High Resolution Wave Forecasting for Protecting Coastal Monuments

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Abstract. The protection of coastal monuments from wave-induced damage is increasingly urgent as climate change accelerates sea level rise and intensifies storms. Historical structures, such as Venetian fortresses and coastal walls, are highly vulnerable to wave energy, overtopping, and inundation, compromising their structural integrity and cultural significance. High-resolution wave forecasting is essential for assessing risks and developing effective mitigation measures. This study integrates high-resolution numerical modeling to analyze wave propagation, energy dissipation, and overtopping hazards affecting the Koules Fortress and Heraklion's coastal Venetian walls extending to Dermatas Bay. Using the SWAN wave model, dynamically downscaled to spatial resolution of 50 by 50 meters, simulations were performed under present and future climate scenarios to evaluate wave dynamics and their impact on these historical structures. The model operates daily, providing real-time assessments of overtopping hazards and supporting early warning systems for coastal management. The analysis incorporates changing wind regimes and storm intensities based on climate projections, highlighting an increase in both wind speeds and the frequency of unfavorable wind directions that exacerbate wave hazards. Modeling results indicate that without intervention, overtopping rates and structural stress will exceed acceptable thresholds, endangering both the monuments and surrounding infrastructure. By integrating high-resolution wave forecasting with vulnerability assessment, this study provides a management framework for safeguarding coastal heritage sites. The proposed methodologies support data-driven risk evaluation and adaptive strategies to ensure the long-term resilience of these cultural treasures against evolving coastal hazards.

Keywords: SWAN model, high-resolution wave models, coastal monuments, Koules Fortress, port infrastructure

1 Introduction

The Venetian fortress of Koules, constructed in 1523 A.D., stands prominently at the entrance of Heraklion harbor on the island of Crete, forming part of the city's historic coastal defenses. Extending beyond the fortress, the Venetian coastal walls of Heraklion stretch westward toward Dermatas Bay, serving as both protective infrastructure and a cultural landmark. These historical structures, integral to the region's heritage, face increasing threats from climate change, including sea-level rise, intensified storm activity, and coastal erosion. The impacts of climate change on coastal areas have been extensively documented, with rising sea levels and extreme weather events leading to accelerated shoreline retreat, increased flooding, and physical damage to built heritage [1]. In response to these challenges, high-resolution wave modeling is required to assess the potential risks to these structures and propose effective mitigation strategies.

Cultural heritage sites like the Koules fortress and the Venetian coastal walls hold profound significance across multiple facets of society. Economically, they serve as catalysts for local development through tourism, generating income and employment opportunities. The United Nations Educational, Scientific and Cultural Organization (UNESCO) emphasizes that cultural and natural heritage is not only an irreplaceable source of identity and inspiration but also a key driving force for sustainable development [2]. Socially, these sites foster community identity and continuity, offering a sense of belonging and historical context. Their preservation contributes to social cohesion by maintaining a tangible connection to shared histories and values. Furthermore, cultural heritage supports the arts by providing inspiration and venues for artistic expression, further enriching the cultural fabric of society. In addition, coastal heritage sites in port cities play a critical role in maritime identity and economic activity. Ports have historically been centers of commerce, defense, and cultural exchange, and their associated monuments, such as Koules, represent a convergence of these aspects. However, the preservation of cultural heritage in port areas presents unique challenges. Ports are dynamic environments subject to constant change due to economic activities, urban development, and environmental factors. The interplay of these factors complicates conservation efforts, as maritime infrastructure development, pollution, and high-energy wave environments pose continuous risks to historic coastal sites [3].

The Mediterranean region, characterized by its extensive coastline and rich cultural history, is particularly susceptible to climatic threats. A study by Reimann et al. (2018) indicates that up to 82% of cultural World Heritage sites in the Mediterranean are at risk from coastal flooding, with over 93% potentially affected by coastal erosion under projected sea-level rise scenarios [4]. Greece, with its numerous ancient coastal structures, is particularly vulnerable, with Koules and the Venetian coastal walls facing similar risks. While these structures have withstood centuries of environmental challenges, the increasing frequency and severity of storms, along with long-term sea-level rise, introduce new threats to their structural integrity.

To assess these risks with the necessary spatial accuracy, we employ a high-resolution wave model, Simulating WAves Nearshore (SWAN), with a grid resolution of 50 x 50 meters. This level of detail allows for precise analysis of wave dynamics, including wave energy dissipation, breaking processes, and nearshore hydrodynamics, all of which directly impact the stability and longevity of these historic structures. High-resolution modeling provides key insights into wave overtopping risks and potential erosion patterns, facilitating targeted intervention measures. The SWAN model operates daily as part of an operational forecasting system, allowing for continuous monitoring of wave overtopping hazards along the Venetian coastal defenses. This real-time assessment functions as an alerting tool, informing decision-makers of high-risk conditions and enabling timely protective actions. By integrating high-resolution wave forecasting with a coastal vulnerability framework, this study contributes to the long-term resilience of Heraklion's historic coastal monuments against evolving climatic and marine hazards.

2 Methodology

2.1 A High-Resolution Wave Modeling with SWAN

The SWAN model is employed in this study to assess wave-induced hazards affecting the Koules fortress, utilizing a high-resolution, nested-grid approach to accurately capture nearshore wave dynamics. SWAN, a third-generation spectral wave model, is widely used for nearshore wave simulations due to its ability to incorporate crucial physical processes such as wind-wave generation, refraction, shoaling, bottom friction, and wave breaking [5]. Given the complexity of wave behavior in port environments, particularly in regions with submerged structures and strong wave-current interactions, the application of a multi-scale grid system ensures an accurate representation of wave transformations as they approach the fortress. Given the complexity of wave behavior in port environments, particularly in regions with submerged structures and strong wave-current interactions, the application of a multi-scale grid system ensures an accurate representation of wave transformations as they approach the fortress.

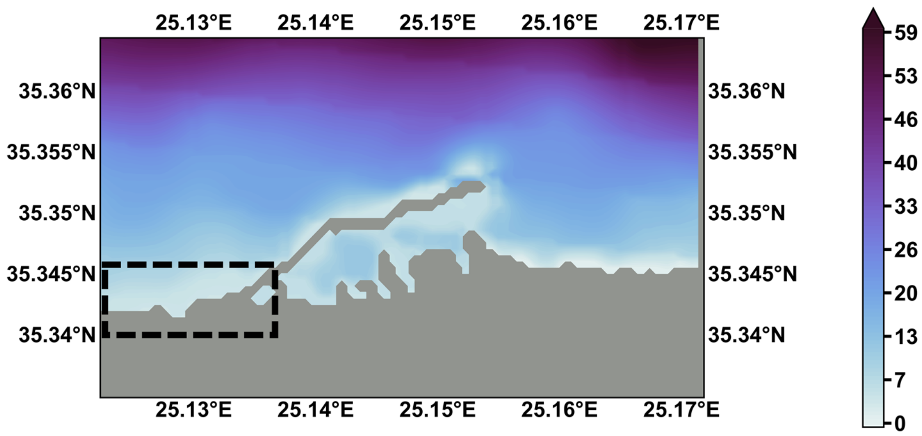

Fig. 1: Bathymetry map (in m) for the SWAN model domain (50 m x 50 m horizontal resolution). The area of interest is marked with a black box, and then shown in Fig. 2 for further categorization of test cases.

For this implementation, a two-step nesting technique is applied, where an outer computational grid is defined over a broad domain extending between 24.95° E–25.315° E and 35.32° N–35.565° N, with a spatial resolution of 500 meters. This coarser grid provides wave boundary conditions for the inner, high-resolution SWAN50 grid shown in Fig. 1, which covers the immediate vicinity of the Koules fortress between 25.122° E–25.172° E and 35.335° N–35.3645° N at a finer resolution of 50 x 50 meters. The nested approach ensures that large-scale wave features are transferred from offshore to the nearshore region with increasing spatial detail, enabling a more precise evaluation of wave energy dissipation, refraction effects, and potential overtopping hazards at the fortress walls [6].

Fig. 2: Map of test case in northwestern coastal area of Heraklion, split in 4 case studies (CS), denoted by different colors and stars indicating points where overtopping will be further analyzed. Aerial view of Heraklion coast from Google Earth, captured on 10/3/2022 (© Google Earth, 2023, LLC).

The boundary conditions for the coarse SWAN grid are sourced from the Copernicus Marine Environment Monitoring Service (CMEMS) wave model, specifically the MEDSEA_ANALYSISFORECAST_WAV_006_017 product, which provides hourly significant wave height, peak wave period, and peak wave direction at a 4.2 km resolution [7]. These offshore wave parameters are used to drive the outer SWAN model, which then supplies wave forcing for the nested SWAN50 grid. Additionally, wind forcing data is incorporated into the model using outputs from a dynamically downscaled WRF (Weather Research and Forecasting) model with a spatial resolution of 3 km, providing hourly 10-meter wind velocity components [8]. Wind input is crucial for accurately simulating wave generation and local sea-state variability, particularly in enclosed harbor environments where local wind patterns significantly influence wave dynamics.

The bathymetric data used in the SWAN simulations is derived from EMODnet Digital Terrain Model (DTM 2022) [9] for the coarse 500-meter grid, while a higher-resolution local bathymetric dataset was created by field measurements, integrated into the SWAN50 domain, ensuring that wave transformation processes over the nearshore seabed are resolved with greater accuracy. The model is configured to run at an hourly time step, producing 2-day forecasts, allowing for detailed temporal analysis of wave propagation and potential structural impacts on the fortress.

The SWAN50 high-resolution outputs are used in conjunction with calculations of overtopping discharges to determine how frequently critical wave thresholds are exceeded and to assess the structural risks posed to the fortress under various environmental conditions. These results will provide valuable input for the development of adaptive strategies, such as reinforcement measures, breakwater extensions, or nature-based solutions, aimed at mitigating the long-term impacts of coastal hazards on this historic site.

2.2 Assessing overtopping discharges at Koules fortress and venetian coastal walls area

To evaluate the vulnerability of the Koules fortress, the Venetian coastal wall, and Dermatas beach to wave overtopping discharges, this study follows the methodologies outlined in EurOtop (2018) [10] and Alexandrakis et al. (2019) [11]. The objective is to assess the potential hazards posed by extreme wave conditions and sea-level rise, using empirical formulas for wave overtopping discharge (q) to quantify the risks to these coastal structures. As sea-level rise accelerates coastal erosion and increases the frequency of extreme wave events, historic structures such as the Koules fortress are becoming increasingly vulnerable [12].

The SWAN model runs operationally on a daily basis, utilizing application packaging for ease of use and interoperability [13], providing real-time wave forecasts that will be used in conjunction with the wave overtopping assessment to serve as a management and alerting tool. By continuously evaluating wave overtopping discharge at key heritage sites such as the Koules fortress and Venetian wall, the system will contribute to early warning mechanisms and mitigation planning, ensuring that decision-makers have timely information for protective actions. Cultural heritage sites worldwide have been recognized as being at significant risk due to climate change, with wave overtopping being a key factor in structural degradation in exposed coastal areas [14].

Wave overtopping occurs when incident waves exceed the crest height of a structure, leading to potential flooding, erosion, and structural deterioration. The mean overtopping discharge (q) in its general form [10] is expressed as:

$$q = 10^3 \sqrt{g H_{m0}^3} \cdot \alpha \exp\left(-\beta \frac{R_c}{H_{m0}} \right) \tag{1}$$

where g is the acceleration due to gravity 9.81 m/s^2, H_{m0} is the significant wave height at the structure toe (m), R_c is the freeboard height (m), α, β are empirical coefficients depending on the structure type and roughness and q is the mean overtopping discharge per unit width, with converted units from $m^3/s/m$ to l/s/m for consistency with the Eurotop manual thresholds [10].

For the 4 different areas shown in Fig. 2, adaptations of the formula (1) should be used due to the different nature of each case. To correctly model each case, we split the area into 4 subareas as seen in Fig. 2, with the characteristics of our case studies 1, 2, 3 and 4 being similar to case studies 10, 1, 6 and 5 respectively from [10]. To be more precise, our case study 1 (CS-1) features a composite vertical wall case, with the relevant formulas found in Eqs. (8.37-8.48) from the Eur0top manual [10]. Our case study 2 (CS-2) can be described as a grass covered dike with Eqs. (8.1-8.9) being used from the manual. Case study 3 (CS-3) can be modelled as a case with no foreshore with Eqs. (8.19-8.26) most fitting for its calculation. Finally, CS-4 has the most common characteristics with a coastal dike, where there is a concrete apron, fronted by concrete revetment and backed by a wave wall. CS-4 is further divided in CS-4a and CS-4b, because of the different wall height. In this last case, Eqs. (8.15-8.18) can model the relevant discharge. The reader can refer to Table 1 for the corresponding equations.

To determine the expected overtopping hazard levels, predefined safety thresholds can be used:

- Safe conditions: $q < 0.1$ (l/s/m) insignificant with respect to strength of crest and rear of structure
- Moderate overtopping requiring monitoring: $0.1 \leq q < 1.0$ (l/s/m) where crest and inner slopes grass and/or clay may start to erode
- Significant overtopping for dikes and embankments: $1.0 \leq q < 10$ (l/s/m), some overtopping for rubble mound breakwaters.
- Severe overtopping requiring structural intervention: $10 \leq q < 100$ (l/s/m) where inner slopes of dikes have to be protected by asphalt or concrete.

Other parameters that are used implicitly in the formulas provided by [10] are the offshore significant wave height (m) and wave period (s) H_s and T_s respectively, and the Iribarren number ξ [15], defined as:

$$\xi = \frac{\tan\beta}{\sqrt{H_s / L_0}} \tag{2}$$

where:

β is the beach or structure slope calculated from detailed bathymetric and topographic surveys , and L_0 is the deep-water wavelength, given by $L_0 = \frac{g}{2\pi}T^2$, with T being the wave period in spectral form, taken empirically from the peak period T_p as $T = T_p / 1.1$.

Quantitative risk assessments for overtopping hazards have been shown to be an essential component in coastal resilience planning, as they provide a systematic approach to defining risk zones and recommending mitigation strategies [16]. This methodology integrates numerical wave modeling data from SWAN, applying the overtopping and run-up equations to evaluate the frequency of extreme events exceeding predefined safety thresholds. The operational daily SWAN runs will be used to generate automated overtopping risk assessments, allowing for real-time monitoring and forecasting of hazardous conditions. This system can serve as an early warning tool for local authorities, aiding in decision-making for protective measures such as restricting public access during high-wave conditions, deploying temporary defenses or reinforcements before extreme events, long-term structural adaptation, such as crest height increases or breakwater adjustments.

The combination of [10] empirical models and [11] case-specific methodology offers a holistic assessment framework, ensuring effective preservation strategies for these historical landmarks while enabling proactive hazard management.

Table 1: Equations for overtopping calculations at each case [10]. In all equations coefficients γ_b, γ_β, γ_f, γ_v = 1. For CS-1 R_c=6.5 m, for CS-2 R_c= 1.5m, for CS-3 R_c= 6.5 m, for CS-4a R_c=2.5 and for CS-4b R_c=0.5.

Case Study	Overtopping Equations
CS-1	$\frac{q}{\sqrt{gH_{mo}^3}} = 0.05exp\left(-2.78\frac{R_c}{H_{m0}}\right)$
CS-2	$\frac{q}{\sqrt{gH_{mo}^3}} = \frac{0.026}{\sqrt{tan\ a}}\gamma_b\xi_{m-1,0}exp\left[\left(-2.5\frac{R_c}{\xi_{m-1,0}\cdot H_{m0}\cdot\gamma_b\cdot\gamma_f\cdot\gamma_\beta\cdot\gamma_v}\right)^{1.3}\right]$
CS-3	$\frac{q}{\sqrt{gH_{mo}^3}} = 0.047exp\left[-\left(2.35\frac{R_c}{H_{m0}}\right)^{1,3}\right]$
CS-4	$\frac{q}{\sqrt{gH_{mo}^3}} = \frac{0.026}{\sqrt{tan\ a}}\gamma_b\xi_{m-1,0}exp\left[\left(-2.5\frac{R_c}{\xi_{m-1,0}\cdot H_{mo}\cdot e^{-0.56}\cdot\gamma_b\cdot\gamma_f\cdot\gamma_\beta\cdot\gamma_v}\right)^{1.3}\right]$,

3 Results

Fig. 3 presents the time evolution of significant wave height and computed overtopping discharges at key locations across the study area. Fig. 3a illustrates the domain-averaged significant wave height derived from the SWAN model at 50-meter resolution, while Fig. 3b–3f display overtopping discharges at the specific points of interest, which are marked by white stars in Fig. 2.

The wave height time series in Fig. 3a demonstrates notable fluctuations throughout the two-month period, with multiple storm events leading to peaks above 2.5 meters. These wave height variations provide the essential forcing conditions for overtopping computations at the identified critical locations.

Examining the overtopping discharge results in Figs. 3b–3f, we observe that at locations CS-4a (Fig. 3e), CS-1 (Fig. 3b), and CS-3 (Fig. 3d), overtopping discharges remain minimal, well below the initial threshold of 0.1 l/s/m. These results indicate that these locations experience limited overtopping events and remain within safe operational limits for coastal infrastructure.

The case of CS-2 (Fig. 3c) presents a more dynamic overtopping pattern, with discharge values occasionally exceeding 20 l/s/m. However, this location corresponds to a beach environment, where such overtopping events do not pose a significant structural threat to the Venetian walls. Instead, the impact at this site is largely localized to beach dynamics and sediment transport.

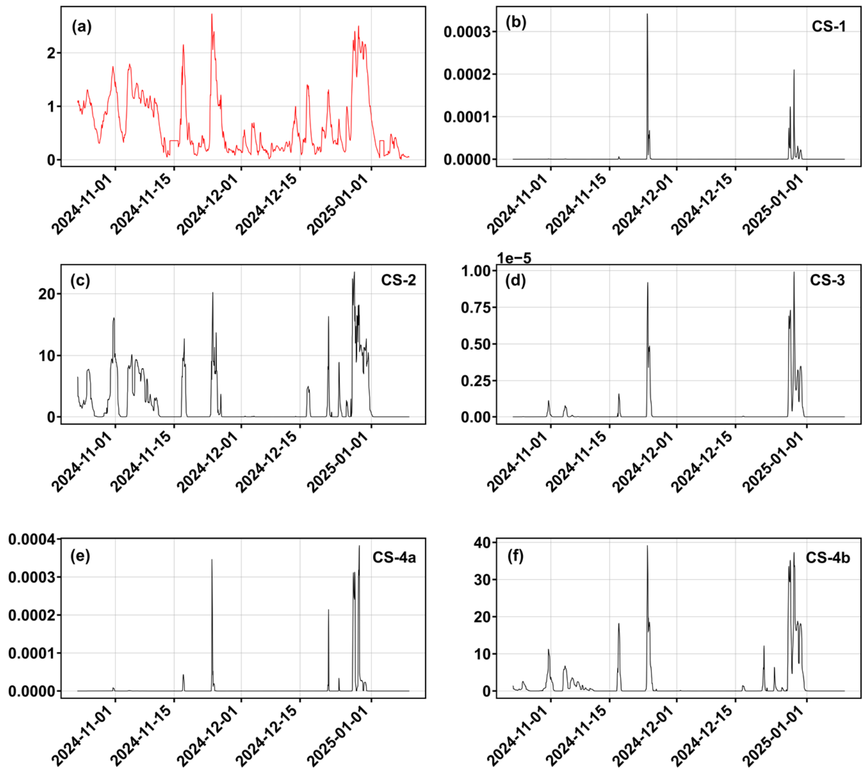

Fig. 3: Time series plots of (a) spatial mean value of Significant wave height Hs (m) and (b-f): computed discharges *q* (l/s/m) at the points indicated by stars in Fig. 2. Case study (CS) 4 has 2 points: 4a being the left one and 4b the right one in front of Koules Fortress (Fig. 2).

The most critical findings emerge for CS-4b, located in front of Koules Fortress (Fig. 3f). Here, the freeboard height is notably low, leading to frequent and intense overtopping events. Over the observed period, there are 13 instances where overtopping discharge exceeds 1 l/s/m, and, more alarmingly, 5 instances where overtopping surpasses 10 l/s/m, a threshold classified as severe overtopping. These events highlight the vulnerability of this historic structure to wave action, with potentially hazardous implications for structural integrity and visitor safety.

The findings emphasize the need for further investigation into potential mitigation measures, particularly for CS-4b, where frequent severe overtopping events could accelerate structural degradation.

Fig. 4 presents the average significant wave height (Hs) on December 29, 2024**,** a day identified as one of the extreme wave events in the time series of Fig. 3a. The spatial distribution of Hs on this day highlights the most exposed areas along the coastline, where wave energy is highest. The offshore wave field shows substantial wave heights propagating toward the coastal structures, emphasizing the forcing conditions leading to overtopping in the examined locations.

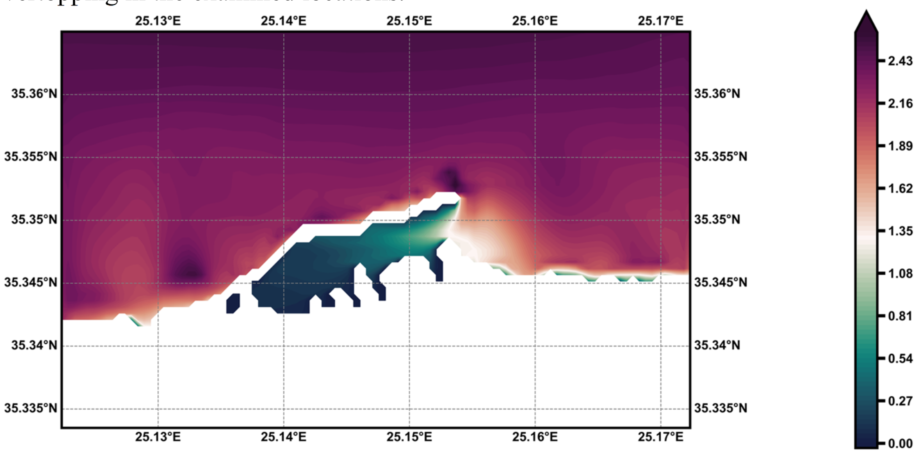

Fig. 4: Surface plot of Significant wave height (Hs, in m) produced by SWAN (50-meter resolution) for an extreme wave case of 29/12/2024.

To further assess the vulnerability of different locations, Figs. 5–8 depict the maximum computed overtopping discharge (q) over the entire simulation period, pinpointing the most critical points for each case study. In CS-1 (Fig. 5), overtopping discharges remain extremely low, with values well below 0.002 l/s/m**.** These results confirm that this site is largely protected from wave overtopping, with wave energy dissipating before reaching critical levels. The limited overtopping at CS-1 indicates that the local bathymetry and coastal structures provide effective shielding, preventing significant overtopping events.

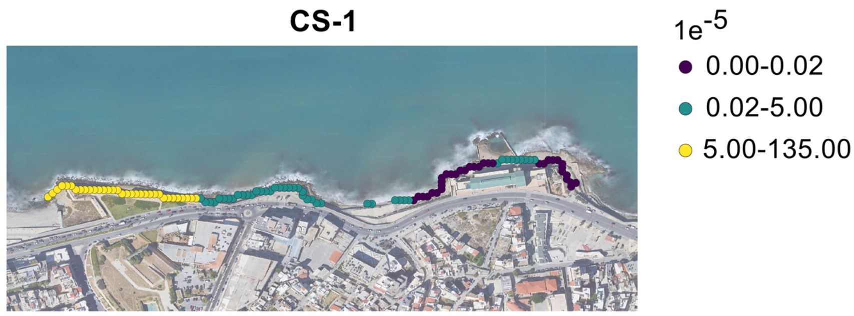

Fig. 5: Maximum value of discharges (q, in l/s/m) computed at each point of case study 1 (Fig. 2) (Satellite image by © Google Earth, 2023, LLC).

A more pronounced overtopping pattern is observed in CS-2 (Fig. 6), where discharge values exceed 30 l/s/m in certain regions. This confirms that CS-2 is subject to higher wave energy and overtopping events. However, given that CS-2 is located on a beach, where there is no wave shielding this level of overtopping does not pose a direct threat to critical structures such as the Venetian walls. The overtopping at this location primarily affects coastal dynamics and sediment transport, rather than infrastructure stability.

Fig. 6: Maximum value of discharges (q, in l/s/m) computed at each point of case study 2 (Fig. 2) (Satellite image by © Google Earth, 2023, LLC).

The observed situation at CS-3 (Fig. 7) is similar to CS-1 where very low overtopping discharges are observed, in the order of 10^{-5} l/s/m across the study period. This location does not experience substantial overtopping due to the wall's vertical surface and the bathymetry, reinforcing the previous time-series analysis that showed negligible values throughout the two-month period. The minor fluctuations observed in the spatial distribution of q suggest localized effects, but overall, CS-3 remains a low-risk area.

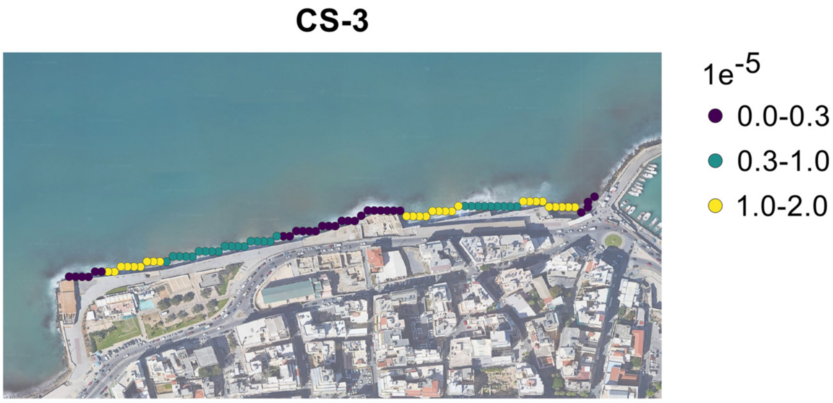

Fig. 7: Maximum value of discharges (q, in l/s/m) computed at each point of case study 3 (Fig. 2 - Koules fortress area) (Satellite image by © Google Earth, 2023, LLC).

The most critical findings emerge from CS-4 (Fig. 8), particularly at CS-4b, the location directly in front of Koules Fortress, where until 2024 there were no sufficient breakwater. Here, the computed overtopping discharge reaches extreme values, exceeding 70 l/s/m in the most exposed sections. The spatial patterns of q indicate that this section of the fortress is highly vulnerable to wave attack, with significant overtopping events occurring repeatedly over the study period. This confirms the earlier findings from Fig. 3, where multiple instances of severe overtopping (q > 10 l/s/m) were identified. The combination of a low freeboard and direct wave exposure at CS-4b results in persistent high discharge values, categorizing it as a high-risk area for structural damage and safety concerns.

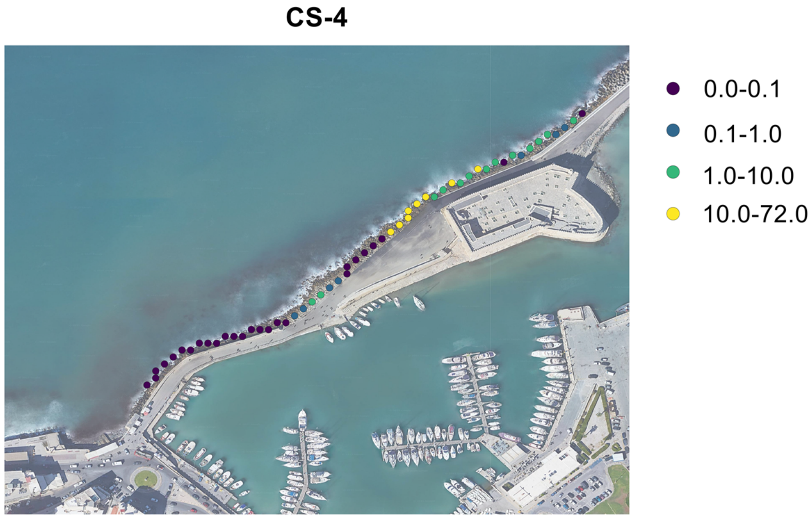

Fig. 8: Maximum value of discharges (q, in l/s/m) computed at each point of case study 4 (Fig. 2 - Koules fortress area) (Satellite image by © Google Earth, 2023, LLC).

The results from Figs. 5–8 illustrate the progression from negligible overtopping (CS-1, CS-3) to moderate levels (CS-2) and finally to extreme overtopping events (CS-4b, Koules Fortress). The findings reinforce the need for immediate attention to CS-4b, as continuous overtopping at this magnitude can contribute to the deterioration of the historic walls and Koules Fortress, and increase risks to public safety. Coastal protection measures should be evaluated to mitigate the impact of extreme wave events in this critical area.

While after 2024 a coastal protection works where constructed based on the design that was the result of EU project HERACLES [17]. The construction included a retrievements, made by rocks with a smooth slope, that reached 60 m of shore and the depth of 6 m. In Fig. 9 the results of the coastal protection structure are presented. These show a significant decrease of the maximum discharges, which is now categorized as safe to moderate, and enhance the protection of the coastal monument.

Fig. 9: Maximum value of discharges (q, in l/s/m) after the construction of the retrievement, computed at each point of case study 4 (Fig. 2 - Koules fortress area) (Satellite image by © Google Earth, 2023, LLC).

4 Discussion/Conclusion

The results of this study demonstrate the effectiveness of operational wave overtopping assessments in quantifying risks to coastal heritage structures such as Koules Fortress, the Venetian coastal wall, and Dermatas Beach. By integrating high-resolution numerical wave modeling using SWAN with empirical overtopping equations from EurOtop (2018) [10], this approach provides a detailed, quantitative evaluation of overtopping hazards under different wave conditions. The analysis has confirmed that while some locations remain within safe overtopping limits, others, like the area of Koules Fortress (CS-4b), experience recurrent and severe overtopping events, with discharge values exceeding critical safety thresholds, before the construction of the protection structure. Before the construction, the overtopping discharges at the area of Koules Fortress (CS-4) exceeded 10 l/s/m multiple times within the study period, reaching values that categorize the events as severe.

The ability to assess overtopping hazards in real time through daily SWAN simulations is a valuable tool for coastal heritage management. The results show a clear spatial differentiation in overtopping risks, where sites like CS-1 and CS-3 exhibit negligible overtopping, CS-2 experiences moderate exceedances, and CS-4b records frequent extreme overtopping events. The impact of these conditions could contribute to structural degradation, erosion, and potential safety risks for visitors and nearby infrastructure.

The results further emphasize that while certain areas, such as Dermatas Beach (CS-2), experience wave overtopping, the impact is more closely related to coastal erosion processes rather than direct structural threats. This could include both temporary reinforcements and long-term solutions, such as structural modifications, improved drainage systems, or nature-based solutions to dissipate wave energy before reaching critical locations.

The low values found in CS-1 and CS-3 indicate that overtopping is practically zero during the simulation period. This is attributed to the structural design of the region, particularly the high walls, combined with the limited simulation period, which restricts the range of Hs observed compared to a longer timeframe.

The operational use of these forecasting tools allows for proactive, data-driven decision-making by local authorities, heritage managers, and coastal engineers. By integrating real-time overtopping assessments into coastal management strategies, timely interventions can be implemented, such as temporary reinforcement measures, early warning systems, or site closures during extreme conditions. One key application of these findings is improving infrastructure resilience. The modeling results highlight areas needing reinforcement, with similar structures as those that were implemented in CS-4b, and indicate upgrades like increasing wall heights or adding berms to reduce overtopping. Additionally, the ability to predict wave overtopping hazards in advance supports long-term resilience planning, ensuring that key heritage sites, like the Koules monument, are protected against increasing wave energy and extreme storm events. Finally, identifying vulnerable areas supports targeted safety measures, early warning systems, and emergency protocols to protect personnel and communities.

As climate change continues to intensify coastal hazards, including rising sea levels and more frequent extreme wave events, the role of continuous operational forecasting will become even more critical. The findings of this study highlight the need for adaptive management strategies that integrate real-time monitoring with impact assessments to protect coastal heritage sites from progressive degradation. Future work should further explore the implications of projected sea-level rise scenarios, which will likely exacerbate overtopping hazards in vulnerable locations such as Koules Fortress. By continuously refining these methodologies and expanding their application, coastal heritage preservation can be strengthened against the increasing challenges posed by a changing marine environment.

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