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Posted Date: 17 September 2024

doi: 10.20944/preprints202409.1265.v1

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Article

# Coastal Protection for Tsunamis

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**Abstract:** A previous research showed the 1755 tsunami would inundate the Marginal Avenue, the railway and the low ground area of Caxias, Oeiras municipality, Portugal. Thus, in this study several proposals for coastal protection are presented. A new Lidar data of local topography allowed the construction of a more accurate DEM, including the representation of the streets of Caxias downtown, to be used in the tsunami numerical model. The results were combined with field survey on Caxias and other coastal areas of Portugal and Japan. The new calculations show the low ground areas up to 6 m in height area inundated by the tsunami. However, with the new proposal DEM the tsunami inundation is restricted to the beaches. The proposal includes the construction of a new sea wall with 7 m in height at Caxias beach, the increase in height of the Barcarena Stream levees and the elevation of the sidewalk at São Bruno beach, with a gentle slope up to 7 m in height. It is also proposed the construction of a third bridge over the Barcarena Stream for pedestrian ranging from 5 to 7 m in height that will serve as a gate for the incoming tsunami waves.

**Keywords:** coastal protection; tsunami; field survey; tsunami numerical model; Portugal

## 1. Introduction

Worldwide coastal areas are quite vulnerable to extreme events such as winter storm surges, hurricanes, typhoons, and tsunamis or meteo-tsunamis. In the past some of these disasters inundated the low ground areas, causing severe damage and fatalities, as presented by, for example, [1,2]. These situations are even more aggravated due to coastal erosion [3] and the sea level rise. Simultaneously, the populations are more attracted to the coastal areas due to urban occupation, tourism or leisure purposes, industry, and services, which increase the population's exposure to these natural disasters [2].

As a consequence, there are many published papers to assess shoreline changes and their impacts on coastal structures in the worldwide coastal evolution. To cope with this problem the Journal of Marine Science and Engineering (MDPI) has published more than 200 papers related to coastal protection, from 2023 till August 2024, and about 100 papers related to tsunamis in the period 2021-2024, too many to conduct a citation of all of them. Still, in this study, several worldwide case studies are presented. For example, [4] presented the installation of buffer blocks in the coastline of Germany. Another study [5] showed that the natural Mangrove belt forests are important not only for the ecosystem, but also for coastal protection. However, the authors pointed out that these natural resources have been disappearing over the decades in Vietnam and artificial breakwaters have been constructed. Thus, they studied the breakwater effectiveness in the prevention of coastal erosion in the Vietnamese Mekong Delta and concluded that these structures are highly effective in reducing wave height impact. Still, structural failures can occur when a tsunami overtops a breakwater [6]. Following the 2004 Indian Ocean Tsunami, the role of mangroves also proved to be very effective in the reduction of the tsunami impact at Banda Aceh, Indonesia [7,8]. On the other hand, other natural features such as vegetation and sand dunes are also very effective in wave attenuation, as discussed in a beach in Florida, EUA [9].

In Portugal, a study [10] showed the complexity of the coastal zone is due mainly to four typologies (Cluster analysis): natural systems in disequilibrium, with predominantly environmental impacts; anthropogenic areas, with high population density, predominantly natural coastal protection, or no protection; natural systems in equilibrium, with few impacts; and predominantly artificial areas, with coastal protection intervention and multiple impacts. On the other hand, another study [11] used the numerical modeling to calculate the wave overtopping phenomenon on a Portuguese alongshore coastal defense structure. Furthermore, [12] showed the assessment of susceptibility to maritime flooding in the Northern coast of Portugal is based mainly on two variables, the wave climate and the morphological state of the beaches. Moreover, another study [13] concluded the average probabilistic calculation for the rising sea level is 0.7 m for a return period of 50 years.

In addition, there are specific guidelines to the Oeiras municipality, Portugal (see location in Figures 1a and 1b). The Municipal Plan of Adaptation to Climate Change of Oeiras [14] claim that “on all the beaches of the municipality is projected that the rise from the mean sea level implies a significant reduction of that capacity, which could derail its beach exploration, with example the Caxias beach. In addition, the Energy and Climate Action Plan of Oeiras (PAECO 2030+) [15], in the Strategic Axis of Water System and Estuarine Edge, the specific measures are to promote the river front adaptation to the average water level rise and flood enlargement, and to promote the protection of buildings at risk of coastal flood or coastal overtopping and existing coastal defense and port structures and beach protection and maintenance.

Previous research [16] has shown the 1755 tsunami arrived at Caxias (Figure 1) 33 minutes after the earthquake, at the beaches inundating the low ground areas of the Caxias downtown (Figure 1c), as well as the Caxias Public Park and Royal Estate of Caxias. In the tsunami inundation zone, there are about 40 buildings: about 25 that are residential, about 10 that are military, two restaurants (#C located at the São Bruno beach, the sewage facility treatment (building #A), one service (building #B) and the São Bruno Fortress (#D). These results are important to understand the overall tsunami impact and evacuation conditions, as discussed by these authors [16]. However, the digital elevation model used in the tsunami numerical model had 9 m of cell size resolution which is not enough to reproduce the detailed local features of Caxias such as the streets of the residential area of Caxias downtown and the parks and gardens layout.

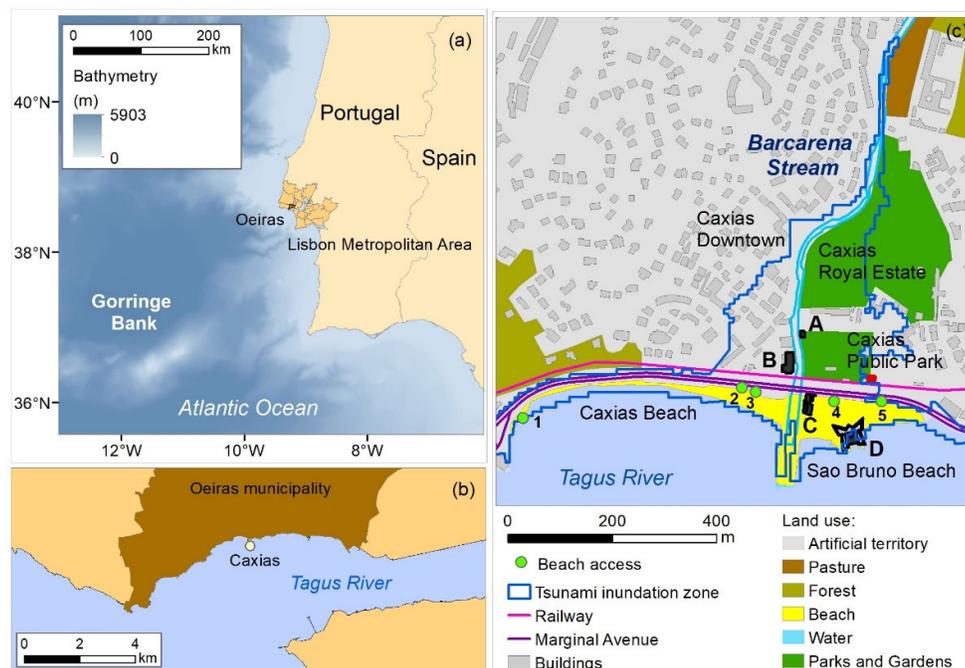
Therefore, the study area taken in this paper is Caxias (Figure 1), which incorporates the Caxias and São Bruno beaches, is localized in Oeiras municipality that is integrated in the Lisbon Metropolitan Area, Portugal. Its geographical coordinates are 38° 41' 55" N, 9° 16' 45" W and 38° 41' 54" N, 9° 16' 27" W. These beaches flank the Barcarena Stream, which is about 25 m wide, and are bordered to the north by the Cascais railway line, built in 1890, and the National Road 6 (Marginal Avenue), inaugurated in 1940 [17]. Two important architectural heritage properties stand out near the beaches: the Caxias Royal Estate and the São Bruno Fortress, which is also inundated by the tsunami (building #C). Built in the 17th century, the Caxias Royal Estate stands out for its unique architectural design, environment, living style and landscape qualities, which constitute a singular cultural heritage [18] while the São Bruno is one of the military defense constructions at the entrance to the Tagus River. Moreover, the location of the Caxias Train Station (red building in Figure 1c) and several parking lots nearby the Caxias and São Bruno beaches make the area even more attractive to residents and tourists.

Moreover, the pandemic situation due to COVID-19 was a unique opportunity to register in real time the present population on both beaches. At the time, the recommendation considering the social distance of 1.5 m [19] for the maximum beach capacity was 1700 people in Caxias beach. In São Bruno beach the maximum capacity was 969 people [20], obtained from a simple rate formula (Maximum beach capacity = beach area / 8.5 m<sup>2</sup>). Thus, the Oeiras City Hall installed turnstiles control data at the beach accesses (#1 to #5, in Figure 1c) to ensure the health safety of beach users. The population data at the beaches consisted on a 24 h records during the summer months of June to September 2021 [20]. The data is still very relevant since there is no available data of the number of present population at both beaches, before and after 2021. The data showed the maximum number of people was registered in Caxias beach on 22 August 2021 between 15h (622 people) and 18 h (734 people). In São Bruno

beach the maximum number of people was register on 4 de July 2021 between 11h (133 people) and 16 h (241 people).

As pointed out by a previous study [16] a basic tsunami scenario is already contemplated in the Municipal Emergency Plan [21] that needs to be reviewed and updated. On the other hand, the Caxias and São Bruno beaches have five accesses: beach access #1 and #5 are stairs, while beach access #2 is a tunnel, and the Beach accesses #3 and #4 are ramps. Although there is high ground nearby, the configuration of these exits may cause some confusion to beach users if an emergency evacuation is necessary, and for that reason, the local tsunami hazard on each beach was classified as High [16].

Thus, the objectives of this research are: (1) to conduct a follow up of a previous publication [16] by using new topographic data to update the tsunami numerical model results of the 1755 event at Caxias and São Bruno Beaches, in the vicinity of Barcarena Stream, in Oeiras municipality, Portugal. (2) Propose several coastal protection measures in order to increase the safety of coastal communities to extreme coastal events on the study area. Moreover, these methods can be applied to other coastal regions in the world particularly on low ground areas.



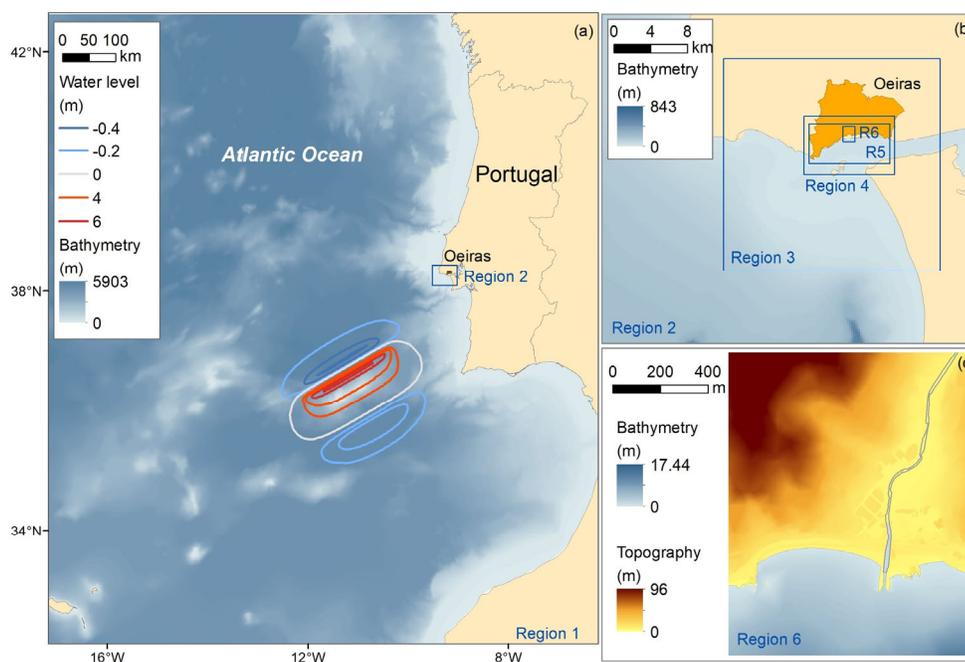
**Figure 1.** Geographical Framework of the study area, with the administrative limits [22]: (a) location of Oeiras municipality; (b) location of the Caxias area in Oeiras municipality; (c) details of the railway, road, buildings [23] and land use (adapted from [24]) at Caxias area. The tsunami inundation zone was calculated by a previous research [16] with cell size resolution of 9m. Highlighted buildings: A- Sewage treatment facility; B-service; C-restaurant; D-São Bruno Fortress; Red building - Caxias train station.

## 2. Materials and Methods

This study is a follow-up of previous research [16], and the methodology is the same. The tsunami numerical modeling was carried out using the TUNAMI-N2 code of Tohoku University which considers the non-linear shallow water equations, discretized with a staggered leap-frog finite difference scheme [25]. The equations were applied to a nesting of six computational regions, where each region has a progressively smaller area and finer grid cell size (from 729 m on region 1 to 3 m on region 6), being included in the previous computational region, as presented in Figure 2. The computational regions 1 to 5 are the same used in a previous publication [16], on which several bathymetry charts and topography maps with different scales.

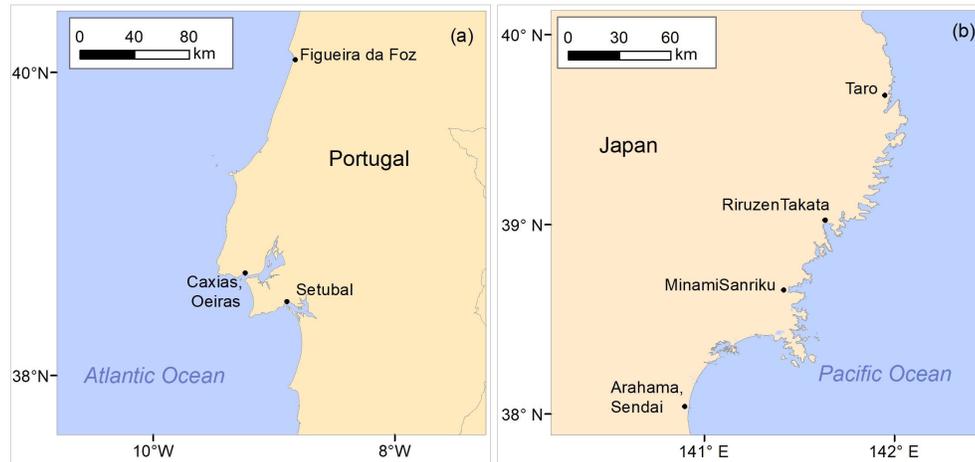
In addition, computational region 6 is new in this study. New topographic data allowed a more detailed and realistic construction of the digital elevation model with 3 m of cell size, to reproduce the local features such as streets, sidewalks and the stream layout. The data collection was based on a laser scan of the study area carried out using a RIEGL VUX laser scanner installed on a helicopter. This mission was carried out on 11 May 2020, at an average altitude of about 61 m (200 feet) and an average speed of about 74 km/h (40 knots). The main technical characteristics of the survey were a nominal point density of a minimum of 16 points per m<sup>2</sup>, a nominal pulse spacing <0.25m, and multiple discrete returns (Minimum potential of 4 per pulse). The absolute vertical accuracy for the LiDAR survey and derived digital elevation model was computed for non-vegetated areas with a RMSEz: <0.10m at more than 95% confidence level.

Also as in the previous research [16], the tsunami source model considered in this study is the 1755 tsunami, calculated by using the Okada formulas [26], on region 1, which led to a maximum uplift of about +6.0 m and a subsidence of -0.4 m (Figure 2a).



**Figure 2.** Conditions of the numerical model setting in Caxias coastal area of Oeiras municipality: (a) Region 1 and initial sea surface displacement of the 1755 tsunami; (b) Region 2 and the placement of regions 3 to 6; (c) Details of computational region 6.

As a complement to the tsunami numerical model, a field survey (Figure 3) was conducted on several occasions. In Portugal (Figure 3a), the surveys were conducted on several spots of Caxias (this study) on different occasions from May 2022 till June 2024. In addition, previous field surveys conducted in 2013 on two other locations of the Portuguese coastline (Figure 3a) help to discuss and interpret the results obtained in this study Cova beach, Figueira da Foz, located at 40° 07' 24" N, 8° 51' 48" W, and Urban Health Park, Setubal, located at 38° 31' 05" N, 8° 54' 11" W. On the other hand, the experience obtained with the field survey in Japan (Figure 3b) in 2012 (after the 2011 Tohoku Tsunami) allow a more comprehensive discussion of the several types of coastal protection. In Japan, the technical visit were conducted in Taro located at 39° 44' 08" N, 141° 58' 19" E, RikuzenTakata located at 39° 00' 13" N, 141° 37' 33" E, MinamiSanriku located at 38° 40' 29" N, 141° 26' 51" E, and Arahama, Sendai located in 38° 13' 15" N, 140° 59' 00" E.



**Figure 3.** Location of places where the several field surveys were conducted, on several occasions: (a) Portugal; (b) Japan.

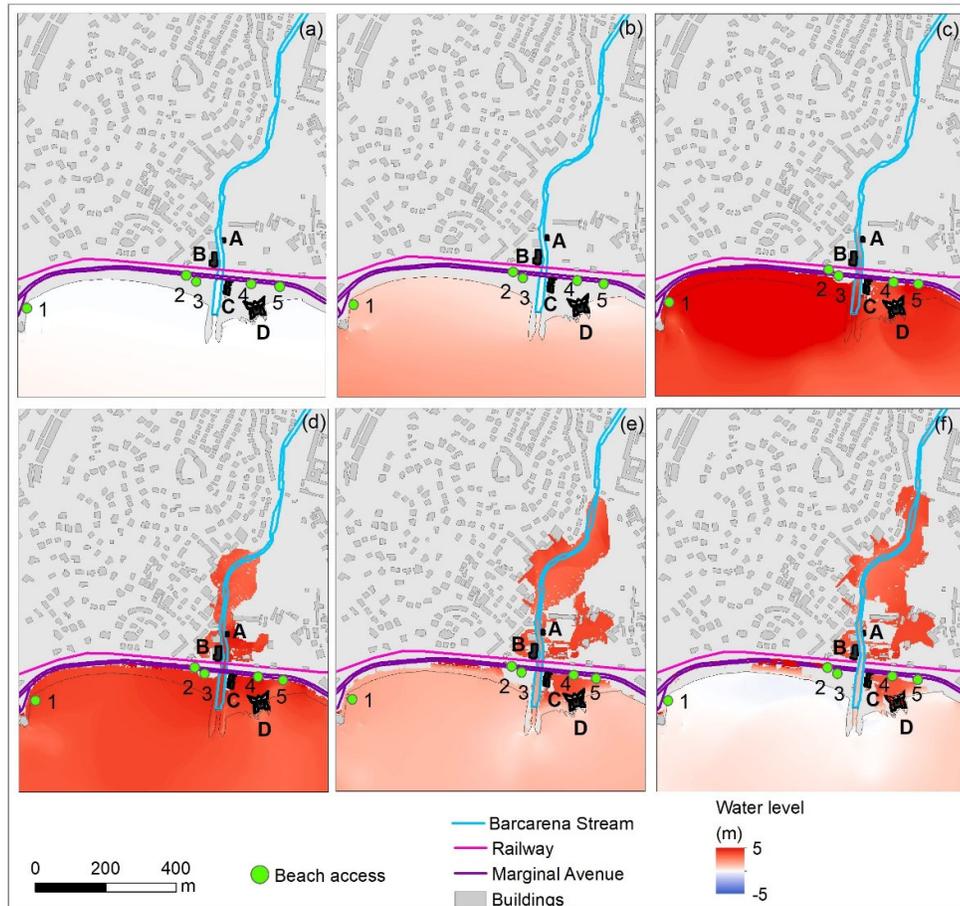
### 3. Results

The tsunami numerical model on computational region 6 produced several output results, such as the water level variation snapshots, inundation depth, maximum water level, and water level time series, as presented in Figures 4 and 6. In addition, the field survey results are presented in Figure 5, by showing a view of the several spots of the study area to help conducting a comprehensive analysis of the tsunami impact.

The water level snapshots results show the first tsunami wave arrives offshore the Caxias and São Bruno beaches at 31 minutes after the earthquake (Figure 4a), taking two more minutes to completely inundate the Caxias beach, the section of the Marginal Avenue (about 460 m length) and the São Bruno beach as well as its sidewalk (Figure 4c). The field survey show the Marginal Avenue has four traffic lanes (Figure 5a), with a total width of about 15 m. On the other hand, the railway, which is not hit by the tsunami, has two lanes with also a total width of about 15 m.

The first wave travels upstream the Barcarena Stream, overtopping its margins which are made of brick and concrete walls with different heights (Figure 5b, 5c), inundating the low ground of the Caxias downtown, the Caxias Public Park, and the Royal Estate of Caxias, from 34 minutes (Figure 4d) after the earthquake, and continue to spread for at least 2 more minutes (Figures 4e, 4f). The field survey show there are sections of the Barcarena Stream that are only protected by a fence, while other parts have vegetation or sea walls (Figures 5b, 5c).

The inundation depth results (Figure 6a) provide the water level above the ground (local topography data), for each computational pixel with cell size of 3 m. The results show that Caxias beach is completely inundated, and the highest value is 6.4 m and the lowest 1.7m. The tsunami also inundates the stretch of the Marginal Avenue with values up to 1.3 m high. Therefore, the road is not a safe place for people to evacuate. The values at São Bruno beach vary between 1.8 m and 5.6 m, and the side walk and the low ground area are completely inundated up to 2.4 m high.



**Figure 4.** Tsunami numerical model results for the elapsed time after the earthquake of water level snapshots showing the arrival of the first tsunami wave: (a) 31 minutes; (b) 32 minutes; (c) 33 minutes; (d) 34 minutes, (e) 35 minutes; (f) 36 minutes. Highlighted buildings: A-Sewage treatment facility; B-service; C-restaurant; D-São Bruno Fortress.

The field survey shows a view of the São Bruno beach and sidewalk (Figure 5d); as the tsunami reaches the seawall of the Marginal Avenue, it may cause some scouring and damages on hit. Although the tsunami does not reach the road which is located above 6 m height, there are only two beach accesses (#4 and #5) that may not be large enough for beach users to safely evacuate the beach.

However, the results on the computational region 6 with pixel cell size of 3 m (this study) show the railway is not hit by the tsunami because it is located on higher ground (from 6.5m height). In the previous study [16] where the tsunami numerical results on computational region 5 were carried out with pixel cell size of 9 m, the tsunami hit the railway and overtopped it, inundating the Caxias downtown and the Caxias Public Park (Figure 1). Two computational factors influenced these results: the new Lidar data allowed a more accurate Digital Elevation model and the setting of the numerical model (Figure 2) allowed the reproduction of the coastal features of the study area.

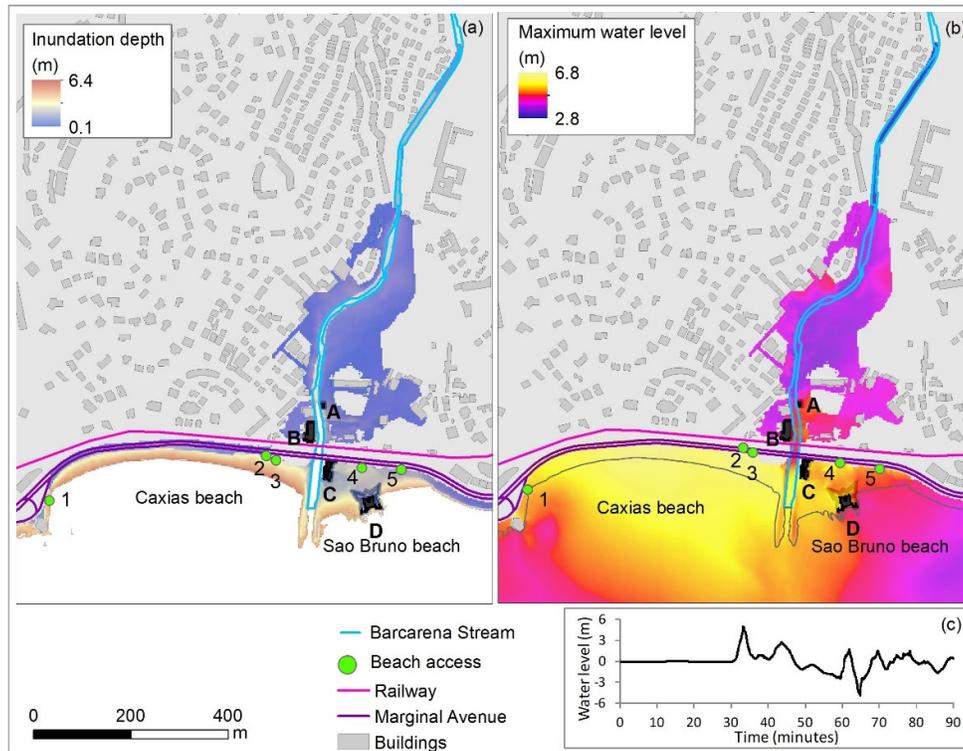


**Figure 5.** Field survey conducted on different spots of the study area. See Figure 1 for locations: (a) Caxias beach, and a view of the Marginal Avenue and railway at 30 April 2024; (b) View of Barcarena Stream in the vicinity of the Caxias Public Park at 2 December 2023. The dashed lines highlight the brick wall at different highs. Building A: Sewage treatment facility; Building B: service. White circle shows an area with only a fence for protection; (c) View of the Barcarena stream in the vicinity of the Caxias downtown and Royal Estate of Caxias. White circle shows an area with the vegetation belt protection with about 2 m high; (d) São Bruno beach on 28 August 2024. Building C-restaurant; building D-São Bruno Fortress; beach access #4 is a ramp; beach access #5 is a stair.

Moreover, the tsunami travel upstream the Barcarena Stream for 1120m, inundating the low ground margins for a section of about 560 m, conducting to an inundation depth at the Caxias downtown up to 3.1m high, up to 2.6 m at the Caxias Public Park and up to 0.9m in the Royal Estate of Caxias.

On the other hand, the maximum water level results (Figure 6b) provide the water level above the mean sea level, for each computational pixel with cell size of 3 m, including on land and offshore outputs. The results show that at Caxias beach the highest value is 6.5 m and the lowest is 5.4 m. The tsunami also inundates the section of the Marginal Avenue with 5.8 m to 6.8 m height, but does not overtops the bridges over the Barcarena Stream (Figures 5a) because they are located at about 6 m height and the maximum water level reaches up to 4.9 m height. In the stretch of the inundated areas of the Caxias downtown and Caxias Royal Estate (about 550 m long) the maximum water level at the Barcarena Stream reaches 4.9 m decreasing gradually upstream till 3.2 m height. In the last stretch of about 370 m where there is no inundation, the water remains restricted within the stream margins and reaches 2.8 m height. The maximum water level at the Caxias downtown varies between 3.9 m and 4.8m height, 4.0 m to 5.0 m height at the Caxias Public Park and 3.2 m to 4.5 m height in the Royal Estate of Caxias. Offshore the São Bruno beach the water level varies between 3.8 m and 5.6 m, and offshore the Caxias beach 4.4 m and 6.4 m.

Finally, the water level time series (Figure 6c) shows the first wave arrives at the coastline of Caxias 31 minutes (picked at the +0.1 m height) after the earthquake and the peak of the first wave is 4.98 m at 33 minutes. The second wave reaches 2.69 m at 44 minutes, followed by other minor waves with maximum water levels between 1.5 and 1.7 m, with sea level variations for 90 minutes.



**Figure 6.** tsunami numerical model results on computational region 6: (a) Inundation depth; (b) maximum water level; (c) Water level time series in Caxias. Highlighted constructions: A-Sewage treatment facility; B-service; C-restaurant; D-São Bruno Fortress.

#### 4. Discussion

Natural landscapes, such as mangrove forests in Asia [5,7,8], or sand dunes [9,27], protect the coastal areas without human intervention. The field survey conducted in Figueira da Foz, Portugal (Figure 7a) shows that sand dunes offer natural protection against extreme coastal events. Nevertheless, constant erosion requires monitoring and, in some places, the construction of spurs and other artificial constructions. However, unlike Figueira da Foz, the Caxias coastal area is not naturally protected by sand dunes. Therefore, other solutions must be planned to allow the coastal protection.

The results presented in Section 3 show the tsunami in the section of the Caxias beach inundates Marginal Avenue. Not only this is a very hazardous situation to the vehicles that circulate on the road, but the air cavity pressure and cavity water depth behaviors when a tsunami overtops a breakwater [6] can cause damage on the sea wall, including the scouring of the foundations. This situation was observed during the 2011 Tohoku Tsunami, in Taro, on which parts of the breakwater were ripped off (Figure 8a). Similar damage due to scoring was also observed in several infrastructures after the 2015 Illapel Tsunami, Chile [28].

In addition, the winter storm surges also raise some concern to the protection of coastal areas, especially during high tides. An example is the Monica Depression that hit Portugal mainland during 7 – 10 March 2024 [29]. The field survey conducted at Caxias beach during and after this storm (Figure 9) shows the waves inundated the beach and the water almost reached the sea wall of the Marginal Avenue.



**Figure 7.** Field survey in Portugal showing natural coastal protection: (a) Cova beach, Figueira da Foz. The sand dunes reach up to 10-14 m height. Photo taken on 2 June 2013; (b) Urban Health Park (Jardim da Saude) with pine trees and elevated ground. Photo taken on 20 June 2013.

To solve this situation, it is proposed to expand the sea wall of the Marginal Avenue, that is, to continue with the silting of the beach, which has been carried out since 19040's. The new area to be constructed must have a height of at least 7m, and at least 10 m wide. In addition, the new area must include some "green belt" with the plantation of several species of bushes and trees. Moreover, the new beach accesses must be done exclusively by ramps (#R1 to R6, in Figures 11 and 12), similar to the existing beach accesses #3 and #4 (Figure 1).



**Figure 8.** Field survey conducted in Japan on 18-19 February 2012: (a) Remains of the breakwater and one building in Taro; (b) Part of the pine tree forest belt at Arahama, Sendai. (c) Only one tree stands from the pine tree forest belt, "The Miracle Pine Tree", Rikuzentakata (d) Tsunami gate at the River Hachiman, Minami-Sanriku.

The "green belt" provides shade, but it is also proved to be an effective barrier to the water pressure [30]. The field survey conducted on several coastal areas show this type of coastal protection has been successfully carried out in Setubal, Portugal (Figure 7b), and in Sendai and Rikuzentakata, Japan (Figures 8b and 8c).

Similarly, the results presented in Section 3 show the São Bruno beach is inundated by the tsunami, hitting the sidewalk. Although the water does not reach the Marginal Avenue, it may cause damage and scoring of the sea wall. To solve this problem, it is proposed to increase the height of the sidewalk (Figure 5d) as a ramp with low slope angle from the current 4m to 7 m. The restaurant (building #D) which is located at about 4 m should also be replaced to a higher topography level of 7 m in height.



**Figure 9.** Field survey conducted on different spots of the study area. See Figure 1 for locations: (a) Beach Access #1 during the Depression Monica on 10 March 2024; (b) Beach Access #1 on 17 December 2023; (c) Sand deposited inside the tunnel (Beach Access #2) due to the Depression Monica on 13 March 2024; (d) Tunnel was cleaned (Beach Access #2) on 30 April 2024.

In addition, the evidence left by the sand and the debris deposited inside the tunnel of Caxias beach (Figure 9c) due to the Depression Monica show the maximum inundation reached about 3.8 m height. On the other hand, the probabilistic estimation for the mean sea level rise to a return period of 50 years is 0.7 m [13]. For these reasons, the new maritime sidewalk to be constructed in Caxias beach, as a continuation the sidewalk at São Bruno beach (Figure 5d), should be constructed at least at 4.5 m height, and about 10 m wide.

Moreover there is evidence that the area of Caxias beach has been decreasing due to the yearly sand erosion combined with lack of maintenance of the beach. Thus, it is important that the sand is replaced to reach 3.5 m in height, and to increase the width of the beach from the current 50 m to 85 m. By consequence, there will be a shift of the coastline.

Nevertheless, it is important to point out that placing a breakwater or buffer blocks offshore the Caxias and São Bruno beaches would decrease the depth of tsunami inundation, as discussed, for example, by [4]. However, this option is not possible to install for coastal protection in the study area because an offshore breakwater is not esthetically appealing for both residents and tourists, as well as may constitute a hazard to the navigation on the Tagus River.

In addition, the quality of the water of Caxias and São Bruno beaches is not very good. Portugal has the Blue Flag Award [31]; each year the blue Flag is granted to the beaches that follow several criteria, including the water quality. In 2024 Caxias and São Bruno beaches did not receive the Blue

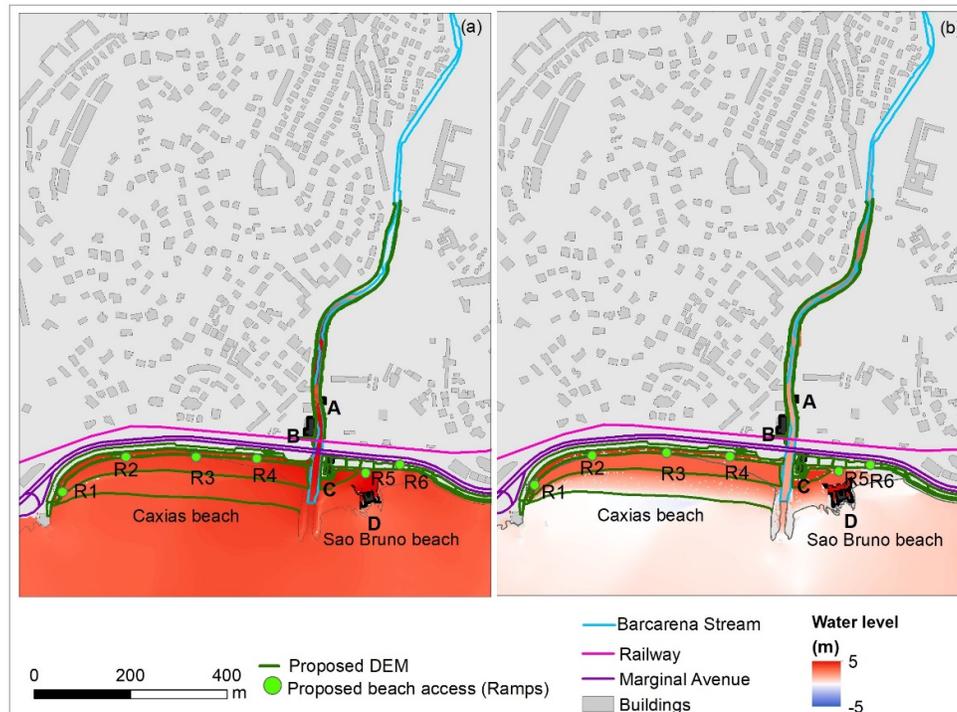
Flag. The water is regularly analyzed by chemical and biological contents of the water [32] showing the beaches are acceptable for public use. Although the water quality analysis is outside the scope of this paper, to improve the water quality at the beaches it is recommended to relocate the sewage treatment facility (Building #A), or to impose more strictly methods to filter the water that is dumped into the Barcarena Stream. Thus, adding off shore breakwaters or buffer blocks may cause the possibility of reducing or even cutting all together the water regeneration in the high-low-tide currents, which in turn would cause a significant decrease of the water quality.



**Figure 10.** Proposal to build a new bridge over the Barcarena Stream. This third bridge is only for pedestrians and bicycles and should have a height ranging from 5 – 7 m, since at the present the Marginal Avenue is at about 6 m height, and the lower part of the bridge is at 5 m height. In addition, the new bridge should have a design to deflect the incoming sea waves.

The results presented in Section 3 show the tsunami overtops the margins of Barcarena Stream. The field survey show there is already some effort to protect the low ground area with sea wall and vegetation (Figures 5b and 5c). Thus, it is proposed the continuation of the construction of the levees and increasing their heights ranging from 4.8 m to 7.2 m at the tsunami inundation zone. Moreover, the field survey in MinamiSanrilu (Figure 8d) shows that tsunami gate could be an effective structure to decrease the tsunami impact upstream the Barcarena Stream. On the other hand, the field survey conducted in MinamiSanriru also show that some sections of the gates failed to low because of damage due to the earthquake. In addition, the cost-benefit makes this option not realistic to be applied in Portugal. Instead it is proposed the construction of a new bridge only for pedestrians (Figure 10). The bridge would allow the passage between the Caxias and São Bruno beaches, as a continuous maritime sidewalk. The damage on bridges related to tsunamis overtopping the upper decks have been analyzed [33, 34]; thus, to avoid this situation, the new proposed bridge in the river mouth of the Barcarena Stream should be at 7 m height.

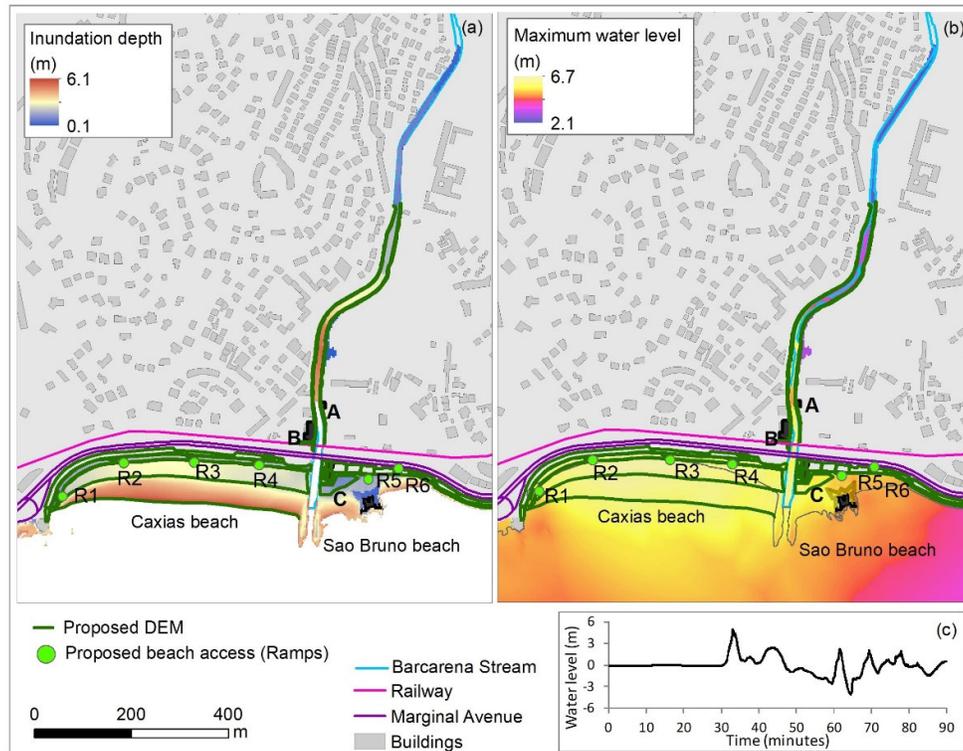
Thus the proposed digital elevation model (DEM) was added to the topography of computational region 6 (Figure 2c) and the tsunami numerical model was carried out again. Figures 11 and 12 show the results of the new simulation, with the proposed DEM that would allow further coastal protection. The first tsunami wave inundates the Caxias beach, its new sidewalk and the São Bruno beach. The first wave travels upstream the Barcarena Stream, but does not overtop its margins (Figure 11).



**Figure 11.** Tsunami numerical model results for the elapsed time after the earthquake of water level snapshots showing the arrival of the first tsunami wave, with the Proposed DEM (digital elevation model) represented by the green line: (a) 34 minutes, (b) 36 minutes; Highlighted buildings: A-Sewage treatment facility; B-service; C-restaurant; D-São Bruno Fortress.

The inundation depth results (Figure 12a) show that Caxias beach is completely inundated, with the lowest value of 1.8 m and the highest value of 6.1 m, and the values at São Bruno beach vary between 1.8 m and 5.3 m, which are very similar to the results obtained with the current DEM (Figure 6a). However, it does not inundate the new seawall at Caxias beach with 7 m height, and therefore the Marginal Avenue is not hit, nor the new sidewalk and restaurant (Building #C) at São Bruno beach.

The maximum water level results (Figure 12b) show that at Caxias beach the lowest is 5.2 m and the highest is 6.1 m. The tsunami does not overtop the bridges over the Barcarena Stream (Figures 5a and 10) because they are located at about 6 m height and the maximum water level ranges between 5.6 m and 5.8 m height. Still, the water may reach the lower part of the bridges that are about 5 m height, and for this reason the new proposed pedestrian bridge should serve as a tsunami gate to protect the existing bridges of the Marginal Avenue and railway (Figure 5a). Still, a careful analysis must be carried out before construction of the new bridge due to the interaction between decks of twin-box bridges [33]. The tsunami travels upstream the Barcarena Stream and the water remains within its margins with the maximum water level ranging between 2.1 m and 5.8m. Finally, the water level time series (Figure 12c) shows the tsunami has the same behavior offshore, with no variation from Figure 6c.



**Figure 12.** Tsunami numerical model results on computational region 6, with the proposed DEM (digital elevation model) represented by the green line: (a) Inundation depth; (b) maximum water level; (c) Water level time series in Caxias. Highlighted buildings: A-Sewage treatment facility; B-service; C-restaurant; D-São Bruno Fortress.

## 5. Conclusions

The new Lidar topographic data allowed the construction of a more accurate digital elevation model of the study area with a cell size pixel of 3 m. The tsunami numerical model results show the 1755 tsunami arrives at Caxias at 33 minutes after the earthquake, inundating the Caxias beach and the Marginal Avenue; the downtown of Caxias is also inundated, including residential buildings. In addition, although tsunamis are rare events, the winter storm surges are more common and have become more severe. The sea level rise is also a concern for low ground areas all over the world. The Depression Monica that hit Caxias in March 2024 reaching a maximum of 3.8 m height, inundated the Caxias beach and the tunnel (beach access #2).

For these reasons, it is proposed to continue the silting process of the Caxias beach, by the construction of a new seawall with 7 m height, and the new sidewalk at the beach should be at least 4.5 m in height. At São Bruno beach is proposed to increase the high of the present sidewalk from the current 4 m height to 7 m height, with a gentle slope. The restaurant on this beach (building #C) should also be raised to a height of 7 m. The levees of the margins of the Barcarena Stream should have a height ranging between 4.8 m to 7.2 m. The numerical simulation considering the proposed DEM shows the tsunami inundates only the low ground areas of the Caxias and São Bruno beaches, and all the seawalls are not hit.

**Author Contributions:** Conceptualization, A.S. and N.M.; methodology, A.S. and N.M.; Calculations and field survey, A.S.; writing—original draft preparation, A.S. and N.M.; writing—review and editing, A.S. and N.M.; visualization, A.S.; All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was supported by Portuguese national funds through the Fundação para a Ciência e a Tecnologia (FCT, I.P.), under the funding “UIDB/GEO/00295/2020” and “UIDP/GEO/00295/2020”.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The data that support the findings of this study are available on request from the corresponding authors.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## References

1. Barui, I.; Bhaktaa, S.; Ghosha, K.; Shawb, R. Assessment of household vulnerability to embankment breaching in the coastal area of the Indian Sundarban. *Inter J Disas R Red* **2024**, *110*, 104632. <https://doi.org/10.1016/j.ijdr.2024.104632>.
2. Cisternas, P. C.; Cifuentes, L.A.; Bronfman, N.C.; Repetto, P. B.; Castaneda, J.V. Household preparedness for multi-natural hazards in coastal communities. *Inter J Disas R Red* **2024**, *109*, 104584. <https://doi.org/10.1016/j.ijdr.2024.104584>.
3. Gasc-Barbier, M.; Mateos, R.M.; Iasio, C.; Chanal, A.; Villatte, A.; Bernardie, S.; Reyes-Carmonab, C.; Sarro, R.; Martínez-Corbella, M.; Luque, J. A.; Viniellese, J. L.; Monserrat, O. Crisis exercise in the framework of coastal geohazards: Experience in the Balearic islands (Spain). *Inter J Disas R Red* **2024**, *102*, 104270. <https://doi.org/10.1016/j.ijdr.2024.104270>.
4. Nageswaran, P.; Oetjen, J.; Harish, S.; Sriram, V.; Sundar, V.; Schüttrumpf, H. Buffer Blocks as Wave Energy Dissipators: Flow Depth Reduction. *J. Mar. Sci. Eng.* **2024**, *12*, 1145. <https://doi.org/10.3390/jmse12071145>.
5. Ty, T.V.; Duy, D.V.; Phat, L.T.; Minh, H.V.T.; Thanh, N.T.; Uyen, N.T.N.; Downes, N.K. Coastal Erosion Dynamics and Protective Measures in the Vietnamese Mekong Delta. *J. Mar. Sci. Eng.* **2024**, *12*, 1094. <https://doi.org/10.3390/jmse12071094>.
6. Kim, T.; Malherbe, J.N.; Shimpalee, S.; Bricker, J.D. Sub-Nappe Air Cavity Pressure and Cavity Water Depth during Caisson Breakwater Overtopping by a Tsunami. *J. Mar. Sci. Eng.* **2024**, *12*, 1135. <https://doi.org/10.3390/jmse12071135>.
7. Yanagisawa, H.; Koshimura, K.; Miyagi, T.; Oie, T.; Imamura, F. The Potential Role of Mitigating Effects of Mangrove Forest against the 2004 Indian Ocean Tsunami in Banda Aceh. *Annual Jour. Coast. Eng.* **2007**, *54*, 246-250 (in Japanese).
8. Yanagisawa, H.; Koshimura, S.; Miyagi, T.; Imamura, F. Tsunami damage reduction performance of a mangrove forest in Banda Aceh, Indonesia inferred from field data and a numerical model. *J. Geophys. Res.* **2010**, *115*, C06032. <http://doi:10.1029/2009JC005587>.
9. Ma, M.; Huang, W.; Jung, S.; Oslon, C.; Yin, K.; Xu, S. Evaluating Vegetation Effects on Wave Attenuation and Dune Erosion during Hurricane. *J. Mar. Sci. Eng.* **2024**, *12*, 1326. <https://doi.org/10.3390/jmse12081326>.
10. Barros, J.L.; Santos, P.P.; Tavares, A. O.; Freire, P.; Fortunato, A. B.; Rilo, A.; Oliveira, F. S.B.F. The complexity of the coastal zone: Definition of typologies in Portugal as a contribution to coastal disaster risk reduction and management. *Intern. J. Dis. R. Red.* **2023**, *86*, 103556. <https://doi.org/10.1016/j.ijdr.2023.103556>.
11. Oliveira, J. N.C.; Oliveira, F. S. B. F.; Neves, M.G.; Clavero, M.; Trigo-Teixeira, A. A. Modeling Wave Overtopping on a Seawall with XBeach, IH2VOF, and Mase Formulas. *Water.* **2020**, *12*, 2526. <https://doi:10.3390/w12092526>.
12. Santos, D.; Abreu, T.; Bernardes, C.; Baptista, P. Coastal flood susceptibility assessment along the Northern coast of Portugal. *Intern. J. Dis. R. Red.* **2024**, *108*, 104556. <https://doi.org/10.1016/j.ijdr.2024.104556>.
13. Antunes, C.; Rocha, C.; Catita, C. Coastal Flood Assessment due to Sea Level Rise and Extreme Storm Events: A Case Study of the Atlantic Coast of Portugal's Mainland. *Geosciences* **2019**, *9*, 239. <http://doi:10.3390/geosciences9050239>.
14. Dias, L.F.; Santos, F.D. Oeiras Municipal Climate Change Adaptation Plan, 27 pp, 2019. (In Portuguese). <https://oeirasinterativa.oeiras.pt/dadosabertos/dataset/pmaaco-sumario-executivo>. (accessed on 12 September 2024).
15. Nunes, E.; Henriques, R. P.; Martins, A. S.; Silva, I.; Lima, P. Oeiras Energy and Climate Action Plan (PAECO 2030+), 37pp, 2023. (In Portuguese) <https://www.oeiras.pt/-/plano-de-acao-energia-e-clima-de-oeiras-paeco-2030>. (accessed on 12 September 2024).
16. Santos, A.; Fernandes, J.; Mileu, N. Tsunami Hazard Assessment at Oeiras Municipality, Portugal. *J. Mar. Sci. Eng.* **2022**, *10*, 1120. <https://doi.org/10.3390/jmse10081120>.

17. Henriques, J. The construction of the Marginal Road – 1940 - When progress meets tradition. *Pedra&Cal – Revista da Conservação do Património Arquitectónico e da Reabilitação do edificado*, n.º 19,2003; pp 32-33 (in Portuguese).
18. Marques, R. Caxias Royal Estate as an architectural and landscape heritage site in the Municipality of Oeiras. A case study. Master Thesis, Faculdade de Ciências Sociais e Humanas, New University of Lisbon, 57 pp, 2020. (in Portuguese). <https://run.unl.pt/bitstream/10362/111668/1/Documento%20Final%20Disserta%C3%A7%C3%A3o%20-%20vers%C3%A3o%20corrigida%20e%20melhorada%20ap%C3%B3s%20defesa%20p%C3%B3s%20defesa%20p%C3%B3s%20defesa%20p%C3%B3s%20defesa.pdf> (accessed on 12 September 2024).
19. Agência Portuguesa do Ambiente (2021). Despacho nº: 05/VPRES/2021, de 08 de maio de 2021, ANEXO II. (in Portuguese). [https://apambiente.pt/sites/default/files/\\_A\\_APA/Comunicacao/Epoca\\_balnear/Anexo\\_II\\_DespachoVP\\_CapacidadeOcupacaoPraias\\_2021.pdf](https://apambiente.pt/sites/default/files/_A_APA/Comunicacao/Epoca_balnear/Anexo_II_DespachoVP_CapacidadeOcupacaoPraias_2021.pdf) (accessed on 12 September 2024).
20. Fernandes, J. Evacuation strategies in case of tsunami on the beaches of the municipality of Oeiras. Master Thesis, Lisbon University, 143 pp, 2023 (in Portuguese). <https://repositorio.ul.pt/handle/10451/64355>.
21. Municipality of Oeiras, Emergency Municipal Plan of Civil Protection, 2018; 1–59. Available online: <http://planos.prociiv.pt/Documents/132131286457737300.pdf> (accessed on 12 September 2022). (In Portuguese).
22. DGT – General Direction of the Territory. Official Administrative Chart of Portugal, 2023. (In Portuguese) <https://www.dgterritorio.gov.pt/cartografia/cartografia-tematica/cao>. (accessed on 12 September 2024).
23. OpenStreetMap Contributors (2024). OpenStreetMap Foundation. Available as open data under the Open Data Commons Open Database License (ODbL) at [openstreetmap.org](https://openstreetmap.org). (accessed on 12 September 2024).
24. COS—Chart of the Land Use. 2018. Available online: <https://www.dgterritorio.gov.pt/Carta-de-Uso-e-Ocupacao-do-Solo-para-2018/> (accessed on 12 September 2024). (In Portuguese)
25. Imamura, F. Review of tsunami simulation with a finite difference method. In *Long-Wave Runup Models*; World Scientific: Singapore, 1995; pp. 25–42.
26. Okada, Y. Surface deformation due to shear and tensile faults in a half space. *Bull. Seismol. Soc. Am.* **1985**, *75*, 1135–1154. <http://doi.org/10.1785/BSSA0750041135>.
27. Maximiliano-Cordova, C.; Silva, R.; Mendoza, E.; Chávez, V.; Martínez, M.L.; Feagin, R.A. Morphological Performance of Vegetated and Non-Vegetated Coastal Dunes with Rocky and Geotextile Tube Cores under Storm Conditions. *J. Mar. Sci. Eng.* **2023**, *11*, 2061. <https://doi.org/10.3390/jmse11112061>.
28. Rodwell, J.; Williams, J.H.; Paulik, R. Empirical Fragility Assessment of Three-Waters and Railway Infrastructure Damaged by the 2015 Illapel Tsunami, Chile. *J. Mar. Sci. Eng.* **2023**, *11*, 1991. <https://doi.org/10.3390/jmse11101991>.
29. IPMA- Instituto Portugues do Mar e da Atmosfera. Boletim Climático Portugal Continental, Março 2024, 20 pp., ISSN 2183-1076. (In Portuguese). Available online: [https://www.ipma.pt/resources.www/docs/im.publicacoes/edicoes.online/20240412/cmzpfBYAMoFvSGMxYtxE/cli\\_20240301\\_20240331\\_pcl\\_mm\\_co\\_pt.pdf](https://www.ipma.pt/resources.www/docs/im.publicacoes/edicoes.online/20240412/cmzpfBYAMoFvSGMxYtxE/cli_20240301_20240331_pcl_mm_co_pt.pdf). (accessed on 12 September 2024).
30. Chau, T.V.; Jung, S.; Kim, M.; Na, W.-B. Analysis of the Bending Height of Flexible Marine Vegetation. *J. Mar. Sci. Eng.* **2024**, *12*, 1054. <https://doi.org/10.3390/jmse12071054>.
31. Blue Flag. 2024. List of award-winning locations by region (in Portuguese). <https://bandeiraazul.abaae.pt/galardoados/galardoados-2024/> (accessed on 12 September 2024).
32. SNIRH – National System of Information of Hydrological Services. 2024. Bathing Waters 2024 (Water quality analysis). [https://snirh.apambiente.pt/snirh/\\_dadossintese/zbalnear/janela/par\\_graficos.php?code\\_cee=PTCQ9L&ano=2024](https://snirh.apambiente.pt/snirh/_dadossintese/zbalnear/janela/par_graficos.php?code_cee=PTCQ9L&ano=2024). (accessed on 12 September 2024).
33. Yan, Q.; Li, X.; Jia, B.; Yu, X.; Luo, Y. Numerical Investigation of Tsunami Wave Force Acting on Twin Box-Girder Bridges. *J. Mar. Sci. Eng.* **2024**, *12*, 1171. <https://doi.org/10.3390/jmse12071171>.
34. Zheng, Y.; Kosa, K.; Sasaki, T. Tsunami damage analysis for bridges in Shizugawa area. *Journal of Structural Engineering.* **2013**, *59A*, 439-449. <https://doi.org/10.11532/structcivil.59A.439>

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