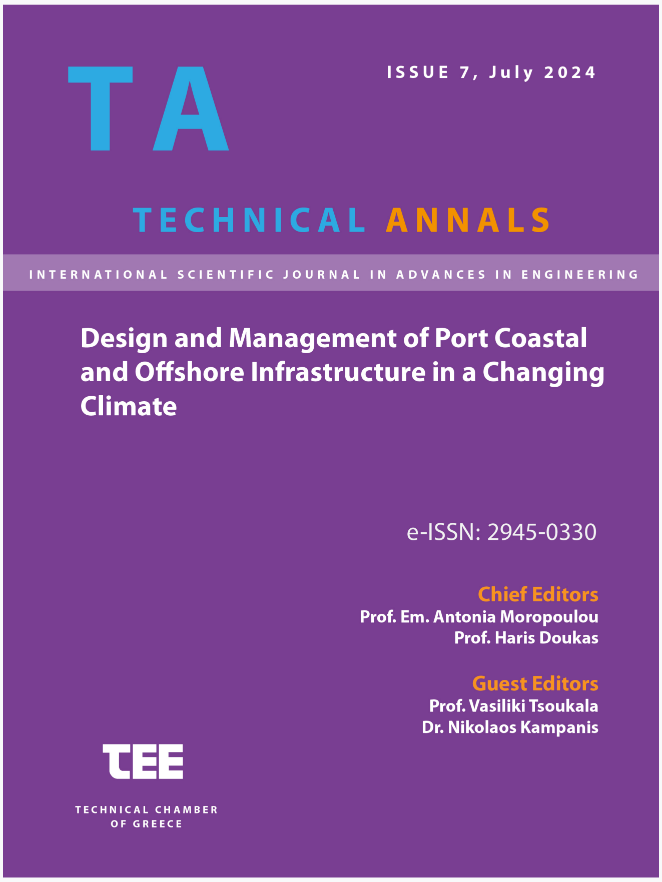
Technical Annals

Vol 1, No 7 (2024)

Technical Annals



The Impact of Sea Level Rise on the Port of Heraklio: Operational Risk Assessment and Economic Implications

Aikaterini Karditsa, Efthimios Roumpis, Fragkiskos` Markozanes, Matina Lesioti, Isavela Monioudi, Serafeim Poulos, Maria Hatzaki, George Vaggelas

doi: 10.12681/ta.40810

The Impact of Sea Level Rise on the Port of Heraklio: Operational Risk Assessment and Economic Implications

A. Karditsa[1], E. Roumpis[1], F. Markozanes[2], S. Lesioti[2], I. Monioudi[3], S. Poulos[2], M. Hatzaki[2] and G. Vaggelas[1]

[1]Department of Ports Management and Shipping, National and Kapodistrian University of Athens, Evripos Campus, Greece
[2]Laboratory of Physical Geography, Sector of Geography and Climatology, Department of Geology and Environment, National and Kapodistrian University of Athens, Greece
[3]Department of Marine Sciences, University of the Aegean, Mytilini, Greece
kkarditsa@pms.uoa.gr

Abstract. Rising sea levels pose a significant threat to coastal infrastructure, particularly seaports, which are vital to global maritime trade. This study assesses the impact of sea level rise (SLR) on the Port of Heraklio, Greece, contributing to the broader discourse on climate change in the port sector while providing a framework for evaluating and quantifying economic consequences. Using Digital Elevation Model (DEM) analysis, historical sea level trends, and projections under the high-emission SSP5-8.5 scenario, the study examines port's vulnerability to operational disruptions. Findings indicate that lower-elevation docks, particularly those of 1.8 m, are highly susceptible to water level exceedances, affecting passenger ferries, cruise ships, and dry bulk cargo operations. Historical analysis (1998–2023) reveals a mean Total Sea Level of 0.61 m, with extreme values reaching 1.14m, while operational sea level thresholds range from 0.91 m to 1.31 m, depending on dock height.The frequency of threshold exceedances has increased from less than one event/year prior to 2005, to approximately four events/ year since then. By 2030, these events are projected to occur on ~44 days annually, escalating to ~186 days by 2050, rendering many docks inoperable. However, docks above 2.1 m remain largely functional, underscoring elevation as a critical resilience factor. Financially, cumulative revenue losses are estimated at €3.1 million by 2030, rising to €32.2 million by 2050.These findings highlight the urgent need for adaptation measures to mitigate economic and operational risks. Practical implications emphasize the necessity of integrating climate resilience strategies into port planning, particularly for insular regions where maritime connectivity is essential.

Keywords: Ports, Climate Change, Resilience.

1 Introduction

Rising sea level is expected to significantly amplify the existing threats of coastal flooding, inundation of low-lying areas, and permanent erosion of shorelines[1]. These changes will have broad consequences for vital coastal infrastructure, particularly seaports, which serve as vital hubs for global maritime trade[2].

Recent studies have highlighted that ports are particularly exposed to multi-climatic factors' extremes and state the risk of growing impacts[3][4] mainly in the absence of effective adaptation measures[5] and considering that ports are infrastructures located on coastlines, vulnerable to climate change impacts. The multi-hazard conditions are projected to escalate dramatically under a very high greenhouse gas (GHGs) emission scenario[6]. This intensification of climate-related risks will generate profound economic and societal repercussions. The heightened vulnerability of ports could lead to widespread disruptions, costly delays, and extensive structural damage, undermining their operational efficiency and resilience. With over 80 % of world trade volume carried by sea - from port to port, they are crucial hubs and strategic assets to future trade and development prospects[7], thus, any climate-induced impairments will reverberate across international trade networks, affecting industries, economies, and livelihoods on a broad scale[8].

Under high warming scenarios, by 2050, Extreme Sea Level (ESL), i.e. the sum of Mean Sea Level, the astronomical tide and the episodic storm surges and wave set-up, is anticipated to increase by up to 0.5 m above the baseline (mean of 1976 – 2005) period values affecting more than half of the large and medium-sized ports, whereas by 2100, ESL is anticipated to be reaching up to 1.6 m affecting more than two thirds of the large and medium-sized ports[9].

Furthermore, the economic implications are substantial. Under current conditions, global average annual storm damage to ports is estimated at roughly US$3 billion. By 2100, additional annual damages and port disruption costs could escalate to up to US$25.3 billion if effective adaptation measures are not implemented[9][10].

Under this concern, climate change emerged as a top-10 priority for the port sector in 2018 and rose to the foremost position by 2022, where it remains[11]. In recent years, there has been a concerted effort to develop environmental regulations aimed at addressing the impacts of climate change on the (trans)port sector. The European Union's Green Deal strategy emphasizes adaptation to climate change as a crucial step.

A significant portion of port infrastructure was developed according to outdated climatic expectations[12] rendering them vulnerable to current and future climate-induced hazards, thus, a timely re-evaluation of established practices is considered to be urgent. Therefore, considering the essential character of ports in the global trading system, enhancing their climate resilience by introducing prevention and mitigation measures addressing climate impacts, becomes a major priority as part of sustainable development and a matter of strategic economic importance[13]. This is a challenge that although many recent studies worldwide underscore[14][15][16]. and is expected to determine the future vulnerability of ports[17], only a limited number of port authorities have begun to address.

The compounded impacts of rising sea levels and extreme weather events underscore the urgent need for adaptive strategies, infrastructural reinforcements, and sustainable mitigation measures to safeguard these essential gateways of commerce. In light of these challenges, it is imperative for stakeholders, including policymakers and industry leaders, to collaborate on developing and implementing comprehensive adaptation strategies. These should focus on enhancing the resilience of port infrastructure, integrating climate risk assessments into port planning and operations, and investing in sustainable technologies to mitigate the adverse effects of climate change on global supply chains[18]. Moreover, climate change adaptation strategies are often considered more effective than mitigation, as they focus on local to regional spatial and short- to medium-term temporal scales, facilitate national and regional cooperation, and can be proactive when based on projected climate impacts[19].

Failure to prepare for climate change could lead to severe economic and infrastructural consequences, whereas investing in climate resilience is not only a prudent strategy but also a financially sound one, as the long-term benefits of preparedness consistently outweigh, and often greatly exceed, the costs associated with adaptation measures[20][21]. It is worth stating that although adapting ports to rising sea levels entails significant investment costs[22], the long-term economic benefits of resilience far outweigh the initial expenditures. According to World Bank projections[23], investing in climate-resilient infrastructure in developing countries could yield net benefits of approximately US$4.2 trillion over the infrastructure's lifetime. This translates to a remarkable return of US$4 in benefits for every dollar allocated to resilience measures, underscoring the critical importance of proactive adaptation strategies in mitigating climate-related risks[9].

Looking beyond 2050, all ports will need to be adapted to climate change focusing on minimizing, eliminating or mitigating its impacts. The potential adverse impacts of climate change are wide-ranging, but they vary considerably depending on the port’s particular characteristics such as physical setting, climate forcing, type of port activities etc. The scope of this study is to develop a framework for climate change impacts in ports with a focus on the physical and operational impacts of sea level rise, in the case study port of Heraklio in Greece, in order to identify adaptive needs and policies in the port aiming at tackling and mitigating these impacts.

2 Study Area

The Port of Heraklio (Figure 1) is located on the north coast of Crete and is one of the most important ports in Greece, both for tourism and trade. Due to its geographical location the port of Heraklio has potentials to be become a hub in the Eastern Mediterranean Sea[24] especially following the engagement of a significant liner shipping operator (Grimaldi Group) in Port Authority’s (PA’s) ownership as the Greek State sold the 67% of the PA’s shares[25]. The port of Heraklio is one of the five Greek ports belonging to the core Trans-European Transport Network (TEN-T) located in the middle of the main shipping lane connecting the Atlantic and Western Mediterranean with the Red Sea and the Indo-Pacific Ocean.

The Port of Heraklio is located at latitude 35º20'35.28" N and longitude 22º08'03.61" E. It extends approximately 2.1 km from east to west and is bounded by the Gulf of Dermata (west) and the boundaries of the municipality of Alikarnassos (east)[26]. The port area includes a water surface of 0.87 km^2 with a minimum depth of 3.5 m and a maximum depth of about 14.2 m. The area belongs to the continental margin of the central Cretan Sea, which is narrow (<10 km) and relatively steep (slope 1.5°) and becomes wider towards the east. The shelf extends to depths ranging between 100 m and 150 m, followed by a relatively steep slope (2°-4°), whereas it is exposed, on an annual basis, to wind-driven waves of mainly NW (23.62%), N (12.43%) and partly E (6.79%) origin, the maximum significant wave height of which is 6.3 m, 5.9 m and 3.2 m, respectively[27]. The average tidal range is less than 10 cm[28] and the meteorologically induced sea level rise may exceed 1 m[29].

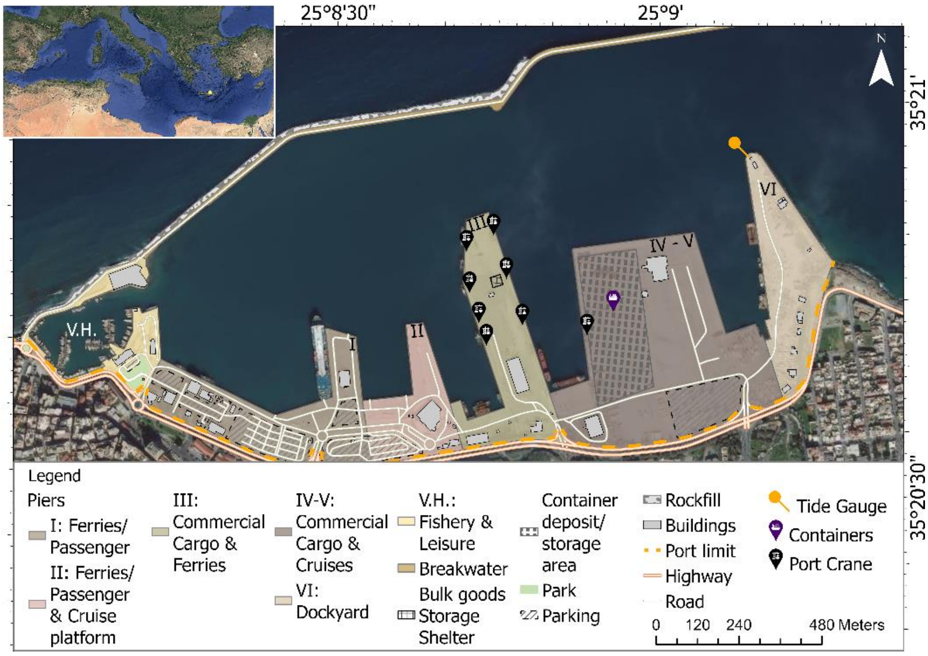


Fig. 1. Presentation of the Port of Heraklio

The port of Heraklio consists of the old Venetian harbour, the Venetian fortress of Koules, 6 piers and the breakwater and a 2.3 km long breakwater-oriented WSW-ENE. In the old Venetian harbour, fishing boats and pleasure craft are moored, while the 6 piers are used for cargo and passenger traffic. More specifically, the activities that take place in the port are: (a) leisure activities and small-scale fishing, (b) facilitation of ferries, (c) cruise ships, (d) RO-RO activities, (e) facilitation of cargoes and (f) shipyard activities. The port is a significant value-added generator for the local economy as in 2023 revenues reached €8.7 million, while it is the main port facilitating the trade needs of Crete Island with a population close to 500.000 people[29]. With approximately 2,600 vessel calls a year of which more than 80% are passenger ships, the port is a critical element for connecting Crete with mainland Greece being a critical infrastructure for the country's social cohesion. In particular, as of 2023 the port served 1.6 million passengers from passenger ships and 380,000 cruise passengers, making it the third busiest cruise destination in the country, behind the ports of Piraeus and Corfu. In cargo operations, the port handled 110,000 tons of dry bulk cargo and 17,000 containers[30].

3 Methodology

The potential risk with respect to SLR examined in this study includes assessing the physical and economic impact in Heraklio port due to disruptions in maneuverability, berthing, and loading/unloading operations within the harbour area induced by high water levels (Table 1). This approach emphasizes the role of climate change in increasing risks to port operations when no adaptation measures are in place. In fact, it refers to the worst-case scenario, as ports are expected to develop and apply adaptive strategies over time to remain competitive within the global trade network.

Table 1. Investigated impacts and associated examined factors

Impact	Examined Factor	Description of factor
Physical	Operational Threshold	Infrastructure (air draft clearance) height
Economic	Commercial Activity	Loss of revenues due to activity disruption

3.1 Data Collection and Analysis

To assess the physical and economic impact of SLR on operational activities in the Heraklio port, the following datasets were collected and analyzed:

(i) A Digital Elevation Model (DEM) (0.5*0.5 m spatial resolution) of the port area along with Drone Imagery (0.25*0.25 m spatial resolution) (Hellenic Cadastre S.A), the combined analysis of which, through in a ArcMapPro resulted in the generation of the 3D map of the port.

(ii) Hourly values of sea level from the tide gauge of the Hellenic Navy Hydrographic Service located at the port of Heraklio, for the period 1998-2023. Based on the station deployment, zero water level coincides with the lowest low water level in the area. Tide gauge recordings were used as baseline information and are perceived as the Total Sea Level (TSL) i.e. the sum of Mean Sea Level, the astronomical tide and the episodic storm surges. Since height elevations in the Digital Elevation Model (DEM) are referenced to mean sea level, while the tide gauge's zero level corresponds to the lowest low water level, a standard adjustment was necessary to align these two reference points. To achieve this, sea level oscillation values were calculated by shifting the mean sea level reference down to the tide gauge's zero level, ensuring consistency in measurements. Further sea level measurements' statistical analysis was executed in R programming language.

(iii) Future Total Sea Level conditions were reached after the aggregation of Sea Level Rise (SLR) projections to the current conditions provided by the analysis of 1997- 2023 timeseries. Given that the planning lifetime of port infrastructure typically spans to approximately 50 years, sea level rise considerations encounter the extreme GHG emissions SSP5-8.5 scenario at the mid of periods 2020- 2040 (i.e. 2030) and 2040-2060 (i.e. 2040)[31], corresponding to 0.15 m (0.09–0.22 m) and 0.32 m (0.22–0.49 m) in the area of Heraklio Port, respectively, above the baseline (1976 – 2005).

(iv) The economic impact of rising sea levels and extreme weather events on port operations. Cargo, vessels and passenger throughput data were used along with financial data in order to estimate the revenue per segment by a specific period of time. The source of data primarily includes the port's annual reports, the Association of GrePorts (2024)[30] and Greek Ports website [31].

3.2 Data Collection and Analysis

The methodology used to assess impact on operational activities is based on operational thresholds used to determine the climatic conditions under which operations might be impeded. To ensure the safe execution of port operations while preserving both the vessel's integrity and overall port functionality, it is crucial to maintain air draft clearance, i.e. the vertical distance between the top of the berth and the water level, within specific safety limits, as it plays a vital role in preventing structural conflicts and operational hazards. These safety limits are carefully determined by factoring in the vessel's structural design, port characteristics, and the specific type of maritime activity (i.e. fishing, leisure and commercial) at the Recommendations for the Design of Maritime Works (ROM 2.0-11)[32]. Accordingly, based on the port's defined safety operating requirements, the recommended minimum air draft clearance —relative to the highest sea level of the outer waters during extreme conditions—should be no less than 1.5 m to prevent overflow risks during commercial operations.

In port operations, an additional safety (operational) margin, prevents accidents caused under adverse conditions by factors like tidal fluctuations, vessel motions, or structural shifts. Therefore, the operational threshold is not exceeded when the air draft clearance, above sea level, is greater (or at least equal) to berth height, safeguarding the existence of a safety margin (Figure 2). Under these criteria, the association of operational thresholds to the given air draft clearance led to the operational principle described in Table 2.

Table 2. Operational principle based on the operating requirements

Status	Principle
Operable	Air Draft Clearance ≥Mean TSL (+SLR) + Operational Requirement
Inoperable	Air Draft Clearance <Mean TSL (+SLR) + Operational Requirement

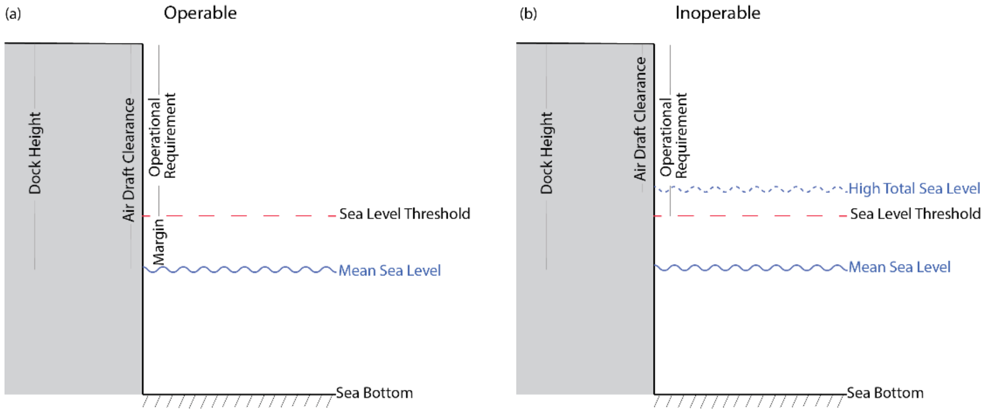


Fig. 2. Presentation of the case where port is (a) Operable and (b) Not Operable

3.3 Economic Impact Assessment

To evaluate the economic impact of climate change for the Port of Heraklio, the potential disruptions in port operations and the resulting loss of revenues, caused by sea level rise and extreme weather events, are assessed. Firstly, a comprehensive analysis of the port's operational profile is conducted, including the types of cargo handling, passenger traffic and vessel calls, to identify key exposures to climate-induced disruptions. Subsequently, for each activity, we integrate annual data over the period 2010-2023 on vessel calls (cargo, passenger and cruise), cargo volume (general, dry bulk and containerized) and the number of passengers. A simple trend analysis is carried out for the considered data, with a prediction period from 2024 to 2050. The assumptions about future growth for cargo throughput and vessel calls up to 2050 are seen in Table 3 and Figure 3.

Table 3. Summary of cargo volume and passenger traffic for the prediction period

Activity	**2024**	**Average annual growth from 2024 to 2050**
Container	22,153	1,1% per year to 29,127 TEU in 2050
Dry bulk cargo	111,100	1,0% per year to 143,903 tons in 2050
General Cargo	66,660	1,0% per year to 86,342 tons in 2050
Vessel calls	2,557	1,9% per year to 4,133 vessels in 2050

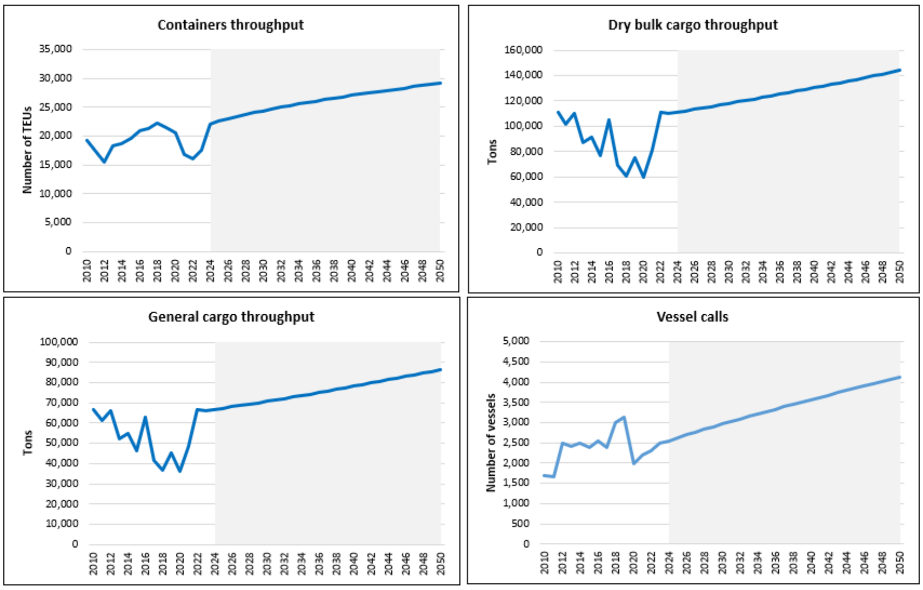


Fig. 3. Cargo volume throughput and vessel calls

Although a port serves as a hub for various activities and generates revenue from multiple sources, an analysis of the revenue streams of the port of Heraklio suggests that most of its revenues comes from services and facilities provided to vessels, cargo, and passengers, accounting for approximately 90% of total revenues. Specifically, revenue streams include revenues from cargo unloading and loading services, storage of cargo services, mooring services, dry docking, the provision of electricity and water to the vessels, the waste handling of the vessels, and income from passenger and vehicle dues. Using revenue data from the annual reports of 2022 and 2023, the revenue per unit cargo and passenger/vehicle is estimated (Table 4). The revenue for containers is 38.5€ per container; bulk cargo and general cargo receive 0.85€ and 1.02€ per ton, respectively. The total passenger and vehicle revenue is 1,532€ per passenger vessel call, the revenue for cruise passengers is 1.53€ per passenger and finally the revenue from vessel port dues is 699€ per vessel call.

Table 4. Operational principle based on the operating requirements

Product/Service	Revenue (€)
Container	38.5 per container
Dry bulk cargo	0.85 per ton
General Cargo	1.02 per ton
Passenger and vehicles	1,532 per vessel call
Cruise passengers	1.53 per passenger
Vessels port dues	699 vessel call

A port disruption can temporarily reduce the revenue a port generates by either limiting its operational capacity or suspending its operations. This study focuses on revenue loss, assuming that port operability gradually declines over time in the absence of adaptation measures. The daily total cost of interruption is estimated based on lost revenue per service and product (calculated using the revenue per unit along with projected cargo throughput and vessel calls) over the period 2024-2050. Then, the annual lost revenue is determined by incorporating the expected number of days per year when sea levels surpass operational thresholds.

4 Results

4.1 Port features

DEM construction revealed the topographic characteristics of the port. A crucial factor in assessing susceptibility to sea level rise (SLR) is the dock height, as lower elevations are more prone to disruptions due to operational threshold exceedances. At the port of Heraklio a significant number of docks have heights at 1.8 m, including the entire Dock I, Dock II-2 to II-4, Dock III-2 to III-4, and Dock IV/V-4. These docks are primarily associated with passenger ferries, cruise ships, and dry bulk cargo operations. Dock III (III-5, III-6) and Dock IV/V (IV/V-1 to IV/V-3, IV/V-5) have heights of 2.1–2.2 m, whilst Dock IV/V, a major freight and cruise hub, stands out with consistently high elevations and large dock areas (Table 5).

Table 5. Characteristics of the port of Heraklio

Dock	Berth	Type of Activity	Dock Height (D_h)	Dock Length (km)	Dock Area (acres)
Dock I	I - 1	Passenger ferries D+A: To Piraeus, Cyclades	1.8	1.02	78.89
	I - 2		1.8		
	I - 3		1.8		
	I - 4		1.8		
	I - 5		1.8		
Dock II	II - 1	Passenger ships/Cruise ships D: To Piraeus, A: Cruises	1.9	0.65	40.66
	II - 2		1.8		
	II - 3		1.8		
	II - 4		1.8		
Dock III	III - 1	Dry bulk and general cargo, cereals, fertilizers in bags and salt	1.9	1.39	67.25
	III - 2		1.8		
	III - 3		1.8		
	III - 4		1.8		
	III - 5		2.2		
	III - 6		2.1		
Dock IV/V	IV/V-1	Freight/Cruise ships D: Containers, B+A: Cruise ships	2.2	1.32	183.91
	IV/V-2		2.2		
	IV/V-3		2.2		
	IV/V-4		1.8		
	IV/V-5		2.1		

4.2 Present and future sea level analysis

The statistical analysis of sea level timeseries by means of Central Tendency and Dispersion, i.e. mean, standard deviation, range, median, variance, quartiles and inter-quartile range for the records of the sea level historical (baseline) period (1998-2023) are presented in Table 6, whilst Sea Level data variability and distribution are displayed in Figure 4. The results show that mean value of the Total Sea Level has been estimated as 0.61 m for the baseline period, whereas extreme sea level values reach 1.14 m.

Table 6. Descriptive Statistics for the sea level time series of the Heraklio Port

Descriptive Statistics Heraklio Port							
Variable	Count (n)	Min	1^{st} Qu.	Median or 2^{nd} Qu.	Mean	3^{rd} Qu	Max
SEA LEVEL RECORD	171.74	0.16	0.56	0.66	0.61	0.73	1.14

Descriptive Statistics Heraklio Port						
				Percentiles		
Variable	Std.Dev.	Obs. Range (min-max)	Vari-ance	0.90%	0.95%	0.99%
SEA LEVEL RECORD	0.125	0.98	0.016	0.79	0.83	0.91

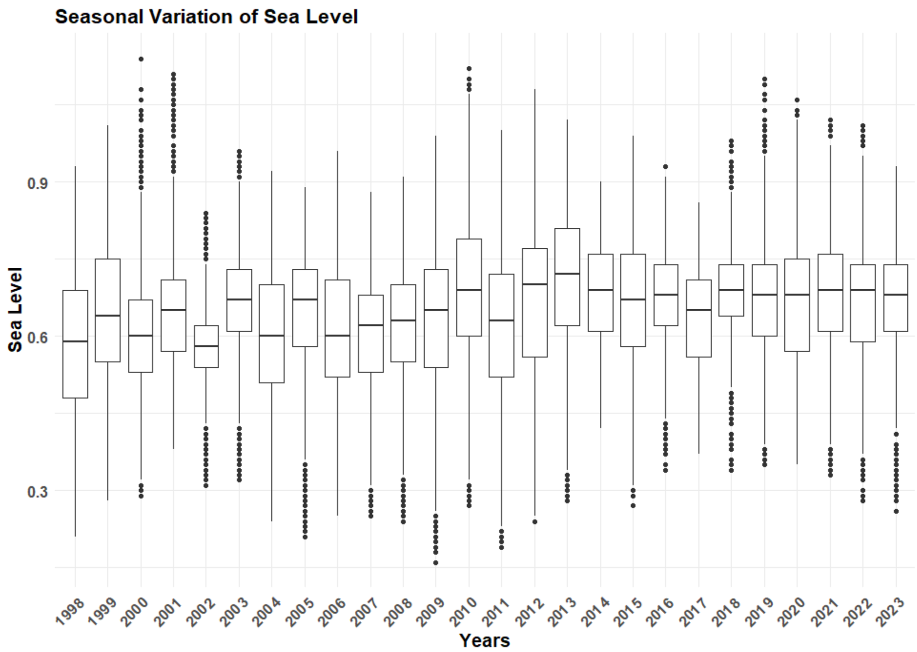


Fig. 4. Annual distribution of the sea level state for the baseline period (1998 – 2023)

Future Total Sea Level conditions were determined by aggregating sea level rise (SLR) projections under the high-emission SSP5-8.5 scenario with existing conditions[33]. Table 7 presents the estimated mean sea level projections values for the two different time periods considered in this study (2020-2040 and 2040-2060), along with the upper and lower bounds, under the SSP5-8.5 emission scenario.

Table 7. Mean estimated values of Sea Level for the periods 2020-2040 and 2040-2060 along with upper and lower values

Period	**Sea level (m)**
1998-2023 (Baseline)	0.61 (0.16, 1.14)
2020-2040 (~2030)	0.76 (0.25, 1.36)
2040-2060 (~2050)	0.95 (0.38, 1.59)

4.3 Present and future impact on port operations

Operational requirements were applied to assess the sea level conditions that might disrupt port operations and define the water level the exceedance of which might lead to adverse effects (sea level threshold exceedance). The implementation of the predetermined operational principle (ie. 1.5 m freeboard)[32] at each side of the piers/ docks indicated that as dock height ranges from 1.8 m (Dock I and II) to 2.2 m (Dock III and IV), operational upper sea level thresholds in Heraklio port range from 0.91 m to 1.31 m, correspondingly.

Following these thresholds, under existing (baseline) mean sea level conditions (0.61 m), all berths generally maintain, an air draft compatible to the requirements, ensuring near-full operability throughout most of the baseline period. Throughout the period, the port has been exposed to inoperability for an extremely low number of events/hours, indicating that the majority of docks are functional under current sea level conditions, with events of exceedance having a minimal impact on overall port operations. Specifically, based on the time series analysed, exceedance events are historically evident with an average of 72.85 hours of exceedance/year, i.e. approximately 3 days/year. The minimum recorded value is only 1 hour of exceedance while the maximum reaches 307 hours of exceedance (Figure 5).

More importantly, Sea level values above the defined threshold are either absent or very sparse during the period 1998-2005 (0.9/year). However, there is a noticeable increase in extreme values, particularly in the years around 2010-2012, where outliers above sea level threshold become more frequent (4.2/year). The number of extreme values remains relatively high during 2013-2022, showing consistent occurrences of values above threshold.

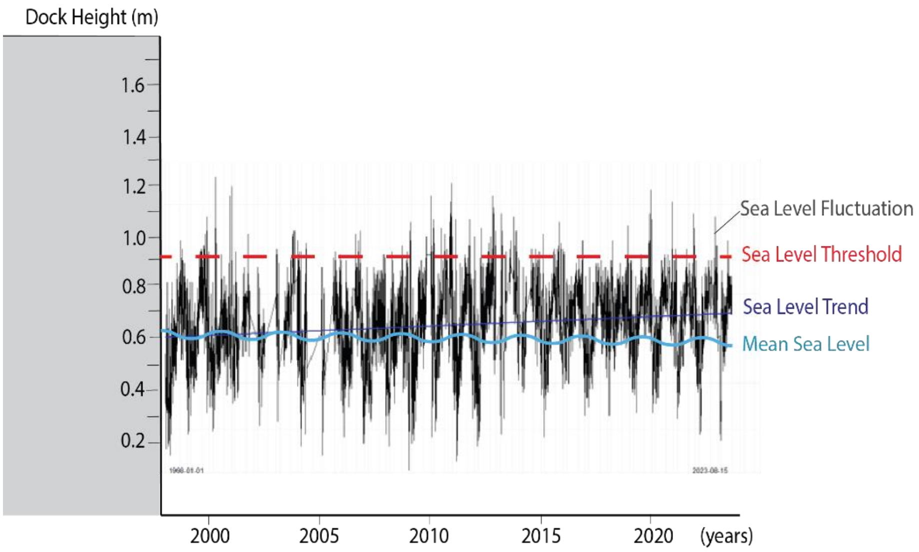


Fig. 5. Annual distribution of the sea level fluctuation with respect to operational threshold and dock height (1.8m)

In terms of future impacts, the application assumes that no adaptation measures are implemented by the port organization, thereby the port maintains the current port topography. The application of the produced thresholds to the expected sea levels indicates a progressive decline in port operability over the 21st century due to sea level rise (SLR), with the severity of the impact varying according to the dock heights. In particular, the analysis indicates a significant increase in inoperability due to sea level rise (SLR) for all piers with heights below 2 m, with the most pronounced impact observed in docks ranging from 1.80 m to 2.0 m. Specifically, Docks I-1, II-3, III-4, and IV/V-4 exhibit a marked rise in the count of exceedances, total hours of exceedance, and percentage of exceedances from 2025 to 2050. This trend suggests that docks within this height range are particularly vulnerable to SLR-induced operational disruptions. In contrast, docks higher than 2 m remain largely unaffected over all periods, suggesting that their heights provide resilience to the projected sea level changes. Notably, Dock IV/V demonstrates consistently low or negligible exceedances in both scenarios, further supporting the notion that sufficient elevation mitigates the risk of exceedances and ensures continued functionality under rising sea levels.

In addition, the number of exceedances observed increases to 1073.31 exceedances/year (≈44.72 days/year) by 2030. The 75th percentile is 35 exceedances/year (≈1.5 days/year), while the 25th percentile is 2357 exceedances/year (98.2 days/year). The wider IQR and elevated median in the box plot indicate that several docks begin to experience significant disruptions, with some exceeding operational limits frequently. The upper whisker extension suggests that certain docks are already facing severe limitations in usability, particularly those with lower clearance heights. This trend signals a shift toward more frequent operational challenges, necessitating early adaptation measures to maintain efficiency.

By 2050, the exceedance count escalates dramatically, with a mean of 4468.54 exceedances/ year (186,2 days). The 75th percentile is 934 exceedances (38.9 days/ year), while the 25th percentile reaches the alarming 6994 exceedances (291.4 days/ year). The box plot (Figure 6) shows the exceptionally large IQR and high upper whisker in (%), emphasizing that exceedance events will become extremely frequent. The median count has increased considerably, highlighting the fact that many docks will be out of service for extended periods, while the port will become permanently disrupted under constant extreme water levels. This scenario suggests that, without mitigation strategies, port functionality will be severely compromised, reinforcing the critical need for infrastructure adaptation to counteract the effects of rising sea levels.

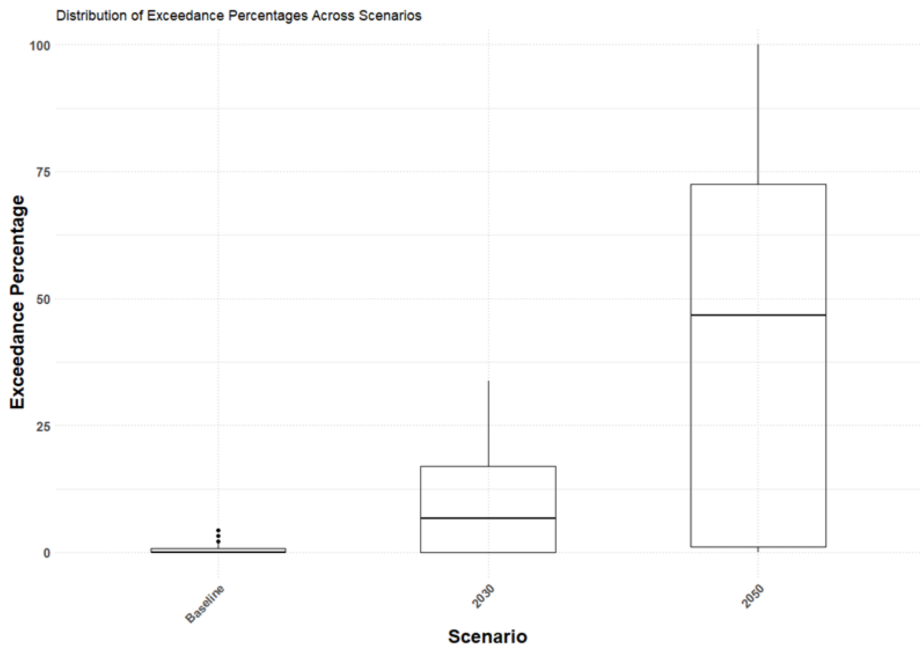


Fig. 6. Annual distribution of sea level fluctuation with respect to operational threshold and dock height (1.8m)

The construction of an operability map for the port of Heraklio following the comparison of the mapped berth heights with the estimated Mean Water Levels illustrates the spatial susceptibility of the port to inoperability mid 2020-2040 (i.e. 2030) and mid 2040-2060 (i.e. 2050) (Figure 7). The data suggests a progressive decline in the number of operable docks over time due to increasing non-operability, likely driven by sea level rise (SLR). In particular, the port area appears to be largely operable in the baseline period. By 2030, a significant proportion of the port docks are likely to be inoperable at high water levels for approximately 12% of the time per year. By 2050, the propensity for dysfunction increases further spatially. Docks that previously experienced minor problems (e.g. east Dock III) will be vulnerable to significant disruption for half the time of the year. The west side of Dock III and the east side of Dock IV/V, which maintain dock heights above 2.1m, remain significantly unaffected by SLR.

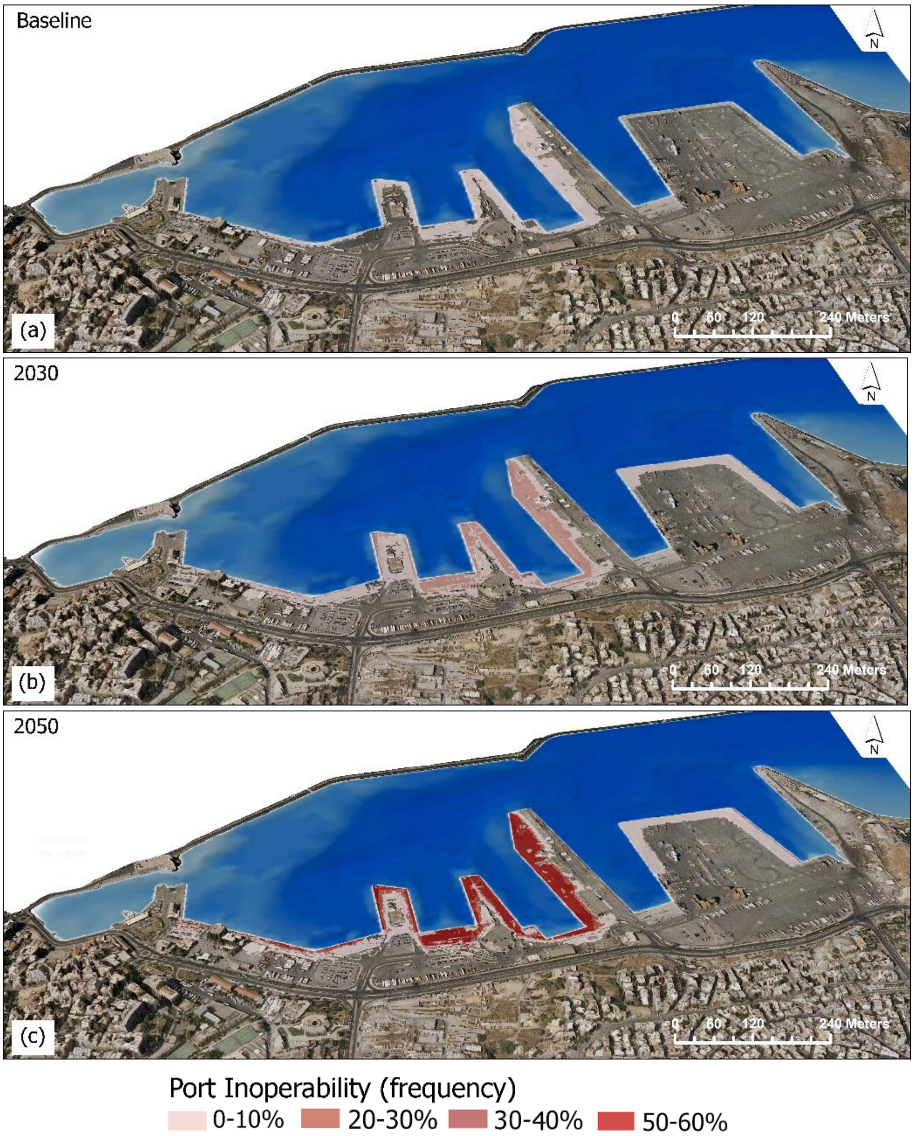


Fig. 7. Operability maps of the port of Heraklio for (a) Baseline period, (b) 2030 and (c) 2050

4.4 Economic Impact Assessment

For the impact assessment analysis, two simplifying assumptions have been made. First, while some docks may remain operational despite rising sea levels, this analysis assumes that any impact on a dock leads to the complete closure of the port. Second, economic implications have been based on annual data. The projected cumulative losses are presented in both undiscounted and discounted terms. Discounted cumulative losses are calculated using the EURIBOR curve plus a 2% spread, reflecting the value of money over time. By 2030, assuming a linear increase in annual port closures from 4 days in 2024 to 44 days in 2030, the cumulative undiscounted income loss is estimated at approximately €3.1 million. The Net Present Value (NPV) of cumulative losses amounts to €2.6 million. The most affected revenue streams are passenger and vehicle services (€1.2 discounted losses) and vessel port dues (€662,828 discounted losses), reflecting the port's heavy reliance on passenger traffic and vessel calls.

As disruptions intensify up to 2040, with closures increasing linearly from 44 days in 2030 to 115 days per year in 2040, cumulative losses rise significantly to €14.9 million (€23.8 million undiscounted losses), considering that till then the Heraklio Port Authority S.A. will further increase its annual revenues. The significant potential for dynamic growth at the port of Heraklion has been highlighted in a recent study by World Bank (2024)[34]. Furthermore, a consortium led by Grimaldi Group has acquired a stake in the port, signaling strong investment interest and future development opportunities[24]. Table 8 presents the relevant revenue loss estimations. The significant increase in lost income indicates the susceptibility of port operations to extended closures, which could severely impact the port's financial performance. Between 2040 and 2050, it is assumed that the annual port closure period continues to increase linearly, reaching 186 days per year by 2050. As a result, cumulative losses escalated to 32.2 million (€68.1 million undiscounted losses), with the passenger and vehicle revenue stream bearing the largest cost at over €16 million in lost revenue. Vessel port dues and revenues from container handling also see a substantial decline, reaching €8.5 million and €4.3 million, respectively.

Table 8. Cumulative expected income losses

	Cumulative loss of income (€/ Undiscounted)			Cumulative loss of income (€/ Discounted)		
Product/Service	Up to 2030	Up to 2040	Up to 2050	Up to 2030	Up to 2040	Up to 2050
Container	452,476	3,336,613	9,110,725	376,444	2,091,017	4,358,950
Dry bulk cargo	39,314	287,081	790,674	32,720	180,012	377,644
General Cargo	28,306	206,699	569,285	23,558	129,609	271,904
Passenger and vehicles	1,503,303	11,767,163	34,177,832	1,249,934	7,331,885	16,109,379
Cruise passengers	269,291	2,022,658	5,539,369	223,940	1,265,766	2,647,311
Vessels port dues	797,232	6,216,645	17,901,832	662,828	3,875,334	8,454,122
Total	3,089,922	23,836,860	68,089,717	2,569,426	14,873,624	32,219,309

5 Discussion

The study examines the implications of climate change on the operability of a multipurpose port, with a focus on sea level rise. Through a case study at the Port of Heraklion (Greece), the research indicates that sea level operational thresholds range from 0.91 m to 1.31 m, depending on the dock heights, which vary from 1.8 m to 2.2 m. The analysis of the historical sea level time series confirm that these thresholds are rarely exceeded (~3 days/year), whilst prior to 2005 this frequency was even lower (<1 day/year), something that might be attributed to the climate change effects.

Future projections reveal that, without adaptation measures, port operability declines progressively over time, with the lower docks (<2m) becoming highly vulnerable. By 2030, exceedances increase dramatically to 1,073.31 per year (~44 days/year), with some docks experiencing frequent disruptions, whilst, by 2050, exceedances escalate to 4,468.54 per year (~186 days/year), with the median value suggesting many docks will be inoperative for extended periods of time. Certain higher docks (>2m) remain largely unaffected, while lower docks face severe usability limitations, potentially leading to permanent operational failure. The results illustrate that by 2030, 12% of the port docks are expected to experience inefficiencies due to high water levels. By 2050, operational disruptions intensify spatially, with docks previously experiencing minor issues (e.g., east Dock III) now dysfunctional for half the year. Higher-elevation docks (e.g., west Dock III and east Dock IV/V) remain relatively unaffected by the projected sea level rise.

As closure days increase linearly from 44 days in 2030 to 115 days per year in 2040, and further to 186 days per year by 2050, the susceptibility of port operations to extended disruptions becomes evident. This prolonged downtime could severely impact the port's financial performance, despite expected revenue growth by the Heraklio Port Authority S.A. The results unveil potential significant disruptions in the supply chains in which the port of Heraklion is embedded whilst it will have a negative impact on social cohesion due to decrease in connectivity of the Crete Island with the Greek mainland. Regarding associated economic impacts, the estimated escalation in disruptions evidents cumulative losses that rise significantly as disruptions intensify, reaching €14.9 million (€23.8 million undiscounted losses) by 2040 and escalating further to €32.2 million (€68.1 million undiscounted losses) by 2050. The largest financial impact stems from passenger and vehicle revenue losses, exceeding €16 million, while vessel port dues and container handling revenues decline to €8.5 million and €4.3 million, respectively.

The analysis suggests that higher-elevation docks (i.e. >2 m) provide potential resilience, reinforcing the importance of infrastructure modifications such as dock height adjustments, flood barriers, and other climate adaptation measures. The dramatic increase in exceedance events projected for 2050—where several docks may become permanently inoperative—underscores the necessity for early intervention to prevent irreversible disruptions. Moreover, the economic impact assessment of climate change on the port of Heraklion highlights the significant revenue losses expected due to increasing port closures caused by rising sea levels. These findings underscore the urgent need for adaptation strategies to address the growing impact of sea level rise (SLR) on port operations. While historical exceedance events have been sporadic, their increasing frequency in recent decades indicates a clear upward trend in extreme sea levels. Without adaptation measures, the port—particularly its lower docks—will face a significant decline in operability, leading to severe economic and logistical disruptions. The rising frequency of these disruptions threatens the port's long-term viability, and the society's wellbeing as it is relied on the port for facilitating its trade needs, making infrastructure upgrades and operational adaptations essential to mitigating revenue losses and ensuring its continued economic sustainability. Without intervention, the escalating occurrence of port closures will result in severe financial consequences.

Besides the significant evidence presented in this study, relevant assessments should also consider its limitations. The analysis focuses solely on inoperabilities caused by water level thresholds and does not consider other major climatic drivers or cascading events, such as wave forcing which may trigger further effects on hydrodynamic and sedimentological conditions within the port[35][36] as well as on port operational efficiency.

Moreover, the uncertainty in sea-level rise projections directly influences the final assessment of port operability. In this study, the SSP5-8.5 scenario has been selected as the most extreme potential outcome. However, to avoid overestimations, the approach was based on assessing the impact of the mean water level; this may exclude the impact of extreme sea levels, yet, the resulting estimates represent the definite boundary of port inoperability and meanings a baseline for targeted adaptation measures. On the other hand, even if the most conservative aspiration of Paris agreement is reached i.e. SSP2.6, Sea-level rise is a delayed response phenomenon that will persist well beyond the point at which temperatures have reached equilibrium[37].

With respect to economic impact, the study considers any impact on a dock as leading to the complete closure of the port, resulting in potential overestimation of total losses. In reality, some docks might remain operational despite rising sea levels, allowing partial port functionality and mitigating the overall economic impact. Moreover, the absence of long term detailed intra-year data, disregards seasonal fluctuations in revenue and port activity due to insufficient intra-year data and limits the level of detail in the analysis. Without this data, it is not possible to conduct a more granular assessment, such as on a seasonal or monthly basis, which could provide a more accurate representation of climate change's economic effects.

In any case, Passengers’ activity Pier II, which appears to be the most severely affected, is also the most profitable sector of the port. Thus, its significance for the port’s overall revenue makes its frequent disruption particularly critical, as it could result in disproportionately high economic damage. Therefore, the assessment of climate change impacts on the port should consider not only the order in which different piers are affected but also their strategic and economic importance.

6 Conclusions

The study highlights the significant impact of sea level rise (SLR) on the operability of the Port of Heraklio, emphasizing the vulnerability of docks with lower elevations. Key findings indicate that docks of up to 1.8 m height, primarily used for passenger ferries, cruise ships, and dry bulk cargo, are susceptible to operational disruptions due to rising water levels. Statistical analysis of sea level records (1998-2023) shows a mean total sea level of 0.61 m, with extreme values reaching 1.14 m. Depending on dock heights operable conditions are feasible at water levels lower than 0.91 m to 1.31 m.

Under the SSP5-8.5 high-emission scenario, projections indicate a progressive decline in port operability. By 2030, exceedance events are estimated at ~44.72 days/year, with certain docks facing severe usability constraints. By 2050, the frequency escalates to ~186 days/year, rendering many docks inoperable for extended periods. The constructed operability map suggests a significant increase in non-operable docks by 2030, with approximately 12% of the port becoming inoperable at high water levels. By 2050, the impact worsens, particularly for docks with heights below 2m, while docks above 2.1m remain largely functional.

The financial consequences of increasing port closures are substantial. By 2030, cumulative income losses are projected at €3.1 million (€2.6 million in net present value). This escalates to €14.9 million by 2040 and reaches €32.2 million by 2050. Passenger services and vessel dues are the most affected revenue streams, with potential long-term threats to the port's financial viability.

These findings emphasize that without intervention, the increasing frequency of port closures will lead to severe financial losses and disrupt port operations. Infrastructure upgrades and operational adaptations, such as dock elevation modifications and improved flood defenses, are critical to ensuring the continued functionality and economic sustainability of the Port of Heraklio.

The outcomes have both scientific and practical value. Regarding its scientific contribution, the research adds to the ongoing dialogue on the potential impacts of climate change on the port industry and, from a macroeconomic perspective, on economic development and societal well-being. Moreover, this study is among the few that examine the implications of climate change for the Greek port industry. On the practical side, the study provides a comprehensive framework for assessing not only the impact of sea level rise on port operability but also a process for quantifying these impacts in monetary terms. The study outcomes can serve as input for port planning, aiming to develop infrastructures that are resilient to future sea level rise. Moreover, the findings highlight the need for a relevant port policy that incorporates climate change implications into port planning and the development of port resilience strategies, especially for ports in insular areas, where such infrastructures often serve as the primary connection to the mainland.

Acknowledgements

The authors acknowledge research project "AdaptPorts- Ports Climate Mitigation and Adaptation Strategy" funded by Green Fund, Priority Axis 3 "RESEARCH AND APPLICATION" "PHYSICAL ENVIRONMENT & INNOVATIVE ACTIONS 2022"Green Fund-Greece. Funding amount: 197.000€.

References

1. MedECC: Summary for Policymakers. In: Climate and Environmental Coastal Risks in the Mediterranean. [Djoundourian, S., Lionello, P., Llasat, M.C., Guiot, J., Cramer, W., Driouech, F., Gattacceca, J.C., Marini, K. (eds.)]. MedECC Reports. MedECC

Secretariat, Marseille, France, pp. 28, ISBN: 978-2-493662-03-3, doi: 10.5281/zenodo.10722133 (2024)
2. UNCTAD: Climate-resilience of seaports: Adequate finance is critical for developing countries but remains a major challenge. UNCTAD Policy Brief No. 103 (2022)
3. UNECE: Climate Change Impacts and Adaptation for Transport Networks and Nodes. Expert Group Report ECE/TRANS/283. United Nations Publications, Geneva (2020)
4. Izaguirre, C., Losada, IJ., Camus, P., Gonzalez-Lamuno, P., Stenek, V.: Seaport climate change impact assessment using a multi-level methodology. Marit Policy Manag 47:544–557 (2020)
5. Portillo Juan, N., Negro Valdecantos, V., del Campo, J.M.: Review of the Impacts of Climate Change on Ports and Harbours and Their Adaptation in Spain. Sustainability 14, 7507 (2022)
6. IPCC: "Climate Change 2022: Impacts, Adaptation, and Vulnerability". Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. Cambridge, UK and New York, NY, USA, doi:10.1017/9781009325844 (2022)
7. Asariotis, R.:Climate change impacts on seaports: A growing threat to sustainable trade and development (2021)
8. UNCTAD: The Bridgetown Covenant. TD/541/Add.2. UNCTAD XV Outcome document (2021)
9. Asariotis, R. et al.: Climate change and seaports: hazards, impacts and policies and legislation for adaptation. Anthropocene coasts 7, 14 (2024)
10. Christodoulou, A., Christidis, P. & Demirel, H.: Sea-level rise in ports: a wider focus on impacts. Marit Econ Logist 21, 482–496. https://doi.org/10.1057/s41278-018-0114-z (2019)
11. ESPO: ESPO Environmental Report 2024, Brussels, Belgium (2024)
12. USCCSP: U.S. Climate Change Science Program (CCSP) "Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I." U.S. Department of Transportation (2008)
13. UNCTAD: "Climate Change Impacts and Adaptation for Coastal Transport Infrastructure: A Compilation of Policies and Practice". ISBN: 978-92-1-112970-0 (2020)
14. Becker, A., Ng A.K. Y., McEvoy, D., Mullett J.:"Implications of climate change for shipping: Ports and supply chains." Wiley Interdisciplinary Reviews: Climate Change: e508. doi: 10.1002/wcc.508. (2017)
15. Ng, A. K.Y., Becker, A., Cahoon, S. and Ling, Sh.: Time to act: The criticality of ports in adapting to the impacts posed by climate change. In: Climate Change and Adaptation Planning for Ports, 1st Edition, Routledge. eBook ISBN 9781315756813 (2015)
16. Monioudi, I.N., Asariotis, R., Becker, A. et al: Climate change impacts on critical international transportation assets of Caribbean Small Island Developing States (SIDS): the case of Jamaica and Saint Lucia. Reg Environ Change 18, 2211–2225 (2018)
17. Becker, A.: Climate change impacts to ports and maritime supply chains". Maritime Policy & Management, 47:7, 849-852, DOI: 10.1080/03088839.2020.1800854 (2020).
18. UNFCCC: National Adaptation Plans (2023)
19. Sharifi, A.: Trade-offs and conflicts between urban climate change mitigation and adaptation measures: A literature review. Journal of Cleaner Production. doi:10.1016/j.jclepro.2020.122813 (2020)

20. PIANC: Supporting a business case to adapt. PTGCC Technical Note No.2. Forthcoming (2024)
21. PIANC: Supporting a business case to adapt. PTGCC Technical Note No.2. Forthcoming (2024)
22. Hanson, SE., Nicholls, RJ.: Demand for Ports to 2050: Climate Policy, Growing Trade and the Impacts of Sea-Level Rise. Earths Future 8:e2020EF001543 (2020)
23. Hallegatte, S., Rentschler, J., Rozenberg, J.: Lifelines: The Resilient Infrastructure Opportunity. The World Bank, Washington, DC (2019)
24. Chatzinikolaou, E. and Arvanitidis, Ch.: Status, values and present threats in Heraklion harbour (Crete, Greece), Regional Studies in Marine Science, Volume 8, Part 2, p. 252-258, ISSN 2352-4855, https://doi.org/10.1016/j.rsma.2016.01.010. (2016)
25. Grimaldi: The Grimaldi Group acquires the majority of the Port of Heraklion. [Press release]. Grimaldi Group. (Accessed March 14, 2025) (2023)
26. Greek Government Gazette (2012)
27. Koukounari, I.N., Paraskevopoulou, V., Karditsa, A., Koulouri, P., Poulos, S.E., Dounas, C.G and Dassenakis, M.: Trace metal concentrations in the offshore surficial sediment of the Heraklio Gulf (Crete Island, East Mediterranean Sea). Mediterranean Marine Science, 21(1), 84-104. https://doi.org/10.12681/mms.20396 (2020)
28. Tsimplis, M.N.: Tidal Oscillations in the Aegean and Ionian Seas. Estuarine, Coastal and Shelf Science, 39 (2), 201-208 (1994)
29. HNHS- Hellenic Navy Hydrographic Service: Tides and tidal data for Greek harbours, (4th ed.) Hellenic Navy Hydrographic Service, Athens (in Greek) (2005)
30. GREPORT: Report on Greek Ports. Ports and Shipping Advisory, Athens, Greece (2024)
31. ELIME, https://elime.gr/ , 2024
32. EPPE: Recommendations for Maritime Works. ROM 2.0-11, Volume I. Recommendations for the design and construction of Berthing and Mooring Structures. Translated version of the original Spanish text. 1st Edition (2019)
33. IPCC: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change". Masson-Delmotte, V., P. (2021)
34. World Bank:Economic Profile: Municipality of Heraklion. Washington, DC: World Bank. (2024)
35. Sánchez-Arcilla, A. et al.: A review of potential physical impacts on harbours in the Mediterranean Sea under climate change. Reg. Environ. Change 16, 2471–2484 (2016).
36. Sierra, J. P., Casas-Prat, M., Virgili, M., Mösso, C. & Sánchez-Arcilla: Impacts on wave-driven harbour agitation due to climate change in Catalan ports. Nat. Hazards Earth Syst. Sci. 15, 1695–1709 (2015)
37. Jevrejeva, S., Moore, J.C., Grinsted, A.: Sea level projections to AD2500 with a new generation of climate change scenarios. Glob. Planet. Chang. 80–81, 14–20 (2012)