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Storm Surge Threats: Assessing İzmir's Transportation Network Vulnerabilities

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A B S T R A C T

Coastal cities are increasingly vulnerable to climate-related hazards – storm surges, sea-level rise, and extreme weather – which threaten transportation systems. Recent disasters highlight the urgent need for resilience planning. This study evaluates the vulnerability of İzmir's transportation network under three storm surge scenarios by integrating high-resolution spatial data, IPCC (Intergovernmental Panel on Climate Change) projections, and historical flood records. The analysis applies an indicator-based approach grounded in the IPCC framework, evaluating vulnerability as a function of exposure, sensitivity, and adaptive capacity. Findings show water intrusion ranging from 330 to 12,000 meters across İzmir Bay, significantly impacting critical infrastructure. Tram lines and ferry piers are most affected, with over 84% and 97% of assets classified as highly or very highly vulnerable. Metro stations (52%) and segments of the İZBAN rail system (34%) are also at risk, particularly in low-lying coastal zones. These disruptions threaten urban mobility, economic stability, and emergency response. The current research provides a spatially explicit vulnerability assessment of İzmir's transport infrastructure under different storm surge scenarios, identifying the most at-risk assets and locations. By applying an indicator-based framework, it quantifies vulnerability in a systematic way and highlights the urgency of targeted adaptation in central districts like Konak and Karşıyaka. The findings offer actionable insights for urban planners and policymakers, emphasizing the need to integrate Nature-based Solutions and engineered protections in areas with low elevation and critical transport functions. The methodological approach can also be adapted to support resilience planning in other coastal cities facing similar climate threats.

1. INTRODUCTION

Rising sea levels and storm surge-induced flooding increasingly threaten coastal cities, with impacts intensified by extreme weather events. These climate-driven hazards endanger critical urban systems - especially transportation networks vital for mobility, economic activity, and emergency response (Xu et al., 2016; UNEP, 2024). Flooding can cause both direct infrastructure damage (e.g., submersion) and indirect disruptions (e.g., loss of connectivity), impairing daily operations and emergency services (Hallegatte et al., 2013; Hinkel et al., 2014; Azevedo de Almeida and Mostafavi, 2016; He et al., 2022).

Under the SSP5-8.5 scenario, sea levels are projected to rise by 0.3–1.1 m globally and 0.6–1.1 m in the Mediterranean by 2100 (IPCC, 2022). Coastal European cities already face escalating inundation risks (Lionello et al., 2021; Falciano et al., 2023), with annual flood-related damages exceeding €1.4 billion and affecting over 100,000 people (Vousdoukas et al., 2020). The World Bank (2022) notes a 122% increase in cities at extreme flood risk, underscoring the urgency of adaptation.

Transportation systems are particularly vulnerable where adaptive capacity is limited. Disruptions can cascade through interconnected systems (Matsumoto and Bohorquez, 2023; Zimmerman et al., 2023), making resilience essential to maintaining urban functionality (Horner and Widener, 2011; Corpade et al., 2012). Effective vulnerability assessments must incorporate exposure, adaptive capacity, and network interdependencies (Tyler and Moench, 2012; Figueiredo et al., 2018).

While recent studies address urban flood risks (Costache et al., 2015; Rahman et al., 2024) and transport system impacts (Rebally et al., 2021; Ansari et al., 2024; Han et al., 2022; Kuleli and Bayazit, 2024), many lack integrated approaches or localized, scenario-based analysis frameworks.

İzmir, a coastal metropolis and regional hub in Türkiye, offers a representative case of transport-related climate vulnerability. Severe coastal flooding in 2020, 2021, and 2023 disrupted roads, rail, and bike infrastructure. National reports identify İzmir as one of Türkiye's most flood-prone cities due to low elevation, dense development, and limited blue-green infrastructure (MGM, 2024), echoing challenges faced by many Mediterranean port cities.

This study evaluates İzmir's transportation network vulnerability under three sea level rise scenarios. Using a spatially explicit, indicator-based framework that integrates exposure, sensitivity, and adaptive capacity, it identifies high-risk areas and informs resilience planning. The findings contribute to climate impact literature and support transferable, context-specific adaptation strategies for coastal cities.

2. STUDY AREA

The study focuses on İzmir's coastal districts, spanning 943.42 km² between 38°37′–38°15′ N and 26°50′–27°20′ E (Fig. 1).

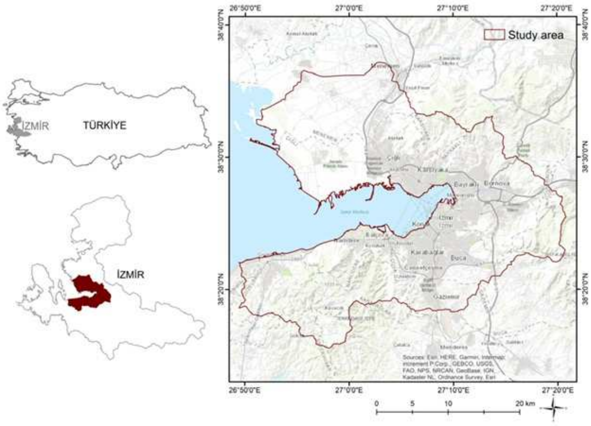


Fig. 1. Study area.

It includes micro-basins within Menemen, Çiğli, Karşıyaka, Bayraklı, Bornova, Konak, Buca, Karabağlar, Gaziemir, Balçova, Narlıdere, Güzelbahçe, Urla, and Seferihisar in western Türkiye. Bordering the Aegean Sea, İzmir is a major metropolitan region with over 6 million residents. Its central coastal districts form a dense urban core with residential, commercial, and industrial zones, along with critical transport infrastructure. These low-lying areas are highly exposed to storm surge flooding due to coastal proximity and infrastructure concentration. Disruptions here can lead to significant economic and mobility challenges. The region has a Mediterranean climate, averaging 18°C in temperature and 712.1 mm of annual precipitation (TSMS, 2025). However, climate change has intensified extreme weather, increasing flood risks. Major events in December 2018, February 2020, and January 2022 damaged roads, bridges, and public transit, causing severe delays and economic losses (MGM, 2024), while also underscoring the vulnerability of İzmir's transportation network.

İzmir's public transportation network including buses, trams, metro lines (Metro and İZBAN), and ferries serves around 1.7 million passengers daily, with key corridors running along the coast. Sea transport is vital to urban mobility, moving over 50.000 passengers and 2.300 cars daily across more than 1.500 trips via nine terminals, helping to ease traffic congestion and improve connectivity. The metro system has two lines: the Metro (27 km, 24 stations) running west–east, and İZBAN (136 km, 41 stations), connecting northern and southern districts. The tram network includes the Konak Tram (12.8 km, 19 stations) on the southern coast and the Karşıyaka Tram (8.8 km, 14 stations) on the northern coast of İzmir Bay. Additionally, a 114 km bike lane network mainly concentrated around the Bay supports mobility in central and outlying districts (IBB, 2019). These multimodal systems ensure broad, efficient coverage across the city.

3. METHODOLOGY

The methodology employed in this study focuses on assessing the vulnerability of İzmir's coastal transportation infrastructure under three storm surge scenarios by integrating high-resolution spatial data, historical flood records, and an indicator-based approach grounded in the IPCC framework (Fig. 2).

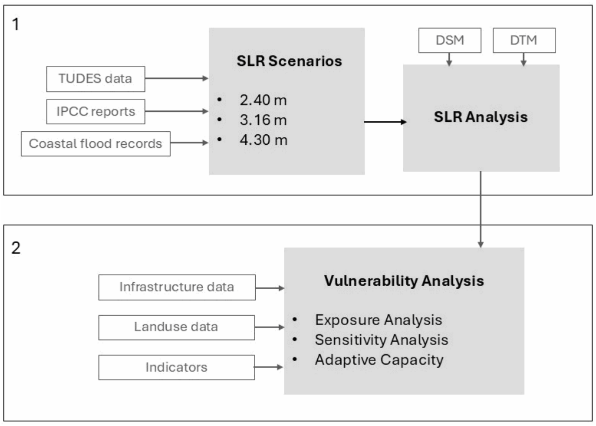


Fig. 2. Diagram of the methodology.

3.1. Data acquisition

This study uses high-resolution geospatial datasets to assess coastal flooding hazards and transportation network vulnerabilities in İzmir. A 30 cm resolution Digital Terrain Model (DTM) and Digital Surface Model (DSM) from the Ministry of Environment, Urbanization, and Climate Change were used to simulate sea-level rise and storm surge impacts. Six orthophoto frames at 30 cm resolution enhanced land surface characterization for exposure analysis (GDLRC, 2024). A land use/land cover (LULC) map was created using 4-band orthophotos from the Ministry of National Defence (HGM), processed through object-based image segmentation. Accuracy scores for classification ranged from 70% to 83%. As a coastal metropolitan area, İzmir features a multimodal transportation network consisting of roads, rail (metro and tram), bicycle lanes, and ferry routes. The transportation network map was compiled using vector data from HGM, municipal records, and field observations. Coastal flood and storm surge data were sourced from the Turkish National Sea Level Monitoring System (TUDES), particularly the Menteş station, covering 24 years of data (2000–2024) (TUDES, 2024). Historical flood records from the İzmir Metropolitan Municipality were also integrated. This combined dataset helped identify flood-exposed corridors and critical infrastructure nodes, supporting a comprehensive vulnerability assessment. The study's methodology includes two phases: (1) sea level rise hazard analysis and (2) vulnerability assessment.

3.2. Sea level rise hazard analysis

To evaluate potential flood exposure in İzmir Bay under three climate scenarios, a combined approach integrating permanent sea level rise (SLR) and coastal storm surge flooding was used. Permanent SLR was based on IPCC Sixth Assessment Report projections, estimating a 0.5–1.1 m rise in the Mediterranean by the century's end under high-emission scenarios. Storm surge values were derived from TUDES tide gauge records and coastal flood data from the İzmir Metropolitan Municipality. Historical maximum sea level anomalies from TUDES were analyzed, and representative surge heights from recent extreme events were combined with SLR projections to define total water level scenarios (Table 1).

Table 1. Values determined for the scenarios.

Scenarios	Sea level rise (m)
1 – 2 – 3	0.58 – 0.80 – 1.1
Coastal flood (m)	**Total (m)**
1.83 – 2.36 – 3.20	2.41 – 3.16 – 4.30

Inundation extents were then simulated in ArcGIS Pro using a Digital Surface Model (DSM) to identify all areas with elevations below these thresholds.

3.3. Vulnerability analysis

Vulnerability is defined as a function of exposure, sensitivity, and adaptive capacity, following the IPCC (2022) framework. This study uses an indicator-based approach to assess transportation network vulnerability in four stages: (1) exposure, (2) sensitivity, (3) adaptive capacity, and (4) vulnerability mapping.

Exposure analysis: A 30 × 30 m fishnet grid was applied to standardize spatial units across the study area. Using ArcGIS Pro's Intersect tool, each cell was assessed for overlap with sea level rise scenarios of 2.41 m, 3.16 m, and 4.30 m. Exposure scores were assigned based on severity: 1 point for Scenario 1, 2 for Scenario 2, and 3 for Scenario 3.

Sensitivity analysis: Sensitivity was calculated through a weighted sum of exposure scores from sea level rise scenarios (2.41 m, 3.16 m, 4.30 m), with weights of 3, 2, and 1, respectively. This approach prioritizes lower-level flooding, which tends to impact broader areas more frequently.

Adaptive capacity analysis: Adaptive capacity was evaluated across three categories: institutional, gray infrastructure, and blue-green infrastructure, using indicators adapted from Taylor and D'Este (2007), OECD (2007), GIZ (2017), Bucak et al. (2021), Serdar et al. (2022), and IPCC (2023). Indicators were scored from 1 (low) to 5 (high) (Table 2). Overall adaptive capacity was calculated using a weighted summation (see Equation 1), with weights (0–1) assigned to each category to emphasize the long-term benefits of blue-green infrastructure in coastal flood resilience: AC = (0.7 × bg_adaptcap) + (0.2 × gray_adaptcap) + (0.1 × instadapcap) (1)

Table 2. Indicators for adaptive capacity (adapted from Taylor and D'Este, 2007; OECD, 2007; GIZ, 2017; Bucak et al., 2021; Serdar et al., 2022; IPCC, 2023; Cangüzel and Coşkun Hepcan, 2024).

Indicators	Value
Institutional capacity	
The existence of climate action plans	1: non-existent, 2: Being prepared, 3: Sustainable energy and climate action plan (SECAP), 4: Climate Action plan, 5: Climate adaptation plan
The existence of climate change projects	1: 0, 2: 1 project, 3: 2 projects, 4: 3 projects, 5: 4≥ projects
Signatories to Covenant of Mayors	1: Not signed, 5: Signed
The existence of disaster risk management plans	1: Non-existent, 5: Existent
National and international city networks	1: 0, 2: 1, 3: 2, 4: 3-4, 5: 5≥
Collaboration with partners and stakeholders	1: Non-existent, 5: Existent
The existence of a climate change department in the local government	1: Non-existent, 5: Existent
The existence of awareness training	1: Non-existent, 5: Existent
The existence of hospitals located in hotspots	1: Non-existent, 5: Existent
Education level	1: Unknown, 2: Primary, 3: Secondary, 4: Highschool, 5: University
The number of environmental non-governmental organizations in the city	1: 10≤, 2: 11-20, 3: 21-30, 4: 31-40, 5:41≥
The level of socio-economic development	1: 1.322≤, 2: 1.632-1.882, 3: 2.031-2.222, 4: 2.902, 5:3.028≥
Gray infrastructure capacity	
The existence of gray solutions on the seaside	1: Non-existent, 5: Existent
The existence of gray solutions	1: Non-existent, 5: Existent
The existence of elevated roads	1: Non-existent, 5: Existent
Blue-green infrastructure capacity	
The percentage of ecosystem in a fishnet	1: 20≤, 2: 21-40, 3: 41-60, 4: 61-80, 5:81≥
Ecosystem quality	2: Arable land, 3: Grass, soil, 5: Wetland, trees
The existence of nature-based solutions	1: Non-existent, 5: Existent
The percentage of permeable surfaces in coastal flood areas	1: 20≤, 2: 21-40, 3: 41-60, 4: 61-80, 5:81≥

Vulnerability Analysis: The overall vulnerability of İzmir's transportation infrastructure was assessed by integrating exposure, sensitivity, and adaptive capacity, following a widely used conceptual framework. Vulnerability was calculated using a standardized formula and classified into five categories: very low, low, medium, high, and very high (Equation 2): (Exposure + Sensitivity) – Adaptive capacity = Vulnerability (2)

4. RESULTS AND DISCUSSION

This section presents the main findings of the study, based on the spatial analysis of İzmir's transportation network. The results are organized into five parts: hazard, exposure, sensitivity, adaptive capacity, and overall vulnerability.

4.1. Hazard

The hazard analysis shows that sea level rise (SLR) and storm surges pose a severe, spatially varied threat to İzmir's coastal districts. Inundation expands from 125.63 km² under 2.41 m SLR to 209.67 km² under 4.30 m (Fig. 3), shaped by topography, land reclamation, and urbanization. Çiğli is the most affected, with seawater advancing 12 km inland due to its low elevation and proximity to the Gediz Delta. In the eastern bay, Bornova and Alsancak face 1.6 km inland flooding because of dense infrastructure and shoreline changes. Southern districts like Balçova, Narlıdere, and Güzelbahçe are also confronted with notable risk becaude of low-lying terrain and past reclamation. SLR significantly impacts İzmir's transport network (Table 3).

Table 3. Transportation network segments coastal flood, storm surge hazard analysis results.

Infrastructure	2.41 m – 1st scenario	3.16 m – 2nd scenario	4.30 m – 3rd scenario
Road (km - %)	1358.66 - 11.56	1743.26 - 15.17	2152.11 -18.74
Metro (km - %)	2.53 - 10.10	4.07 -16.24	5.32 - 21.22
Izban (km - %)	9.88 - 21.65	13.18 - 28.88	17.11 - 37.5
Tram (km - %)	26.88 - 81.58	29.89 - 90.71	31.15 - 94.54
Bicycle lane (km - %)	49.39 - 45.73	58.01 - 53.52	62.10 - 57.51
Pier (no. - %)	43 - 100	43 - 100	43 - 100
Elevated road (km - %)	-	-	-
Metro station (no. - %)	38 - 41.76	49 - 53.85	52 - 57.14

Under the 4.30 m scenario, 94.54% of tram lines, 57.51% of bike lanes, and 37.5% of the İZBAN system are flood-prone. All 43 ferry piers are exposed in every scenario, confirming persistent maritime vulnerability. Metro station exposure rises from 41.76% to 57.14%, and affected road segments increase from 11.56% to 18.74%. These findings highlight the acute exposure of low-lying, waterfront transit assets especially in dense zones like Konak, Karşıyaka, and Alsancak stressing the need for region-specific adaptation. The high exposure of tram lines and piers, in particular, calls for integrating flood risk into future infrastructure planning.

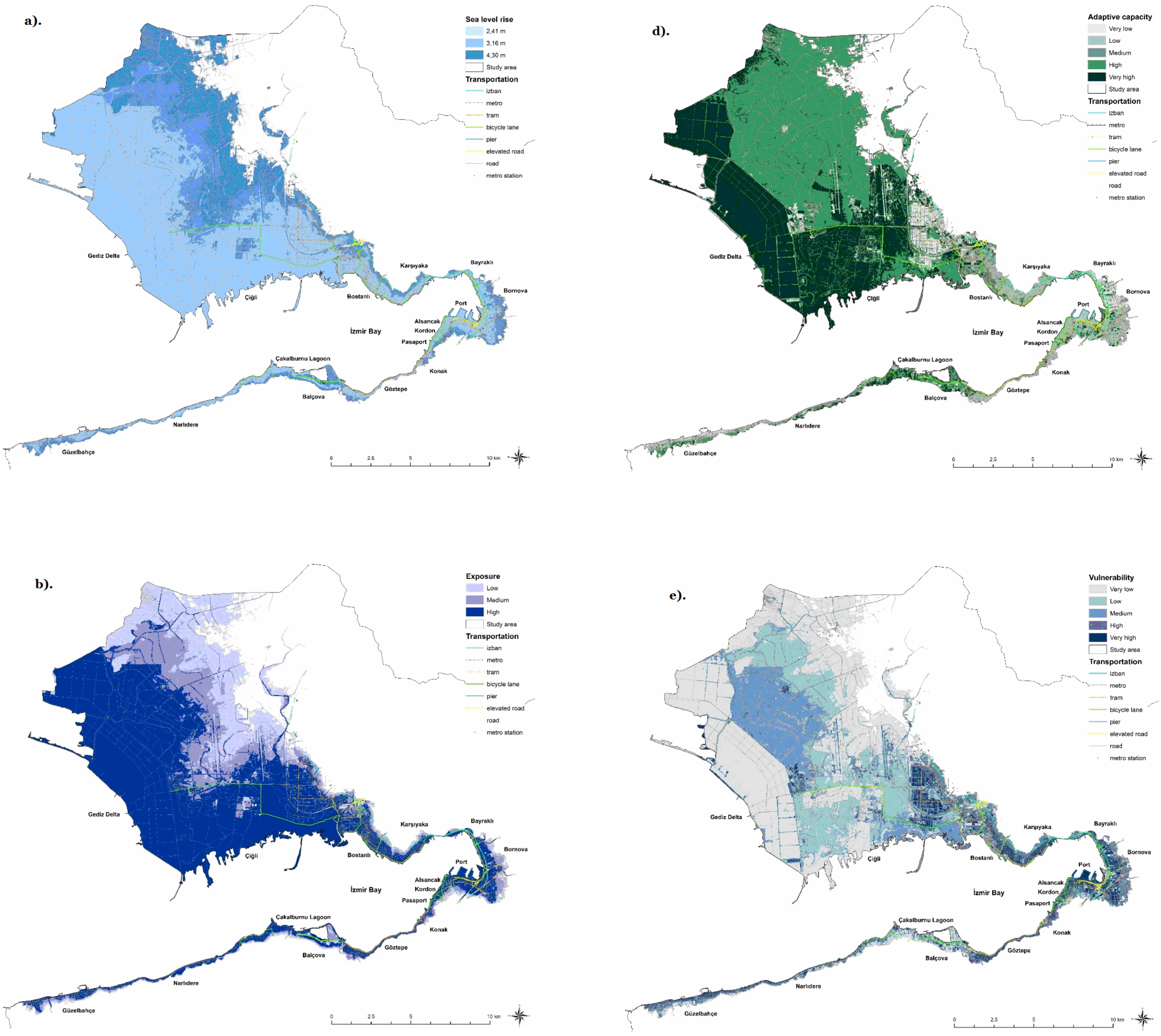
4.2. Exposure

Exposure analysis indicates İzmir's transportation infrastructure is highly threatened by sea level rise and storm surges, especially in low-lying coastal zones like the Çiğli wetlands, Alsancak-Kordon, and Balçova shoreline (Fig. 3b). These areas, often built on reclaimed or flat alluvial land, face the highest exposure, while inland and elevated districts are less at risk. As shown in Table 4, 11.83% of roads, 10.10% of metro lines, and 21.66% of the İZBAN network fall within high-exposure zones. The tram system is the most impacted, with 81.57% of its length exposed. Bicycle lanes (45.74%) and metro stations (41.76%) also show high exposure, and all 43 ferry piers are flood-prone under all hazard scenarios. Medium-exposure areas like Karşıyaka, Bayraklı, and Bornova represent transitional urban zones shaped by elevation and density. Here, 6.16% of metro lines, 7.24% of İZBAN lines, and 12.09% of metro stations are affected. Low-exposure zones, mostly inland or elevated, include just 3.56% of roads and 4.97% of metro lines. Exposure patterns reflect İzmir's geomorphology: flat terrain in Alsancak, Kordon, and Çiğli increases flood risk, while narrow coastal corridors bordered by hills compress infrastructure into vulnerable areas (Table 4).

Table 4. Transportation network segments coastal flood, storm surge exposure analysis results.

Infrastructure	Low	Medium	High
Road (km - %)	408.85 - 3.56	384.60 - 3.35	1358.66 - 11.83
Metro (km - %)	1.24 - 4.97	1.54 - 6.16	2.53 - 10.10
Izban (km - %)	3.92 - 8.59	3.30 - 7.24	9.88 - 21.66
Tram (km - %)	1.25 - 3.80	3.02 - 9.17	26.88 - 81.57
Bicycle lane (km - %)	4.09 - 3.79	8.63 - 7.99	49.39 - 45.74
Pier (no. - %)	43 - 100	43 - 100	43 - 100
Elevated road (km - %)	-	-	-
Metro station (no. - %)	3 - 3.30	11 - 12.09	38 - 41.76

The location of assets like the İzmir Tram Line and waterfront metro stations emphasizes the exposure of critical infrastructure. Some elevated road segments are also exposed, suggesting elevation alone doesn't guarantee protection particularly near the shore. These findings align with earlier research: Dalfes and Avcı (2023) identified İzmir's lowlands as highly flood-prone by 2100, and Demirkesen et al. (2007), using Landsat and SRTM data, identified high-risk areas in the northwestern bay. Despite methodological differences, these studies confirm İzmir's significant transport vulnerability to coastal hazards.



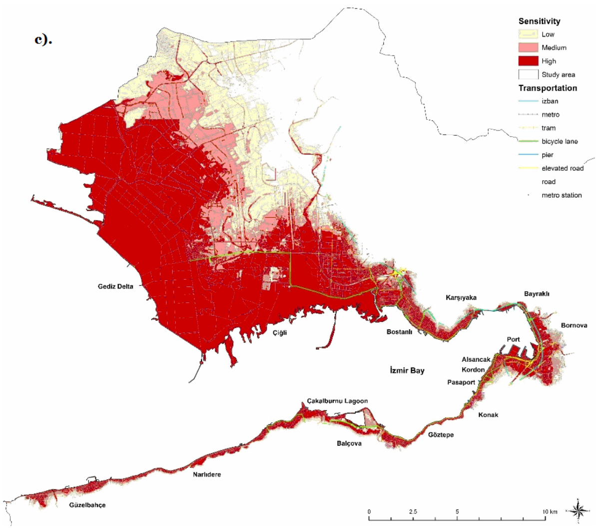


Fig. 3. Transportation network coastal flood, storm surge: *a). Hazard map; b). Exposure map; c). Sensitivity map; d). Adaptive capacity map; e). Vulnerability map.*

These findings align with earlier research: Dalfes and Avcı (2023) identified İzmir's lowlands as highly flood-prone by 2100, and Demirkesen et al. (2007), using Landsat and SRTM data, identified high-risk areas in the northwestern bay. Despite methodological differences, these studies confirm İzmir's significant transport vulnerability to coastal hazards.

4.3. Sensitivity

The sensitivity analysis indicates İzmir's transportation infrastructure is highly vulnerable to sea level rise, especially in low-lying, dense districts like Konak, Karşıyaka, and Çiğli (Fig. 3c). Based on weighted hazard exposure, large portions of the network are highly sensitive (Table 5): 11.83% of roads, 10.10% of metro lines, 21.66% of İZBAN, 45.74% of bike lanes, 81.57% of tram lines, all 43 ferry piers, and 41.76% of metro stations. These include 1.358 km of roads, 49.39 km of bike lanes, 26.88 km of tram lines, and 38 metro stations, mostly in low-elevation coastal zones. Medium sensitivity affects 3.35% of roads, 6.16% of metro lines, 7.24% of İZBAN, and 12.09% of metro stations; low-sensitivity areas are mainly at higher elevations. Sensitivity closely mirrors exposure, with hotspots concentrated in coastal and reclaimed areas. The İzmir Tram Line (Konak, Karşıyaka) and immovable ferry piers are key vulnerabilities, underscoring the link between geography, land use, and susceptibility.

Table 5. Transportation network segments coastal flood, storm surge adaptive sensitivity analysis results.

Infrastructure	Sensitivity		
	Low	Medium	High
Road (km - %)	408.85 - 3.56	384.60 -3.35	1358.66 - 11.83
Metro (km - %)	1.24 - 4.97	1.54 - 6.16	2.53 - 10.10
Izban (km - %)	3.92 - 8.59	3.30 - 7.24	9.88 - 21.66
Tram (km - %)	1.25 - 3.80	3.02 - 9.17	26.88 - 81.57
Bicycle lane (km - %)	4.09 - 3.79	8.63 - 7.99	49.39 - 45.74
Pier (no. - %)	-	-	43 - 100
Elevated road (km - %)	-	-	-
Metro station (no. - %)	3 - 3.30	11 - 12.09	38 - 41.76

4.4. Adaptive capacity

The adaptive capacity analysis reveals substantial variation in İzmir's transportation system response to sea level rise. As shown in Figure 3d and Table 6, 9% of roads and 24% of bike lanes are rated high to very high in capacity, while 31% of railways, 67% of ferry piers, and 62% of metro stations fall into low to very low categories (Table 6).

Table 6. Transportation network segments coastal flood, storm surge adaptive capacity analysis results.

Infrastructure	Adaptive Capacity				
	Very low	Low	Medium	High	Very high
Road (km - %)	236.51 - 2.06	527.07 - 4.59	305.23 - 2.66	779.38 - 6.79	303.92 - 2.65
Metro (km - %)	0.28 - 1.12	2.23 - 8.90	1.26 - 5.03	1.38 - 5.51	0.17 - 0.68
Izban (km - %)	3.38 - 7.42	7.87 - 17.25	3.57 - 7.83	2.15 - 4.70	0.13 - 0.29
Tram (km - %)	3.11 - 9.44	13.66 - 41.46	7.95 - 24.13	5.12 - 15.54	1.31 - 3.98
Bicycle lane (km - %)	5.37 - 4.98	15.03 - 13.92	15.50 - 14.36	19.22 - 17.80	6.98 - 6.47
Pier (no. - %)	20 - 46.51	14 - 32.56	8 - 18.60	-	1 - 2.33
Elevated road (km - %)	2.13 - 3.75	6.02 - 10.57	9.50 - 16.68	7.75 - 13.60	1.27 - 2.23
Metro station (no. - %)	8 - 8.79	21 - 23.08	16 - 17.58	6 - 6.59	1 - 1.10

The assessment is based on an indicator framework covering institutional, gray, and blue-green capacities, drawing from OECD (2007), Bucak et al. (2021), and IPCC (2023). Indicators include climate action plans, flood protection, ecosystem coverage, and socio-economic factors. Scores range from 1 (low) to 5 (high), with weights of 0.7 for blue-green, 0.2 for gray, and 0.1 for institutional capacity, emphasizing Nature-based Solutions (NbS).

The northern İzmir Bay, especially near the Çiğli wetlands, shows the highest capacity due to natural buffers like salt marshes. In contrast, dense coastal areas such as Konak, Alsancak, Kordon, and Karşıyaka score lower due to limited green space and high infrastructure density. Roads show mixed capacity: 6.79% high, 4.59% low, and 2.06% very low. Elevated segments perform better, but many coastal and reclaimed roads remain underprepared. Ferry piers and metro stations are persistently vulnerable, 67% and 62% falling in the lowest categories due to lack of engineered protection.

Recent gray infrastructure includes raising the northern bay promenade by 50–100 cm and constructing a 1.7 km, 90 cm-high flood barrier along Kordon. These localized efforts help but are spatially limited compared to Venice or Rotterdam (Coastal Cities, 2024). Ferry operations remain especially vulnerable in the southern bay, frequently suspended during storms due to exposed terminals and the bay's semi-enclosed form (OECD, 2007; Arcadis, 2020).

Institutionally, İzmir lacks a coastal early warning system (EWS), reducing its readiness. In contrast, New York, Sydney, and Colombo have operational EWSs (UNISDR, 2010). Global initiatives like the UN's Early Warnings for All and WMO (UN, 2023; WMO, 2022; Swail et al., 2019) emphasize their importance. Cities like New York (NYC, 2017), Copenhagen, Rotterdam, and Tokyo offer models that combine stormwater tunnels, green buffers, and adaptive governance (C40 Cities, 2016). Currently, İzmir's 2024 Disaster Risk Reduction Plan (AFAD, 2024) focuses on riverine flooding, and the 2030 Transportation Master Plan (IBB, 2019) lacks coastal adaptation strategies. Integrating sea-level rise and climate resilience into these plans is essential to enhance long-term infrastructure preparedness.

4.5. Vulnerability

The vulnerability analysis reveals that İzmir's transportation infrastructure faces significant risks, particularly in low-lying coastal corridors (Fig. 3e). Based on the IPCC Sixth Assessment Report framework, integrating exposure, sensitivity, and adaptive capacity, tram lines (84.75%) and ferry piers (97.67%) are the most vulnerable components (Table 7).

Table 7. Transportation network segments coastal flood, storm surge vulnerability analysis results.

Infrastructure	Vulnerability				
	Very low	Low	Medium	High	Very high
Road (km - %)	391.83 - 3.41	207.00 - 1.80	314.92 - 2.74	829.31 - 7.22	409.04 - 3.56
Metro (km - %)	0.21 - 0.87	0.22 - 0.90	0.52 - 2.11	3.46 - 13.82	0.88 - 3.53
Izban (km - %)	0.24 - 0.54	0.43 - 0.95	0.96 - 2.12	9.51 - 20.86	5.94 - 13.02
Tram (km - %)	1.18 - 3.59	0.79 - 2.41	1.25 - 3.81	17.46 - 53.01	10.45 - 31.74
Bicycle lane (km - %)	5.72 - 5.31	5.13 - 4.75	8.40 - 7.78	27.69 - 25.65	15.14 - 14.03
Pier (no. - %)	-	1 - 2.33	-	11 - 25.58	31 - 72.09
Elevated road (km - %)	1.27 - 2.23	7.74 - 2.20	9.49 - 16.68	6.02 - 10.57	2.13 - 3.75
Metro station (no. - %)	2 - 2.20	-	2 - 2.20	32 - 35.16	16 - 17.58

Metro stations (52.38%) and İZBAN segments (33.88%) also show high vulnerability. While bicycle lanes (39.68%) and road segments (10.78%) vary in distribution, elevated roads show more resilience (only 3.75% highly vulnerable), reflecting the influence of elevation and proximity to the coast. Hotspots include Konak, Alsancak, and Karşıyaka, where sea-level proximity, inadequate adaptive capacity (e.g., lack of EWS and flood defenses), and high infrastructure density exacerbate vulnerability. Vulnerable areas overlap with past flood events (2021–2024), especially in reclaimed zones such as Kordon, Göztepe, and Üçkuyular, where low elevation and poor soil stability heighten flood risks. In contrast, moderate vulnerability is seen in areas like Çiğli and the Gediz Delta generated by sedimentation and land-use factors. These findings align with prior studies (Demirkesen et al., 2007; Restrepo, 2011; Sılaydın Aydın et al., 2017; Giannakidou et al., 2020; Cangüzel and Coşkun Hepcan, 2024). Recent studies in other coastal cities offer valuable comparisons. In New York City, the impact of Hurricane Sandy highlighted vulnerabilities in subway and ferry infrastructure and led to substantial investment in resilient urban design (Aerts et al., 2014). In Semarang, Indonesia, land subsidence combined with inadequate drainage has increased flood exposure, particularly in low-lying areas with critical infrastructure (Abidin et al., 2012). Similarly, Rotterdam has developed a multilayered strategy using flood defences, green infrastructure, and community awareness programs to manage flood risks (Jha et al., 2012). These examples illustrate how integrated, adaptive measures can reduce vulnerability, an approach İzmir could adopt in its post-disaster planning efforts.

The analysis underscores the urgent need for integrated adaptation. NbS such as wetland protection, vegetated buffer zones, and flood-absorbing landscapes can reduce risks while enhancing ecological resilience. Coupling NbS with grey measures like elevated roads, adaptive drainage, and risk-informed land-use planning offers a comprehensive resilience strategy.

Particular concern centers on reclaimed areas along the southern coast (Konak, Alsancak, Kordon, Göztepe, Üçkuyular), where infrastructure is built on unstable, low-elevation fill. Coastal roads between Alsancak and Balçova are among the most vulnerable. In contrast, naturally elevated districts like Balçova and Narlıdere show lower vulnerability. Recent grey measures such as the 1.7 km-long, 90 cm-high concrete barriers along Kordon and the elevation of promenades with rock wave breakers have helped locally, but remain limited in coverage. Hybrid solutions are needed: flip-up barriers, bioswales, and automated pumping systems. International examples such as England's Severn Estuary barriers and Brooklyn's BMCR project offer practical models.

Critical transport routes especially in Konak, Alsancak, and Karşıyaka urgently require intervention. Their location on reclaimed, flood-prone land increases both hazard exposure and post-disaster response risk, as seen in 2020. Storm surge events also impact emergency response. İzmir's road and transit systems are crucial for post-disaster mobility. During the 2020 earthquake, access was severely hampered by coastal damage and congestion, prompting traffic restrictions for emergency access. As a port city, İzmir must climate-proof ferry terminals, as future scenarios may rely on maritime logistics for relief operations.

Integrating NbS with engineered infrastructure, urban design, and updated policy is essential for long-term resilience. NbS not only mitigate flood risk but also deliver co-benefits such as biodiversity, recreation, and adaptive capacity. Their cost-effectiveness and multifunctionality complement grey infrastructure. Combined with elevated roads, bioswales, automated barriers, and improved drainage, As Ruangpan et al. (2020) stated, NbS can transform vulnerability hotspots into resilient urban systems.

This study is based on storm surge projections from IPCC sea level rise scenarios, historical flood data, and DTM/DSM elevation models. Due to limited access to discharge and drainage data, full hydrodynamic modeling incorporating wind, waves, and rainfall, was not feasible (Castrucci and Tahvildari, 2017; Forero-Ortiz, 2020; Jibhakate et al., 2023). Advanced methods like network-based modeling (Helderop and Grubesic, 2019), computational simulations (Dube et al., 2010; Chen et al., 2015), and vulnerability indexing (Amin et al., 2018) were beyond this study's scope. Additionally, the analysis did not disaggregate transport modes or accessibility impacts during flood events, as seen in Li et al. (2018), Fang et al. (2020), and Ayu and Mirchandani (2021). Despite these limitations, this study offers a spatially explicit, infrastructure-focused vulnerability assessment for İzmir.

Future research should incorporate multi-hazard modeling, real-time infrastructure data, and urban growth dynamics to refine and expand these findings.

5. CONCLUSIONS

This study assessed the vulnerability of İzmir's transportation infrastructure to projected storm surge scenarios by integrating the IPCC's vulnerability components: exposure, sensitivity, and adaptive capacity. Using high-resolution spatial datasets and an indicator-based framework, the analysis identified critical hotspots, particularly in low-lying, reclaimed coastal districts. These areas such as Konak, Alsancak, and Göztepe host key transportation assets including ferry piers, metro stations, and tram lines, all of which exhibit high to very high vulnerability under future flood scenarios.

The findings underscore a growing risk for coastal cities like İzmir, where the legacy of the urban fabric and existing infrastructure were not designed to withstand the increasing frequency and severity of storm surges expected in the Mediterranean region. Disruptions to İzmir's multimodal transport network pose serious challenges not only to daily mobility but also to emergency response and economic continuity during climate-related disasters.

Resilient transportation in such contexts must be robust, adaptable, and rapidly recoverable. A multi-layered strategy is required, one that integrates structural engineering with ecological thinking. NbS, including vegetated buffer zones, wetlands, and permeable surfaces, should be actively promoted alongside gray infrastructure interventions such as elevated roads, storm-resilient metro entrances, and mobile flood barriers. Ferry terminals, in particular, need physical reinforcement given their fixed and coastal nature.

Beyond infrastructure, resilience depends on institutional coordination and preparedness. Strengthening early warning systems, enhancing modal diversity, ensuring redundancy in the network, and involving local communities in planning are essential steps. Cities must endorse context-specific adaptation strategies that blend natural and engineered systems.

In İzmir's case, a twofold approach is essential: prioritize interventions in high-risk districts such as Konak, Alsancak, and Göztepe, while conserving and enhancing natural buffer zones like the Gediz Delta. As sea-level rise and storm surge threats intensify, cities must shift from reactive to anticipatory planning.

This study offers spatially grounded evidence to support such forward-looking, climate-resilient strategies. Building resilience also requires robust governance-early warning systems, network redundancy, and modal diversity must be strengthened through coordinated efforts across agencies, policymakers, and communities. Blending NbS with engineered infrastructure presents a viable and context-sensitive path toward long-term urban resilience, both for İzmir and other vulnerable coastal cities.

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