



Assessment of Flood Risk Hotspots in Port Areas: A Multi-Hazard Approach For Antalya Port

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ABSTRACT

Ports are critical infrastructures highly vulnerable to river and coastal floods, exacerbated by climate change. This study presents a high-resolution, quantitative multi-hazard damage assessment for a representative Mediterranean port, Antalya. An established land-use-based depth-damage function methodology was integrated with local data, including river flood maps for nine return periods (10- to 500-year) and coastal flood scenarios under sea-level rise projections. The results reveal a multi-billion Euro risk profile dominated by high-frequency events; over 70% of the maximum potential damage from a 500-year flood (€4.59 billion) already occurs during a frequent 10-year event. Damage is overwhelmingly concentrated (>97%) in industrial and commercial zones. Hotspot analysis confirmed that this risk is not random, identifying statistically significant and persistent high-damage clusters in the port's northern industrial areas. These findings suggest port risk profiles may be characterized by high-frequency, high-impact events rather than rare catastrophes, providing an evidence-based foundation for spatially prioritizing adaptation strategies.

1. Introduction.

Ports are essential coastal infrastructures that have evolved from historical maritime gateways into complex modern hubs of commerce and industry. As indispensable sea-land interfaces within the global transportation system, they facilitate approximately 80% of global trade by volume, making them central to international commerce and supply chains. Beyond cargo handling, ports host diverse industrial, logistical, and commercial activities, generating substantial wealth, fostering employment, and contributing significantly to national GDP and re-

gional economic development (UNCTAD, 2011; Chua et al., 2021).

Notwithstanding their crucial role for socio-economic development, the characteristic placement of ports within low-lying coastal zones, estuaries, and river deltas renders them highly susceptible to a range of natural hazards, which are significantly amplified by climate change. These vulnerabilities are driven by both gradual changes, such as sea-level rise (SLR) and accelerated coastal erosion, and the escalating frequency and intensity of extreme weather events like storm surges and heavy precipitation (UNCTAD, 2017; IPCC, 2021). Ports are projected to experience persistently intensified inundation risks from both coastal and river floods (Houtven et al., 2022). These dual hazards posed by climate change indicates that previously infrequent nuisance flooding is anticipated to become dramatically more common, posing significant challenges to the structural integrity, operational continuity, accessibility, and long-term sustainability of port facilities (IPCC, 2021; UNCTAD,

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2017; Yang and Ge, 2020; Houtven et al., 2022).

Among the diverse hazards, floods are significant, manifesting as river, coastal, or pluvial events that can cause widespread damage on ports (Koks et al., 2019; Verschuur et al., 2023). The consequences are typically delineated into direct physical damage to critical assets (e.g., warehouses, terminal buildings, cranes), indirect economic losses from operational downtime, and cascading effects that ripple through global supply chains (UNCTAD, 2011). Empirical evidence vividly illustrates that both fluvial and coastal flooding can trigger significant disruptions across regional and global trade networks, cementing their position as one of the costliest disasters for transportation infrastructures (Fahie, 2019; Koks et al., 2019). For instance, coastal flood due to hurricanes (i.e. Katrina in 2002, Florence in 2018) extensively devastated port facilities in the U.S (Houtven et al., 2022); the 2019 Mississippi River floods resulted in a 38-day closure of St. Louis Harbor (Fahie, 2019); post-monsoon rain flooding in Thailand led to close local manufacturing industries, hinder port-hinterland traffic, stop inbound container receiving due to yard congestion (UNCTAD, 2022) and resulted in a 30% reduction in trade volume for affected ports (Port Strategy, 2011); severe flooding in Chennai, India (in 2015), critically impaired container operations at the nation's second-largest port (JOC, 2015).

Historically, port vulnerability assessments have often prioritized catastrophic, low - frequency events like earthquakes, tsunamis and tropical cyclons (Xinhu, 2018). However, there is a growing consensus that floods represent a more frequent and cumulatively damaging threat for critical coastal infrastructures like ports (Ward et al., 2011; UNCTAD, 2017). Recent studies highlighted that, river flooding is identified as the most significant natural hazard in terms of incurred economic damage, surpassing even coastal flooding and earthquakes in terms of estimated global financial losses (Koks et al., 2019, Verschuur et al., 2023, Abrar et al., 2024). Despite this critical and escalating flood risk profile for ports, significant gaps persist in the existing literature. A recognized scarcity of studies focuses specifically on the direct damage impacts of floods on seaports, particularly those that conduct systematic multi-hazard risk assessments considering both river and coastal flood variables (Xinhu, 2018; Chua et al., 2021). Furthermore, the development of reliable flood damage models for critical infrastructure at site-specific port locations remains limited, often forcing reliance on broader regional assessments (Bolangi, 2022; Jian et al., 2019).

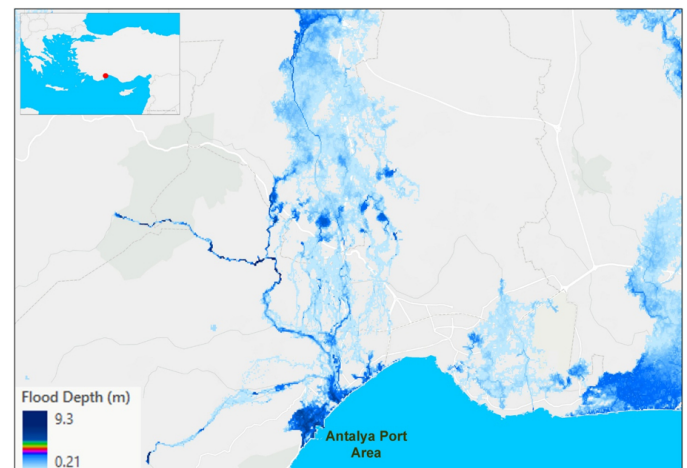
This study addresses the identified gaps in the literature by providing a detailed, quantitative flood damage assessment for the Antalya Port Region, a representative Mediterranean port exposed to both river and coastal flood hazards. The primary objectives are to: (1) apply and adapt a standardized, land-use-based damage assessment methodology to a specific port case study; (2) estimate the potential direct economic damage from river floods across a granular range of nine return periods (10- to 500-year); (3) separately assess the damage from coastal inundation under future sea-level rise (SLR) scenarios; and (4) identify statistically significant spatial clusters of high-damage areas (hotspots) for each scenario. By extending the analysis

beyond the immediate port operational area to include the adjacent industrial free zone, storage areas, and container yards, this research provides a comprehensive risk profile essential for developing evidence-based and spatially explicit adaptation strategies. By quantifying the anticipated flood damage under multiple return periods and SLR scenarios, this research offers critical, evidence-based insights for decision-makers, engineers, and planners to formulate robust adaptation strategies for enhancing port resilience. The application of a widely recognized flood hazard assessment methodology to a detailed, local-scale case study contributes a transferable framework applicable to a broader range of ports, directly addressing the identified need for more port-specific flood damage assessments, thereby providing a robust baseline for future comparative analyses.

2. Study Area.

The focus of this study is Antalya, one of Turkey's most significant tourism and trade centers, located on the Mediterranean coast in the southwest of the country. The specific study area selected is the Antalya Port and its immediate vicinity (Figure 1). This choice is predicated on three key characteristics of the region: its high socio-economic value, its increasing and complex exposure to climate change-induced flood hazards, and the need for a detailed, local-scale risk analysis.

Figure 1: Location of the study area and the flood hazard map for the 500-year return period (Q500). The map illustrates the geographical position of the Antalya Port Area within the Mediterranean region (inset map). The main figure displays the maximum flood depth (m) for the Q500 river flood scenario, derived from the Copernicus/JRC dataset. Darker blue shades indicate greater water depths, highlighting the inundation extent across the coastal plain where the port is located.



Source: Authors.

Situated in the Mediterranean climate zone, Antalya experiences a regime of hot, dry summers and mild, rainy winters. In recent years, an increasing frequency of extreme precipitation events has been reported for the region, leading to the rapid onset of flash floods and surface runoff (SECAP, 2022). The

region's topography is characterized by short, steep rivers (notably the Boğaçayı and Aksu rivers) that descend rapidly from the Taurus Mountains to the north. This hydrological structure creates a natural predisposition to sudden river floods, particularly on the coastal plains. Indeed, historical flood events have been documented to cause significant infrastructural and economic losses in areas adjacent to the port, such as the Boğaçay Basin (Özmen, 2015).

In addition to the river flood risk, Antalya's extensive coastline makes the region vulnerable to coastal flood hazards, including sea-level rise (SLR) and storm surges. The Antalya Basin Flood Management Plan highlights that these two flood types evolve with different dynamics, underscoring the region's complex risk profile at the intersection of both marine and terrestrial hazards (MoFA, 2024). The concentration of population and economic activities largely on this at-risk coastal plain further amplifies its vulnerability. The Antalya Provincial Disaster Risk Reduction Plan (AFAD, 2021) also identifies the Konyaaltı district, where the port is located, as one of the most susceptible areas to flood risk.

Despite this complex risk profile, detailed scientific studies that holistically quantify the potential direct economic damage to strategic infrastructure like Antalya Port from both river and coastal floods under various probabilities are limited. However, the region offers significant advantages for such an analysis due to the availability of historical flood records, flood maps produced under national projects (State Hydraulic Works), and high-resolution geospatial datasets (from the Municipality and Directorate General for Mapping). For these reasons, the Antalya Port and its surroundings (Antalya Port region) were selected as an ideal case study area to apply a globally recognized damage assessment methodology on a local scale and to establish an evidence-based foundation for climate change adaptation strategies.

3. Data and methods.

In this section, the analytical framework, datasets, and computational procedures used to assess the potential direct economic damage in the Antalya Port region from river (RF) and coastal (CF) flood hazards are detailed. The methodology is based on the integration of spatial analysis within a GIS environment and an established land-use-based damage assessment framework. First, the primary hazard, geospatial, and economic datasets that served as inputs are described. Subsequently, the multi-stage methodology is explained, detailing the preparation of hazard layers, the parameterization of vulnerability based on JRC functions, the spatial calculation of monetary damage, and the statistical analysis of the results.

3.1. Data.

The analysis of potential flood damage in the Antalya Port region was based on four main categories of geospatial and economic data. All spatial datasets were processed and projected to the WGS 84 / UTM Zone 36N coordinate system to ensure consistency.

3.1.1. River Flood Hazard Maps.

The primary input for river flood analysis was the river flood hazard dataset for Europe and the Mediterranean Basin, produced by the Copernicus Emergency Management Service - (CEMS) and published by the Joint Research Centre (JRC) (Baugh et al., 2024). The methodology and validation of this dataset are detailed in Dottori et al. (2022). This raster dataset, with a 100-meter spatial resolution, provides maximum water depth (m) for nine different return periods (10, 20, 30, 40, 50, 75, 100, 200, and 500-year). The data was generated using the LISFLOOD hydrological and LISFLOOD-FP hydrodynamic models. It was noted that this dataset is not an official flood hazard map and does not account for local flood protection structures (Baugh et al., 2024).

3.1.2. Local Flood Modeling Data.

For reference and contextual validation of the general inundation extent, data from flood modeling studies conducted by the Turkish State Hydraulic Works (DSİ) for the Boğaçay and Sarısu rivers were utilized (AFAD, 2021). These data included vector polygon flood extent boundaries for the 100-year (Q100) and 500-year (Q500) return periods, along with their corresponding peak discharge values. These local model results were used to confirm the general inundation patterns produced by the Copernicus/JRC data within the study area.

3.1.3. Digital Elevation Model.

The European Digital Elevation Model (EU-DEM), version 1.0, produced within the Copernicus program, was employed for modeling coastal flood scenarios resulting from sea-level rise (CLMS, 2016). This dataset has a spatial resolution of 25 meters. Although technically a Digital Surface Model (DSM) based on SRTM and ASTER GDEM data, it is edited to ensure hydrographical consistency and represents the bare-earth elevation for the purposes of this large-scale analysis.

3.1.4. Land Use Data.

To determine the spatial distribution and type of economic assets, the 1:5,000 scale Master Development Plan, officially approved and provided by the Antalya Konyaaltı Municipality, was used (AMM, 2025). This vector polygon dataset delineates functional zones such as Commercial Area, Industrial Area, Port Area, and Infrastructure Area, and served as the primary input for assigning damage classes in the subsequent analysis.

3.1.5. Damage Assessment Methodology Reference.

The fundamental parameters for the damage assessment, including depth-damage functions and base maximum damage values, were derived from the JRC technical report Global flood depth-damage functions: Methodology and the database with guidelines and its associated database (Huizinga et al., 2017). This source provides the necessary damage ratios and 2010-based maximum damage values (€/m²) for different land-use classes.

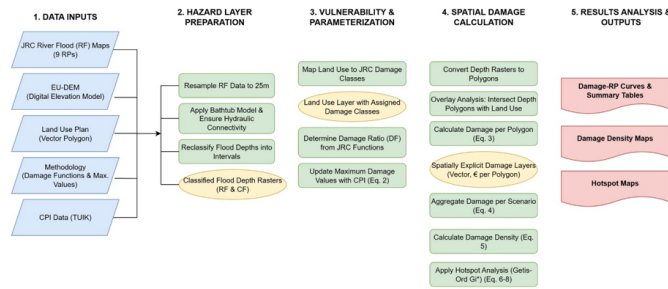
3.1.6. Economic Update Data.

To adjust the 2010-based monetary values to current economic conditions, Consumer Price Index (CPI, 2003=100) data published by the Turkish Statistical Institute (TUIK, 2025) were used. The ratio between the CPI values of January 2010 and January 2025 was calculated and applied as an economic update factor in the damage assessment.

3.2. Methods.

To estimate the potential direct economic damage in the Antalya Port region under various river flood (RF) and coastal flood (CF) scenarios, a multi-stage methodology integrating spatial analysis with established damage functions was employed. The analytical workflow, summarized in Figure 2, consists of four main stages: (1) preparation of flood hazard layers, (2) vulnerability analysis and parameterization, (3) spatial damage calculation, and (4) results analysis and spatial statistics.

Figure 2: Methodological workflow of the flood damage assessment.



Source: Authors.

3.2.1. Hazard Layer Preparation.

Spatial flood hazard information, representing water depth and inundation extent, was prepared separately for the two flood types. The objective was to produce high-resolution, classified water depth maps for each scenario covering the study area.

3.2.2. River Floods.

The 100m resolution river flood (RF) depth maps provided by Copernicus/JRC for nine different return periods (10- to 500-year) were resampled to ensure spatial compatibility with other high-resolution (25m) layers used in the analysis. This process resulted in 25m resolution raster hazard layers representing water depth for each return period.

3.2.3. Coastal Floods.

Inundation maps for coastal flood (CF) were simulated using a static bathtub model based on the 25m resolution EU-DEM and sea-level rise (SLR) projections under the IPCC's SSP8.5 scenario. To prevent the erroneous inundation of hydrologically disconnected low-lying inland areas, only pixels with a direct hydraulic connection to the sea were included in the analysis. For these connected pixels, the water depth was calculated using Eq. 1:

$$D_{CF} = S - h \quad (1)$$

where;

D_{CF} : Inundation Depth (m).

S : Projected Sea Level (m).

h : Land elevation (m).

This process yielded raster hazard layers representing water depth for each SLR scenario. Finally, the resulting flood depth rasters for both RF and CF were reclassified into the flood depth intervals in Table 1, and each interval was assigned an integer class code (gridcode) starting from 1.

Table 1: The flood depth intervals for damage classes.

Flood depth (m)
0
0.5
1
1.5
2
3
4
5
6
6<

Source: Authors.

3.2.4. Damage Classification.

Functional land-use types from the Master Development Plan were mapped to four primary damage classes (Damage_Class): Commerce, Industry, Infrastructure, and Transport (Table 2).

Table 2: Damage Class conversion table from the Master Development Plan.

1/5.000 Scale Master Development Plan	Damage Classes
Beach	Commerce
Commercial Area	Commerce
Commercial and Tourism Area	Commerce
Education Areas	Commerce
Flammable, Combustible and Explosive Materials Production and Storage Area	Industry
Free Zone	Industry
Fuel Filling and Service Station	Industry
Military Area	Infrastructure
Port Area	Transport
Recreation Area (Rekreasyon Alanı)	Commerce
Road	Infrastructure
Storage Area	Industry

Source: Authors.

3.2.5. Vulnerability Analysis and Parameterization.

This stage aimed to classify the assets within the study area according to their economic value and susceptibility to flooding, and to determine the appropriate damage parameters based on the JRC methodology (Huizinga et al., 2017).

3.2.6. Depth-Damage Functions.

The Damage Function (DF), a dimensionless coefficient representing the vulnerability of each damage class to different flood depths, was determined using the reference values provided in Table 3. This ratio expresses the percentage of maximum damage (from 0 to 1) corresponding to a specific inundation depth class (gridcode).

Table 3: Damage Function according to Flood Depth and Damage Classes.

Flood depth (m)	Residential	Commercial	Industrial	Transport	Infrastructure-roads
0	0.00	0.00	0.00	0.00	0.00
0.5	0.25	0.15	0.15	0.32	0.25
1	0.40	0.30	0.27	0.54	0.42
1.5	0.50	0.45	0.40	0.70	0.55
2	0.60	0.55	0.52	0.83	0.65
3	0.75	0.75	0.70	1.00	0.80
4	0.85	0.90	0.85	1.00	0.90
5	0.95	1.00	1.00	1.00	1.00
6	1.00	1.00	1.00	1.00	1.00
6<	1.00	1.00	1.00	1.00	1.00

Source: Authors.

3.2.7. Updating Maximum Damage Values.

The 2010-based maximum damage values (€/m²) provided by JRC were updated to the January 2025 price level using CPI data from the Turkish Statistical Institute (TUIK). This adjustment was performed using Eq. 2:

$$D_{Max(2025)} = D_{Max(2010)} \times \left[\frac{CPI_{2025}}{CPI_{2010}} \right] \quad (2)$$

where;

$D_{Max(2025)}$: Updated Maximum Damage, 2025 (€/m²).

$D_{Max(2010)}$: Maximum Damage 2010 (€/m²).

CPI_{2025} : Consumer Price Index 2025.

CPI_{2010} : Consumer Price Index 2010.

As a result of this calculation, the maximum potential damage values per unit area, reflecting current economic conditions, were obtained for each damage class.

3.2.8. Spatial Damage Calculation.

The objective of this stage was to spatially integrate the hazard layers with the vulnerability parameters to calculate the potential economic damage for each geographic unit.

First, the classified flood depth rasters were converted to vector polygons, representing homogeneous depth zones. Subsequently, these flood depth polygons were spatially intersected with the land-use layer through an overlay analysis, creating homogeneous analysis units (polygons) that contain information on both the flood depth class (gridcode) and the damage class (Damage_Class).

For each analysis unit (polygon i), the potential economic damage (D_i) was calculated using Eq. 3, which combines the unit's area (A_i), its assigned damage ratio (DF_i), and the updated maximum damage value ($MD_{updated}$) for its respective damage class:

$$D_i = A_i \times DF_i \times D_{2025} \quad (3)$$

where ;

D_i : The potential economic damage for unit (polygon i) (€).

A_i : Area for unit (polygon i) (m²).

DF_i : Assigned damage ratio.

D_{2025} : updated maximum damage value (€/m²).

This process was repeated for each flood scenario (both RF and CF). The final output of this stage is a series of vector layers, one for each scenario, containing the calculated monetary damage value (D_i) in the attribute table of each polygon, thus representing the spatial distribution of damage. These layers form the basis for the subsequent results analysis.

3.2.9. Results Analysis and Spatial Statistics.

To generate the final damage curves and risk maps, the polygon-based damage data obtained in the previous step were aggregated and subjected to spatial statistical analysis.

3.2.10. Total Damage.

The total damage for each flood scenario was calculated by summing the damage values of all constituent polygons (Eq. 4). These aggregated damage values were used to construct the Damage-RP curves, illustrating the change in damage across different return periods.

$$D_{Total} = \sum D_i \quad (4)$$

where ;

D_{Total} : Total Damage (€).

D_i : The potential economic damage for unit (polygon i) (€).

3.2.11. Spatial Analysis.

To analyze the spatial distribution and concentration of damage, thematic maps of Damage Density were produced by calculating the damage per unit area (Eq. 5).

$$D_{Density} = \frac{D_i}{A_i} \quad (5)$$

where ;

$D_{Density}$: Damage Density (€/m²).

D_i : The potential economic damage for unit (polygon i) (€).

A_i : Area for unit (polygon i) (m²).

Furthermore, to identify spatial clustering patterns of damage values and to determine statistically significant hot spots (high-damage clusters) and cold spots (low-damage clusters), Hotspot Analysis (Getis-Ord G_i^*) was applied for each scenario (Getis and Ord, 1992). The G_i^* statistic for each analysis unit (polygon i) was calculated using the following formula (Eq. 6, 7 and 8):

$$G_i^* = \frac{\sum_{j=1}^n w_{i,j} x_j - \bar{X} \sum_{j=1}^n w_{i,j}}{S \sqrt{\frac{[n \sum_{j=1}^n w_{i,j}^2 - (\sum_{j=1}^n w_{i,j})^2]}{n-1}}} \quad (6)$$

$$\bar{X} = \frac{\sum_{j=1}^n x_j}{n} \quad (7)$$

$$S = \sqrt{\frac{\sum_{j=1}^n x_j^2}{n} - (\bar{X})^2} \quad (8)$$

where;

G_i^* : The Getis-Ord G_i^* statistic calculated for feature i (polygon), indicating the statistical significance of spatial clustering.

x_i : The attribute value for feature j (in this study, the calculated damage in Euro (€) or damage density in €/m²).

$w_{i,j}$: $w_{i,j}$: The spatial weight between feature i and j . This defines the spatial relationship; in this context, it is 1 if feature j is a neighbor of feature i , and 0 otherwise.

$\bar{X}$: The mean of the attribute values for all features (e.g., the average damage).

S : The standard deviation of the attribute values for all features.

n : The total number of features (polygons) included in the analysis.

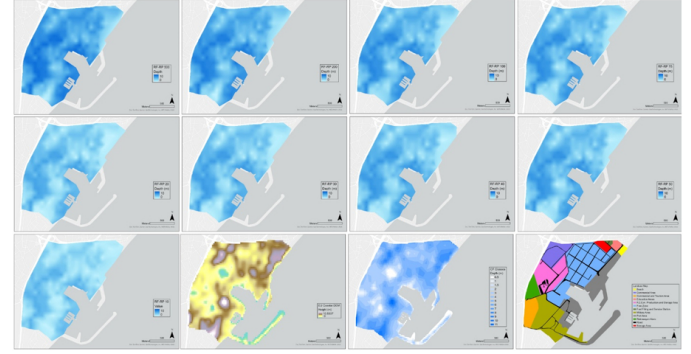
The resulting Z-score (GiZScore) and p-value (GiPValue) from this analysis were used to determine whether each area represented a statistically significant hot spot or cold spot relative to a random distribution. As a result of these analyses, hotspot maps were generated for each scenario, illustrating where the risk is spatially concentrated.

4. Results.

This section presents the findings of the damage assessment conducted for the Antalya Port region under various river flood (RF) and coastal flood (CF) scenarios. The results are presented under three main headings. First, the fundamental spatial data layers and the generated flood hazard maps for different return periods are visually introduced. Second, the total potential economic damage calculated for each flood scenario is detailed both numerically and graphically, broken down by damage class (Commerce, Industry, Infrastructure, and Transport). Finally, the spatial distribution of the damage and statistically significant risk clusters are examined through damage density and hotspot analysis maps.

The primary spatial datasets and hazard maps for the analyzed river flood (RF) and coastal flood (CF) scenarios are presented in Figure 3. As illustrated in the figure, the Antalya Port and its vicinity are exposed to river flood risk across all evaluated return periods (RPs). Even the most frequent scenario, the 10-year return period flood (RP10), inundates a significant portion of the study area, reaching a maximum flood depth of 6.0 meters. The flood risk markedly intensifies in terms of both extent and depth as the return period increases. In the most extreme scenario considered, the 500-year return period flood (RP500), the inundated area covers nearly the entire port region, with maximum water depths exceeding 10.0 meters.

Figure 3: Overview of Spatial Data Layers Used in the Flood Damage Assessment. The figure displays the primary spatial inputs for the study area. The top nine figures show the river flood (RF) inundation depth maps for return periods ranging from 10 to 500 years. The bottom row illustrates the EU Coastal DEM used for elevation data, the resulting coastal flood (CF) depth classes under a specified SLR scenario, and the detailed land use map derived from the local Master Development Plan.



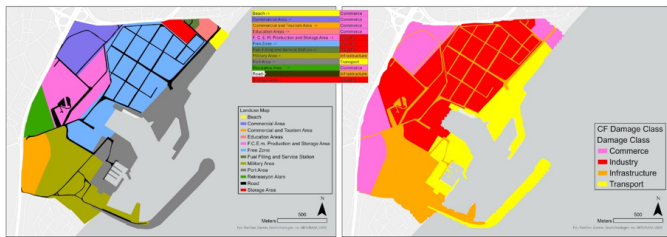
Source: Authors.

The three maps following the RP500 in the bottom row of the Figure 3 display the other foundational layers of the analysis. The EU-DEM map reveals the topographical structure of the study area, indicating that the highest bare-earth elevation in the region is approximately 10.5 meters. The coastal flood (CF) scenario, modeled using this elevation data, exhibits a different inundation pattern compared to the river floods, with flooding concentrated primarily along the coastline and at lower elevations. Finally, the land-use map, derived from the Master Development Plan, illustrates the spatial distribution of the economic assets (classified as Industry, Commerce, Infrastructure, and Transport) exposed to these flood hazards. When viewed collectively, the figure clearly demonstrates that the Antalya Port is highly vulnerable to both frequent (low-RP) and rare (high-RP) river floods, and that coastal flooding introduces an additional layer of risk to the region. A preliminary observation suggests that the low-lying industrial areas in the northern and northwestern sections are the most affected zones by both flood types.

To analyze the spatial distribution of potential economic damage, the heterogeneous land-use structure of the study area was converted into standardized damage classes, which form the basis for the vulnerability analysis. This classification process is illustrated in Figure 4. The left map of the Figure 4 presents the detailed land-use types derived from the Master Development Plan, which were subsequently reclassified into four primary damage classes according to the mapping rules detailed in the methodology section. The resulting final damage classification, presented in the right map of the Figure 4, reveals the spatial distribution of economic assets within the port region. The analysis determined that the largest portion of the study area is composed of the Industry class, which primarily encompasses storage and free zone activities in the northern and northwestern sections. It was observed that the Commerce class represents the second-largest area, located closer to the

coastline and main transportation axes. Damage class of quay zone including piers, berths and docks at the center of port operations was classified as Transport, while the remaining roads and military areas were classified as Infrastructure. This spatial distribution of assets plays a key role in determining the sectoral components of total damage and identifying which areas are most economically vulnerable under different flood scenarios.

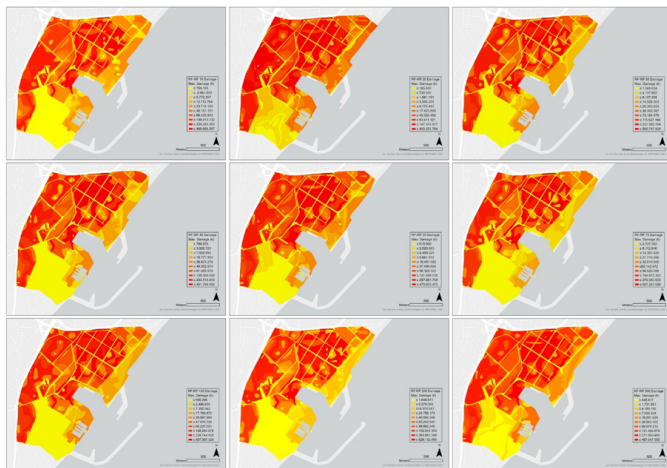
Figure 4: Classification of land use into Damage Classes for the study area. The left figure shows the detailed land use map of the Antalya Port region, derived from the 1:5,000 scale Master Development Plan. The right figure illustrates the reclassification of these detailed land use types into the four primary damage classes used in the flood damage assessment: Commerce, Industry, Infrastructure, and Transport.



Source: Authors.

The spatial distribution of potential economic damage for the river flood (RF) scenarios across nine different return periods (RP) is presented in Figure 5. The maps illustrate that both the magnitude and the spatial concentration of flood risk vary significantly depending on the probability of the flood event.

Figure 5: Spatial distribution of maximum potential economic damage for nine river flood (RF) return periods. The maps illustrate the calculated direct damage (€) for each analysis unit across the study area, from the 10-year (top-left) to the 500-year (bottom-right) return period. Red and orange shades indicate areas with the highest monetary damage, while yellow shades represent areas with lower potential damage.



Source: Authors.

In the most frequent scenario, RF-RP 10 (10-year flood), the damage is widespread across a large portion of the port region. However, the highest monetary losses (red shades) are observed to be clustered in specific, low-lying areas, particularly the industrial free zone in the north and the storage areas in the west. In this scenario, the central operational areas and quay zones of the port remain in lower damage categories (yellow shades).

As the return period increases (from RP20 to RP500), two primary patterns are observed. First, alongside the increase in total damage, there is a spatial expansion of high-damage areas (red zones). For instance, the high-damage zones, which appear as isolated pockets in the RP10 scenario, merge and expand to become a large, contiguous high-risk area covering almost the entirety of the northern and western sections by the RP100 scenario. This indicates that more severe floods not only result in greater depths but also elevate previously less affected adjacent areas into high-damage categories.

Second, with the increase in the return period, the damage levels in the central and southern parts of the port, previously considered less risky, also escalate. In an extreme scenario such as RP500, even the quay zone and marina area (the location of the finger piers in the south-west of the port), initially identified with low damage (yellow), transition into medium-damage categories (light orange). This finding reveals that the entire port region holds significant vulnerability potential against rare but severe flood events.

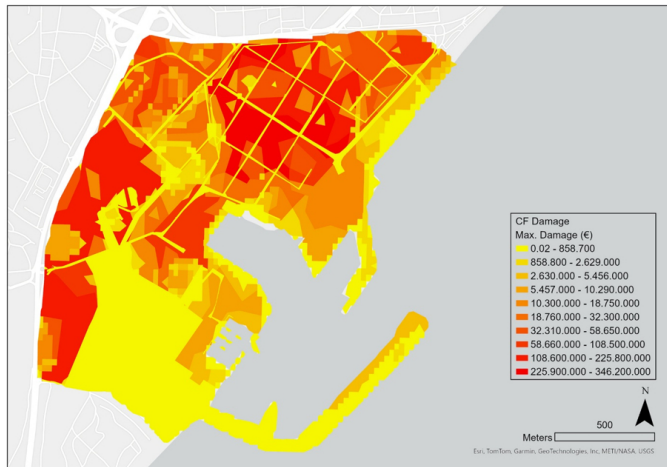
Overall, the damage distribution maps confirm that the industrial and storage zones in the north and northwest of the port are the most chronic and highest-risk areas across all flood scenarios. These zones stand out as the priority areas to be addressed when developing adaptation strategies.

The spatial distribution of the total potential economic damage for the coastal flood (CF) scenario, based on the maximum sea-level rise projection under IPCC's SSP8.5, is presented in Figure 6. The map illustrates the direct monetary damage (€) calculated for each individual analysis unit (polygon), revealing distinct spatial patterns of risk.

As seen in the Figure 6, the findings indicates that the highest potential damages (shown in red and dark orange) are predominantly concentrated in the western and northwestern sections of the study area. These high-damage zones correspond to industrial and storage areas located adjacent to the main highway, which are characterized by both low elevation and high maximum damage values assigned to the Industry damage class. In contrast, the main operational areas of the port, including the quays, piers, and marina, exhibit relatively lower damage values (yellow and light orange shades) compared to industry and transport classes.

This damage pattern is a direct result of the interplay between three key factors calculated for each of the 913 analysis units (polygons): (1) the inundation depth, determined by subtracting the EU-DEM elevation from the projected sea level; (2) the land use type, which dictates the applicable damage class and maximum damage value; (3) the area of the inundated unit, and (4) updated maximum damage unit price. The concentration of high damage values in the industrial zones highlights their significant contribution to the total economic risk under a

Figure 6: Spatial distribution of maximum potential economic damage for the coastal flood (CF) scenario. The map displays the calculated direct damage (€) for each inundated analysis unit, based on the maximum sea-level rise projection. Red and orange shades indicate areas with the highest monetary damage, concentrated in the industrial zones, while yellow shades represent areas with lower potential damage.



Source: Authors.

coastal flooding scenario. The lower damage in the central port areas can be attributed to a combination of slightly higher topographic elevations and the comparatively lower maximum damage values assigned to the Transport and Infrastructure classes within the applied assessment framework.

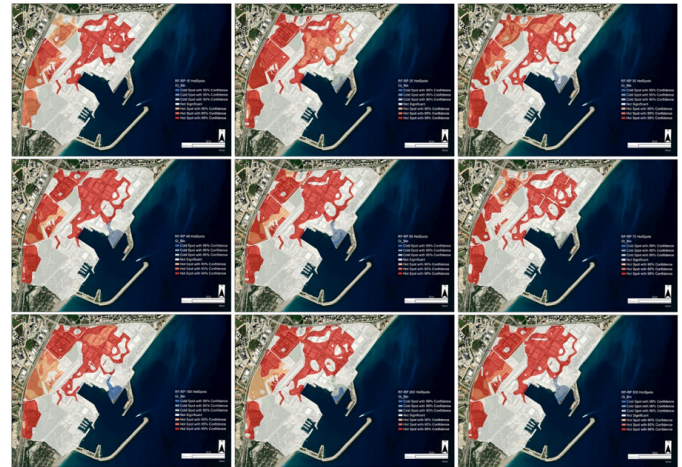
The spatial clustering patterns of potential economic damage were investigated using Hotspot Analysis (Getis-Ord Gi*) for each river flood (RF) return period (RP) scenario. The analysis reveals that the distribution of damage within the port region is not random, exhibiting distinct patterns across different flood probabilities (Figure 7).

A primary finding is the presence of persistent hotspots in the northern and northwestern sections of the port region, corresponding predominantly to industrial and commercial land uses. These areas were identified as statistically significant hotspots at 90% and 95% confidence levels even under the most frequent flood scenario, the 10-year return period (RF-RP 10). As the return period increases, both the spatial extent and the statistical significance of these hotspots intensify markedly. This demonstrates that these industrial and commercial zones are the most chronically and high-priority risk areas within the study area.

Conversely, statistically significant coldspots are observed only under high-magnitude, low-frequency flood scenarios (specifically, RP100 and above). These clusters of low damage values are located in the main quay zone and marina areas of the port, corresponding to the Infrastructure and Transport damage classes.

Finally, the proportion of the area classified as Not Significant increases as the return period decreases (i.e., for more frequent floods). This indicates that while the spatial distribu-

Figure 7: Hotspot analysis (Getis-Ord Gi*) of potential economic damage for nine river flood (RF) return periods (RP). Maps illustrate the spatial evolution of statistically significant clusters. Red and orange shades indicate hotspots (high-damage clusters), blue shades indicate coldspots (low-damage clusters), and grey areas are not statistically significant. The analysis shows the persistence and expansion of hotspots in the northern industrial zones as flood magnitude increases.



Source: Authors.

tion of damage is more dispersed in low- to medium-magnitude floods, the risk becomes more spatially defined and concentrated in specific hotspots as the flood severity increases.

The spatial clustering patterns of potential economic damage calculated under the coastal flood (CF) scenario were investigated using Hotspot Analysis (Getis-Ord Gi*) (Figure 8). The analysis reveals that statistically significant hotspots (high-damage clusters) are less widespread and are concentrated in specific areas.

The results indicate that the hotspots with the highest statistical confidence (99%) are clustered in the northern and northwestern sections of the study area, corresponding to industrial and storage zones. Hotspots with lower confidence levels (90% and 95%) are found in smaller pockets surrounding these primary clusters and along the western edge of the port. In contrast to the river flood scenarios, it was observed that hotspots are less prominent in the inner parts of the port under the CF scenario.

Another notable finding is that no statistically significant coldspots were detected in the CF scenario. A large portion of the map falls under the Not Significant category, indicating that the damage distribution exhibits a statistically random pattern across much of the area.

To assess the local context and validity of the Copernicus / JRC-based river flood scenarios, the flood risk map prepared by the Turkish State Hydraulic Works (DSİ) for the Boğazay and Sarisu rivers was examined as a reference (Figure 9). This map, obtained from the AFAD (2021) report, shows the probable inundation extent boundaries modeled for the 100-year (Q100) and 500-year (Q500) return periods, based on peak discharge

Figure 8: Hotspot analysis (Getis-Ord Gi*) of potential economic damage for the coastal flood (CF) scenario. The map illustrates statistically significant spatial clusters based on the maximum sea-level rise projection. Red and orange shades indicate hotspots (high-damage clusters), while grey areas are not statistically significant. No significant coldspots were identified in this scenario.



Source: Authors.

values of $1355 \text{ m}^3/\text{s}$ and $1892 \text{ m}^3/\text{s}$, respectively.

Figure 9: Flood risk map for the Boğaçayı and Sarısu rivers, prepared by the Turkish State Hydraulic Works (DSİ). The map illustrates the probable inundation extent boundaries for the 100-year (Q100) and 500-year (Q500) return periods. These local model results were used as a reference to evaluate the general validity of the Copernicus/JRC data (Source: Adapted from AFAD, 2021).



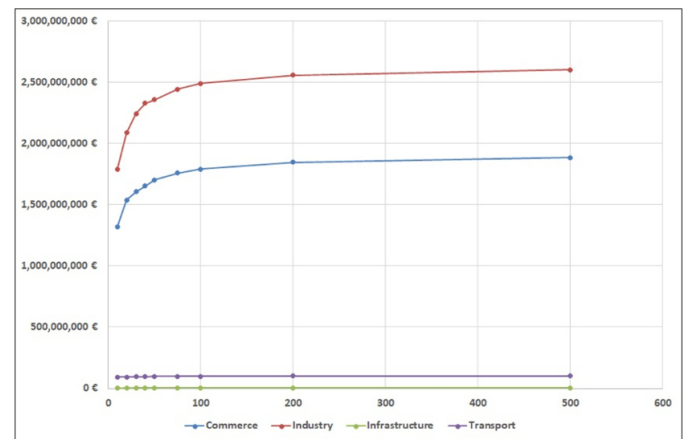
Source: Authors.

A visual comparison reveals a high general concordance between the inundation areas modeled by DSİ and the JRC-RF scenarios used in this study. Critically, the Antalya Port and its surrounding industrial and commercial zones are identified as flood-prone areas in both model sets for both the Q100 and

Q500 scenarios. The DSİ map specifies that the Q100 event affects an area of 1530 hectares, while the Q500 event affects 1620 hectares. This finding from the local model suggests that the global-scale JRC-RF data can provide a reasonable and consistent basis for identifying areas at risk of flooding in the specific case of the Antalya Port.

The potential economic impacts of river floods (RF) for different return periods (RP) were analyzed for four primary damage classes. Figure 10 illustrates the change in total calculated damage for each class as a function of the return period. The results reveal that the total damage in the port region is overwhelmingly driven by the Industry and Commerce classes, while the contribution from Infrastructure and Transport classes remains marginal.

Figure 10: Maximum flood damage per damage class for different river flood return periods (RP). The graph illustrates the estimated economic damage (€) for Commerce, Industry, Infrastructure, and Transport classes across nine return periods.



Source: Authors.

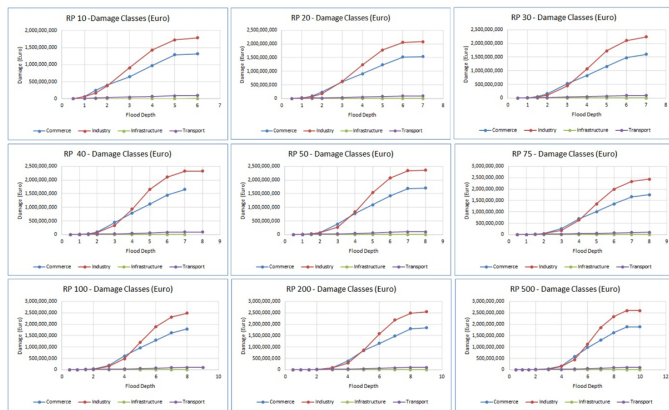
As shown in the graph, even in the most frequent flood scenario (RP10), the Industry class accounts for the highest share of damage, with an estimated loss of approximately €1.79 billion. This is followed by the Commerce class with approximately €1.32 billion. While damage increases in both classes with longer return periods, the dominance of the Industry class persists. For instance, in the RP100 scenario, damage to the Industry class reaches approximately €2.49 billion, compared to €1.79 billion for Commerce. This highlights the decisive role of the large spatial extent of the land (consists of mainly storage facilities and free zone) classified as Industry within the study area in determining the overall damage potential.

All damage curves exhibit a logarithmic saturation trend as the return period increases. The sharpest increase in damage magnitude is observed for the more frequent flood periods between RP10 and RP100. For rarer events beyond RP100 (i.e., RP200, RP500), the rate of damage increase slows considerably. For example, while the damage in the Industry class increases by 39% from RP10 to RP100, it increases by only 4.4% from RP100 to RP500. This pattern suggests that the most vulnerable and economically valuable assets in the port region

are already significantly affected by medium- to high-frequency flood events.

The sectoral components of the total damage and their distribution according to flood depth for each return period (RP) scenario are detailed in Figure 11. These graphs illustrate how floods of different probabilities affect the four main damage classes (Commerce, Industry, Infrastructure, and Transport) within the port region in distinct ways, and reveal the water depths at which the damage is concentrated.

Figure 11: Damage-depth curves for each damage class across nine river flood (RF) return periods. Each panel shows the damage (€) by flood depth (m) for the Commerce, Industry, Infrastructure, and Transport classes under a specific return period, ranging from RP 10 (top-left) to RP 500 (bottom-right).



Source: Authors.

The sectoral distribution of damage as a function of flood depth for the 10-year return period (RP10), representing the most frequent flood scenario, is presented in Figure 11 (RP 10). The analysis indicates that the maximum flood depth in the RP10 event reaches 6 meters, resulting in a total estimated economic damage of approximately €3.2 billion for Antalya Port region. At the maximum depth of 6 meters, the damage in the Industry class alone reaches approximately €1.79 billion, the damage in the Commerce class is calculated to be approximately €1.32 billion. Nevertheless, the damages to the Transport and Infrastructure classes are considerably lower at the maximum depth of 6 meter in comparison to industry and commerce. As the graph illustrates, the damage contributions from the Commerce and Industry classes are comparable at lower flood depths (between 0.5m and 2m). However, as the water depth exceeds 2 meters, the damage caused by the Industry class (red curve) significantly surpasses that of the Commerce class (blue curve), indicating that deeper waters have a greater impact on the extensive industrial areas within the port region. On the other hand, the damage to the Transport class increases rapidly after 1.5 meters, reaching €91.8 million at 6 meters and far exceeding the damage to Infrastructure (≈€4.2 million). This finding highlights that the port-hinterland networks (roads), which are critical for the port's operational continuity, are under flood risk even during frequent flood events, although relatively much more lower damage recorded.

In the 20-year return period (RP20) flood scenario, the maximum water depth was found to increase to 7 meters, with a corresponding total potential economic damage of approximately €3.72 billion for Antalya Port region. This represents a 16% increase in total damage compared to the RP10 scenario (Figure 11, RP 20). The sectoral damage distribution trend observed in the RP10 scenario continues in RP20, with the Industry and Commerce classes constituting the main components of the total damage. The damage to the Industry class surpasses that of the Commerce class once the flood depth exceeds 2 meters, and the gap between them widens as the depth increases. At the maximum depth of 7 meters, the total damage for the Industry class reaches approximately €2.09 billion, while the damage for the Commerce class remains at €1.54 billion. This indicates that an increase in flood severity further accentuates the economic impact on the extensive industrial areas of the port. While the damage in the Transport and Infrastructure classes also increases, their absolute values remain low in comparison. In the RP20 scenario, the damage to the Transport class reaches approximately €92.7 million, confirming that the port's operational areas are under significant risk even during medium-frequency flood events.

Upon analyzing the 30-year return period (RP30) flood scenario, the maximum water depth was observed to remain at 7 meters, while the total potential economic damage was calculated to be approximately €3.95 billion for Antalya Port region. This indicates a 6.2% increase in total damage compared to the RP20 scenario (Figure 11, RP 30). An examination of the sectoral damage distribution shows that the Industry and Commerce classes continue to be the main components of the total damage. Similar to the RP20 scenario, the damage to the Industry class surpasses that of the Commerce class once the flood depth exceeds the 2-3 meter range. At the maximum depth of 7 meters, the total damage for the Industry class reaches approximately €2.24 billion, whereas the damage for the Commerce class is calculated at €1.60 billion. This suggests that an increase in flood severity further accentuates the economic impact, particularly on the extensive industrial areas of the port. While damage in the Transport and Infrastructure classes also increases, their absolute values remain low in comparison. In the RP30 scenario, the damage to the Transport class reaches approximately €95.3 million, with the Infrastructure damage at a level of €4.6 million.

For the 40-year return period (RP40) scenario, the maximum flood depth was observed to increase to 8 meters, with the total potential economic damage calculated at approximately €4.08 billion for Antalya Port region. This value indicates a 3.3% increase in total damage compared to the RP30 scenario (Figure 11, RP 40). In the sectoral damage distribution, the trends observed in previous scenarios persist. The Industry and Commerce classes remain the primary components of the total damage. The damage to the Industry class surpasses that of the Commerce class once the flood depth exceeds 4 meters, reaching a maximum damage value of approximately €2.33 billion at a maximum depth of 8 meters for industry. The Commerce class follows with an estimated damage of approximately €1.65 billion at the maximum depth. Damage to the Transport class

increased to approximately €97.2 million, while damage to the Infrastructure class rose to €4.8 million. These increases suggest that the vulnerability of all functional areas within the port escalates with the increasing severity of the flood event.

In the analysis of the 50-year return period (RP50) scenario, the maximum flood depth was observed to remain at 8 meters, while the total potential economic damage was calculated to be approximately €4.16 billion. This value corresponds to a 2% increase in total damage compared to the RP40 scenario (Figure 11, RP 50). The slowing rate of damage increase suggests that the inundation of new areas in this scenario is limited, with the rise in damage primarily resulting from increased depths within previously flooded zones. Examining the sectoral damage distribution, the dominance of the Industry class becomes more pronounced in this scenario. The maximum damage occurs in the Industry class at approximately €2.36 billion, and in the Commerce class at approximately €1.70 billion. The gap between the two main damage classes continues to widen in favor of Industry after the 4-meter depth mark. The damage values for the Transport and Infrastructure classes reached approximately €98 million and €4.9 million, respectively. Although these values remain low in absolute terms, they indicate a gradual increase in risk to critical components that can affect the port's basic functionality, even in medium- to high-frequency flood events.

In the analysis for the 75-year return period (RP75), the maximum flood depth was observed to be 8 meters, with the total potential economic damage calculated to be approximately €4.30 billion. This corresponds to a 3.4% increase in total damage compared to the RP50 scenario (Figure 11, RP 75). The sectoral damage distribution shows a trend consistent with the previous scenarios. The Industry class continues to account for the highest damage with approximately €2.44 billion, while the damage in the Commerce class reaches approximately €1.76 billion. The gap between the two main damage classes continues to widen in favor of Industry after the 4-meter depth mark. The damage values for the Transport and Infrastructure classes were calculated to be approximately €99.4 million and €5 million, respectively. These gradual increases indicate that the vulnerability of all functional areas of the port escalates with the increasing severity of the flood event.

In the analysis for the 100-year return period (RP100), the maximum flood depth was observed to approach 9.0 meters, with the total potential economic damage calculated to be approximately €4.39 billion. This corresponds to a 2% increase in total damage compared to the RP75 scenario (Figure 11, RP 100). The sectoral damage distribution shows a trend consistent with the previous scenarios. The Industry class continues to account for the highest damage with approximately €2.49 billion, while the damage in the Commerce class reaches approximately €1.79 billion. The gap between the two main damage classes continues to widen in favor of Industry after the 4-meter depth mark. The damage values for the Transport and Infrastructure classes were calculated to be approximately €100 million and €5.1 million, respectively. These gradual increases indicate that the vulnerability of all functional areas of the port escalates with the increasing severity of the flood event.

In the analysis for the 200-year return period (RP200), the maximum flood depth was observed to reach 9 meters, with the total potential economic damage calculated to be approximately €4.51 billion. This corresponds to a 2.7% increase in total damage compared to the RP100 scenario (Figure 11, RP 200). The sectoral damage distribution shows a trend consistent with the previous scenarios. The Industry class continues to account for the highest damage with approximately €2.56 billion, while the damage in the Commerce class reaches approximately €1.84 billion. The damage values for the Transport and Infrastructure classes were calculated to be approximately €101.7 million and €5.2 million, respectively. Despite the slowing rate of increase, it is evident that even rare events contribute to the cumulative total risk across all functional areas of the port.

In the analysis of the 500-year return period (RP500), representing the rarest and most severe flood scenario, the maximum flood depth was observed to reach up to 10 meters, with the total potential economic damage calculated at approximately €4.59 billion. This value indicates a 1.8% increase in total damage compared to the RP200 scenario (Figure 11, RP 500). In the sectoral damage distribution, the Industry class stands out as the most dominant with approximately €2.60 billion, while the damage in the Commerce class reaches approximately €1.88 billion at the maximum depth of 10 meter. Unlike previous RF-RP scenarios, in the most extreme scenario, industry surpasses commercial damage after 5-6 meters, and the Industry class becomes dominant in deeper waters. The damage values for the Transport and Infrastructure classes were calculated to be approximately €103 million and €5.3 million, respectively. This extreme scenario reveals the maximum potential damage that all economic assets in the port region would be exposed to, establishing an upper-bound reference for adaptation strategies.

The analysis of the nine river flood (RF) scenarios reveals several key patterns regarding the magnitude, sectoral distribution, and spatial extent of maximum potential economic damage. The total potential damage exhibits a logarithmic trend with increasing return periods (RP). The most significant increase in damage occurs between RP10 (€3.20 billion) and RP100 (€4.39 billion), representing an approximate 37% rise. In contrast, the damage increases by only 4.5% from RP100 to the most extreme scenario, RP500 (€4.59 billion). This pattern indicates that the potential damage approaches a saturation point at higher return periods.

Across all flood scenarios, over 96% of the total estimated damage originates from the Industry and Commerce classes combined. The contributions from the Infrastructure and Transport classes remain marginal, accounting for only 0.1% and 2.2% of the total damage, respectively, even in the RP500 scenario.

While Industry damage is higher than Commerce damage in the most frequent scenario (RP10), the gap narrows in medium-frequency events. The dominance of the Industry class becomes more pronounced again at higher return periods, with its total damage exceeding that of the Commerce class by approximately €715 million in the RP500 scenario. This highlights a non-linear relationship in the vulnerability of the two primary economic sectors as flood severity increases.

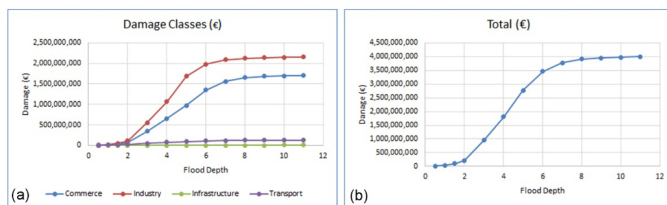
The total affected area remains remarkably stable across all return periods, varying minimally between approximately 2.36 million m² for both RP10 and for RP500. This finding indicates that even the most frequent flood event (RP10) is capable of inundating nearly the entire damage-prone portion of the study area which is approximately 2.5 million m².

The maximum flood depth progressively increases from 6.0 meters at RP10 to 9.0 meters at RP100, and reaches 10.0 meters at RP500. The observed deceleration of damage increase at higher RPs is therefore primarily associated with the saturation of the depth-damage functions rather than a significant expansion of the inundated area.

A notable discrepancy in magnitude exists between the Transport and Infrastructure classes. Damage to the Transport class ranges from approximately €92 million at RP10 to €103 million at RP500. In contrast, damage to the Infrastructure class only increases from €4.2 million to €5.3 million across the same range of scenarios, representing a nearly 20-fold difference in magnitude.

The sectoral and total damage distribution as a function of flood depth for the coastal flood (CF) scenario, developed based on sea-level rise (SLR), is presented in Figure 12. The analysis indicates that the maximum flood depth in the CF scenario reaches up to 11 meters. The graph (b) of the Figure 12 shows the damage curve, which reaches a maximum potential economic damage of approximately €3.99 billion.

Figure 12: Damage-depth curves for the coastal flood (CF) scenario. The graph (a) shows the cumulative damage (€) by flood depth (m) for each damage class (Commerce, Industry, Infrastructure, Transport). The graph (b) shows the total cumulative damage (€) for all classes combined, based on the maximum sea-level rise projection.



Source: Authors.

The graph (a) in Figure 12 details the sectoral breakdown of this total damage. Unlike some river flood scenarios, the damage to the Industry class is consistently higher than that of the Commerce class at all flood depths. The sharpest increase in damage for both main classes is observed between the 2 and 7-meter depth range. At the maximum depth of 11 meters, the Industry class alone accounts for approximately €2.16 billion in damage, while the Commerce class damage is calculated at approximately €1.71 billion. This suggests that the spatial extent of the SLR-induced inundation affects the large industrial areas within the port region more significantly than the commercial zones.

The contribution of the Transport and Infrastructure classes to the total maximum potential damage remains limited in this

CF scenario. The damage to the Transport class reaches approximately €127 million, and the Infrastructure class reaches approximately €5 million. All damage curves, including the total damage curve, begin to show saturation at around 7-8 meters of depth, indicating that deeper waters do not generate significant additional damage for these classes in this scenario.

A comparative analysis of the numerical results and damage curves for the river flood (RF) and coastal flood (CF) scenarios reveals that while both hazard types pose a multi-billion Euro potential damage risk to the port region, they exhibit distinct differences in magnitude and sectoral distribution.

When comparing the most extreme scenarios, the 500-year river flood (RF-Q500) results in the highest total damage at approximately €4.59 billion, whereas the maximum sea-level rise (CF-SLR) scenario is estimated at approximately €4.09 billion. The RF-Q500 scenario thus presents a potential damage that is roughly 12% greater than the CF scenario. The onset of damage also differs by depth; significant damages in the CF scenario begin at depths shallower than 1 meter, whereas in the RF scenarios, meaningful damage generally requires flood depths exceeding 2 meters. The damage curves indicate that potential maximum damage continues to increase up to a depth of 10 meters in the RF scenarios and saturated after RP100, while it reaches saturation after 7-8 meters in the CF scenario.

In both scenarios, over 96% of the total damage is attributed to the Industry and Commerce classes. However, the relative dominance of these two classes varies between the scenarios. In the CF scenario, damage to the Industry class is consistently higher than that of the Commerce class across all flood depths. In the RF scenarios, Commerce damage approaches or briefly surpasses Industry damage at intermediate depths, but the Industry class becomes definitively dominant in deeper waters. This suggests that the different depth profiles of the two flood types affect the land-use classes at different proportions.

In summary, the quantitative analyses confirm that the Antalya Port is under serious threat from both river and coastal flood risks. While river floods carry a greater total economic damage potential, coastal floods can initiate damage at much shallower depths. These differences in the sectoral distribution of risk underscore the need for an integrated adaptation strategy that considers the unique dynamics of both hazard types.

5. Discussion.

In this study, the complex and multidimensional risk profile of the Antalya Port Region concerning river (RF) and coastal (CF) flood hazards was quantitatively established. In this section, the obtained findings are interpreted, evaluations are made within the context of the existing scientific literature, the strengths and limitations of the employed methodology are addressed, and the implications of the results for policy, adaptation planning, and future research are discussed. The primary aim is to articulate the original contribution of this local-scale, multi-hazard damage analysis, conducted for the specific case of the Antalya Port, to the scientific body of knowledge on climate change-induced risks to critical coastal infrastructure.

One of the most striking findings of this research is that the Antalya Port Region carries a high risk of direct economic damage even under high-frequency flood events (e.g., RP10), for both river and coastal floods. The coastal flood scenario, based on sea-level rise (SLR) under a high-emission scenario, was also found to pose a similarly severe threat.

The dynamics underlying this high potential for economic damage appear to define the risk characteristics of the port region. A critical finding is the logarithmic saturation of the damage-return period curve. While the maximum potential damage increases significantly by approximately 37% from RP10 to RP100, the increase from RP100 to RP500 is only 4.5%. The primary reason for this trend is that the total inundated area remains remarkably stable across all scenarios (approximately 2.36 million m²). This indicates that even the most frequent flood event (RP10) is capable of inundating nearly all of the damage-prone assets within the study area. Consequently, the increase in damage during rarer events is observed to be driven more by rising water depths in already inundated areas rather than the expansion into new ones. However, due to the non-linear nature of the employed depth-damage functions, the rate of damage increase decelerates and reaches a plateau after a certain depth.

The findings point to a different outcome compared to traditional approaches in port risk management. Typically, infrastructure planning and insurance risk modeling reference extreme events, such as 100- or 500-year floods, to determine design standards and probable maximum loss. However, the results of this study reveal that approximately 70% of the maximum potential damage expected from a 500-year event already occurs during a 10-year event, which is statistically far more frequent. Similarly, previous studies emphasized that floods with short return periods have a significant impact on annual risk, and despite the relatively low economic damage per event caused by these flood events, they should be taken seriously in flood risk assessments (Ward et al., 2011; Baky et al., 2020). This suggests that the risk profile of Antalya Port is characterized less by rare (extreme) catastrophes and more by chronic, severe, and recurrent events. In this context, the term nuisance flooding seems inadequate; it is considered more appropriate to define these as high-frequency, high-impact events which has a potential to greater the annual risk for . As a result of this finding, a fundamental shift in adaptation policies may be required. Rather than developing engineering solutions solely against an extreme and low-probability event, a strategy that prioritizes managing and mitigating the impacts of floods statistically likely to occur multiple times within the operational lifetime of the infrastructure could be expected to be more effective.

Another important dimension of the risk profile is the spatial and sectoral distribution of damage. In all flood scenarios, it was determined that over 96% of the total direct damage is concentrated in the Industry (storage areas, free zone) and Commerce (commercial and tourism areas) land-use classes. This shows that the economic vulnerability of the port stems largely from the economic activities in its hinterland, rather than from its primary operational infrastructure (quay zone in-

cluding piers, berths and docks). The Getis-Ord Gi* hotspot analysis also reveals that this high-damage cost risk is not randomly distributed geographically, but instead clusters in a statistically significant and persistent manner in the industrial and commercial zones of the north and northwest across all scenarios. These super hotspots represent the economic epicenter of the port's vulnerability. This spatial pattern is shown to be a direct consequence of the combination of the low topography of these areas (as seen in the EU-DEM data) and the high economic value assigned to Industry and Commerce land uses in the damage model. This finding transforms an abstract, port-wide damage figure into a geographically sensitive risk map. For decision-makers, this can be a significant and concrete step in transitioning from general resilience planning to targeted and spatially-specific adaptation interventions.

The local findings obtained in this study for Antalya Port not only quantify a significant site-specific risk but are also considered to provide noteworthy validation and detail for recent findings from global-scale multi-hazard risk assessments of critical infrastructure. In particular, the emergence of river flooding as a dominant threat suggests that this hazard may be an underappreciated risk factor for port ecosystems worldwide relative to extreme catastrophic events like tsunamis, earthquake and tropical cyclons (Koks et al. 2019; Chua et al., 2021; Yavuz et al. 2022).

A multi-hazard risk analysis for 1,350 global ports by Verschuur et al. (2023) revealed that the total annual port-specific risk is USD 7.6 billion, mainly driven by floods (both river and coastal), alongside tropical cyclones, being among the most widespread and damaging hazards. They also revealed the share of ports at risk of river flooding is 80-84% of global ports and that the contribution of river floods to the total risk is 22.6% highlights the importance of site-specific studies on floods (Verschuur et al. 2023). Our finding that the potential damage from the most extreme river flood scenario (RP500) is higher than that from the extreme coastal flood scenario strongly supports this global assessment with high-resolution local evidence. Similarly, a pioneering global analysis on road and railway infrastructure by Koks et al. (2019) found that a large portion (~73%) of the approximately USD 22 billion in annual maximum damages stems from surface and river floods (Koks et al., 2019). Although that study did not focus directly on ports, our findings extend this thematic conclusion to the interconnected infrastructure within a port complex, reinforcing the paradigm that river floods are a primary risk factor for transport-related assets on a global scale.

The calculated damage magnitudes are also comparable to those of major historical disaster events. For instance, the damage to Louisiana's ports from Hurricane Katrina was estimated at approximately USD 1.7 billion (Verschuur et al., 2020). The damage estimate calculated in our study for a frequent 10-year event indicates that the potential risk in Antalya is of a similar order of magnitude to that observed in some of the best-documented port disasters.

In the regional Mediterranean context, recent assessments for Greek ports emphasize a significant vulnerability to coastal flooding from sea-level rise and extreme sea levels (ESL) (UN-

ECE, 2025). Studies in ports such as Chios and Volos predict the future inundation of main quays and coastal roads (UNECE, 2025). Our coastal flood analysis for Antalya aligns with this regional trend of increasing coastal risk for Mediterranean port cities by projecting widespread inundation of low-elevation industrial and commercial areas (MedECC, 2024). However, the dual-hazard focus of our study (river and coastal) reveals a critical nuance: while coastal flooding is a known and growing threat in the Mediterranean, the risk originating from short, steep river systems like the Boğaçayı—a common feature of the region's topography—may contribute even more significantly to direct economic damage for port regions. This is considered a notable contribution to the regional risk assessment literature.

The methodological framework employed in this study, integrates globally standardized hazard data and vulnerability functions with high-resolution local land-use data, offers a robust and transferable approach for port-specific risk assessment. Nevertheless, the inherent assumptions and generalizations within this framework necessitate a critical acknowledgment of its limitations, which in turn define clear pathways for future research. One of the primary strengths of the methodology is the application of JRC's global flood depth-damage functions (Huizinga et al., 2017). This approach grounds our local assessment in an internationally recognized, standardized methodology, making the results more comparable to other regional and global studies that use the same framework. This is a significant advantage in a field where ad-hoc and often incomparable damage assessments are common (Huizinga et al. 2017). The use of the Copernicus/JRC river flood hazard dataset, generated via the LISFLOOD model, provided a consistent and multi-return-period hazard assessment. The high general concordance observed between the JRC flood extents and those produced by local DSI models for the Q100 and Q500 events served as a critical local validation, increasing confidence in the suitability of the global dataset for this specific case study. Finally, the integration of the 1:5,000 scale Master Development Plan as the basis for asset classification is a significant advantage over the coarse-resolution, grid-based land-use datasets typically used in larger-scale assessments. This landuse-based approach allowed for a more precise spatial delineation of economic assets, resulting in more reliable damage estimates and hotspot detection (Genovese, 2006; Duo et al., 2025).

Nevertheless, the limitations of the methodology must be carefully considered. Although standardized, the JRC depth-damage functions are continental-level averages and have not been calibrated for the specific building typologies, construction materials, or economic conditions of ports in Turkey (Huizinga et al. 2017). As the literature indicates, the transferability of such functions is a significant source of uncertainty, and local validation is essential for accuracy (Ghamrawi et al., 2025). Therefore, our results should be interpreted not as a precise prediction of actual losses, but as a robust indicator of the order of magnitude of the risk.

Secondly, the Copernicus/JRC dataset does not explicitly account for local flood protection structures (e.g., levees, coastal walls). This means our damage estimates represent a potential or worst-case scenario under the assumption of either the ab-

sence or failure of such defenses, a critical context for interpreting the results. The use of a static bathtub model for the coastal flood scenario is also a simplification, as it does not account for hydrodynamic processes, wave effects, or the complex connectivity between coastal and inland water bodies that can influence real-world inundation patterns.

Finally, this study exclusively measures direct, tangible damages (i.e., the cost of repairing or replacing physical assets). It does not account for indirect economic losses such as business interruption, supply chain disruptions, and broader macroeconomic impacts (Botzen et al., 2019). As extensively documented in the literature, these indirect losses can often equal or exceed direct damages, particularly for critical infrastructure like ports that function as nodes in global supply chains (Verschuur et al., 2020). Therefore, the multi-billion Euro figures we found likely represent a conservative lower bound of the total potential economic impact of a major flood event.

This methodological limitation also exposes a critical blind spot in standard direct damage assessments. Our results indicate that the direct damage to Transport and Infrastructure classes is numerically insignificant compared to the Industry class. This is a direct consequence of a damage assessment methodology based on physical replacement cost per square meter. However, the function of the port is entirely dependent on its hinterland accessibility and infrastructure availability. Even a damage to a single, low-value access road could halt billions of Euros in trade and paralyze high-value industrial and commercial assets. This demonstrates that standard direct damage assessments measure asset value, but not systemic function. Consequently, for network infrastructures like ports, a direct damage assessment alone may be insufficient and potentially misleading for resilience planning. The true risk lies in the cascading consequences of operational failure, which are outside the scope of our model.

The quantitative and spatial findings of this study provide port authorities and municipal planners in Antalya with an evidence-based starting point to transition from reactive disaster response to proactive, risk-informed adaptation planning. This aligns with the academic imperative for transport stakeholders, including supply chain managers, to engage in proactive rational planning for natural hazards (Knemeyer et al., 2009). The results strongly support a targeted approach that prioritizes the protection of specific high-risk zones and port-related sectors.

One of the most tangible outputs of the findings is the persistent identification of statistically significant high - damage hotspots in the northern and northwestern industry areas (free zone and storages). Although the building and content based damage is out of the scope of this research, it is worthy to mention that hotspot zone adjacent to the quay part of the dock host key economic sector for the region, which is yacht building. This should provide a clear directive for adaptation investments. Instead of applying uniform protection standards across the entire port region, resources should be strategically allocated to these critical areas. This marks a significant advancement from traditional planning, which often relies on hazard maps (e.g., the DSI flood extent map). A hazard map shows where flooding may occur, and all inundated areas are generally treated equally.

This study, however, combines hazard with exposure (what assets are there) and vulnerability (how susceptible they are) to create a risk map measured in monetary terms. This can enable a paradigm shift in planning and allocation of resources. A low-value recreational park and a high-value industrial zone may be in the same hazard area, but our analysis demonstrates that protecting the industrial zone provides a much greater benefit in terms of avoided damage. The hotspot maps can be used as a direct policy tool for this risk-based prioritization (Armaroli et al., 2019).

This targeted approach can also guide the selection of appropriate adaptation strategies. For the identified hotspots, structural measures such as constructing localized flood walls, elevating critical industrial equipment and electrical substations, and improving stormwater drainage capacity could be highly effective (Indiana University Environmental Resilience Institute, 2025). Given that river floods pose the greatest monetary threat, adaptation planning must explicitly address the management of the Boğaçayı and Sarısu river basins. This extends beyond the port's boundaries and requires integrated planning with regional water management authorities (DSİ) and the municipality.

Finally, the concentration of high-value industrial and commercial assets in low-lying, flood-prone areas is the main driver of the massive risk profile. Future master development plans should incorporate this flood risk data to guide zoning decisions, potentially restricting new high-value developments in the most hazardous zones or mandating flood-resilient building codes.

While this study provides a comprehensive baseline assessment of direct flood damage for a port region, it also highlights several critical areas where further research is needed to refine risk estimates and develop more holistic resilience strategies for the Antalya Port and similar coastal infrastructures.

A primary area for advancement is moving beyond the generalized JRC functions. Future research should focus on developing depth-damage functions specifically calibrated for industrial, commercial, and port infrastructure typologies in Turkey, using empirical data from past flood events, expert elicitation, and structural analysis. This would significantly reduce the uncertainty in damage estimations (Ghamrawi et al., 2025).

Second, the static models used here should be replaced by dynamic 2D hydrodynamic models for both river and coastal flood scenarios. Such models could provide more realistic inundation scenarios by incorporating the effects of existing and proposed flood defenses, wave dynamics, and the complex interactions between storm surge and river discharge.

As highlighted in the limitations, the exclusion of indirect damages is a significant shortcoming. Future work should employ economic models (e.g., Input-Output or Computable General Equilibrium models) to quantify business interruption losses and supply chain disruptions resulting from port downtime due to inundation. This would offer a much more comprehensive picture of the total economic risk (Botzen et al., 2019). Furthermore, this study analyzed river and coastal floods separately. Future research should investigate the risk from compound events, where extreme precipitation (causing river floods)

and storm surge (causing coastal floods) occur concurrently, as these can lead to significantly more severe flooding than either event in isolation. Finally, building upon this and similar risk assessments, future studies should conduct detailed cost-benefit analyses of specific adaptation measures (e.g., comparing the construction of a coastal wall around the industrial zone versus the elevation of individual assets) under various future climate change scenarios (e.g., IPCC SSPs) to identify the most economically optimal adaptation pathways.

6. Conclusion.

This study has quantitatively assessed the direct economic vulnerability of the Antalya Port Region to both river and coastal flood hazards by integrating a standardized methodology with high-resolution local data. The principal findings reveal that, contrary to general expectations, the port's flood risk profile is dominated not by rare, extreme events, but by a high susceptibility to more frequent, low- to medium-return-period floods. Furthermore, it was determined that the economic risk is not randomly distributed; instead, it is spatially concentrated, forming statistically significant and persistent hotspots in the low-lying industrial and commercial zones in the northern and north-western sections of the port.

The primary scientific contribution of this work is that it helps to fill a significant gap in the literature by providing a port-specific, multi-hazard (RF+CF), and spatially explicit quantitative damage assessment. It also presents a transferable framework demonstrating how a global-scale damage methodology can be successfully integrated with high-resolution local data. In practical terms, these findings provide an evidence-based foundation for decision-makers to spatially prioritize adaptation strategies (focusing on hotspots) and to identify cost-effective protection levels (e.g., the RP100 tipping point).

It should be noted that the results must be interpreted within the context of certain limitations, such as the analysis focusing solely on direct physical damage while excluding indirect economic losses, and the inherent assumptions of the models used. Nevertheless, this study underscores the importance and urgency of detailed, evidence-based risk analyses for enhancing the resilience of critical coastal infrastructures like the Antalya Port in the era of climate change. Future research should build upon this foundation to include the modeling of indirect economic impacts and to conduct comprehensive cost-benefit analyses of different adaptation scenarios.

Credit Authorship Contribution Statement.

Seyma Bayazit: Conceptualization, Investigation, Methodology, Resources, Data curation, Formal analysis, Validation, Writing – original draft, Writing – review and editing. Tunçay Kuleli: Conceptualization, Methodology, Resources, Software, Formal analysis, Supervision, Validation, Visualization.

Declaration of Competing Interest.

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability.

Data will be made available on request.

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