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Coastal Vulnerability Assessment and Its Implications for ICZM Plan Validity: A Case Study of Bursa, Türkiye

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Coastal Vulnerability Assessment and Its Implications for ICZM Plan Validity: A Case Study of Bursa, Türkiye

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ABSTRACT

Sea-level rise (SLR) induced by climate change poses a fundamental threat to coastal settlements, yet spatial planning frameworks often fail to integrate these dynamic risks into legal zoning decisions. This study examines the impacts of SLR on the coastal areas of Bursa, Turkey, and evaluates the validity of the existing Integrated Coastal Zone Management (ICZM) Plan under future climate scenarios. By aligning spatial planning with the United Nations' Sustainable Development Goal 11 (SDG 11) - specifically Target 11.b, which calls for integrated policies toward climate change adaptation and disaster resilience- this research addresses the growing vulnerability of urban settlements. A three-stage methodology was employed: (1) modeling inundation extents for IPCC scenarios (years 2100–2500); (2) calculating a multi-dimensional Coastal Vulnerability Index (CVI); and (3) cross-referencing these risk zones with approved ICZM plan decisions. The results reveal distinct vulnerability profiles: while the Karacabey district faces physical inundation affecting critical wetlands, the Gemlik district exhibits "very high" vulnerability (CVI: 0.84–1.00) due to intense urbanization. Crucially, the overlay analysis demonstrates that the current ICZM plan sites critical infrastructure—including marinas and hazardous material zones—within projected inundation areas. The study concludes that current planning operates under static environmental assumptions that are inadequate for future climate conditions, highlighting an urgent need for adaptive spatial strategies to fulfill global commitments for sustainable and resilient cities.

KEYWORDS

Sea Level Rise, Coastal Vulnerability Index (CVI), Integrated Coastal Zone Management (ICZM), Climate Change Adaptation, Spatial Planning, GIS, Urban Resilience, Bursa.

1. INTRODUCTION

Sea level rise (SLR) stands as one of the most irreversible and spatially defining consequences of anthropogenic climate change, posing a fundamental threat to coastal zones through progressive inundation, accelerated erosion, and saltwater intrusion (IPCC, 2021; Matthews et al., 2015). The Intergovernmental Panel on Climate Change (IPCC) projects that global mean sea levels could rise by 0.83 meters by 2100 under high-emission scenarios, with the potential to exceed 6 meters by 2500 (IPCC, 2021). These projections carry profound implications for Low-Elevation Coastal Zones (LECZs), defined as areas less than 10 meters above sea level, which host critical infrastructure, dense urban populations, and fragile ecosystems (McGranahan et al., 2007). In this context, ensuring the resilience of coastal urban areas has become a pivotal focus of the 2030 Agenda for Sustainable Development. Sustainable Development Goal 11 (SDG 11) emphasizes the urgent need to make cities and human settlements inclusive, safe, resilient, and sustainable, particularly through enhanced disaster risk management (Target 11.5). However, a critical paradox has emerged in the governance of these vulnerable areas: while climate science increasingly emphasizes dynamic, long-term risks, spatial planning frameworks- specifically Integrated Coastal Zone Management (ICZM) plans- often continue to operate under static environmental assumptions (Government of South Australia, 2021; UNFCCC, 2025).

Historically, coastal planning aimed to balance economic development with environmental protection. The concept of Integrated Coastal Zone Management (ICZM) evolved to address the inadequacies of single-sector management by integrating physical, socio-economic, and ecological dimensions (Cicin-Sain & Knecht, 1998; Sorensen, 1993). Despite this holistic mandate, the practical implementation of ICZM, particularly in developing nations, often fails to integrate long-term climate projections. In Turkey, for instance, coastal planning is frequently driven by short-term development goals in tourism, industry, and transportation, lacking the flexibility required to adapt to future SLR scenarios (Ercanlı & Savaşır, 2022). This disconnection creates a risk of "maladaptation," running contrary to the objectives of SDG Target 11.b, which advocates for the adoption and implementation of integrated plans for climate adaptation. Approved infrastructure projects- such as marinas, passenger terminals, and industrial zones- are sited in locations that may become obsolete or hazardous within the century.

To address this planning gap, spatially explicit vulnerability assessments are essential. The Coastal Vulnerability Index (CVI) has established itself as a robust method for quantifying

susceptibility by synthesizing physical variables (geomorphology, slope, sea-level change) with socio-economic stressors (population density, land use) (Gornitz, 1991; Koroglu et al., 2019). While numerous studies have employed CVI to map physical risks (Hamid et al., 2019; Tragaki et al., 2018), there is a significant scarcity of research that systematically overlays these vulnerability models onto legal spatial plans to test the validity of future land-use decisions (Ercanlı & Savaşır, 2022).

This study addresses this critical knowledge gap by evaluating the validity of the Integrated Coastal Zone Management (ICZM) Plan decisions for Bursa, Turkey, under future climate scenarios. Bursa represents a microcosm of the Mediterranean coastal challenge, characterized by a complex interface of heavy industrial zones (Gemlik), rapidly urbanizing tourism corridors (Mudanya), and ecologically sensitive deltaic plains (Karacabey) (Güney, 2013). The convergence of high seismic risk, industrial pressure, and ecological sensitivity renders this region a critical case study for examining adaptation challenges.

The primary objective of this research is to move beyond traditional risk mapping by answering a specific policy question: Are the current spatial strategies and infrastructure decisions defined in the Bursa ICZM Plan viable under IPCC projected sea-level rise scenarios for 2100 and 2500? To achieve this, the study employs a three-stage methodology: (1) modeling inundation extents using a hydrologically-connected bathtub model based on high-resolution Digital Elevation Models (DEMs) (Yunus et al., 2016); (2) calculating a multi-dimensional Coastal Vulnerability Index (CVI) utilizing an equal-weighting approach to minimize researcher bias (McLaughlin & Cooper, 2010); and (3) cross-referencing these risk zones with specific ICZM plan decisions (Çevre ve Şehircilik Bakanlığı, 2015). By identifying specific conflicts between approved planning decisions- such as the siting of hazardous material anchorage zones and tourism facilities- and future flood zones, this study aims to provide evidence-based recommendations for the urgent revision of coastal planning instruments in Turkey and similar developing coastal regions. Ultimately, this research serves as a local roadmap for achieving global sustainability targets, demonstrating how spatial data can be operationalized to protect coastal urban populations and infrastructure in accordance with the principles of SDG 11.

2. REVIEW of the LITERATURE

Historically, coastal zones have served as the most magnetic geographies for human settlement and economic activity; however, they have evolved into "risk frontiers" subject to the most

devastating impacts of anthropogenic climate change. This phenomenon is debated in the literature as the "coastal paradox" - a term articulating the conflict between the continued concentration of global population and economic assets in Low Elevation Coastal Zones (LECZs) and the escalating risk of Sea Level Rise (SLR) (McGranahan et al., 2007). Scientific data indicate that under high-emission scenarios, global mean sea levels could exceed 0.83 meters by 2100 and 2 meters by 2300 (IPCC, 2021). Nevertheless, the discipline of spatial planning encounters a "structural" difficulty in integrating this dynamic threat into legal frameworks and land-use decisions.

The primary theoretical impediment to adaptation in spatial planning is the phenomenon defined in the literature as the "stationarity assumption." Traditional planning approaches generate land-use decisions based on the premise that environmental conditions- such as shorelines, storm surge frequency, and water levels - will continue to oscillate within historical averages in the future (Government of South Australia, 2021). Conversely, climate change is a "non-stationary" and non-linear process. Matthews et al. (2015) emphasize that spatial planners tend to disregard these risks by prioritizing short-term economic gains over managing the uncertainty inherent in climate models.

This situation precipitates a perilous process known as "spatial lock-in" within coastal zones. The direction of long-lifecycle infrastructure investments (ports, energy facilities, housing) by existing plans into areas likely to be inundated in the future paradoxically exacerbates future vulnerability and potential damage costs. This phenomenon is characterized in planning literature as "maladaptation" and is identified as the weakest link in coastal management policies (Ercanlı & Savaşır, 2022; UNFCCC, 2025).

Regarding the quantification of coastal vulnerability, the Coastal Vulnerability Index (CVI), developed by Gornitz (1991), offers a robust analytical tool for determining the spatial distribution of risk by synthesizing geomorphology, slope, and shoreline change.

The Coastal Vulnerability Index (CVI) is a simplified, widely utilized approach for assessing the vulnerability and resilience of coastal regions against physical and social risks arising from climate change impacts like sea-level rise (SLR), erosion, and storm surges (Gornitz et al., 1991; Koroglu et al., 2019). CVI is conceptualized as an integration of the coast's physical sensitivity and social vulnerability, often resulting in complex indices that account for geophysical, socio-environmental, and socio-economic dimensions (Gargiulo et al., 2020). The CVI approach simplifies these

complex parameters into a standardized metric by aggregating sub-variables across main groups representing coastal sensitivity (McLaughlin, 2010). Integrating data from diverse sources to combine geophysical and social vulnerability indices is essential for understanding the intricate relationships between variables (Preston & Jones, 2008).

In the literature, the majority of CVI studies, including those employing the blending of a Socio-economic Vulnerability Index (SVI) and a Physical Vulnerability Index (PVI), rely on geomorphological and socio-economic factors as core features, often determining risk variables using vulnerability grades that range from 1 to 5 (Noor & Abdul Maulud, 2022). Although most variables are measurable, their classifications and rankings often vary based on the geographical area's characteristics, highlighting the degree of discretion involved in assessments (Zampazas et al., 2022, please also see Appendix Table 1 and 2).

Based on the literature review, the most frequently recurring parameters in coastal vulnerability studies are included in this model (See Appendices). These core components, which provide input to the index calculation, are defined as follows:

Coastal Area: Defined as the zone where the sea meets the land and extends inland, hosting various crucial functions such as settlements, agriculture, and industry (Simav, 2012).

Coastal Structure/Type (Geomorphology): Pertains to the resistance level of coastal landforms- from high cliffs to sandy beaches- which is crucial for calculating the vulnerability of natural assets (Gazioğlu et al., 2015).

Coastal Slope: A key characteristic that provides information on the change in coastal elevation relative to SLR. Low-sloping regions are expected to be highly impacted, while steep slopes are considered negligible risk areas (Görmüş & Atay, 2020).

Population Density: A social variable representing the number of people in a coastal area likely to be affected by flooding. High density correlates with high vulnerability, reflecting resource needs (Marchant, 2017).

Socio-economic Development Level: An indicator reflecting a population's capacity to overcome the impacts of SLR, often quantified using metrics like the Human Development Index or socio-economic ranking studies (Zor, 2020).

Vegetation: Natural vegetation protects against storms and water erosion. The percentage of vegetation cover is calculated, often using data sources like CORINE land cover (Görmüş & Atay, 2020).

Exposure to Natural Disasters: Relates to the number of people affected in regions prone to disasters like storms and tsunamis, and is used as a data input in CVI calculations (Simav, 2012; Gazioğlu et al., 2015).

Sea Level Rise: Determined from long-term measurements at tidal stations or climate change model results (such as IPCC scenarios), this parameter is a crucial component in vulnerability assessments (Koroglu et al., 2019).

Despite similarities in parameter selection, complex index applications show variations in classification and evaluation, as exemplified by the diverse scaling levels for physical and social vulnerability parameters shown in Table 1.

Table 1. Scaling levels of coastal vulnerability index parameters

Parameter	Scaling Level					Reference
	1-Lowest	2- Low	3- Middle	4- High	5- Highest	
Elevation	> 30	> 20 and < 30	> 10 and < 20	> 5 and < 10	> 0 and < 5	Gornitz(1991),Kwasi A.
	> 20	15 and 20	10 and 15	5 and 10	< 5	Sherein El-Shahat (2021)
Slope	≥ 3˚	2.0˚ and 3.0˚	1.5˚ and 2.0˚	0.5˚ and 1.0˚	≤ 0.5˚	Sherein El-Shahat (2021)
	> 1/10˚	1/10 and 1/20˚	1/20 and 1/30˚	1/30 and 1/50˚	1/50 and 1/100˚	Özyurt (2007)
	> 1	1 and 0.5	0.5 and 0.1	0.1 and 0.05	< 0.05	Manik Mahapatra (2015)
Maximum significant wave height (m)	> 0 and < 3	> 3 and < 5	> 5 and < 6	> 6 and < 6.9	≥ 6.9	Kwasi A.(2013)
	< 0.5	0.5 and 3	3 and 6	6 and 8	> 8.0	Özyurt (2007)
	< 0.55	0.55–0.85	0.85–1.05	1.05–1.25	> 1.25	Manik Mahapatra (2015)

Parameter	Scaling Level					Reference
	1-Lowest	2- Low	3- Middle	4- High	5- Highest	
Mean tidal range (m)	< 1	> 1 and < 2	> 2 and < 4	> 4 and < 6	> 6	Manik Mahapatra (2015)
	≤0.99	1-1.9	2 and 4	4.1 and 6	≥ 6.1	Gornitz (1991)
	> 6	4 and 6	2 and 4	0.5 and 2	< 0.5	Özyurt (2007)
Mean shoreline displacement (m/year)	> 2	> 1 and < 1	> -1 and < 1	> -2 and < -1	≥ -2 and erosion	Kwasi A.(2013)
	-	> -5	-15 and -5	-30 and -15	< -30	Pham and ark.(2005)
	> 15	5 and 15	-5 and 5	-15 and -5	< -15	Dwarakish and ark.(2009)
Distance to shore (m)	≥ 1000	200 and 1000	50 and 200	20 and 50	≤ 20	Mc Laughlin and Cooper
	> 10000	7500 and 10000	5000 and 7500	2500 and 5000	0 and 2500	Sherein El-Shahat (2021)
	> 1000	700 and 1000	400 and 700	100 and 400	< 100	
Sea Level Rise (mm/year)	<1	1 and 2	2 and 5	5 and 7	7 and 9	Gornitz (1991)
	≤1.1	-1 and 0.99	1 and 2	2.1 and 4	≥ 4.1	Özyurt (2007)
	< 1.8	1.8 and 2.5	2.5 and 3	3 and 3.4	> 3.4	Alexandra T. (2018)
Land Use	Water bodies; marshes, sparse vegetation.	Coastal sands.	Forestry	Agriculture	Urban and industrial infrastructures.	Mc Laughlin and Cooper
	Areas free of snow and ice.	Savannahs, barren or sparsely vegetated areas: Invaluable areas.	Grasses: Semi-valuable areas.	Closed or open shrublands: Valuable areas.	Water, forest, wetland, cultivated areas, urban, plant mosaic: Highly valuable areas.	Sherein El-Shahat (2021)
	Water bodies.	Minimum use, nature conservation, potential agriculture.	Livestock grazing, irrigated gardening, forestland.	Residential areas.	Transportation and communication.	Preston and et al.(2008)

Parameter	Scaling Level					Reference
	1-Lowest	2- Low	3- Middle	4- High	5- Highest	
Geomorphology	Upland areas, rocky coastlines	Coastal plains, vegetated dunes	High-tide mudflats, salt marshes, coastal ridges, shores supported by artificial structures.	Low depressions, lagoons, estuarine streams.	Beaches, mangroves, coral reefs, intertidal and subtidal mudflats.	Manik Mahapatra (2015)
	Rock cliff beach.	-	-	-	Low and sandy beach.	Mc Laughlin and Cooper
	Rocky cliffs and dark bays	Medium cliffs and indented shores	Low cliffs, glacial slides, and alluvial plains	Cobblestone beaches, estuaries, and lagoons	Barrier beaches, sand beaches, salt marshes, mudflats, and deltas	Özyurt (2007)

In recent studies, CVI methodology is enriched with socio-economic parameters to generate "integrated risk maps" (Koroglu et al., 2019; McLaughlin & Cooper, 2010). For instance, studies by Simav et al. (2013) in the Çukurova Delta and Tragaki et al. (2018) in the Peloponnese Peninsula have demonstrated high-resolution risk analyses by combining physical and social data.

However, a fundamental critique within planning literature is the failure to effectively transpose these scientific risk maps into legal zoning plans. In their specific examination of Turkey, Ercanlı and Savaşır (2022) identified a significant "mismatch" between risk areas indicated by scientific studies and official planning decisions. This disconnection at the science-policy integration is attributed to the technical capacity deficits of planners, legal resistance stemming from property rights, and the "certainty" sought by decision-makers. Consequently, CVI studies frequently remain academic exercises, while "approved plans" persist as static documents detached from climatic realities (Government of South Australia, 2021).

Planning theory delineates three fundamental spatial strategies in the face of SLR: (1) Protection, (2) Accommodation, and (3) Managed Retreat (Linham & Nicholls, 2010). Traditional planning

reflexes, aiming to preserve existing urban values, predominantly focus on "hard engineering" solutions such as sea walls. However, Nicholls et al. (2011) argue that a purely protection-oriented approach will become economically unsustainable in the face of sea-level rise expected to exceed 1 meter by the end of the 21st century.

At this juncture, "Managed Retreat" represents the most contentious subject in contemporary planning literature. Although this strategy- which envisions the planned relocation of settlements from risky coastal strips to inland areas- represents the most effective long-term solution, it is the option least reflected in plans due to social acceptability and political costs (Hinkel et al., 2018). Similarly, Integrated Coastal Zone Management (ICZM) Plans in Turkey are generally based on the principle of "in-situ protection" of existing uses and lack a retreat scenario aligned with future shoreline changes (Ministry of Environment and Urbanization, 2015). In this context, subjecting existing plan decisions to "stress-testing" with IPCC scenarios emerges as the primary and most critical step in adaptation planning.

3. STUDY AREA: BURSA COASTAL AREAS (GEMLİK, MUDANYA, KARACABEY DISTRICTS)

Bursa province is located in northwestern Turkey, between 40 degrees North latitude and 28-30 degrees East longitude, situated to the southeast of the Sea of Marmara. With a total surface area of 10,819 square kilometers, three of Bursa's 17 districts—Karacabey, Mudanya, and Gemlik—possess a total coastline of 115 kilometers along the Sea of Marmara. According to the 2024 census data from the Turkish Statistical Institute (TÜİK), the province has a population of 3,238,618, with an approximately equal male-to-female ratio (Web 2, 2025).

Bursa is Turkey's third-largest city among coastal provinces and hosts the fourth-largest coastal settlement area. The region is characterized by organized industrial zones and ports established in the coastal hinterlands. Consequently, the coastal zones are heavily utilized for maritime transportation and accommodate numerous coastal structures (ÇŞB, 2015). In particular, Gemlik Bay hosts significant port facilities, organized industrial zones, and commercial enterprises.
For this reason, the coastal area of Bursa province was selected as the study region to conduct inundation analyses for sea-level rise induced by climate change, examine its spatial dimensions, and correlate these findings with coastal vulnerability analyses (Fig. 1).

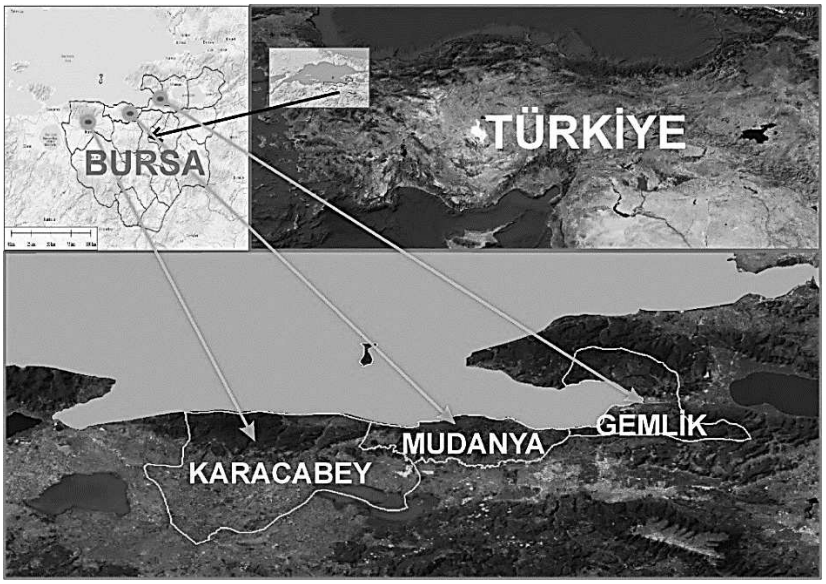


Figure 1. Study Area

The research area, defined according to the boundaries and sub-regions of the Bursa Integrated Coastal Zone Management (ICZM) Plan, encompasses the coastline extending along the Sea of Marmara and the entirety of its terrestrial and marine interaction zones. This area was primarily divided into three main regions (Gemlik Region, Mudanya Region, and Karacabey Region) to scientifically determine the current vulnerability and susceptibility levels based on fundamental criteria such as coastal morphology, natural character, ecological sensitivity, the density and nature of existing coastal construction, and socio-economic use potential. To generate more detailed analyses and findings, these three main regions were further divided into a total of seven sub-regions (Fig. 2).

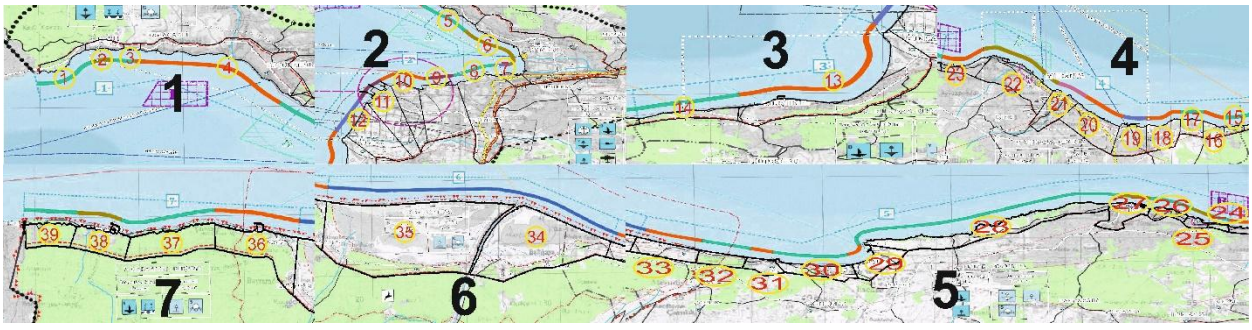


Figure 2. Research Units

In this context, to conduct vulnerability and susceptibility assessments and land-use suitability studies with greater precision, the area was detailed based on dominant coastal hinterland uses and segmented into a total of 39 coastal land-use units. These units were classified according to

dominant functions, including urban and rural settlement areas, tourism and summer housing zones, port hinterlands and storage areas, industrial facilities, sandy beaches, forest and agricultural areas, as well as wetlands and floodplain (longoz) forests.
This multi-layered classification enables the determination of risks and potentials specific to the ecological, physical, and socio-economic characteristics of each coastal segment; thereby allowing for the differentiation of planning decisions at the micro-scale and the establishment of a more effective balance between conservation and use. (ÇŞB, 2015).

4. METHODOLOGY

The flowchart of the CVI creation method is presented in Figure 3. The methodology of this study comprises three fundamental stages and their respective sub-steps:

- The first stage encompasses basic preparation and modeling. It involves identifying the areas within the study site that would be affected by sea-level rise under selected scenarios using the "bathtub model."
- The second stage focuses on calculating and indexing the coastal vulnerability level of the study areas, assuming the spatial status quo remains constant.
- The third stage involves the analysis and integration of areas affected by sea-level rise to evaluate the spatial strategies foreseen for the Bursa coast within the Bursa Integrated Coastal Zone Management Plan (ICZM Plan) through evaluations depend on overlays.

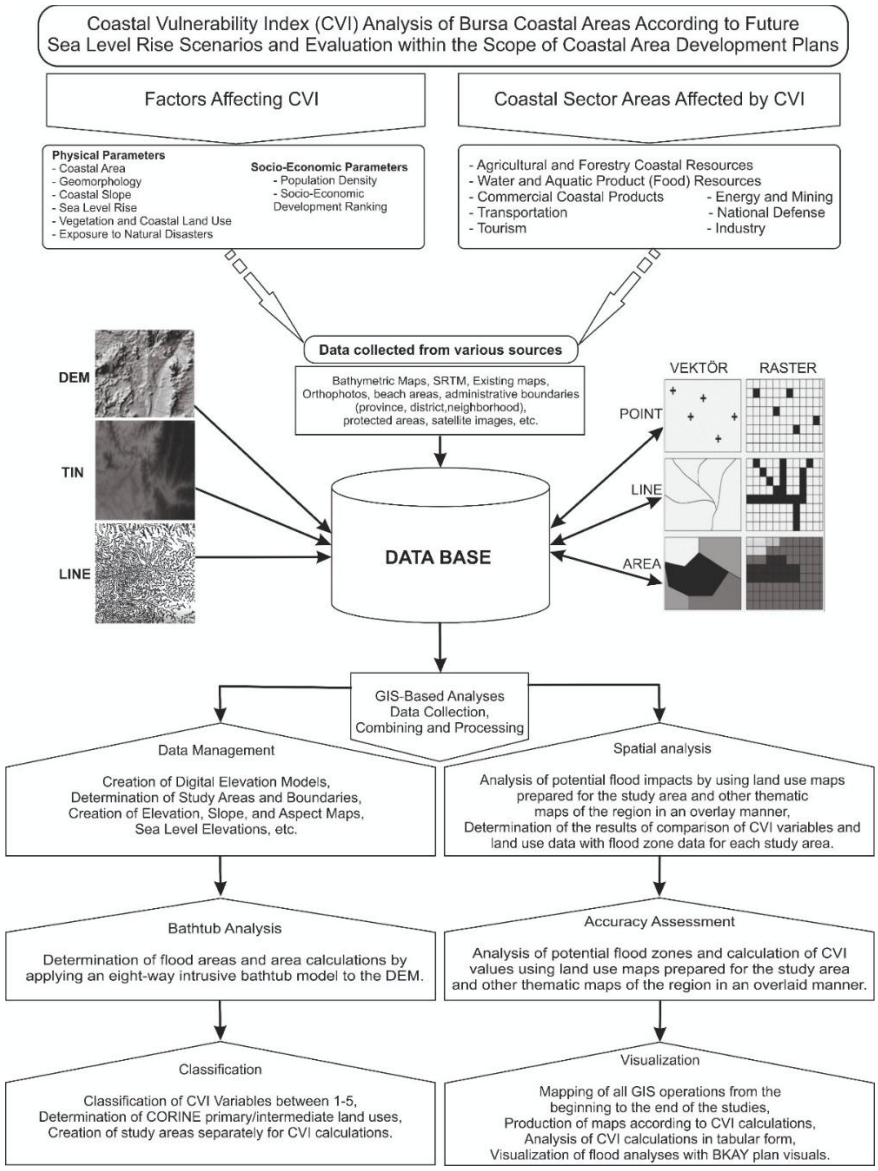


Figure 3. Design of the Study

In the first stage of the methodology, a database was established by collecting regional data. A Digital Elevation Model (DEM) representing the Bursa coastal area with high accuracy was prepared by applying transformation and data generation processes to the obtained data. The "Bathtub Analysis" method was employed within a Geographic Information Systems (GIS) framework to conduct physical impact analyses of flooding based on the generated DEM. This model is structured on the assumption that areas below a certain elevation will flood like a "bathtub" in the event of sea-level rise. It calculates inundation by comparing the elevation differences between two models, assuming that areas falling below the sea level are submerged. The bathtub model is utilized in two forms: hydrologically connected and hydrologically

disconnected. In global literature, modeling coastal flooding as hydrologically connected is recommended, as it is argued that this approach yields more accurate results for the analysis and mapping of integrated coastal zones (Kazinja, 2017). In this study, the hydrologically connected **Eight-Direction Connectivity Bathtub Model Method** (Yunus et. al., 2016) was used to calculate the zones subject to flooding in terrestrial areas due to rising sea levels (Figure 4.).

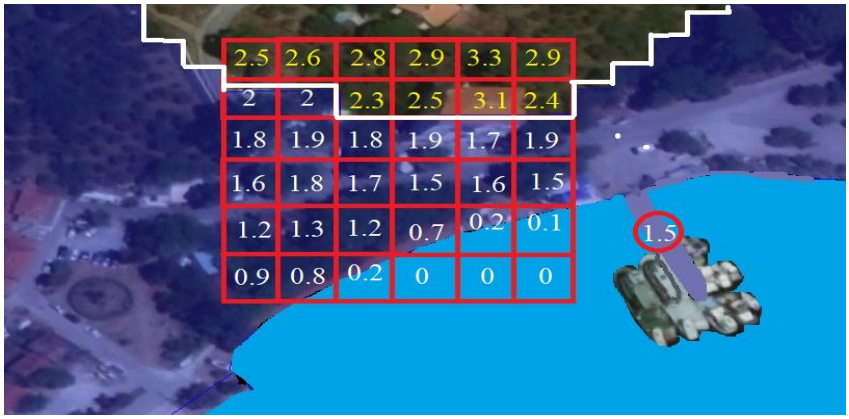


Figure 4. 2m rise in sea water and flooding application with eight-way connection.

In this method, hydrological connections were also incorporated into the calculation. With the sea-level rise integrated onto the DEM cells, it is observed that areas on the terrain with lower or equal elevation are submerged. The eight-direction dominant bathtub model was executed in Global Mapper software by adding Sea of Marmara bathymetric data and five distinct sea-level rise scenario values onto the DEM created for the study area. As a result of the calculation, visuals of water rise and an analysis of the spatial use ratios of inundated areas were obtained.

A coastal vulnerability risk analysis was performed by superimposing the coastal inundation layer generated on the DEM onto the CORINE 2018 spatial land use (Fig. 5) GIS layers for the Bursa coastal area. The land cover submerged as a result of flooding was classified under main and sub-headings such as artificial surfaces, agricultural areas, forests and semi-natural areas, wetlands, and water bodies. As a result of these procedures, parameters deepening the Bursa province coastal vulnerability index assessment were obtained.

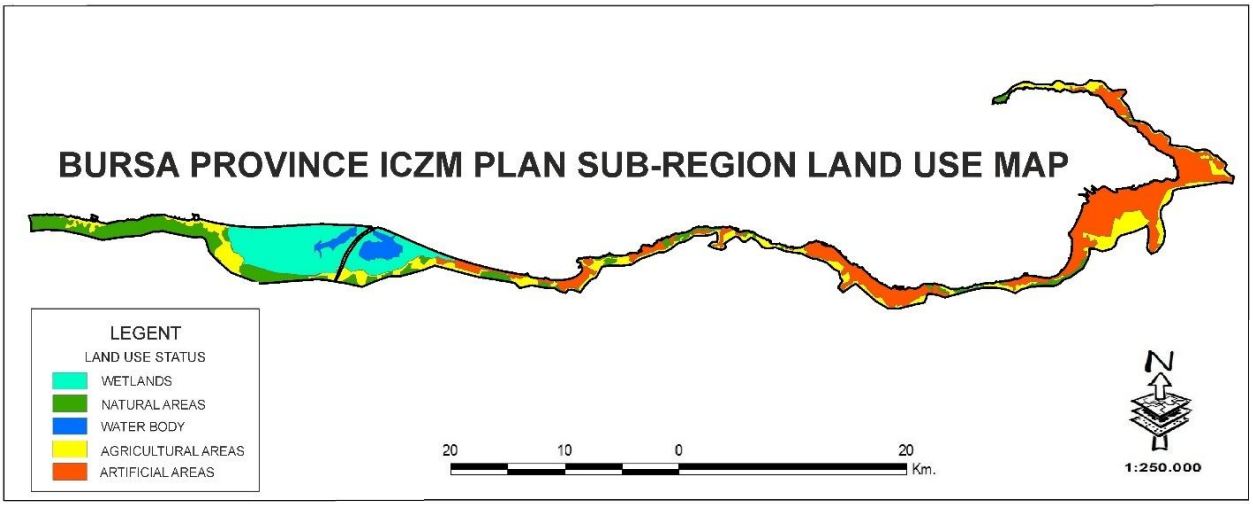


Figure 5. CORINE (2018) land use map of the Study Area

The outcome of the second stage is the determination of the Coastal Vulnerability Level. To achieve this, the parameters included in the calculation—specifically coastal area, human development index, slope, population density, vegetation cover, and geomorphology—were calculated respectively, and the Coastal Vulnerability Level was determined by standardizing all these data on a sub-region basis.

The database developed by Gornitz et al. (1991) is used in contemporary applications as a model calculation method for the coastal vulnerability index based on physical parameters. An index is created by assigning a risk value (ranging from 1 to 5) to each parameter according to the order of vulnerability, where the magnitude of impact on physical change in the coastal area increases as the sea level rises. A risk ranking is established by representing both quantitative and qualitative information in the database based on data value ranges (1: Very Low Risk, 2: Low Risk, 3: Medium Risk, 4: High Risk, and 5: Very High Risk), thereby ensuring that non-numerical parameters are ranked according to their relative position within a specific landform.

In this study, Equation (1) was used to calculate coastal vulnerability:

$$CVI = [(PD) + (NED) + (1\text{-}VC) + (TC) - (SEDI)]$$

- Population Density (PD): Population density indicates the demand for spatial land uses, infrastructure, and various coastal resources such as freshwater. It expresses the distribution of the human population in a specific region relative to the surface area of that region.

- Natural Event Exposure Status (NED): This refers to the number of people affected in events where natural disasters impact coastal regions.
- Low Vegetation Cover (1-VC): This expresses the condition where the natural vegetation cover of the region is minimal or non-existent. It is obtained using the ratio of forest cover to coastal areas.
- Topographic Characteristics (TC): Relative topographic features express the landforms and slope characteristics of a region. It is obtained by the percentage of flat areas with an elevation of less than 50 m and the ratio of the total border length to the coastal length.
- Socio-Economic Development Index (SEDI): This concept reflects the economic activities, social indicators, and living standards of individuals in the region. A ranking index measured by factors such as education, health, quality of life, finance, demographics, employment, social security, competitiveness, and innovation was used (SEGE, 2022).

To calculate the physical and social vulnerability level index of coastal areas in the face of climate change via GIS, physical variables such as geomorphology, coastal slope, and sea-level rise, as well as social variable data such as population density, exposure to natural disasters, and land use, were collected from relevant institutions and organizations. The data obtained for use in the study, data sources, and feature classifications are presented in Table 2.

Table 2. Data set used to determine Bursa coastal area vulnerability.

DATA	SOURCE	VULNERABILITY CLASSIFICATION
Sea level rise (m/year)	IPCC 5th Assessment Report.	The year 2100 0.83m. The year 2200 2.03m. The year 2300 3.59m. The year 2400 5.17m. The year 2500 6.63m.
Geomorphology/coastal type	Bursa Province ICZM Plan Area	1. High cliff (> 20 m) 2. Average-height cliff (10-20 m) 3. Low-height cliff (< 10 m) 4. Pebble beach, river mouth, artificial (breakwater, revetment, etc.) 5. Sandy beach, delta, bay, barrier beach, longoz.
Land use	Corine Land Cover (2018)	1. Water bodies, waterbeds 2. Vegetation, forest 3. Green urban areas, marshes 4. Agricultural areas, orchards, Mining, construction 5. Urbanization, industry, commerce and transportation units, sports and cultural facilities, beaches, dunes, salt marshes, lagoons.

DATA	SOURCE	VULNERABILITY CLASSIFICATION
Coastal slope (%)	Bursa Metropolitan Municipality	1. Areas with a slope of 0 to 5 degrees, 2. Areas with a slope of 5 to 10 degrees, 3. Areas with a slope of 10 to 15 degrees, 4. Areas with a slope of 15 to 20 degrees, 5. Areas with a slope of 20 to <.
Base map, orthophoto, protected areas, beach areas, administrative boundaries (province, district, neighborhood)	Bursa Metropolitan Municipality	1/1000 Scale.
Population density	TÜİK 2020	Population of provinces, districts and neighborhoods.
Bathymetry	SHOD Presidency	Nautical charts.
Human development status	State Planning Organization (DPT)	Numerical value.

The inputs used for the CVI calculation were obtained by calculating separately for the entire coastal area of Bursa province, its districts (Gemlik, Mudanya, Karacabey), and sub-regions. The obtained data, which had different scale ranges and measurement units, were standardized using the minimum/maximum method. In the calculation of CVI, the scaling of data was ensured through the normalization statistical method using Equation (3.4).

In the calculation of CVI, data scaling was performed using the statistical normalization method in Equation below.

$$CVI\ Indicators = (x - x\ min) / (x\ max - x\ min)$$

After the CVI calculation was performed with the obtained data, the equation results were rescaled according to minimum and maximum values using Equation (3.5), and the total CVI results were standardized by calculating values between 0 and 1.

$$CVI_{STD} = (x - x\ min) / (x\ max - x\ min)$$

In this study, an 'Equal Weighting' approach was adopted for the aggregation of parameters in the Coastal Vulnerability Index (CVI). While weighted methods such as AHP are present in the literature, they often introduce subjectivity and expert bias into the vulnerability assessment (McLaughlin & Cooper, 2010). In complex coastal systems like Bursa, which exhibit a heterogeneous mix of industrial, touristic, and protected natural areas, there is no universal consensus on the precise physical or socio-economic dominance of one variable over another.

Given this uncertainty, equal weighting was selected as the most parsimonious and unbiased approach to minimize subjectivity. Furthermore, this choice aligns with the foundational CVI methodologies established by Gornitz (1991) and Thieler and Hammar-Klose (1999), ensuring that the results are comparable with broader international literature. This approach allows the study to focus on its primary objective—assessing the validity of ICZM plans—using a transparent and standardized risk baseline, rather than obscuring policy implications with complex, subjective weighting schemes.

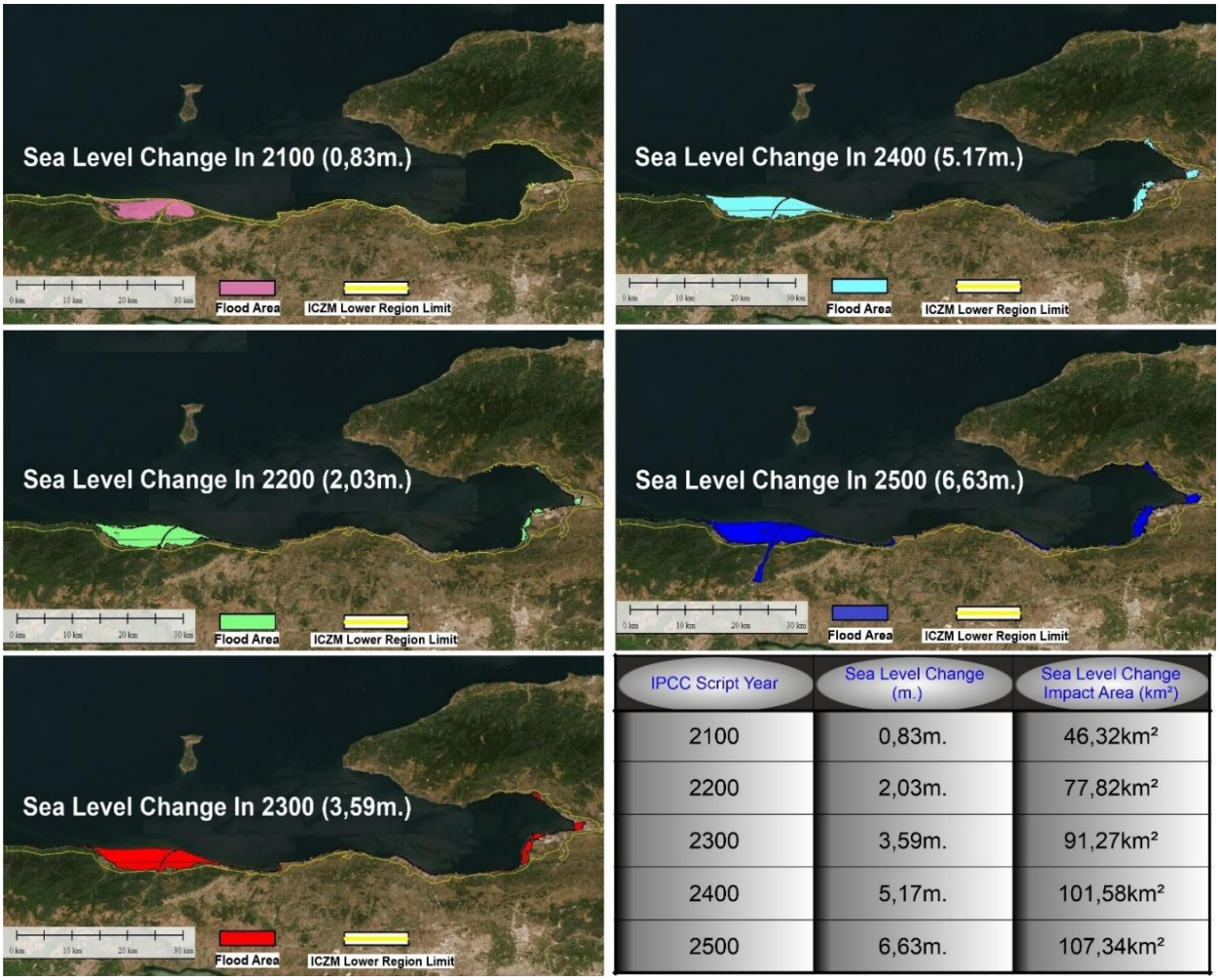
According to the Standardized CVI values representing the general vulnerability level: values between 0.0 and 0.2 represent very low, 0.2 to 0.4 low, 0.4 to 0.6 medium, 0.6 to 0.8 high, and 0.8 to 1.0 very high vulnerability levels.

In the final stage, the data produced in the first stage were utilized; the areas submerged as a result of the Bathtub Model derived from these data according to years were superimposed with the 7 sub-regions in the ICZM plan through overlay analyses and interpreted.

5. RESULTS

5.1. Vulnerability of the Existing Coastal Built Environment to Future SLR Scenarios

Detailed analyses conducted in Bursa's coastal region have visualized the effects of sea level rise on coastal areas using a color-coded mapping method based on years. These analyses clearly reveal the land losses and at-risk areas caused by sea level changes in different time periods along the coastline. The findings are presented in Figure 6.



IPCC Script Year	Sea Level Change (m.)	Sea Level Change Impact Area (km²)
2100	0,83m.	46,32km²
2200	2,03m.	77,82km²
2300	3,59m.	91,27km²
2400	5,17m.	101,58km²
2500	6,63m.	107,34km²

Figure 6. Impact of Sea Level Rise on Low-Lying Coastal Areas in Bursa According to IPCC Scenarios for 2100-2500

Analyses conducted under the scenario of a projected sea level rise (SLR) of 0.83 meters by 2100 reveal that different land cover classes in the Bursa coastal region will be affected to varying degrees by this process. The detailed distribution of these effects and the area losses that each land cover class will experience are shown in Table 3.

Table 3. ICZM Flood Analysis by Land Use (According to the 2100 Sea Level Rise Scenario (0.83 m)).

Land Use	Area (ha)	Ratio %
Marshes	3296.14	71.16
Pastures	0.72	0.02
Forests	51.93	1.12

Land Use	Area (ha)	Ratio %
Water Surfaces	1044.65	22.55
Agriculture	155.81	3.36
Settlements	82.54	1.78
TOTAL	**4631.79**	**100.00**

The inundation models indicate that marshes (71.16%) and water surfaces (22.55%) will bear the brunt of this encroachment. This highlights the acute vulnerability of low-lying coastal ecosystems to rising water levels. Although these zones currently function as critical natural carbon sinks, their submersion poses a severe threat to regional biodiversity and jeopardizes the functional integrity of wetland ecosystems.

Conversely, the spatial footprint on agricultural land (3.36%), forests (1.12%), and settlements (1.78%) appears relatively limited in percentage terms. However, these figures obscure the severity of the potential socio-economic fallout. These land-use classes are predominantly situated in Gemlik and Mudanya, areas characterized by dense urbanization and heavy industrial activity. Consequently, the economic and social costs of inundation in these zones are expected to be disproportionately high compared to the physical area lost.

In an overall assessment, distinct vulnerability profiles emerge across the districts:

- Karacabey exhibits the most extensive physical exposure to inundation.
- Gemlik stands out as the region with the highest socio-economic fragility.
- Mudanya demonstrates relative geomorphological resilience due to its topographical characteristics.

According to the data presented in Table 4, the effects on land use and cover under the projected sea level rise scenario until 2100 vary in different sub-regions of the Bursa coastal area, but these effects are most pronounced and intense in the Karacabey district.

Table 4. ICZM sub-region district flood analysis (2100 Sea Level Rise (0,83m)).

District Name	Land Use	Area (ha)	Ratio %
Gemlik	Forest	0.15	0.00
Gemlik	Agriculture	2.35	0.05
Gemlik	Settlement	34.58	0.75

District Name	Land Use	Area (ha)	Ratio %
Karacabey	Swamp	3342.58	72.17
Karacabey	Forest	47.45	1.02
Karacabey	Water Surface	1044.65	22.55
Karacabey	Agriculture	135.33	2.92
Mudanya	Swamp	1.80	0.04
Mudanya	Pastureland	0.72	0.02
Mudanya	Forest	1.00	0.02
Mudanya	Agriculture	3.09	0.07
Mudanya	Settlement	18.09	0.39
Total		**4631.79**	**100.00**

Here, marshes, lagoons, and water surfaces face near-total inundation, with impact rates reaching 98%. While this reflects the preservation of the area's natural character, it simultaneously underscores the extreme susceptibility of its low-elevation deltaic plains to seawater intrusion. Ecologically, Karacabey represents the most critical zone for potential habitat loss along the Bursa coast.

In Gemlik and Mudanya, while the inundated area is smaller, the convergence of population density and economic assets creates a high-risk scenario. Specifically, in Gemlik's coastal neighborhoods—Ata, Gençali, Halitpaşa, Hamidiye, Kumla, and Ömerbey—the projected impact zone exceeds 30 hectares. Unlike the ecological pressure observed in Karacabey, the risk here is fundamentally socio-economic. Similarly, in Mudanya, the neighborhoods of Esence, Güzelyalı, Mesudiye, and Tirilye are exposed; however, the steeper coastal topography limits the spatial extent of the flooding.

The Coastal Vulnerability Index (CVI) analysis reveals significant disparities in risk profiles across Bursa's coastal districts. Gemlik falls within the "very high" vulnerability category, Mudanya ranges from "low" to "medium," and Karacabey displays a mixed profile from "very low" to "medium".

The Coastal Vulnerability Index (CVI) analysis results, presented in detail in Table 5, reveal that different sub-regions of Bursa's coastal areas exhibit significant differences in risk of sea level rise and related coastal hazards.

Table 5. Vulnerability Index by Sub-Region

Bursa Province	Low Vegetation Indicator	Topographic Indicator	Coastal Length Ratios (D/C)	Topographic Characteristics	Coastal Population Density Indicator	Socio-Economic Development Ranking (2022)	**CVI**	Standardized CVI	Vulnerability Level
Gemlik-1	0,075	79%	0,0990	0,892	0,880	0,743	**1,104**	0,408	MIDDLE
Gemlik-2	0,344	79%	0,1063	0,899	0,880	0,743	**1,380**	0,588	MIDDLE
Gemlik-3	0,865	79%	0,2155	1,008	0,880	0,743	**2,010**	0,998	VERY HIGH
Gemlik-4	0,955	79%	0,0287	0,822	0,880	0,743	**1,913**	0,935	VERY HIGH
Gemlik-5	0,927	79%	0,0777	0,871	0,880	0,743	**1,934**	0,949	VERY HIGH
Gemlik-6	0,742	79%	0,1130	0,906	0,880	0,743	**1,784**	0,851	VERY HIGH
Gemlik-7	0,828	79%	0,0160	0,809	0,880	0,743	**1,774**	0,844	VERY HIGH
Gemlik-8	0,979	79%	0,1048	0,898	0,880	0,743	**2,013**	1,000	VERY HIGH
Gemlik-9	1,000	79%	0,0134	0,806	0,880	0,743	**1,943**	0,954	VERY HIGH
Gemlik-10	0,959	79%	0,0254	0,818	0,880	0,743	**1,914**	0,935	VERY HIGH
Gemlik-11	0,908	79%	0,0165	0,809	0,880	0,743	**1,854**	0,896	VERY HIGH
Gemlik-12	0,877	79%	0,0157	0,809	0,880	0,743	**1,823**	0,876	VERY HIGH
Gemlik-13	0,836	79%	0,0268	0,820	0,880	0,743	**1,792**	0,856	VERY HIGH
Gemlik-14	0,649	79%	0,0264	0,819	0,880	0,743	**1,605**	0,734	HIGH
Gemlik-15	0,635	79%	0,0667	0,860	0,880	0,743	**1,632**	0,752	HIGH
Mudanya-16	0,598	0%	0,1567	0,157	1,000	1,037	**0,718**	0,157	VERY LOW
Mudanya-17	0,506	0%	0,1075	0,107	1,000	1,037	**0,576**	0,065	VERY LOW
Mudanya-18	0,654	0%	0,0880	0,088	1,000	1,037	**0,705**	0,149	VERY LOW
Mudanya-19	0,819	0%	0,0575	0,057	1,000	1,037	**0,839**	0,236	LOW
Mudanya-20	0,943	0%	0,0336	0,034	1,000	1,037	**0,940**	0,301	LOW
Mudanya-21	0,994	0%	0,0443	0,044	1,000	1,037	**1,001**	0,341	LOW
Mudanya-22	0,947	0%	0,0425	0,043	1,000	1,037	**0,952**	0,309	LOW
Mudanya-23	0,878	0%	0,0433	0,043	1,000	1,037	**0,884**	0,265	LOW
Mudanya-24	0,841	0%	0,0831	0,083	1,000	1,037	**0,887**	0,267	LOW
Mudanya-25	0,667	0%	0,1375	0,138	1,000	1,037	**0,768**	0,189	VERY LOW
Mudanya-26	0,544	0%	0,1371	0,137	1,000	1,037	**0,645**	0,109	VERY LOW
Mudanya-27	0,614	0%	0,0913	0,091	1,000	1,037	**0,668**	0,125	VERY LOW
Mudanya-28	0,602	0%	0,0486	0,049	1,000	1,037	**0,613**	0,089	VERY LOW
Mudanya-29	0,817	0%	0,0237	0,024	1,000	1,037	**0,803**	0,213	LOW
Mudanya-30	0,907	0%	0,0383	0,038	1,000	1,037	**0,908**	0,281	LOW

Bursa Province	Low Vegetation Indicator	Topographic Indicator	Coastal Length Ratios (D/C)	Topographic Characteristics	Coastal Population Density Indicator	Socio-Economic Development Ranking (2022)	**CVI**	Standardized CVI	Vulnerability Level
Mudanya-31	0,715	0%	0,0523	0,052	1,000	1,037	**0,730**	0,165	VERY LOW
Mudanya-32	0,746	0%	0,0537	0,054	1,000	1,037	**0,763**	0,187	VERY LOW
Mudanya-33	0,634	0%	0,0709	0,071	1,000	1,037	**0,668**	0,125	VERY LOW
Mudanya-34	0,639	0%	0,0546	0,055	1,000	1,037	**0,657**	0,117	VERY LOW
Karacabey-35	0,772	100%	0,0127	1,013	0,000	0,560	**1,225**	0,487	MIDDLE
Karacabey-36	0,077	100%	0,0230	1,023	0,000	0,560	**0,540**	0,041	VERY LOW
Karacabey-37	0,000	100%	0,0364	1,036	0,000	0,560	**0,476**	0,000	VERY LOW
Karacabey-38	0,028	100%	0,0335	1,034	0,000	0,560	**0,501**	0,016	VERY LOW
Karacabey-39	0,103	100%	0,0569	1,057	0,000	0,560	**0,600**	0,080	VERY LOW

Gemlik is particularly sensitive to even minor sea-level fluctuations due to the combination of a narrow coastal plain and intense industrial-urban pressure. CVI values in Gemlik's sub-regions range between 0.84 and 1.00, identifying them as the most critical hotspots where physical hazards intersect with high anthropogenic exposure. Notably, all sub-regions from Gemlik-3 to Gemlik-13 are classified as "very high" risk, necessitating an integrated, district-wide risk management strategy.

Mudanya benefits from generally higher topographic elevations, offering relative protection against coastal inundation. Its CVI values (0.06–0.34) place it largely in the "very low" to "low" vulnerability categories. However, the high density of tourism infrastructure and secondary housing suggests a latent risk: future socio-economic pressures could amplify this vulnerability if adaptation measures are not integrated into infrastructure planning.

In Karacabey, the index largely indicates "very low" vulnerability (0.00–0.08). This score is heavily influenced by the presence of extensive wetlands, forests, and natural buffer zones which lack dense human settlement. However, a "very low" score should not be misinterpreted as "no risk." The Karacabey Delta and Longoz forests are physically defenseless against seawater intrusion. Any degradation in these ecosystems could lead to a collapse in the region's biological productivity.

Consequently, the CVI results delineate three distinct risk typologies:

- Gemlik: Immediate Risk (driven by high socio-economic and structural exposure).
- Karacabey: Ecological Risk (driven by the sensitivity of extensive wetlands in the medium term).
- Mudanya: Latent Risk (driven by long-term development pressures).

Thematic maps prepared for Bursa province, covering both the overall coastal area and each district, based on data obtained from Coastal Vulnerability Index (CVI) calculations, provide significant assistance to coastal planning experts and decision-makers in understanding the spatial distribution of vulnerability levels. These maps visually represent CVI values, contributing to the prioritization of risky areas and the development of sustainable management strategies. A map reflecting the overall vulnerability level of Bursa's coastal area is presented in Figure 7.

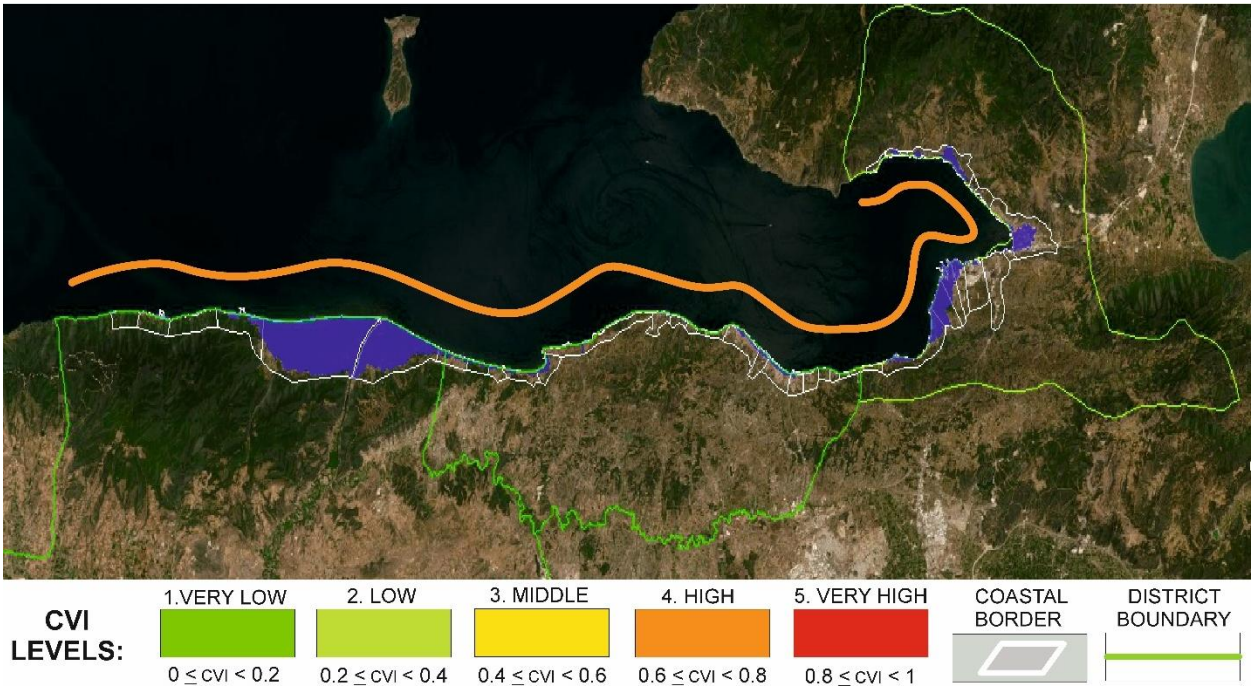


Figure 7. Coastal vulnerability level of Study Area.

The CVI analysis results for the Gemlik district coast, which is the study area, show that the region generally carries a high risk. The coastline was divided into 15 parts according to its spatial use characteristics, the vulnerability level of each section was calculated, and this distribution was mapped in Figure 8.

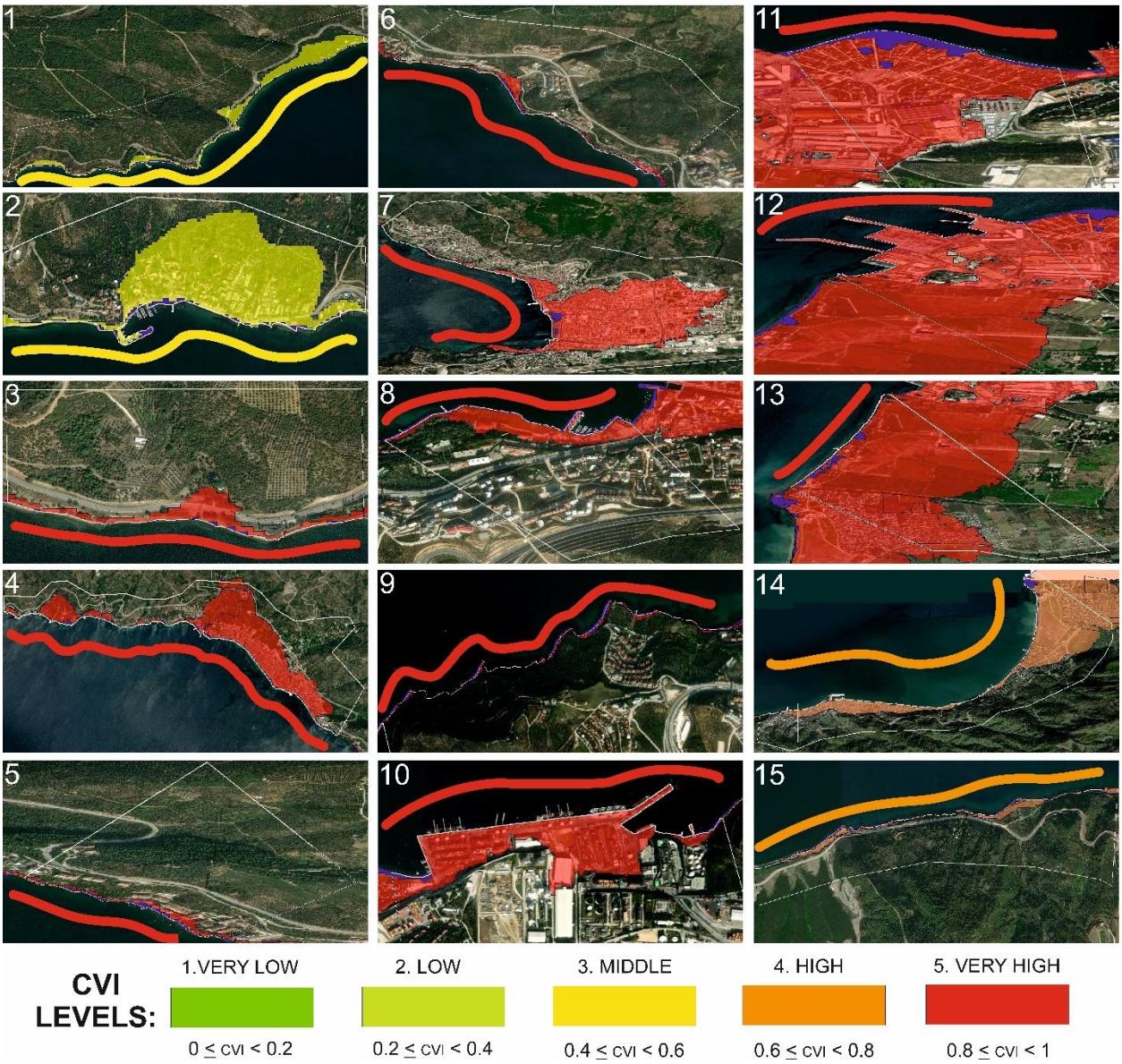


Figure 8. Coastal vulnerability level of Gemlik district.

The coastal vulnerability level of the Mudanya district coastal area was analyzed by dividing it into 19 different segments based on spatial land use characteristics, and the results of this analysis are mapped in Figure 9.

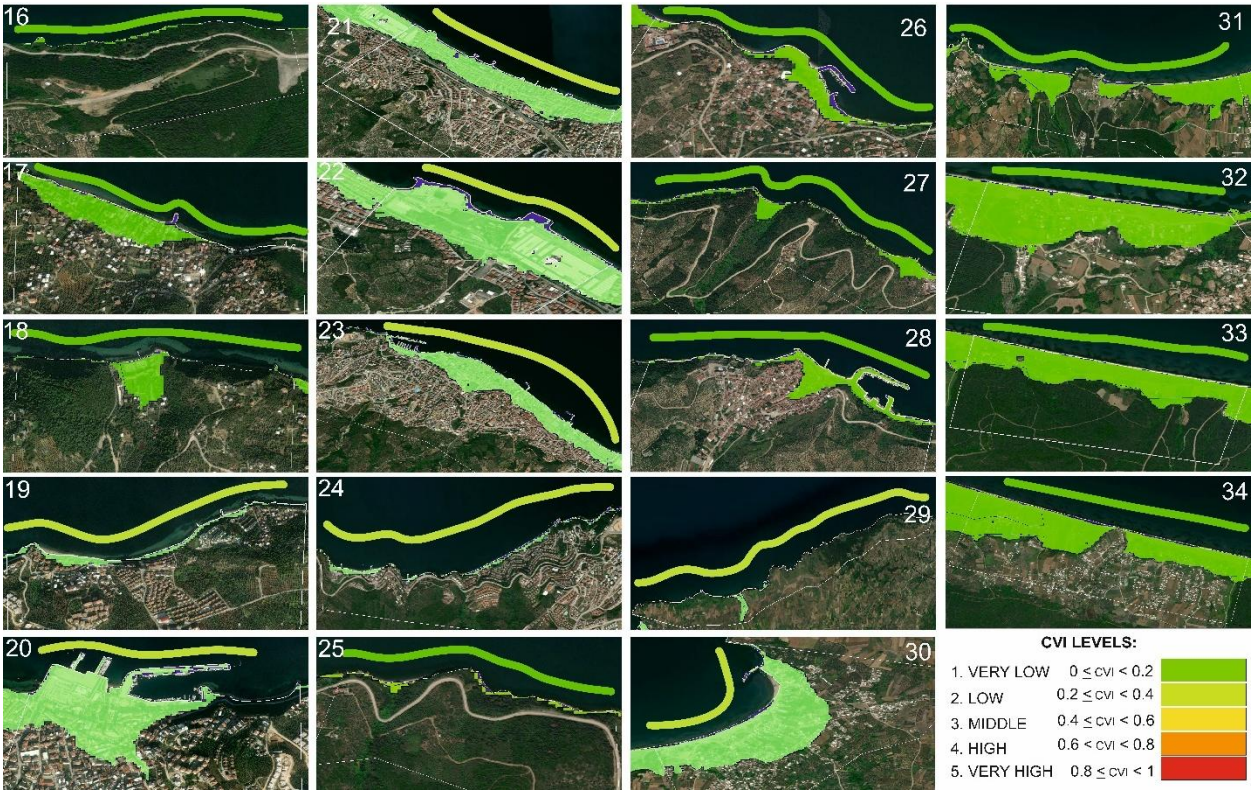


Figure 9. Coastal vulnerability level of Mudanya district.

The coastal vulnerability map of the Karacabey district's coastal area was prepared by dividing the area into 5 different regions based on its spatial land use characteristics and is presented in Figure 10.

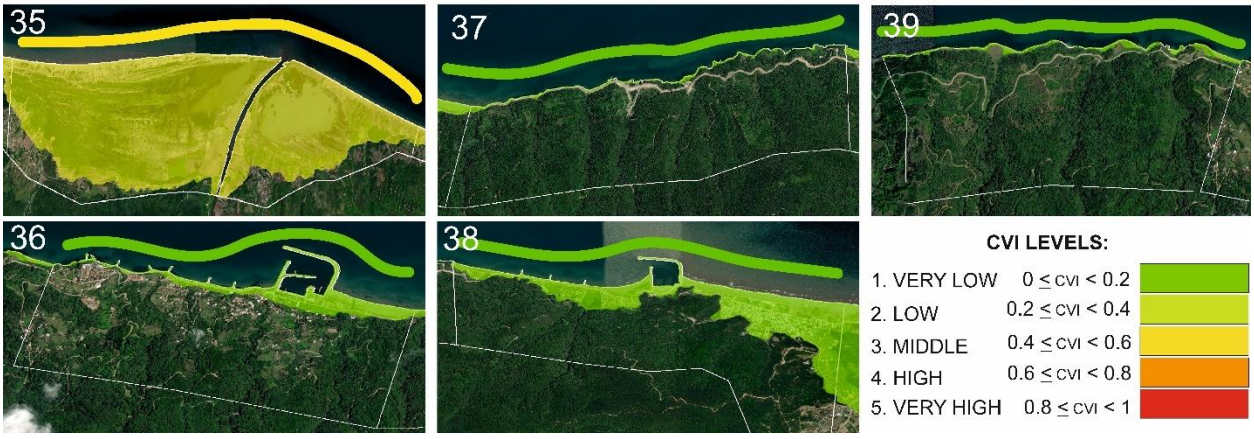


Figure 10. Coastal vulnerability level of Karacabey.

5.2. Coastal Vulnerability of Bursa Integrated Coastal Zone Management (ICZM) Plan

Integrated Coastal Zone Management (ICZM) plans are formulated to guide planning and

implementation processes, aiming to ensure the balanced spatial use and conservation of marine, terrestrial, ecological, and biological assets within the defined coastal zone. In the Bursa ICZM Plan, the coastal area is divided into seven sub-regions. The plan incorporates comprehensive assessments of existing marine and coastal structures—such as fishery shelters, commercial ports, marinas, tourism and recreational fill areas, coastal protection structures, and piers—alongside evaluations of maritime transport, logistics, marine pollution, bathymetric-oceanographic conditions, fisheries, and tourism. These investigations are designed to maintain and enhance the current status of coastal areas while addressing projected future needs.

Field studies conducted across the seven sub-regions of the Bursa ICZM Plan indicate that general decisions have been adopted to control coastal formations and regulate coastal structures intended for urban use, transportation, and commercial purposes. A significant portion of these decisions are strategic in nature and do not specify precise physical locations. However, priority facilities or land uses deemed necessary for development have been defined through 1/5000 scale coastal structure schematic plans. In the context of potential sea-level rise, identifying high-risk zones within these seven areas is crucial for ensuring integrated and sustainable planning. This includes reconsidering site selection for land use, implementing disaster prevention measures, and taking necessary precautions in the planning of priority facilities (Fig.11).

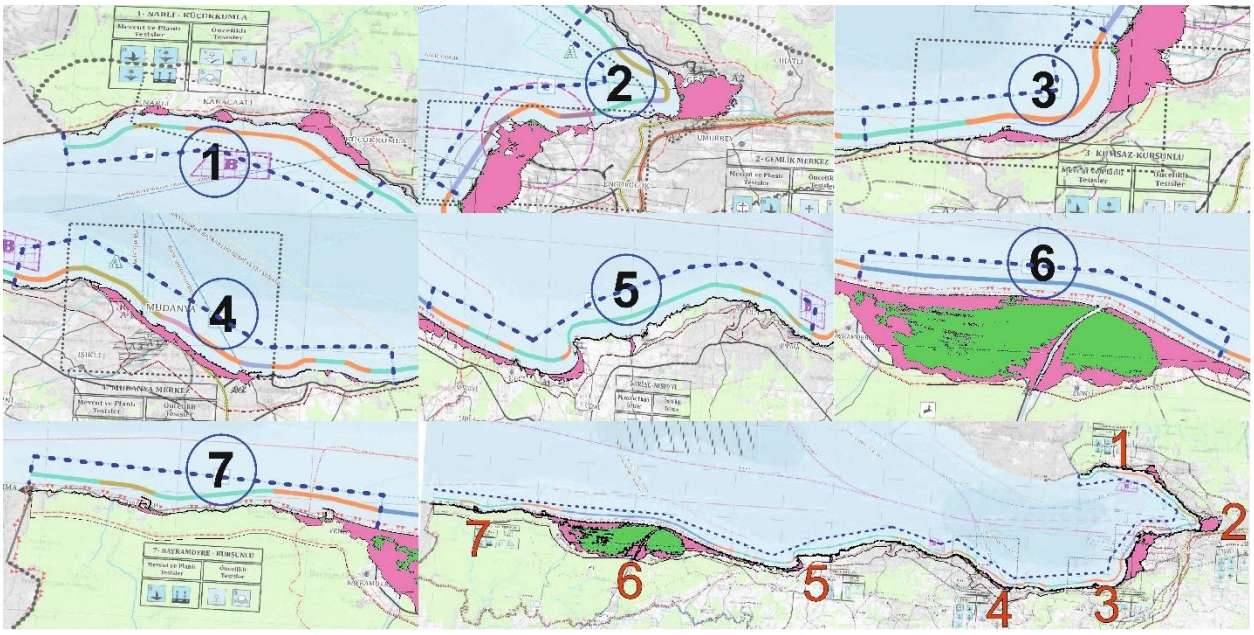


Figure 11. Sea Level Rise Flood Risk Analysis – ICZM Plan Area (Green: 2100 Scenario, Pink: 2500 Scenario)

Consequently, evaluations correlating current and projected spatial planning decisions with regional analyses are detailed below:

Narlı-Küçükkumla Sub-Region: According to the sea-level rise analysis, the site selection for tourism and recreational coastal arrangements proposed within the ICZM plan for the Narlı, Karacaali, and Küçükkumla settlements—including passenger pier developments, recreational area arrangements, open and green spaces, pedestrian and bicycle paths, and water sports facilities—must be reviewed in light of the projected flood extent and location. Considering that areas with high settlement density, such as tourism zones, summer housing, camps, and beaches, are projected to be inundated, the anchorage zone designated for vessels carrying hazardous materials—located within one nautical mile of these areas and on the maritime traffic route—poses a significant threat to the region and public health in the event of a maritime accident. It is recommended that anchorage zones be revised in coordination with the port authority, based on local measurements of depth, currents, and seabed characteristics.

Gemlik Center Sub-Region: The bathtub analysis indicates that the Gemlik settlement center, coastal roads, and infrastructure will be submerged under sea-level rise conditions. Consequently, urban settlement must be redirected away from these risk zones. The analysis results predict that a certain portion of the commercial port area in Gemlik will also be inundated. Given the strategic decisions to develop this region as a logistical base connecting Anatolia and Thrace, decisions regarding the expansion of industrial facilities, port hinterlands, and storage facilities must be made with careful consideration of these risk zones.

Kumsaz – Kurşunlu Sub-Region: An examination of areas likely to be submerged reveals that the coastline and beaches are high-risk zones. It is assessed that the construction of proposed facilities such as marinas, passenger terminals, ferry piers, and other coastal arrangements should be subject to site selection or modification based on the condition of flood zones.

Mudanya Sub-Region: In the site selection for priority marinas and passenger terminals intended to increase maritime transport to the district, it is deemed beneficial to revise the boundaries of the 1/5000 scale coastal structure schemes to align with areas unaffected by sea-level rise as per the analysis. Decisions to support intercity maritime transport and develop marina and passenger terminal facilities will increase population density in these areas. Therefore, the anchorage zone for ships carrying dangerous goods, located in close proximity to the coast, is considered a threat

to the region and human health in the event of an accident. Revising these anchorage zones in coordination with the port authority, based on local bathymetric and oceanographic measurements, is advisable.

Tirilye-Mesudiye Sub-Region: For priority facility projections aimed at increasing maritime transport between Bursa's coastal settlements and intercity routes, it is recommended that site selection processes take into account areas subject to sea-level rise.

Kocaçay Delta Sub-Region: Designated as a distinct zone, this area possesses unique natural characteristics in terms of biodiversity, hosting floodplain (*longoz*) forests, dune vegetation, lakes, and marshes. The plan's explanatory report notes that wastewater from Bursa's industry and terrestrial pollutants threaten the vitality of the Kocaçay Delta, necessitating reactive measures. Furthermore, sea-level rise may cause changes in salinity levels, potentially leading to ecological problems within the delta. It is evaluated that sensitive areas with ecological character, such as the Kocaçay Delta, require monitoring through periodic risk assessments, and engineering studies should be conducted to implement necessary precautionary measures based on the results.

Bayramdere-Kurşunlu Sub-Region: In the event of sea-level rise, waters are observed to reach only up to the coastal road, with the exception of certain sections of the settlements, indicating a very low level of risk. In this context, it is suggested that the proposal to transform the Bayramdere (Yeniköy) Fishery Shelter into a yacht berthing and mooring place be reviewed and potentially revised by examining the flood rate and area.

DISCUSSION AND CONCLUSION

This research, conducted in the coastal areas of Bursa, is among the current studies that integrate IPCC sea level rise scenarios (2100-2500) with spatial planning decisions through the use of high-resolution Digital Elevation Models (DEM) and Hydrologically Connected Bathtub Analysis, derived from the processing of fundamental spatial data within a Geographic Information System (GIS) environment. Beyond studies that address which areas will be submerged under classic sea-level rise conditions and evaluate this in a multi-criteria context of coastal vulnerability levels, this study aims to contribute to the literature by assessing the validity of spatial planning decisions in coastal cities—developed regarding what cities will look like in the future—against sea-level rise scenarios through Integrated Coastal Zone Management (ICZM) plans.

The findings revealed a significantly differentiated vulnerability profile among Bursa's coastal regions. It was determined that the Gemlik district possesses "very high" coastal vulnerability (CVI: 0.84-1.00), Mudanya remains at a "low-medium" level (CVI: 0.06-0.34), and Karacabey, despite having the largest area in terms of physical exposure, is at a "very low-medium" vulnerability level (CVI: 0.00-0.08) due to socioeconomic factors. These differences are consistent with existing literature emphasizing the high physical susceptibility of low-slope coastal areas, such as low-elevation deltas and plains, to sea-level rise (Simav et al., 2013; Hamid et al., 2019). Specifically, similar studies conducted in the Küçük Menderes delta determined that the delta is affected by sea-level rise up to approximately 22 km inland, with more than 55% of the infrastructure falling into high or very high vulnerability classes (Simav et al., 2015; Anfuso et al., 2021). However, this study also demonstrated the critical importance of integrating socioeconomic factors alongside physical vulnerability (VanZomeren & Acevedo-Mackey, 2019).

Considering that traditional coastal vulnerability studies mostly address the vulnerability of the current situation against future sea-level scenarios (Hegde & Reju, 2007; Pendleton et al., 2004; Pantusa et al., 2018; Koroglu et al., 2019), whereas urban planning produces detailed decisions regarding future land use, population, and construction conditions, the approach of this study offers a significant methodological expansion. The lack of systematic investigation into sea-level rise through spatial plans regarding the future of cities constitutes a significant gap in the literature (Ercanlı, 2022). However, urban planning produces long-term strategic decisions, and the validity of these decisions must be questioned under future climate conditions (Government of South Australia, 2021; UNFCCC, 2025).

This study has concretely demonstrated the necessity of re-evaluating planning decisions in terms of climate adaptation by superimposing the marinas, passenger terminals, recreation areas, anchorage zones, and infrastructure projects proposed in the ICZM plans with sea-level rise scenarios. Similarly, Torresan et al. (2012) used hot spot analysis to identify areas of high vulnerability to climate change and coastal hazards in the North Adriatic Sea region but did not specifically focus on coastal infrastructure. This study, however, differs from the literature with its infrastructure-oriented approach.

Analysis results indicated that under the 2100 scenario (0.83 m rise), 71.16% of marshlands and 22.55% of water surfaces would be affected. Our finding that the Karacabey delta is particularly vulnerable parallels previous studies stating that deltas and wetlands have high physical

sensitivity to sea-level rise (IPCC, 2022; Kantamaneni et al., 2019). As emphasized in the IPCC (2021) report, global mean sea levels could exceed 0.83 meters by 2100 and potentially 6 meters by 2500 under high emission scenarios. However, the impact on urban infrastructure, port facilities, and settlement areas in Gemlik points to the potential for creating socioeconomic damages greater than the physical impact. These findings align with recent research emphasizing the necessity of evaluating socioeconomic factors together with physical characteristics (Tragaki et al., 2018; Koks et al., 2019).

One of the most important contributions of this study is the generation of concrete proposals for the re-evaluation of ICZM plan decisions in the context of climate change. It was determined that the site selection for port facilities and urban settlement areas in Gemlik, marinas and passenger terminals in Mudanya, and tourism and recreation facilities in the Narlı-Küçükkumla sub-region should be revised according to sea-level rise scenarios. In particular, it was determined that anchorage areas designated for ships carrying dangerous goods could threaten dense population and tourism areas in the event of a maritime accident. These findings appear to coincide with international studies highlighting the necessity of developing adaptive spatial strategies and protecting critical infrastructure (Linham & Nicholls, 2010).

In a similar study conducted in the Küçük Menderes delta, it was shown that the integration of CVI and hot spot analysis provides a deeper understanding of vulnerability across different infrastructure types and locations compared to studies relying solely on CVI (Simav et al., 2013; Simav et al., 2015). Furthermore, high vulnerability infrastructure clusters were identified even in areas with moderate CVI scores; this situation highlights the limitations of relying solely on CVI and the value of a site-specific approach. Similar findings were obtained in the Gemlik region in this study, where areas carrying high socioeconomic vulnerability were detected within moderate risk zones.

The fact that coastal planning practice in developing countries generally operates under static environmental assumptions and lacks the integration of long-term climate projections (Ercanlı, 2022) is also observed in the context of Turkey. This study revealed that sea-level rise scenarios are not sufficiently taken into account during the preparation process of ICZM plans and that revising plan decisions starting from today is of critical importance. Since climate change will not affect every coastal region at the same rate, the effectiveness of ICZM plans needs to be reviewed according to the physical, socioeconomic, and ecological parameters of geographical locations

(Matthews et al., 2021).

The study has some limitations. The limited accessibility of high-resolution bathymetric data, up-to-date coastal geomorphological maps, and socioeconomic data infrastructure in Turkey restricted the scope of the analyses. In particular, the lack of detailed spatial data regarding settlement areas, infrastructure facilities, and economic activities made it difficult to deepen socioeconomic vulnerability assessments. Similar data constraints have been reported in other coastal vulnerability studies conducted in developing countries (Güney, 2013). Including critical system components in the nature of point data, such as wastewater treatment plants, energy grids, and communication infrastructure, in future analyses will provide a more holistic vulnerability assessment.

In conclusion, this study is a pioneering research that systematically evaluates the effects of sea-level rise on coastal area planning, questions existing plan decisions in terms of climate adaptation, and generates concrete revision proposals. The findings demonstrate once again that strengthening legal frameworks for sustainable coastal management in Turkey, standardizing data collection and evaluation methods, integrating ICZM plans with dynamic climate scenarios, and developing proactive, adaptive spatial strategies are necessary (Cicin-Sain & Knecht, 1998; Sorensen, 1993), and that climate-resilient planning has now become an inevitable necessity for the safety and welfare of future generations (Godschalk, 2003; Walker et al., 2006).

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DECLARATIONS

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Authors' contributions Conceptualization, TS, RB; Methodology, TS, RB; Software, RB, TS; Validation, TS, RB; Formal Analysis, RB, TS; Investigation, RB, TS; Resources, TS; Data Curation, RB; Writing—Original Draft Preparation, TS, RB; Writing—Review and Editing, TS; Visualization, RB; Supervision, TS; Project Administration, TS. All authors have read and agreed to the final version of the manuscript.

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APPENDIX

Table 1. Social parameters of the coastal vulnerability index used in different geographies.

Author	Year	Region Population Age	Annual Income	Employment	Population (Total Numbers and Population Density)	Housing Units	Building Preservation	Race	Access to Resources	Land Use	Cultural Heritage	Infrastructure Dependency	Tourism	Awareness	Economic Openness/Dependency
Wu et al.	2002				X	X									
Cutter and et al.	2003	X	X	X	X	X		X	X			X			X
Briguglio and Galea	2003														X
Boruff and et al.	2005	X	X	X	X			X	X			X			X
Chakraborty and et al.	2005				X				X						
Kleinosky and et al.	2007	X													
Tate and et al.	2010	X			X			X							
McLaughlin and Cooper	2010				X					X	X				
Li and Li	2011	X			X					X	X				X
Mackey and Russell	2011		X		X										
Balica and et al.	2012				X						X			X	
Yin and et al.	2012									X					
Mani Murali and et al.	2013				X					X	X	X			
Satta	2014	X			X					X	X	X	X	X	
Alexandrakis and et al.	2014									X	X	X			X
Ahsan and Warner	2014		X												X
Satta and et al.	2015				X								X		
Guillard-Goncąlands	2015	X		X	X			X	X						
Zanetti and et al.	2016	X	X		X					X					
Kantamaneni	2016				X										
Toimil and et al.	2017				X	X				X					
Çalil and et al.	2017				X										
Tragaki and et al.	2018	X			X										
Debortoli and et al.	2019											X			

Author	Year	Region Population Age	Annual Income	Employment	Population (Total Numbers and Population Density)	Housing Units	Building Preservation	Race	Access to Resources	Land Use	Cultural Heritage	Infrastructure Dependency	Tourism	Awareness	Economic Openness/Dependency
Gargiulo and et al.	2020	X		X			X			X					
Hawchar and et al.	2020											X			
El-Zein and et al.	2021	X	X	X						X					
NUMBER OF REPEATS :		11	6	5	18	3	1	4	4	10	6	7	2	2	6

Table 2. Physical parameters of the coastal vulnerability index used in different geographies.

Author	Year	Geomorphology (Slope, Elevation, Shoreline Type, Rock Type, Beach Type, Solid and Drift Geology)	Sea Leandl Rise	Erosion and Shoreline Change	Tidal Range	Storm Waand	Waand Height	Number of Extreme Eandnts	Coastline	Distance from Shore	Elevation	Land Coandr	Hazardous Maps	Coastal Flood Protection
Gornitz	1991	X		X	X	X								
Shaw and et al.	1998	X	X	X	X	X								
Thieler and Hammar-Klose	1999	X		X	X	X								
Pendleton and et al.	2004	X	X	X	X	X								
Doukakis	2005	X	X		X	X								
Boruff and et al.	2005	X		X	X	X								

Author	Year	Geomorphology (Slope, Elevation, Shoreline Type, Rock Type, Beach Type, Solid and Drift Geology)	Sea Leandl Rise	Erosion and Shoreline Change	Tidal Range	Storm Waand	Waand Height	Number of Extreme Eandnts	Coastline	Distance from Shore	Elevation	Land Coandr	Hazardous Maps	Coastal Flood Protection
Abuodha and Woodroffe	2006	X	X	X	X	X					X			
Kleinosky and et al.	2007												X	
Rao and et al.	2008	X			X	X								
Mendoza and Jiménez	2009	X		X			X				X			
Tate and et al.	2010												X	
Gaki-Papanastassiou and et el.	2010	X	X	X	X	X								
McLaughlin and Cooper	2010	X			X	X					X			
Li and Li	2011					X								X
Karymbalis and et al.	2012	X	X	X	X	X								
Balica and et al.	2012	X					X	X	X			X	X	X
Yin and et al.	2012	X	X		X	X					X			
Tibbetts and van Proosdij	2013	X		X	X	X		X		X				
Addo	2013	X		X	X	X								
Mani Murali and et al.	2013	X	X	X	X	X						X		
Alexandrakis and et al.	2014	X	X	X	X	X								
Kokkinos and et al.	2014	X		X			X				X			
Ahsan and Warner	2014	X	X											
Satta	2014	X	X	X						X	X	X	X	X
Satta and et al.	2015	X	X	X						X	X	X		
Bagdanavičiute and et al.	2015	X		X		X							X	
Guillard-Goncąlands and et al.	2015												X	
Zanetti and et al.	2016	X	X	X	X			X		X				
Kantamaneni	2016		X											
Toimil and et al.	2017		X		X		X							
Calil and et al.	2017					X	X	X				X		
Tragaki and et al.	2018	X	X	X	X	X								
Pantusa and et al.	2018		X	X	X	X								
Gargiulo and et al.	2020	X								X				
Hawchar and et al.	2020		X					X					X	
El-Zein and et al.	2021	X												
Zampazas and et al.	2022	X	X	X	X	X								

NUMBER OF REPEATS:	Author
	Year
28	Geomorphology (Slope, Elevation, Shoreline Type, Rock Type, Beach Type, Solid and Drift Geology)
19	Sea Leandl Rise
21	Erosion and Shoreline Change
21	Tidal Range
22	Storm Waand
5	Waand Height
5	Number of Extreme Eandnts
1	Coastline
5	Distance from Shore
7	Elevation
5	Land Coandr
7	Hazardous Maps
3	Coastal Flood Protection