Fifths quantile
SLR [54]	0–20 cm	20–40 cm	40–60 cm	60–80 cm	80–100 cm

2.2.4 Wind, wave, and storm surge

The wind and wave exposures were processed with NOAA Wave Watch III data, readily available as the default data in the InVEST program bundle. This dataset is structured as a point shapefile, providing a wide variety of data that could be harnessed to establish a model for hurricane wind speed and observed wave energy in specific geographic areas. The model evaluated the potential for hurricane waves by quantifying the distance between the continental shelf's border and the coast. The continental shelf data also relied on a global dataset provided by the InVEST software. In general, during a hurricane event, the further the coastline was from the border of the continental shelf at an identified location, the greater the likelihood of experiencing higher hurricane waves.

2.2.5 SLR

The SLR data used in this study is obtained from the Regional Sea Level Trends covering from January 1993 to August 2022, provided by AVISO. This data is available in a grid format and was obtained through several multi-mission satellites, including Jason-1, Jason-2, Jason-3, TopEx/Poseidon and Sentinel-6MF, as well as several additional missions such as SARAL/AltiKa, Envisat, ERS-1, ERS-2, Cryosat-2, and Copernicus Sentinel-3A, which were employed as reference missions. These various multi-mission altimetry satellites allow changes in spatial patterns related to heat distribution and ocean circulation to be effectively visualized. For future projections, we used the scenario from [54].

2.3 Methods

Figures 2, 3 presents the overall flowchart of the research framework to assess the risk of vulnerable people along the coastal area in both pilot sites. The following are the steps of this research framework. In the first step, we calculated HI by using seven physical parameters (Table 1), rank variables (Table 2), and Eq. 1 at the present condition with the actual habitat (Sects. 2.2, 2.2.1, and 2.2.2). Then, we estimated HI using SLR and a habitat scenario (Sect. 2.3). Once HI was estimated using four type scenarios (present with habitat, present without habitat, future with habitat, and future without habitat), we estimated the risk to vulnerable people by overlaying the socio dataset along coastal area (Sect. 2.4). These scenarios were built to quantify the role of natural habitat in local communities.

2.4 Hazard index

We employed the InVEST CVM to examine the risk that inhabitants of two pilot studies face from coastal hazards, both in the present and in the near future, under climate change scenarios. According to [9, 31, 32], the CVM is a tool for decision-making that utilizes an index-based methodology to comprehend the opposed vulnerability of local society to the hazards and pinpoints in which ecosystems have the highest likelihood capacity to provide coastal safeguard. This approach expands upon earlier, comparable indices (for example [29, 30, 55, 56],) by taking into account ecosystems' role in offering coastal defence and integrating data on residents, assets, and other pertinent metrics in the risk framework. These indices consider the biophysical and climatic features that regulate exposure to disasters resulting from hazards along the coast. Throughout the Bintan and Seribu Islands coast, we evaluated the

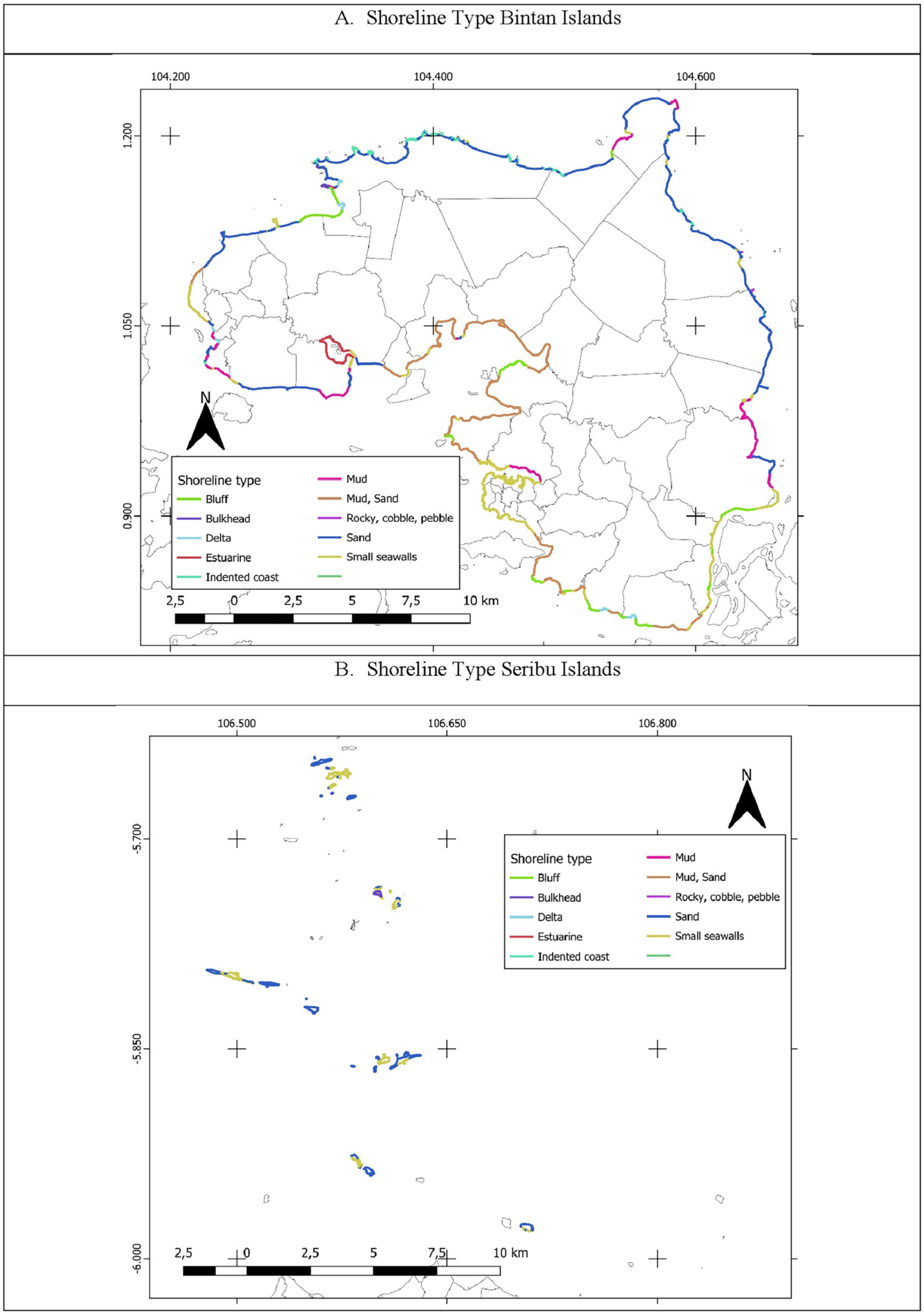


Fig. 2 Shoreline types of two study sites: Bintan Islands (**A**) and Seribu Islands (**B**)

potential risk that climate hazards pose to local inhabitants at a spatial resolution of 250 m2 under SLR and habitat scenarios. A range of various parameters: SLR, storm surge potential, wind, wave exposure, shoreline type, elevation, and habitat type, as well as the coverage —we calculated a HI using the InVEST CVM, in which this index ranked the comparative exposure of the coastal hazards. The factors indicated above were ranked from minimum (i.e., rank = 1) to maximum exposure (i.e., rank = 5) on every 250 m coastal section according to a mix of actual and comparative ranking of predicted and measured data, as shown in Table 1. Then, the hazard index was determined by calculating the geometric mean of the ranked parameters (i.e., R was defined as rank, and whole parameters were assigned weight equally). The findings show the comparative exposure to coastal hazard threats for every 250 m coastline section as opposed to all other sections in the pilot sites in both SLR and habitat scenarios (Eq. 1).

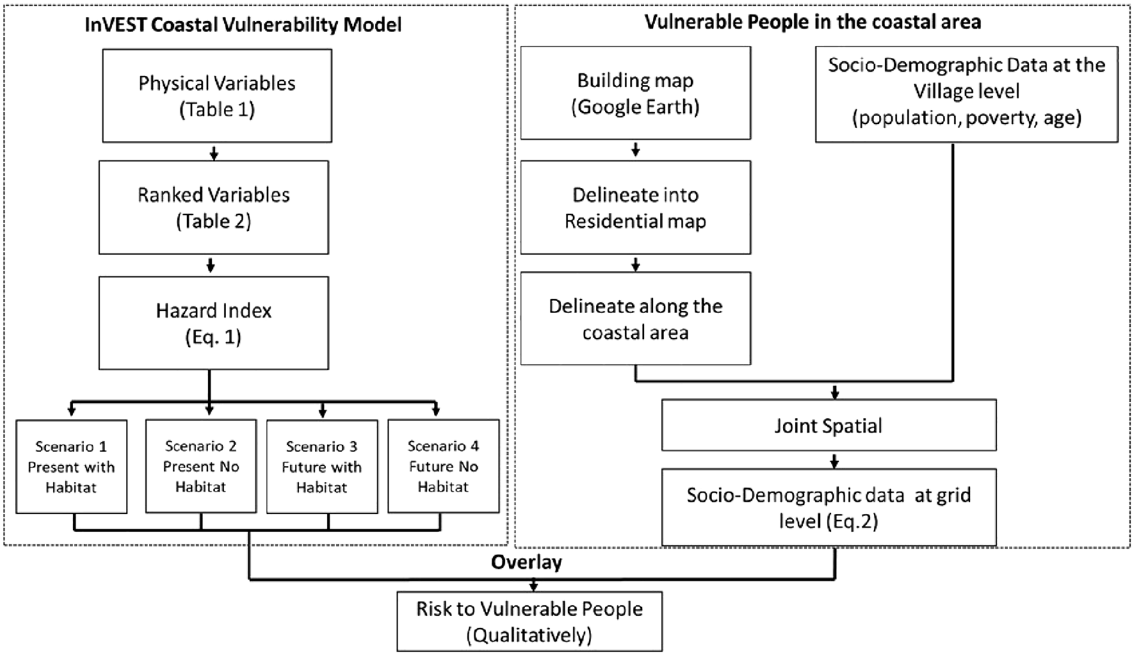


Fig. 3 Research framework to assess the risk to vulnerable people along the coastal areas

$$Hazard\ Index = \sqrt[7]{R_{Habitat}R_{shorelinetype}R_{winds}R_{SLR}R_{stormsurge}R_{relief}R_{waves}} \quad (1)$$

Since coastal interactions and processes between factors that comprise coastal ecosystems are fundamentally non-linear [57], we followed [58] and [56] in employing a multiplicative approach for the index of exposure. This is because a linear formula is prone to "eclipsing," in which one of the factors could be less, yet the whole index remains unchanged [59]. Many environmental index models employ the geometric mean as the combining function since it settles to the same scale of the inputs and yields understandable outcomes. For Instance, [60] illustrate its superior prediction accuracy in water quality versus other formulations. Moreover, Other studies discovered an excellent association between the magnitude of HI generated by this multiplicative technique and data points observed on hazard incidents and damages in the coastal areas of the United States [31].

In order to visualize the hazards, we divided the whole spatial pattern of the hazard index magnitude (which ranges from one to five) into three groups. We identified regions with the highest risk (> 2.6; represents the top 25% of the hazard index), intermediate risk (2.6 -1.9), and lowest risk (< 1.9 represent the lowest 25% of the hazard index). The categories of highest, high, intermediate, and low were used in the following sections to represent relative exposure to coastal risks. In order to quantify risk from coastal hazards along the coastline areas across pilot projects, we then integrate the exposure estimates from the HI and the socio-demographic information we utilized to identify at-risk groups. The following sections cover risk mapping and quantification for coastal communities in more detail.

2.4.1 Habitat rank

Each type of coastal habitat was ranked according to variations in physical characteristics and assumed capacity to minimize erosion, waves, and storm surges. A habitat rank of 1 indicates the highest level of protection, a score of 4 is the lowest, and a score of 5 indicates the absence of any habitat-based protection. Also, within the habitat ranking approach, we did not include any process-driven surge, wave reduction, or attenuation mechanism. The views of experts and peer-reviewed research—such as those assessed by [9, 31]—are the foundations for the habitat rankings shown in Table 2. To show the extent of the coastline that will probably be protected from a particular habitat type, a "protective distance" that is particular to that habitat was also designated. These distances are not hydrodynamic or ecological parameters; instead, they are merely a technical shortcut as the algorithm does not consider numerous variables such as channel structure, depth, distance from the coast, etc., which might affect the distance which this habitat alters potentially noticeable [9, 31, 61]; this model helps us to assess which areas of the coastline are safeguarded by zones of habitat-based at various ranges of the cell grid.

Finally, we incorporated into the index the shielding generated by many habitat types to shoreline sections [62]. Many coastlines may solely contain coral reefs, while others might feature mangroves, seagrass, and coral reefs. According to [61], the rankings are set so that, while a single low-ranking habitat like a coral reef performs better than typically, many associated high-ranking habitats—like short mangrove and seagrass—perform more beneficial than one by themselves. As new findings in this area become available, our ranking approach will be adjusted to reflect better the importance of diverse ecosystems in lowering coastal risk across such a wide geographic area.

2.4.2 Rank of other variables

This section defines other variables as shoreline types, relief, wave exposure, winds, storm surges, and SLR. We employed high-resolution satellite data (i.e., Google Earth) and ground truth data with a selected sample site in two pilot areas to map the shoreline types. Three natural types of were categorized for two pilot sites: sandy beaches -rank "5", muddy shorelines -rank "4", and rocky shorelines -rank "3". Meanwhile, seawalls were assigned a ranking of "2" detailed information on seawall sites was unavailable within Indonesia. Therefore, ground truth was conducted. Furthermore, seawalls frequently have an edge effect, which causes erosion to be magnified near the margins. The model can capture this, but we elected not to include it in our research because our seawall coverage was insufficient.

Furthermore, to determine the rank of wave exposure, surge potential, winds, and SLR, we utilized a quantile approach, as explained by [9]. However, it was a bit different for SLR since we utilized the scenario from [54] to rank the variables. Based on Canaby et al. 2016 [54], the worst-case SLR scenario for 2100 was 1 m in the Singapore Bay. Therefore, we ranked the SLR as follows: 0–20 cm (Rank 1), 20–40 cm (Rank 2), 40–60 cm (Rank 3), 60–80 cm (Rank 4), and 80–100 cm (Rank 5).

2.5 Habitat and SLR scenario

2.5.1 Habitat scenario

The main objective of this research was to estimate the capacity of coastal habitats to minimize the risk of coastal hazards in two case studies of small islands in Indonesia. Thus, we quantify the role by creating two scenarios: hazard index with natural habitat and hazard index when there is no natural habitat (i.e., we assumed the habitat is lost and cannot protect the areas) within the coastal areas. Calculating the hazard index with no natural habitat could assess where and to what extent the natural capital could save the local communities. In this study, we changed the habitat rank to “5” when we estimated the scenario without natural habitat.

2.5.2 SLR scenarios

The present research compared the degree of HI at the coastal areas with baseline period SLR (2016) to various future SLR scenarios (2040, 2100). Since our study was conducted in nearly a national development planning process (Vision 2045), we mainly concentrated on 2040. We utilized satellite-based estimates with rough spatial resolution since there was insufficient local tide gauge dataset to estimate SLR spatially across the pilot sites. Considering the expected SLR graph for the most severe RCP scenario, we evaluated the proportional change in sea level across timesteps, as mentioned in Sect. 3.2. We evaluated the total increase at the present condition (2016) inside the first quantile (10.12 cm), applying the curve, and attributed a rating of "1." The estimated increase for 2040 was 25 cm, giving it a rank of "2" (Table 1). This represents an easy method to reflect the increasing vulnerability to coastal risks projected as SLR. In this study, we also consider the long-term scenario (2100), whereas the total rise forecast for 2100 was 1.0 m [54].

2.6 Risk to vulnerable people

To connect hazards with those at risk, we initially mapped demographic factors for the pilot sites, such as total population (people/500 m and people/250 m, elderly people (older than 65 years old), and kids (younger than 5 years old) and people living in poverty. Since the grid system of demographic information is not available within the country, we estimated using the following equation:

$$Population = \sum_{i=1}^{n} B_i x P_j \tag{2}$$

whereas Population represents the number of people within one grid, Bi indicates the number of buildings, and Pj is the estimated number of people living in one building in a certain village. For other demographic information, such as elderly people and kids, we applied the ratio based on district-level statistical agency information. In this study, we only overlaid the hazard index with the number of vulnerable people and calculated the number of people at risk.

3 Result

3.1 Coastal hazard spatial distribution and its drivers

Figure 4 shows the general overview of the coastal hazard index in the Bintan main islands (4A) and Seribu Islands (4B). We classified the hazard index into three classes, whereas green, yellow, and red dots indicated the lowest, intermediate, and highest hazard index of the two pilot sites. Modeled results found that the highest exposure under present and with the habitat existence scenarios of both pilot sites were primarily located in the northern part of the study areas (Fig. 4-left side). The right side of Fig. 4 summarizes the highly exposed coastline and population of the modeled result under four type scenarios: present with habitat, present without habitat, future with habitat, and future without habitat. The figure shows, under current habitat scenarios, about 18.24% and 21.8% of the Bintan and Seribu Islands' coastline area were highly exposed to climate hazards, and it will affect the coastal population of Bintan and Seribu Islands, nearly 15 thousand people and 6.6 thousand people, respectively. In addition, under the projected SLR and habitat existence scenarios, we revealed that the portion of the coastline most vulnerable to coastal hazards would roughly double, with around 33–42% of the population living in the most significant risk areas (Fig. 4-right).

Coastal and adjacent ecosystems can be found along the pilot sites' entire coastline (Fig. 1), with several habitats facing parts of the coast (for instance, coral reefs protected by mangroves and seagrass). The results indicate that if these ecosystems are gone, even at present SLR, the length of vulnerable coastlines across the region will treble (Fig. 4-right). Moreover, the total length of coastline at the highest exposure expands threefold in Seribu Islands and nearly fourfold in Bintan main island with habitat loss and predicted future SLR (Fig. 4-Right), placing an estimated two-thirds of the coastal communities at risk. These findings emphasize the critical role ecosystems could serve in ensuring coastal protection, present and future. Further, based on population estimates, we assumed a steady 2022 population because no projections for 2040 were available; however, considering that the coastal inhabitants are expanding in the pilot sites, this outcome is probably underestimating future risks.

3.1.1 Bintan

Figure 5 shows the drivers of the spatial distribution of the hazard index in Bintan mainland. Within this study area, we analyzed the hazard index at the village level (i.e., in a total of 35 villages along the coastline). According to Figure 4, the northern and eastern parts of Bintan Island were notably the highest exposed coastline, as indicated by the red dots. Also, we identified a highly vulnerable coastline on Bintan Island, mainly found along the sides of islands standing on broad, shallow banks, where a substantial storm surge is likely (Fig. 5F), and directly facing the South China Seas, where wind and wave exposure is severe (Fig. 5B, C). For example, Berakit, Malang Rapat, and Teluk Bakau Village have a dominant area of very high exposure (Rank 5) to wind, waves, and surge potential (Fig. 5B, C). Moreover, nineteen coastal villages have very high exposure to shoreline types, where more than 50% of their shoreline type were categorized as sand (Fig. 5F), whereas this type of shoreline is prone to erosion. Regarding the natural habitat, all the coastal villages were protected by a natural ecosystem (Fig. 5A); thus, in the proxy of natural habitats, all coastline villages were primarily clustered with very low exposure (Rank 1).

Bintan is the main island under the Riau Islands province, whereas Tanjung Pinang was notably the province's capital city. As seen in the supplementary materials (Supplementary A1), Tanjung Pinang has the densest population (The southeastern part of the island), whereas the population ranges between 400 and 3940 people within 500 m^2. Within the city (i.e., Tanjung Pinang Barat, Kampung Baru, Tanjung Ayun Sakti, Tanjung Unggat, Kemboja, and Kampung Bugis Villages), the hazard index was categorized as the lowest to intermediate level and under the present condition the highly

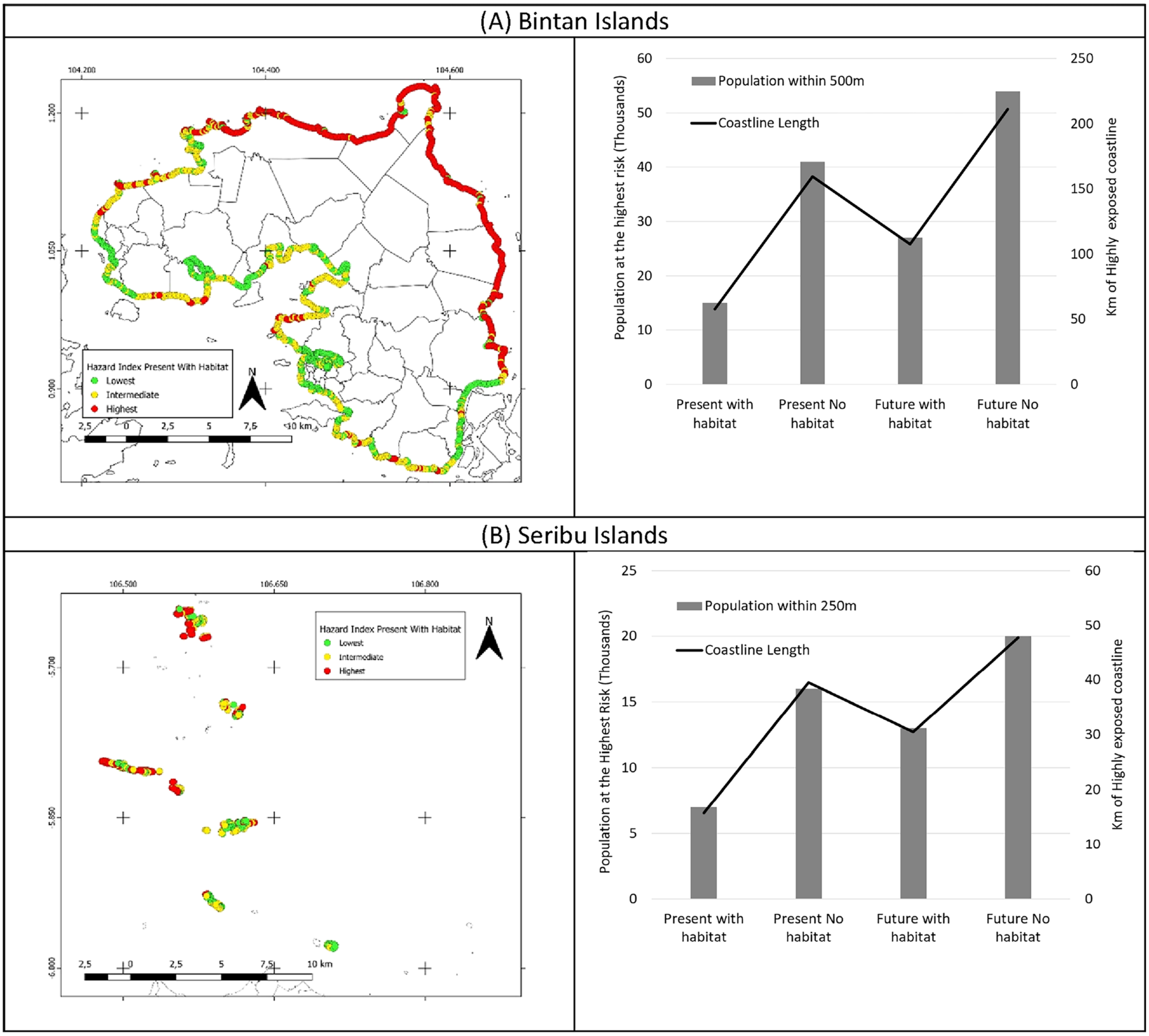


Fig. 4 Coastal hazard index in Bintan Island (**A**) and Seribu Island (**B**)

exposed area was not found (Fig. 4A). It may due to the existence of natural habitat (Fig. 5A) and low exposure of wind, wave, surge potential and shoreline type. (Fig. 5B–F).

3.1.2 Seribu Islands

Figure 6 shows the spatial distributions of proxy drivers of the coastal hazard index in the Seribu Islands. Seribu Islands consist of more than 100 islands with 11 inhabitants [49], where administratively, one village may consist of two or more islands. In this paper, we limit our assessment to inhabitants' islands, consisting of only five villages: Pulau Tidung, Pulau Pari, Pulau Kelapa, Pulau Untung Jawa, and Pulau Panggang. Among five villages, Pulau Kelapa has four proxies categorized as very high exposure, such as surge potential, shoreline types, and wind and wave exposure. Meanwhile, Pulau Tidung and Pulau Pari have three proxies categorized as very high exposure: shoreline type, wind, and wave exposure.

Moreover, Pulau Untung Jawa and Pulau Panggang were the least exposed among those islands. Regarding the natural habitat, all the coastal villages were protected by a natural ecosystem (Fig. 1), where the rank was predominantly low exposure. Pari Islands has the densest natural habitats among the five villages; 40% of the area was clustered as very low exposure (Fig. 6A). Moreover, the elevation was categorized as intermediate and tended to be similar in the whole

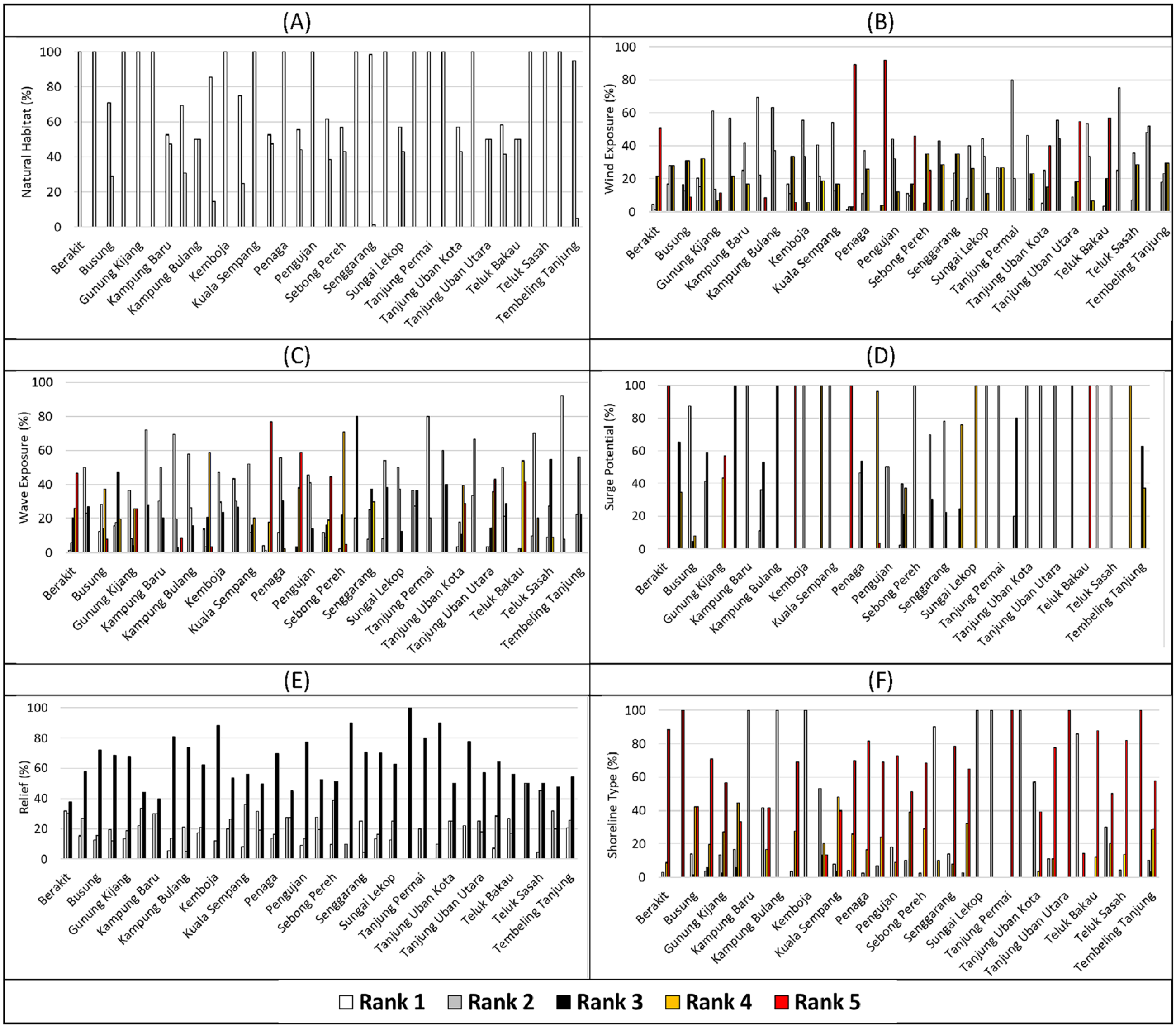


Fig. 5 The rank distribution of each parameter in the coastal hazard in Bintan Island

region. Further, Pulau Harapan and Pulau Panggang were two villages with low exposure in shoreline types, whereas their primary shoreline type was seawall. The seawalls were mainly built in those two villages because Harapan is the leading tourist destination, and Pramuka Islands (Part of Panggang Village) is the capital city of the Seribu Islands.

Supplementary Materials (A.2) shows that all villages were primarily categorized as very dense population areas, whereas Pulau Kelapa and Pulau Panggang were the densest areas. The dense population was found in Pulau Kelapa, where nearly 2400 people live within 250 m^2 areas, followed by Panggang island, where about 2200 people live within 250 m^2 of land. Pulau Kelapa, in particular, faces a severe risk of climate hazards since this area was categorized as the highest exposure village and, at the same time, has the highest population density.

3.2 The role of coastal ecosystems at present and under SLR projection

The results of the models revealed that natural habitats are critical for minimizing the hazard exposure for both pilot sites. Also, we identified that habitats offer coastal defence for areas whose exposure is fundamentally strong caused by various proxies (e.g., wave, tidal, storm surge, etc.) and are just as crucial for keeping other territories' exposure minimal. For instance, the Seribu Islands have every island's most severely exposed shoreline, and more than 70% of Bintan's coastline was categorized as medium to severe risk. Yet, coral reefs, mangroves, large seagrass beds, and terrestrial plants protect

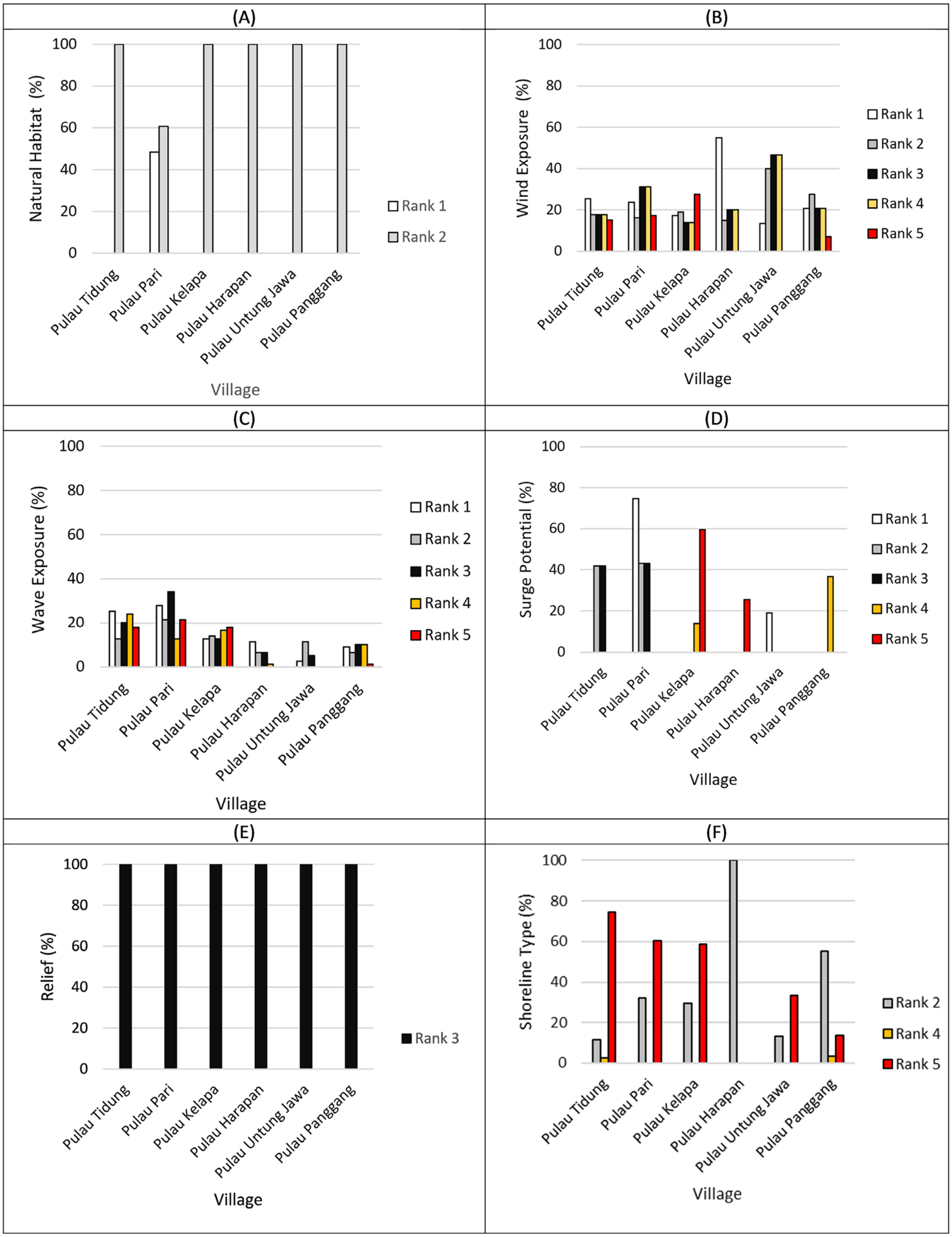


Fig. 6 The rank distribution of each parameter in the coastal hazard on Seribu Island

more than 73 km of the Seribu island's coastlines and 317 km of the Bintan Islands (Figs. 4, 7, 8, 9, 10). Also, our findings indicate that if these habitats vanish, more than half of the Bintan and Seribu Islands coastline will be severely exposed to climate hazards (Figs. 7 and 9).

The research also illustrates the possible significance of ecosystems in limiting elevated coastal hazard exposure owing to SLR throughout the study areas. Since modeled SLR predicts a rise in exposure at all pilot sites, our findings imply that the existence of coastal natural habitat can dramatically lower the length of the most susceptible coastline for all regions by up to 9.6 fold in Bintan (Fig. 7B) and 2.1 fold in Seribu Islands (Fig. 9B). In the SLR scenario, for example, the share of the highly exposed shoreline between Bintan and Seribu Islands grows in average around 86.2% and 93.6%, and when combined with habitat loss, practically the two-third of the island is severely exposed.

In comparison, if ecosystems are preserved, only 34% and 42% of the Bintan and Seribu Islands shoreline will be highly exposed in the future (Figs. 7B and 9B). The disparity in exposure with and without ecosystems shows that the existence of ecosystems on the island can lower possible rises in exposure to hazards related to the SLR by 24% or more (Figs. 7B and 9B). Although these projections are relative and involve some assumptions and simplifications of the assessment, they generally apply to all islands in the nation's territory (to varied degrees), implying that habitats play an important role in minimizing future risks.

The qualitative results remained consistent if a more extreme SLR scenario—the year 2100—was considered. The hazard level generally rises with SLR and habitat loss, while the risk increases with greater SLR. We also noticed that the likelihood of ecosystems offering protection is diminished in a more severe SLR scenario. According to our findings, the length of shoreline at high risk is reduced by 56–96% under the 2040 SLR scenario (Fig. 3B) and by 29–49% under the 2100 SLR scenario due to the coastal defence provided through natural habitat (Supplementary A.3).

3.2.1 Bintan Islands

Figure 7 illustrates the highly exposed village of Bintan under four scenarios. Meanwhile, Fig. 8 shows the example condition of the highest hazard index within the study areas. According to Fig. 7A, with the current natural habitat extended, only six villages were highly exposed to climate hazards. Still, if all coastal habitats were gone, 27 villages would be exposed (i.e., about 79% of coastal villages would be affected). Moreover, using the modeled SLR with the current natural habitat extension, nearly 19 villages will be highly exposed. Still, when the coastal ecosystem diminishes, 31 villages (91%) will be severely exposed to coastal hazards (Fig. 7B). Moreover, without coastal habitat and under SLR projection, more than fifty percent of the coastline will be highly exposed to the 18 coastal villages in Bintan Region. Further, Teluk Bakau, Pengudang, Malang Rapat, Berakit, Tanjung Uban Utara, and Kawal will be the most severely affected since more than 85% of the villages will be highly exposed.

Therefore, in Fig. 8, we only limit the visualization of the coastal habitat, hazard index, and population in the most affected areas, such as Malang Rapat, Teluk Bakau, and Kawal village. In those villages, the most dominant coastal habitats were seagrass and coral reefs, while mangroves can only be found in Kawal. Moreover, Kawal was the densest population among the three visualized villages, as shown in Fig. 8B. As seen in Fig. 8B, the role of natural habitat is crucial since the loss of natural habitat could make the whole of Kawal village highly exposed to climate hazards.

3.2.2 Seribu Islands

Figure 9 shows the hazard index status in Seribu Island under four scenarios. Among six villages, Kelapa Island and Tidung Island were the most exposed to climate hazards. Moreover, Fig. 9A revealed that coastal habitat played an essential role since it reduced the length of the highly exposed coastline by nearly 21-fold (i.e., Pari Island). Moreover, under modeled SLR, coastal habitat could reduce the length of the highly exposed coastline by twofold (i.e., Pari Island) (Fig. 9B). Moreover, among six villages, Pulau Tidung and Pulau Kelapa were the most affected areas. At the same time, Pulau Untung Jawa was the least affected village.

Figure 10 shows the spatial distribution of natural capital, hazard index, and population in Kelapa Village, the most highly exposed coastline on Seribu Island. As seen in Fig. 10A, Kelapa village has all types of coastal habitats; among those islands, Kelapa Island has the densest population, as shown in Fig. 10B. Kelapa Island has the lowest exposure (Fig. 10B-left), but if all coastal habitat is destroyed, most of the island will be highly exposed to coastal hazards (Fig. 10B-right). Moreover, since the island has the densest population, the role of the ecosystem will be a vital approach to reducing the risk.

3.3 The role of natural habitat for local communities

We identified that approximately 32% of Bintan and Seribu Islands presently receive safeguards from marine habitats; without these ecosystems, they will be most vulnerable to coastal disasters. If coastal habitats are gone, the proportion of the most susceptible living there will nearly triple or rise by an order of magnitude for the major Bintan and Seribu populated islands. According to the results of the model, many island inhabitants benefit from the coastal protection

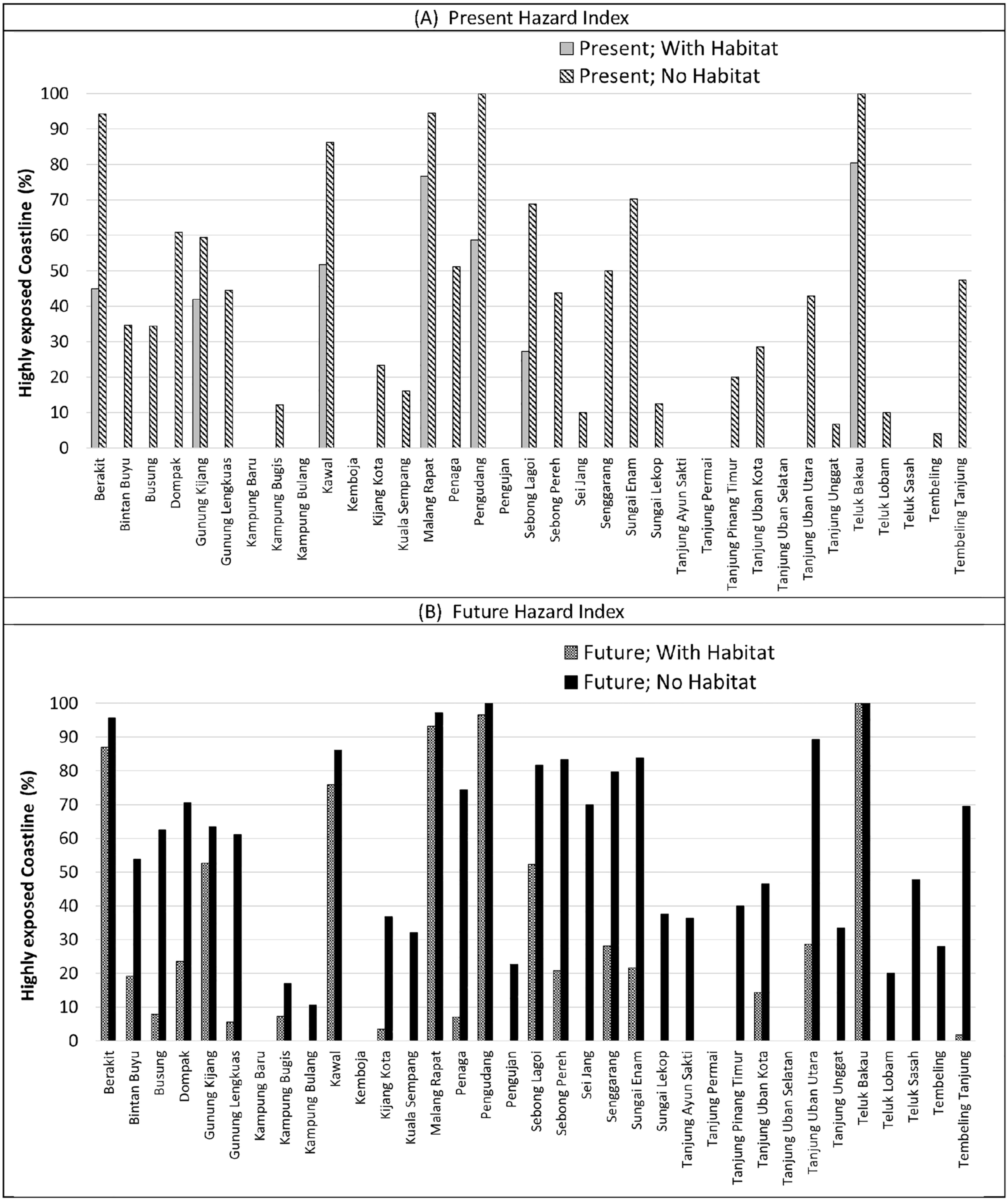


Fig. 7 The ratio of highly exposed coastline in each coastal village in Bintan Island under the present (**A**) and future conditions (**B**)

of these ecosystems. For instance, approximately 4% and 8% of Bintan and Seribu Island's population is estimated to be presently residing in regions at highest risk; yet, if habitats are gone, roughly eleven and forty percent of the islands' inhabitants will be at most elevated danger (Fig. 11).

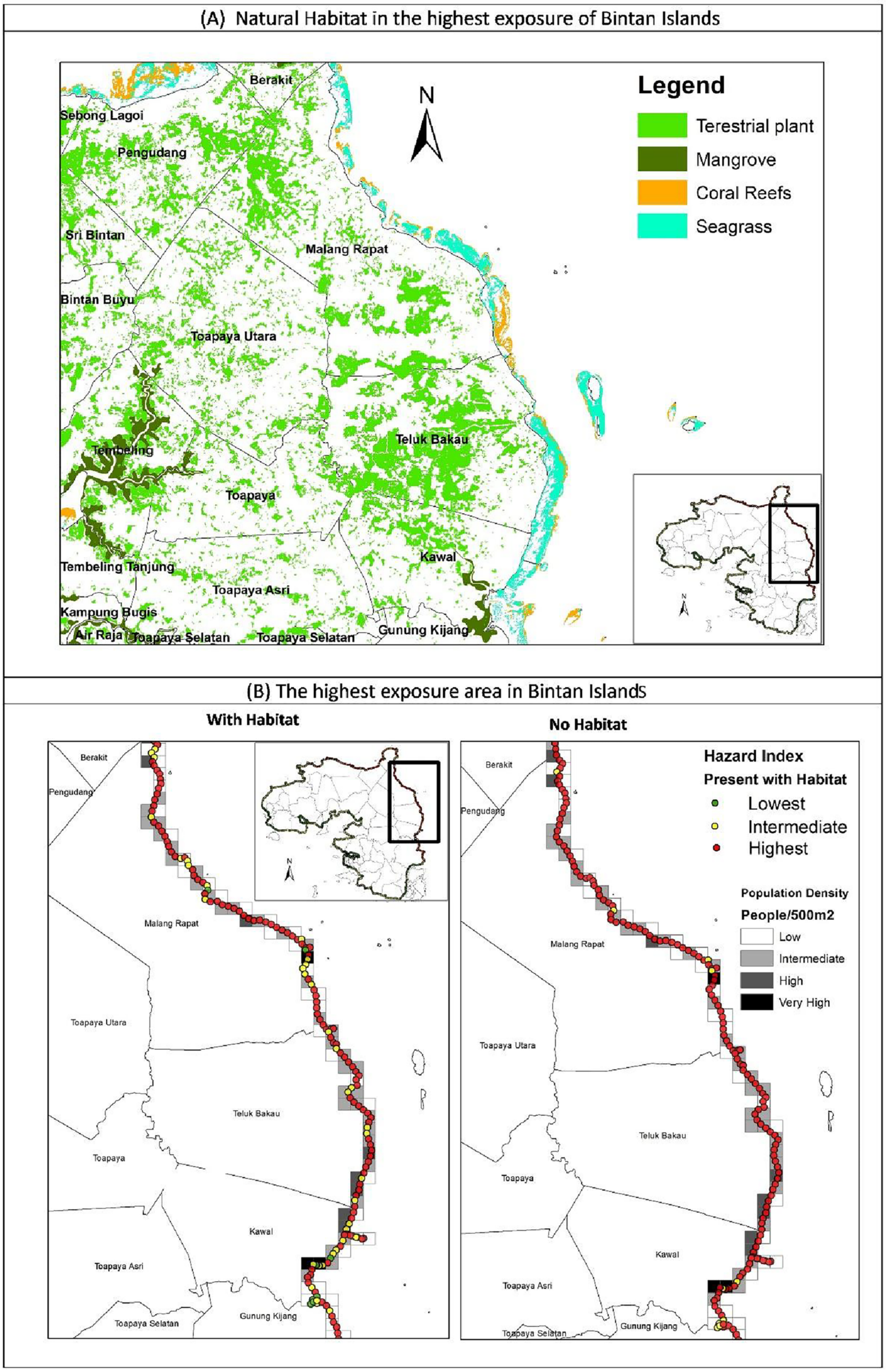
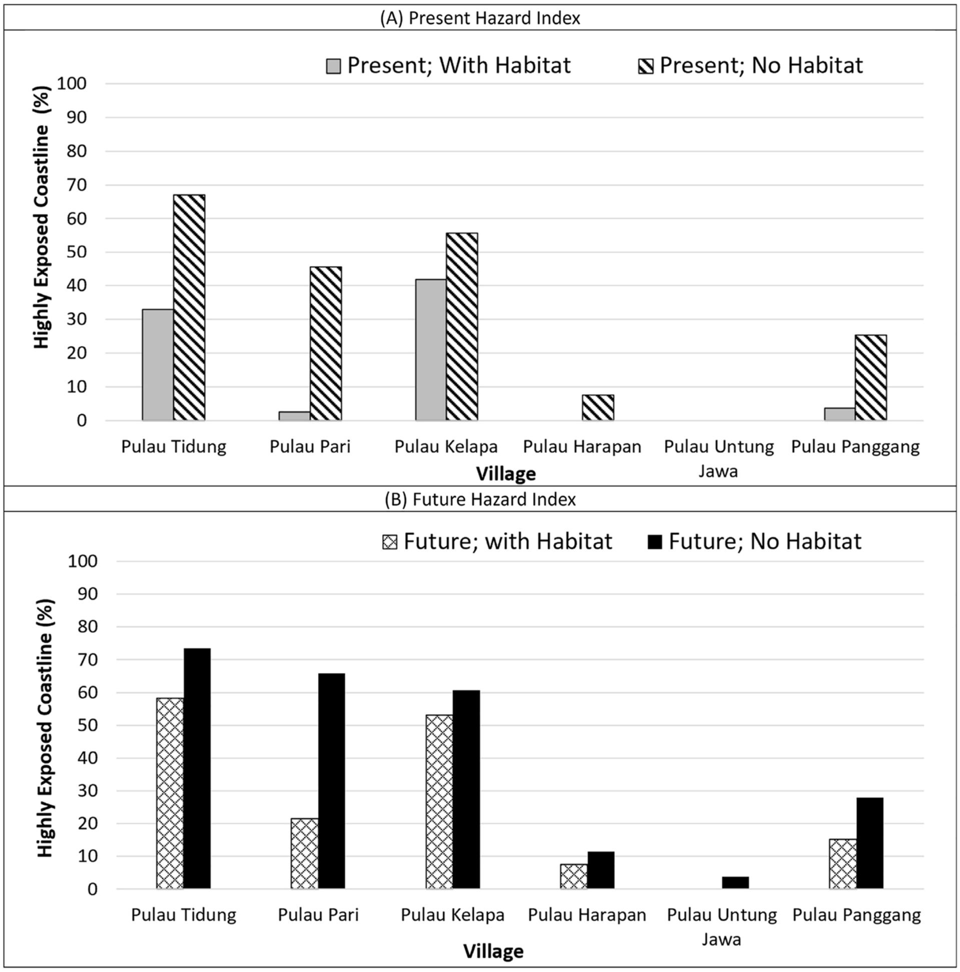


Fig. 8 The spatial distribution of natural habitat in the highest exposure coastline (**A**) and the overlaid image of the highest exposure and the coastal population within 500 m (**B**) in Bintan

As shown in Figs. 7, 8, and 11A, Malang Rapat, Teluk Bakau, and Kawal villages have the highest risk of climate hazards due to the highest risk of hazard index and the highest ratio of vulnerable people within Bintan Island. Moreover, Pulau Kelapa and Pulau Pari within Seribu Islands are found to be the highest-risk areas of climate hazard since they have the highest risk of hazard index and the highest proportion of vulnerable groups (Figs. 9 and 11B). Our study also identifies the locations where ecosystems protect socially susceptible communities. For instance, approximately 6.5% of the population in Bintan Island in 2022 is under five, while nearly four percent are old (> 65), and 25% live in poverty. Meanwhile, in Seribu Islands, 18% of the population is younger than five years old, 3% is elderly, and nearly 40% is living

Fig. 9 The ratio of highly exposed coastline in each coastal village in Seribu Islands under the present (**A**) and future conditions (**B**)



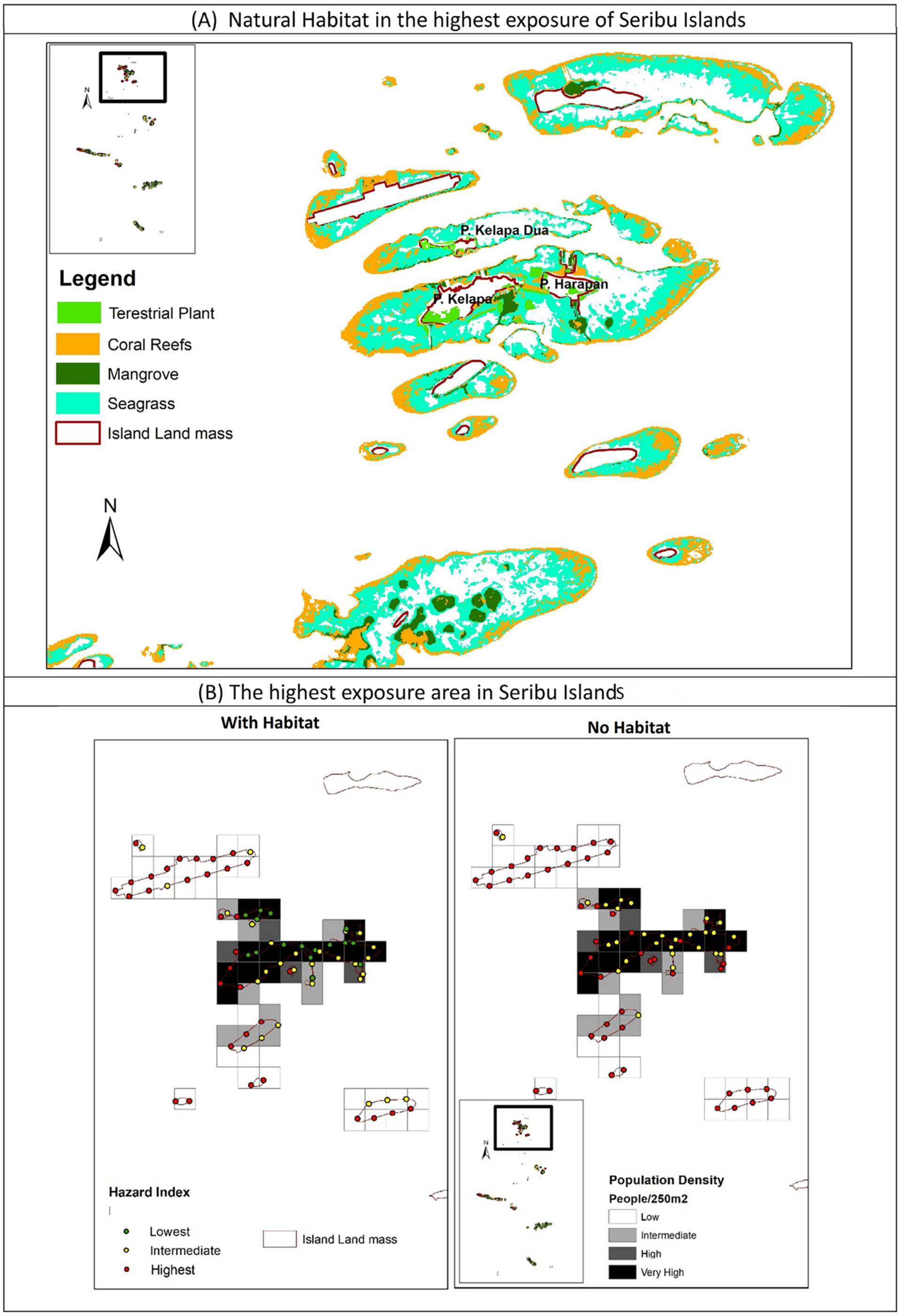
in poverty. By looking at these vulnerable communities and the hazard index level, Seribu Island seems more at a higher risk than Bintan Island.

4 Discussion

There has been a significant increase in studies investigating the positive effects of natural ecosystems on coastal protection in the past few years (e.g. [9, 63–65]). However, there is limited evidence on how these ecosystems are connected to the vulnerable groups that will gain the most from them. Additionally, there is a lack of evidence on how the integration of socio-ecological science has translated into practical measures for restoring and conserving these ecosystems for risk reduction. Increasing sea levels, coastal populations, and area development threaten aquatic environments. Thus, developing new strategies incorporating nature-based solutions within a wider socio-ecological setting is crucial, as it offers straightforward and understandable tools for stakeholders to consider alternative options. To address this need, we proposed a modeling technique that assesses where coastal ecosystems are most important to society under present-day and future SLR scenarios. Our models demonstrate the significant risk reduction provided by the ecosystems in both present-day and future SLR scenarios (Figs. 4, 5, 6, 7, 8, 9, 10). Furthermore, our findings point to specific locations where this ecosystem-based risk reduction is particularly crucial (Figs. 7, 8, 9, 10). Therefore, preserving the existing distribution of current natural habitats and preventing future habitat loss should be prioritized in public policy for disaster risk reduction (DRR) and climate change adaptation.

Previous research has shown that ecosystems are essential in mitigating climate hazards (e.g., [66–68]). Furthermore, given a future SLR scenario, we projected that coastal habitats might reduce shoreline extent and the affected vulnerable people to coastal risks at two pilot locations by more than 50% (Figs. 4, 7B and 9B). Because the capacity

Fig. 10 The spatial distribution of natural habitat in the highest exposure coastline (**A**) and the overlaid image of the highest exposure and the coastal population within 500 m (**B**) in Seribu island



of habitats to serve as coastal defence relies on their physical feature, distribution, and prevailing conditions, it isn't easy to generalize their protective capabilities. We applied prior research findings (i.e., [9]) by modifying methodologies and approaches for illustrating geographical variation in reducing risk to assist planning and decision-making. Also, we highlighted lowland areas with relatively erodible soil materials and various ecosystems as critical sites to put first for conservation if we want to sustain coastal protection advantages in the future, mainly due to sea-level rises. For instance, our assessment of Pari Island (Fig. 9A) revealed that it poses a severe threat to climate hazards if it loses its marine ecosystem. Previous research also reported that Pari Island experienced a massive abrasion and frequent coastal flooding that caused lower life quality standards [49]. Thus, our research can contribute to better

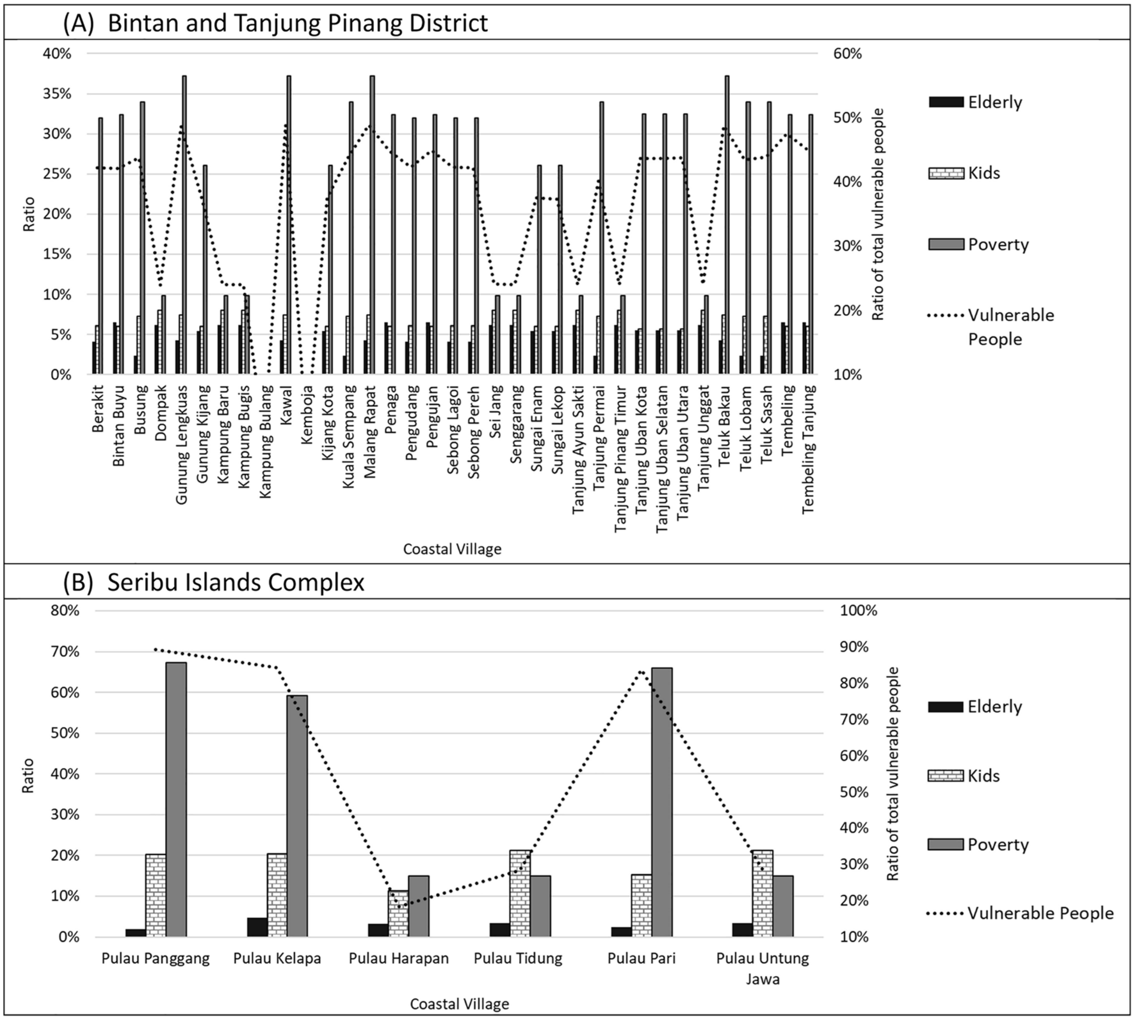


Fig. 11 Vulnerable communities in Bintan Island (**A**) and Seribu Island (**B**)

assessing and adopting nature-based solutions in the two study sites and other regions by identifying the scenarios under which habitats may be of utmost importance for coastal resilience.

The literature on coastal protection often focuses on the biological and physical aspects, which lead to the risk mitigation given by natural habitat over the community and economic advantages [27, 69]. In Indonesia, coastal vulnerability studies mainly focused on the physical parameters, neglecting the role of natural capital and without considering future climate scenarios [29, 30, 70]. This study addressed this gap by integrating hazard index, climate projections, population statistics, and natural habitat datasets. Our study identifies areas where the most socially vulnerable populations, including the elderly, children, and impoverished communities on small islands, coexist with habitats that reduce risk. Poverty and age are key indicators of social vulnerability to coastal hazards during and after natural disasters, a trend observed in resource-rich and resource-poor nations (e.g. [5, 71],). For instance, a significant proportion of the victims affected by Hurricane Katrina in Louisiana were elderly individuals, constituting approximately 60% of the total casualties [9]. Similarly, the fatality rate in Hurricane Sandy increased with age, with individuals aged 65 and above accounting for more than 30% of the fatalities [72]. Low-income households in rural Sri Lankan communities that rely only on natural resources are more susceptible to financial losses caused by climate hazards and are subject to more severe crises [71].

Furthermore, the prevalence of elderly individuals is higher on certain remote Indonesian islands due to the migration of working-age individuals to the capital city for better employment opportunities. In disasters, nature-based solutions such as fisheries for nutrition can provide significant benefits, mainly when local resources are the sole means of community support. Such self-sufficiency is crucial for DRR and sustainable development in island nations like Indonesia, where many vulnerable populations remain beyond the immediate reach of emergency aid following a disaster [73]. For the safety of small island populations, developing coastal resilience has become a priority and a national goal, mainly because the destruction caused by most hydrometeorological disasters accounts for 99.1% across Indonesia [40]. Building capacity and offering direction about when and in which location to employ sustainable coastal protection are critical components of continuous national and island-level planning initiatives.

Between 2011 and 2021, Bintan experienced over seventy climate-related disasters [46]; meanwhile, tidal flooding and tornados were the most common disasters in Seribu Islands, which occurred more frequently in recent years [49]. The approach to reducing the risk of those hazards differed between the two study locations. In Bintan, the local authority focused on developing infrastructure like seawalls, drainage systems, and fire-fighting infrastructure and implementing soft approaches such as rescue programs and community participation in disaster response [46]. However, the ecosystem-based approach has not been considered yet in Bintan's strategic planning for climate change adaptation [46]. Moreover, local authorities did not see the importance of coastal habitat restoration at a village level since massive oil spills from the South China Sea frequently destroyed coastal habitats in the northern part of Bintan. On the other hand, local government in Seribu Islands employed a combination of hard infrastructure, soft approaches, and ecosystem-based approaches (e.g., mangrove restoration). However, in the densely populated island, local inhabitants did massive land reclamation, which could potentially destroy coastal habitats, such as coral reefs and seagrass [49].

Our study addresses this situation through an index-based assessment for risk mapping by simulating the worst-case scenario of natural habitat destruction. This proposed index has a big potential to extend to the whole Indonesian region so that it can be used to support planning documents at the national level. However, among the seven parameters, shoreline type (Fig. 2) remained the biggest challenge since it's not available in the national database, nor will it be a huge bias if we did it only through a land use map. Moreover, several challenges occur in mapping the shoreline type, such as environmental variability, which includes tidal (i.e., daily high/low tide) and seasonal variations (vegetation growth, sediment deposition, and erosion), coastal development, extreme weather, which causes severe disasters, and remote sensing technology limitations. Therefore, in our study, we conducted a field survey of the most vulnerable areas to identify the real condition of shoreline type while remaining area using the open street map. Thus, decision-makers could use this simulation result as a basis for the development of risk reduction policies, particularly in small islands. As confidence and ownership of outcomes are critical for their adoption, decision-makers must be empowered to interact directly with the inputs and outputs of simulation [9, 74].

Index-based assessment (i.e., InVEST-CVM model) has been implemented in different countries such as the Bahamas-United States [27, 75], Oman [33], China [34, 76, 77] and East Africa [78]. However, this assessment has not been applied in Southeast Asia, including Indonesia [79]. As coastal ecosystems in the region are degrading, assessing coastal vulnerability by considering the existence of coastal habitats is crucial. This initial assessment can help the government understand the role of coastal ecosystems in reducing risks. By using various models, we can determine the most suitable natural habitats and address the time needed for project feasibility evaluation. This research serves as a positive example for other nations and communities on how simple models that integrate ecological, social, and physical aspects can guide the implementation of ecosystem-based initiatives for coastal risk reduction.

However, index-based assessments, including this proposed index, still need to be improved in validating the result. The research mentioned above on index analysis for the coastal area (e.g. [27, 29, 30, 70, 75],), also did not mentioned validation assessment in their research. Nevertheless, the validation is still a crucial step. Therefore, we did a simple qualitative validation approach due to the unavailability of the spatial distribution of climate hazard magnitude at the village level. We interviewed 21 respondents from local communities in each pilot site's highest exposed coastal village and discussed it with local authorities. The result stated that all of the respondents in Bintan Island agreed that those four villages (Berakit, Malang Rapat, Teluk Bakau, and Kawal) and four islands (Panggang, Pramuka, Kelapa, and Pari) are often hit by climate hazards such as tornados, flooding, tidal flooding, and forest fire (Supplementary A.4 and A.5). However, this qualitative validation approach was not still enough; thus for future research of index assessment there is a need to develop on how to validate the result using a quantitative approach.

Since natural capital is not considered in Bintan's disaster risk reduction strategy, there was a massive destruction of coastal natural capital, particularly in Kawal Village, as shown in Fig. 12. The figure shows a substantial transformation from mangrove to open land area. If this trend of land clearing continues without effective mangrove protection measures, mangroves, and associated coastal habitats will disappear. This finding supports a previous study by Setiawati et al. 2023a [46], revealing that the open land on Bintan Island has nearly doubled, while the mangrove forest has decreased by 15% between 1990 and 2020. Moreover, as seen in Figs. 7 and 11A, Kawal village is one of the coastal villages most exposed to climate hazards; nearly half the population is categorized as vulnerable. If the coastal habitat continues to deteriorate, almost 90% of the Kawal population will face severe impacts by climate hazards (Fig. 7). Therefore, it is imperative to provide local policymakers with an initial simulation highlighting the potential consequences for their people and assets if the coastal habitat disappears.

In the Seribu Islands, local authorities and communities are seriously concerned about using natural resources to mitigate climate-related disasters [49]. However, their priority remains to enhance hard infrastructure to combat erosion and coastal flooding [49]. For instance, the local authorities constructed seawalls along the coastline at the densest village (i.e., Panggang and Kelapa Villages). The seawall construction not only minimizes the risk of climate hazards but also restricts massive land reclamation within the area [49]. However, among five villages, Pari will face severe climate hazards if they fail to protect their natural ecosystem (Fig. 7A). Even though this island has a community that is actively involved in mangrove restoration, abrasion still occurs and coastal flooding is getting worse year by year (Supplementary A.5). This phenomenon explains that the restoration technique has yet to be optimal because most of the mangrove forest on the island has a typically very dense area with short trees and small diameters. This excessive density hinders the growth of the trees and their ability to break up ocean waves. Therefore, addressing the technique for optimum mangrove restoration in the future is crucial.

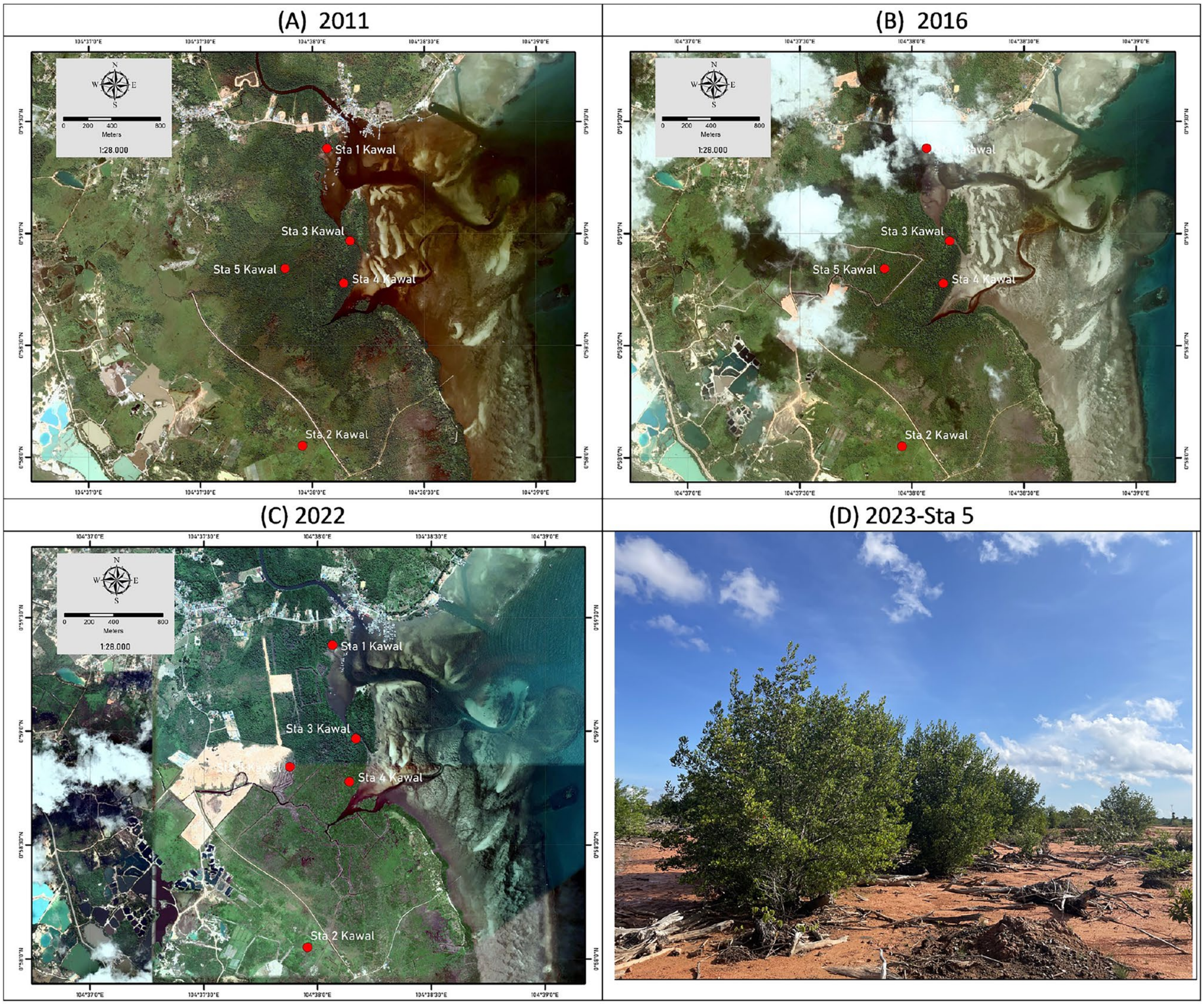

(A) 2011
(B) 2016
(C) 2022
(D) 2023-Sta 5

Fig. 12 The visualization of mangrove cover in Kawal Village in 2011 (**A**), 2016 (**B**), and 2022 (**C**) from Google Earth Time Slider. Meanwhile, the "**D**" picture shows a station 5 mangrove observation plot during the field visit on July 16, 2023, in Kawal Village

5 Conclusion

Our study emphasizes the importance of considering coastal habitats and the impacts of climate change on vulnerable communities of small islands in Indonesia. We found that coastal habitat is crucial in protecting the coastline of Bintan Island and Seribu Islands from coastal hazards and rising sea levels. Here are the key findings of this study:

- Currently, the existing coastal habitat provides protection for approximately one-third of the shoreline length of both locations.
- Under the projected SLR in 2040, the coastal habitat could safeguard about 50% and 96% of Seribu and Bintan Island's highly exposed coastal areas, respectively.
- The coastal habitat could save about 33% and 63% of the most vulnerable communities along the Bintan and Seribu Islands coastal regions

This initial assessment is crucial as the first step to introducing the role of coastal habitat in reducing the risk of climate hazards quantitively, and it could be an effective tool to address habitat degradation within the study areas. However, we acknowledge some limitations in this study, including using a global data set for winds, storm surges, and waves, the fact that there is no future projection for coastal populations, and the qualitative approach for validation. Future studies should consider incorporating more model scenarios for this assessment, such as determining the specific ratio at which the coastal habitat is reduced, future projection of the coastal population, and economic valuation of the coastal habitat. Moreover, the development of a method to conduct validation for index-based approaches needs to be considered in the future. Further, the tools could be used to advocate for nature-based solutions for disaster risk reduction to policymakers and local communities.

Author contributions MS: Conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, supervision, validation, visualization, writing–original draft, writing–review, and editing. MN: Conceptualization, investigation, methodology, visualization, writing–original draft. HR: Methodology, Writing–original draft. UC: Conceptualization, Writing–review, and editing. AM: Conceptualization, Funding Acquisition, Writing–review and editing. LA: Investigation, Validation, Investigation, TE: Conceptualization, NA: Conceptualization, Writing–review and editing, IS: Investigation, Validation. NH: Conceptualization, Investigation, Writing–review and editing, BP: Investigation. YD: Investigation, AO: Investigation, Validation. SS: Project Administration, Investigation, JR: Investigation, validation, S W: Investigation, validation, UH: Writing–review and editing.

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Data availability All input datasets are available by request to the corresponding author.

Declarations

Consent for publication The article contains no such material that may be unlawful, defamatory, or which would, if published, in any way whatsoever, violate the terms and conditions as laid down in the agreement. All authors are given their concern for publication of this research.

Competing interests The authors declare no competing interests.

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