

Article

Episodic vs. Sea Level Rise Coastal Flooding Scenarios at the Urban Scale: Extreme Event Analysis and Adaptation Strategies

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Abstract

Sea level rise (SLR) and increased urbanisation of coastal areas have exacerbated coastal flood threats, making them even more severe in important cultural sites. In this context, the role of hard coastal defences such as promenades and embankments needs to be carefully assessed. Here, a thorough investigation is conducted in Grado, one of the most significant coastal and historical towns in the Friuli Venezia Giulia region of Italy. Grado is located on a barrier island of the homonymous lagoon, the northernmost of the Adriatic Sea, and is prone to flooding from both the sea and the back lagoon. The mean and maximum sea levels from the historical dataset of Venice (1950–2023) were analysed using the Gumbel-type distribution, allowing for the identification of annual extremes based on their respective return periods (RPs). Grado and Trieste sea level datasets (1991–2023) were used to calibrate the statistics of the extremes and to calculate the local component (subsidence) of relative SLR. The research examined the occurrence of annual exceedance of the minimum threshold water level of 110 cm, indicating Grado's initial notable marine ingression. The study includes a detailed analysis of flood impacts on the urban fabric, categorised into sectors based on the promenade elevation on the lagoon side, the most vulnerable to flooding. Inundated areas were obtained using a high-resolution digital terrain model through a GIS-based technique, assessing both the magnitude and exposure of the urban environment to flood risk due to storm surges, also considering relative SLR projections for 2050 and 2100. Currently, approximately 42% of Grado's inhabited area is inundated with a sea level threshold value of 151 cm, which occurs during surge episodes with a 30-year RP. By 2100, with an optimistic forecast (SSP1-2.6) of local SLR of around +53 cm, the same threshold will be met with a surge of ca. 100 cm, which occurs once a year. Thus, extreme levels linked with more catastrophic events with current secular RPs will be achieved with a multi-year frequency, inundating more than 60% of the urbanized area. Grado, like Venice, exemplifies trends that may impact other coastal regions and historically significant towns of national importance. As a result, the generated simulations, as well as detailed analyses of urban sectors where coastal flooding may occur, are critical for medium- to long-term urban planning aimed at adopting proper adaptation measures.

Keywords: sea level rise; storm surge; coastal flooding; extreme water levels; urban planning; local adaptation strategy; risk management; northern Adriatic Sea

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1. Introduction

Sea level rise (SLR) is already affecting the Mediterranean and Adriatic coasts. Defined as a hot spot of climate change [1], especially in terms of extreme events [2], this area is gradually warming 20% faster than global trends [3–6], as the effects are expected to be more intense than in other areas of the planet [7,8]. Globally, the imminent effects of SLR will lead to heightened risks of erosion, salinisation, and particularly coastal flooding [9,10]. The primary consequences include the loss of low-lying and sandy shoreline areas, shoreline retreat, saline intrusion [11], and the degradation of ecosystems [12–15]. In recent decades, coastal flooding events in the Mediterranean have intensified and become more frequent, linked to significant storms and severe surge phenomena [16–18]. Flooding is especially pertinent to the Adriatic Sea, where storm surge components are more pronounced than in other regions of the Mediterranean basin [19,20].

The northern Adriatic is noteworthy regarding meteorological and marine forcing [21]. The highest sea levels, resulting from storm surge events, may exceed the elevation of one meter in certain instances [22]. Extreme levels are attained during the autumn season, specifically in November, when the surge effect is pronounced due to the interplay of various factors, including the combined influence of strong Sirocco winds from the southeast [21] and the inverse effect of atmospheric pressure. South-easterly winds propel the water mass for durations of hours or days along the Adriatic Sea, leading to flooding events [23]. The impact of the generated storm surge is significantly greater in the shallow waters of the northern Adriatic [21,22,24,25].

The increase in sea level, coupled with the storm surge, can result in an enhanced response, particularly when combined with subsidence, notably for alluvial plain and deltaic-lagoon coastlines. For these reasons, whole northern Adriatic coastlines, encompassing the Venice and Grado-Marano lagoons along with the Po Delta territory, are among the Mediterranean regions most vulnerable to relative sea level rise (RSLR) and marine flooding [26–28], particularly during extreme events [29].

Furthermore, Rizzi et al. [30], Melet et al. [31], and Bonaldo et al. [32] have observed that sensitivity to SLR in Mediterranean regions, especially the northern Adriatic Sea (or the Nile Delta), is intensified by the high population density and significance concentrated along coastal strips [33,34]. Moreover, the coastal territories of the study area include several historical cities and important tourist destinations.

Densely populated coastal regions, which hold significant economic and tourism value, face the risk of disappearance due to a combination of factors [35,36]. Alongside the global and regional effects of SLR, rapid urban development has notably increased flood risks in coastal areas [37,38]. This has led to socio-economic damage [39–44], attributed to a growing population at risk of flooding [45] and recurring critical issues within urban environments [12]. This encompasses issues such as transport disruptions [46], vehicle accidents, and building collapses [47], along with impacts on land use [15] and human activities [48], thereby endangering significant cultural sites in certain coastal regions [49,50].

For this reason, careful studies should be carried out to analyse and define the impact and effects of marine flooding, especially in urbanised coastal areas [51].

The need to develop adaptation and mitigation plans [52–54] in response to the effects of climate change, sometimes by making substantial modifications to the territory at risk of extreme events [6,55], has increased public awareness and concern about political responsibilities in translating these issues into urban planning programmes [56]. Since 2008, starting with the Covenants of Mayor, European local governments have signed SECAPs, Sustainable Energy and Climate Action Plans, committing to increasing energy efficiency and the use of renewable energy sources, as well as incorporating adaptation measures and climate mitigation strategies [57]. Following the SECAP's guidelines, it was possible, for instance, to draw up coastal flood hazard maps for the urban area of Trieste

[58], to assess the incidence of flooding at a local scale. Multiple studies [56,59–64] indicate that ad-hoc simulations are essential for designing flood management plans and for regular urban maintenance programs. This approach aids regional and municipal governments in formulating effective planning strategies and mitigation actions, thereby significantly reducing management costs in the short term [65].

In this work, we present a comprehensive study of flooding scenarios for the town of Grado, situated in the northern Adriatic Sea, which is recognised as one of the most significant coastal and heritage towns in Friuli Venezia Giulia. The town is built on a barrier island and experiences flooding, both from the sea and from the lagoon located behind it. In recent years, the local Civil Protection of the Friuli Venezia Giulia region has been quite active regarding flooding issues, particularly due to the challenges posed by water ingress from the lagoon side and the resulting inconveniences within the urban fabric. The objective of this work arises from the necessity to explore the criticality of flooding at an urban detail scale, where we can achieve sufficiently accurate altimetric precision to conduct various types of flooding simulations, including surge occurrence and RSLR projections. The analyses hold significant relevance for coastal areas like Grado, which has faced considerable challenges, particularly over the past decade.

2. Study Area

2.1. The Town of Grado

The municipality of Grado lies in the easternmost part of the Grado and Marano lagoon, bordering the northern part of the Adriatic Sea, in the Friuli Venezia Giulia region, Italy (Figure 1). The municipality has a total area of 115.5 km², 45 km² of dry land and 70.5 km² of lagoon [66]. The dry land represents the easternmost part of the barrier island systems bordering the Grado Lagoon and is almost entirely devoted to tourism and agriculture [67]. Despite having just over 7550 inhabitants [68], a number that triples during the summer season, it represents one of the most important tourist hubs in the region with 1.4 million visitors per year [69]. The settlement is connected to the mainland by a long artificial dam and includes a scenic lagoon-type core, around which more recent districts have developed. After the post-war period, the major urban development of the town took place, alongside the expansion of coastal accommodations and bathing facilities, including the “Costa Azzurra” popular beach, the seawall protecting the historic centre and the Main Beach [70].



Figure 1. Overview of the municipality area of Grado, located in the northern Adriatic Sea: (a) northern Adriatic Sea; (b) the eastern part of the northern Adriatic Sea and Grado and Marano Lagoon. The position of the DWRG1 wave buoy is also reported. The white rectangle identifies the study site; (c) orthophotography representing in detail the town of Grado.

Grado, after Aquileia, is an important archaeological site. Over the decades, significant cultural heritage has been discovered, ranging from the Roman to the early Christian and early medieval periods. Numerous relics have been discovered along the shoreline, particularly in front of the Grado seawall, including old church dykes and Roman structures [71–73]. The most significant remains are found in what is known as the *castrum*, the historic centre (Figure 1) that corresponds to the original urban core. Early Christian architectural relics include the St. Eufemia Cathedral, the baptistery and church of Santa Maria delle Grazie, and the ruins of the Basilica delle Corte.

2.2. Oceanographic and Meteorological Forcing

The northern Adriatic wind climate is marked by the dominance of Bora winds, primarily originating from the E-NE direction, in both frequency and intensity [74,75]. The Sirocco winds originating from the southeast are also significant. The warm and humid Sirocco winds exhibit lower intensity compared to the Bora winds, yet they are distinguished by a significantly extended fetch of approximately 800 km. Under particularly persistent conditions, the Sirocco can produce waves of considerable heights along the North Adriatic coast [76].

Data from the wave buoy OGS-DWRG1 (coordinates 13.24° E, 45.56° N, −15.2 m depth) indicate that the mean significant wave height (H_s) is below 0.5 m. Events with significant wave heights exceeding 0.5 m constitute 25% of the total dataset, with predominant wave directions from the southeast (10.7%) and east-northeast (10.5%). The Sirocco exhibits the highest recorded wave heights, with H_s measured at 4.4 m [75]. The annual wave energy flux for the northern Adriatic region is 1.95 kW/m. Longshore drift is oriented westward from the mouth of the Isonzo River [77]. The astronomical tide in the Gulf of Trieste is semi-diurnal, with a mean value of 76 cm [78], 105 cm for spring tide, and 22 cm for neap tide [79]. The combination of spring tide, seiche, and low-pressure forcing, as

well as strong SE winds that push the water mass below the coast, causes a significant rise in sea level [21,80], also known as surge or locally “acqua alta”. The waves are bimodal due to the Bora and Scirocco winds [74].

3. Materials and Methods

The elaboration developed in this work includes a series of statistical analyses on tide gauge data and flooding map construction according to the following steps.

- Analysing the time series of sea level data recorded in three important tide gauges in the northern Adriatic Sea, to define the return period (RP) of extreme sea levels.
- Defining the threshold for the urban flooding of the city of Grado and estimating the occurrence and possible exceedance above the threshold.
- Using the LiDAR-derived digital terrain model (DTM), dividing the Grado territory into sectors with varying levels of vulnerability to obtain a series of downscaling maps of episodic flood-inducing extreme events with different RPs. The analysis also includes a detailed inspection of the promenade elevation along the lagoon border.
- Estimating relative sea level rise (RSLR) for the town of Grado, by comparing the IPCC AR6 Report [35], tide gauge data from Trieste and Grado, and the literature, for inferring the vertical land motion (VLM) component.
- Combining the RSLR predictions for 2050 and 2100 with the episodic events statistics and RPs, in order to assess the reduction of the same RPs of given flooding thresholds.

3.1. Statistics of the Extreme Water Levels

The total water level (TWL) data were derived from the records of the Meteo-Mareographic Network of the Lagoon of Venice (RMLV), pertaining to the Zero Mare Punta della Salute 1897 (ZMPS datum). The historical series spanning 1950 to 2023 was examined to evaluate the likelihood of severe level occurrences. Given the large number of years available, we simplify our approach by adopting the Gumbel distribution, a specific case of the Generalized Extreme Value (GEV), using the Block Maxima (BM) methodology [81] in order to identify maximum values for uniform time intervals. The use of over 70 years of data provides a sufficient number of annual maxima to support a statistically sound application of the GEV-BM approach. As shown by Caruso and Marani [82], GEV-BM applied to the long time series of Venice exhibits low estimation uncertainty for return periods up to approximately 100 years, particularly when long calibration windows are available. Additionally, from the perspective of risk management, the moderate overestimation of return levels by GEV-BM in the short-to-intermediate return period range obtained by [82] can be interpreted as conservative, providing an additional safety margin in applications such as coastal infrastructure design, as in the case of Grado.

Annual maximum values exceeding 110 cm, referenced to ZMPS, were retrieved from the time series. The data spanning from 1950 to 2020 (prior to the closure system of the Venice Lagoon, called Mo.S.E.) are sourced from the ‘Centro Previsione e Segnalazioni Maree’ of the Municipality of Venice [83], whereas the data from 2021 to 2023 are provided by the same organisation but recorded offshore Venice by the ‘Piattaforma Oceanografica Acqua Alta ISMAR-CNR’ during the Mo.S.E operation. The subsequent procedure entailed a calibration process of the studied historical series about the SLR trend. A SLR rate of roughly 2.5 mm per year was utilised. The reference rate utilised was derived using the 1996–2023 reference period to examine the latest trends, based on the local history series documented by the Trieste tide gauge (Table 1), in relation to the national IGM datum (ref. Genova 1942).

Table 1. List of tide gauges in the northern Adriatic considered in this study.

Site	Station Name	Latitude (°)	Longitude (°)
Venice	RMLV	45° 25′ 50.49″	12° 20′ 11.97″
Trieste	Molo Sartorio	45° 38′ 50.00″	13° 45′ 33.90″
Grado	RMLV	45° 40′ 59.26″	13° 23′ 00.38″

The analysis of extremes utilised 2006 as the reference year, with a baseline from 1995 to 2014, according to the latest IPCC report [35], which reflects the most recent trends. A detrending operation was performed on the overall historical series values from 1950 to 2023, adjusting them based on 2006 as the barycentre of the baseline. Consequently, SLR rates should be subtracted from the years following the baseline and added to the years preceding the baseline, in relation to the trend observed from 1950 to 2023. The extreme values sample underwent statistical inference analysis to ascertain the parameters of the Gumbel distribution [84]. The data sample was arranged in descending order, and for each m -th value, the sample frequency of non-exceedance is computed using the plotting position formula based on Gringorten's formulation [85]. The least squares method was subsequently applied.

Once the non-exceedance probability function was defined, considering that this is linked to the return time of the value, it was possible to evaluate the extreme sea level value corresponding to an assigned RP. Finally, the obtained thresholds were adjusted according to the IGM datum, subtracting 23.56 cm from the level value referred to the ZMPS datum [86].

3.2. Annual Exceedance of Flooding Threshold

The analysis initially assessed the mean SLR trend for Grado concerning the duration of exceedances of the previously updated extreme thresholds. The sea level trend recorded by the tide gauge station in Grado (Table 1), reference ZMPS, is accessible in the ISPRA database [87]. The data, accessible since 1991, were collected at 5-min intervals until 2019 and at 10-min intervals from 2020 to 2023. The data were subsequently converted to the IGM datum by subtracting 23.56 cm from the ZMPS reference level value. The mean sea level trend was compared to the maximum levels trend recorded in Grado, in order to check whether there was also a significant increase in extreme events, as reported by [82]. After comparing the trends, the issue arising from the duration of the events was evaluated to consider only events with a significant impact. The analysis was conducted by comparing the maximum recorded values against their duration, taking into account the total number of records for each year. The threshold value is here defined as the cumulative duration at the extreme 99.96 percentile, which represents approximately 0.04% of the total time, or 3 h.

3.3. Base for Downscaling Analysis

Flood hazard maps were developed concerning the urban and territorial context of the city of Grado. A “bathtub approach” [88] was employed using high-resolution DTMs with ESRI ArcGIS Pro 3.1.0 software. The objective involves assessing the elevations of the town's perimeter promenade (Figure 2a) to identify critical issues concerning both current water levels and projected future levels. To analyse the elevation of the lagoonal promenade and embankment, the procedure adopted is as follows. The Grado Digital Terrain Model (DTM), derived from a LiDAR survey conducted in 2018 (courtesy of Regione Friuli Venezia Giulia), was initially utilised. The derived DTM product exhibits a spatial resolution of 0.5×0.5 m. A 6-m-thick buffer was generated from the DTM elevations, derived from the outermost section of the promenade, specifically the part nearest

to the water, moving inward. Given the different elevation statistics, the promenade has been segmented into four sectors (Figure 2b). This approach enabled a detailed analysis of the promenade and embankment elevations, assessing both point-specific and area-wide criticalities.



Figure 2. Downscaling area analysis: (a) elevation of the lagoon promenade considered in the study, represented by 10 classes subdivided every 0.10 m of elevation. (b) The subdivision of the promenade and lagoon embankment into 4 macro sectors; the extent of the inhabited area of Grado municipality is also reported, treating the streets as unobstructed surfaces for water flow while omitting buildings and uninhabited areas.

The calculation of the elevation value for the extracted cells became necessary to obtain averaged elevation information surrounding the cells, based on the fixed-width buffer. A GIS analysis tool (Cell Statistics, part of the Spatial Analyst extension in ArcGIS Pro 3.1.0) was used to perform this operation, enabling the calculation of an average value over a 6m radius for the entire length of the embankment section examined. To finalise the survey, the elevation values at the centre of the previously considered cells were extracted and subsequently subjected to statistical analysis. The analysed elevation points were filtered to exclude negative elevations exceeding a specified threshold. To assess bank heights in relation to extreme events, a range of heights from 70 cm to a maximum of 155 cm was evaluated, contingent upon the specific bank stretch examined. The heights obtained were represented through a graph illustrating the cumulative statistics as a function of the considered height ranges, indicating the percentage of embankment in safety relative to the threshold value of an extreme event associated with the return time.

3.4. Short-Term (Surge) Analysis

To represent the effects of storm surge events through water level thresholds, updated for recent decades, scenarios with varying probabilities of occurrence were analysed. The processing aims to create a mapping of flood hazards resulting from extreme events, serving as the foundation for assessing and managing flood risks, in accordance with the Flood Directive 2007/60/CE, which was later implemented in Italy through Legislative Decree 49/2010. The Flood Directive allows for reference solely to extreme events, contingent upon an evaluation of the protection level. Some Italian methodological reports on coastal flooding, such as those from the Sardinia region, have indicated that the absence of a precise regulatory definition of the “adequate level of protection” [89] suggests refraining from utilising this prerogative. In contrast, based on territorial urban planning and civil protection measures, particularly in Emilia Romagna [90–92], a region with a comparable coastal physiography to Friuli Venezia Giulia, an assessment was conducted to evaluate the impact of marine events with short RPs. Consequently, the development of flood hazard maps for RPs of 2, 10, 30, and 100 years was undertaken. The maps were developed by assessing the inhabited regions according to the boundaries of the municipality of Grado, treating the streets as unobstructed surfaces for water flow while omitting buildings and uninhabited areas. The analysis primarily concentrated on the historical centre, the area exhibiting the highest vulnerability, and extended in an eastward direction. The analysed municipal area of Grado extends for approximately 0.96 km² (Figure 2b).

3.5. Long-Term (RSLR) Analysis

To develop a projection of RSLR over the medium to long term, the mean sea level of Grado was analysed for the period from 1991 to 2023. To compare the data from Grado and assess their significance, the dataset from Trieste was utilised. The temporal trend of sea level is assessed by CNR-ISMAR in Trieste and is accessible in the database of the Permanent Service for Mean Sea Level [93]. The analysed data encompasses the recorded sea level and the subsidence component, a critical factor for long-term level projections. To undertake a long-term analysis, subsidence data from Da Lio and Tosi [94] and Areggi et al. [95] were used as a reference. The computed value for Grado, acquired using SAR and GNSS interferometry between 2003 and 2010 [94] and 2015 and 2019 [95], was then compared to the residual produced by correlating Grado and Trieste’s sea level changes. The mean value was used to generate long-term RSLR projections for 2050 and 2100. Using the values recorded by satellite and reported by the NASA Sea Level Projection Tool [96] for Trieste, the RSLR and tectonic contribution data were adjusted based on a correction factor, averaged across the territory of Grado. After calculating the increases for 2050 and 2100 based on ongoing climate changes, the reductions in RPs for certain significant episodic events were evaluated.

This analysis assessed both the magnitude of flooding and the exposure of the urban environment to flood risk. The scenarios mentioned focus on a single short-term event related to the threshold update, followed by that event along with sea level predictions for 2050 and 2100, as detailed in the latest IPCC AR6 Report [35].

4. Results and Discussion

4.1. Extreme Water Levels

The results of the sample fit analysis to Gumbel’s distribution law on extreme water levels are shown in Figure 3. The RPs indicated in Table 2 (reference baseline: 1995–2014; central year: 2006) are paired with the corresponding updated extreme thresholds. According to the Flood Risk Management Plan of the Eastern Alps Hydrographic District for Zone

2 (PGRA) [97], the values obtained are related to the mere water component, or to the sum of the meteorological component, astronomical tide, and mean sea level component.

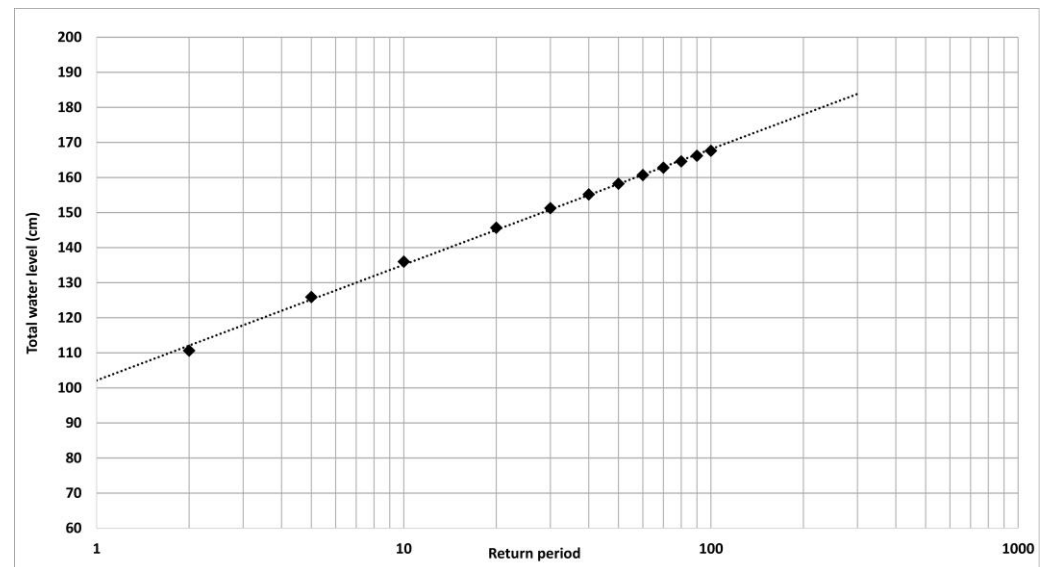


Figure 3. Extreme water level statistical analysis (Gumbel distribution) observed at the RMLV meteo-mareographic station in Venice (reference period 1950–2023).

Table 2. Updated extreme level values as a function of return period (reference year 2006, Gumbel distribution).

Return Period (Years)	Extreme Water Levels (cm)	Confidence Interval (95%)
2	111	107–115
10	136	125–146
30	151	136–165
100	168	147–186

The values listed in Table 2 serve as an update to the PGRA, which is based on the time baseline of 1985–2005 and includes data from the severe tidal level statistics compiled by Pirazzoli and Tomasin [98]. The extreme water levels reported within the PGRA, relating to events with a RP of 30 and 100 years, are lower by approximately 8/10 cm.

4.2. Analysis of Mean vs. Max Levels and Threshold Exceedance

The evolution of mean sea level is commonly utilised for long-term projections; however, in the short and medium term, the temporal changes in maximum levels may offer more pertinent information regarding the risk of storm surge. Our aim is to compare the evolution of mean sea level with that of maximum levels, as illustrated in Figure 4. The selected time interval spans just over 30 years, providing a sufficiently extensive historical series to assess the annual inter-variability of the meteorological component [99].

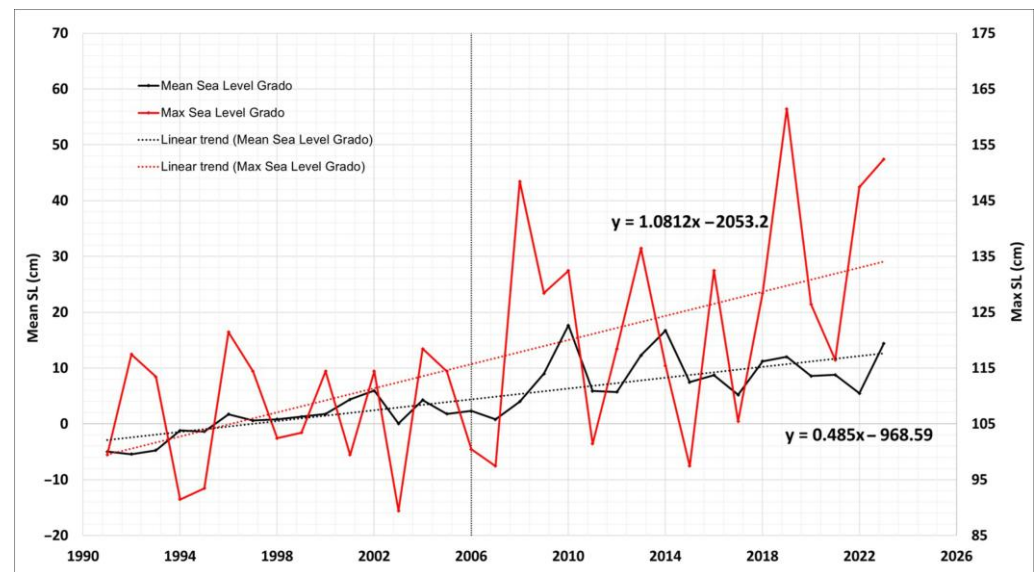


Figure 4. Comparison of the mean sea level (black line) and the maximum sea level (red line) observed in Grado from 1991 to 2023 (IGM42 reference). The left axis indicates the scale for mean sea level, whereas the right axis signifies the maximum levels.

The maximum levels observed are rising at a rate of 10.8 mm/y, which is more than double the mean values of 4.9 mm/y. This suggests, within the limits of thirty-year statistics, that the risk is escalating more substantially than indicated by current projections.

The risk associated with storm surge events is not solely determined by the peak levels attained but also by the duration of the events. Consequently, it was determined to evaluate the level exceeded over a specified duration within a year, specifically a minimum of 3 h. The graph in Figure 5 illustrates the temporal trend of maximum levels recorded in Grado that persisted for a minimum of 3 h. The 2006 as the barycentric year for the thirty-year reference trend, consistently corresponds to the latest IPCC AR6 report [35], thus allowing for projections that are approximately aligned with the most recent trend.

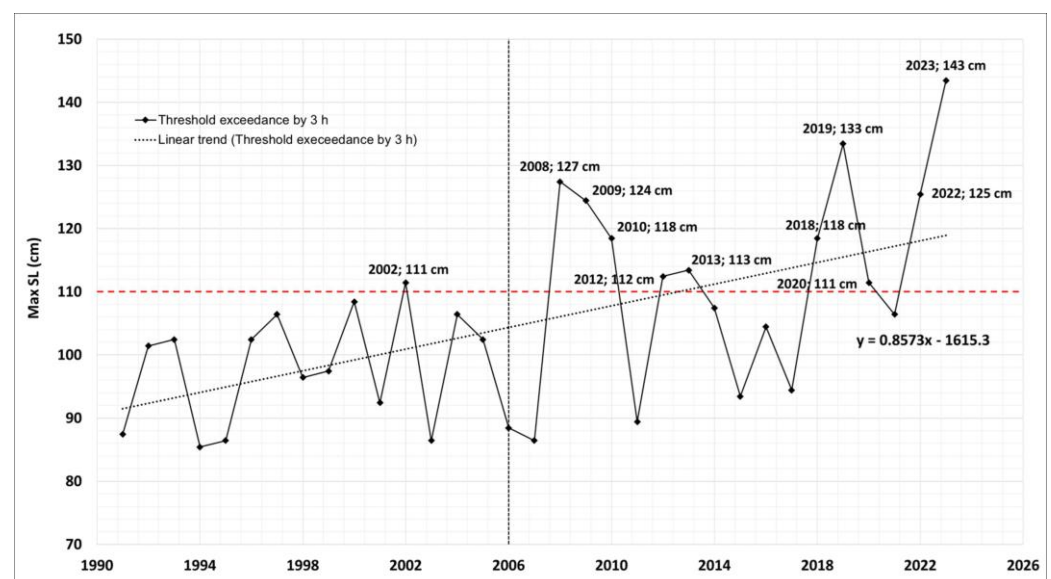


Figure 5. The 30-year trend of maximum sea levels recorded in Grado that persisted for a minimum of 3 h (threshold exceedance by 3 h). The threshold level of 110 cm (ref. IGM42 datum) is here reported as a reference value for flooding phenomena in the ‘Old Town’ (see Figure S1 in the Supplementary Materials).

By observing the graph in Figure 5, an analysis can be conducted on the average trend of sea level maxima exceeding a minimum of 3 h annually. The angular coefficient is 8.6 mm/y. The average value indicated by the trend line demonstrates a duration of 3 h for events commencing in 1991, with an initial extrapolated value of 93 cm, increasing to approximately 118 cm by 2023. Over a period of slightly more than 30 years, maximum levels have risen by 25 cm. The graph indicates a minimum threshold value of 110 cm, serving as a precautionary reference. This value corresponds to an event with an approximate RP of 2 years and a high probability of occurrence. In the town of Grado, an ingress level of 110 cm indicates substantial submersion in the historic centre, particularly along the docks of the Mandracchio Canal. In 10 of the past 18 years, the city of Grado has experienced flooding events with water levels exceeding 110 cm for a duration of almost 3 h.

4.3. Downscaling Analysis of Short-Term Flooding

This section presents and discusses various marine flooding hazard maps derived from the results of the developed flood scenarios. The elaborations depict the episodic event scenario along with the corresponding RP. Each event is defined by a critical threshold that indicates the total elevation of the water mass throughout the event. The simulations employed a static methodology alongside qualitative data analysis, omitting variables such as ingress speed and flooding duration from consideration. The wave component was excluded from the analysis, as the water mass traverses the Grado inlet (see Figure 1c) and propagates into the lagoon, resulting in a progressive damping of the wave set-up parameter.

Table 3 depicts a summary diagram of the many scenarios evaluated, represented by the RP associated with the threshold value, as well as the overall extension of the inhabited region impacted by marine ingress, expressed in square kilometres and as a percentage of the entire municipality.

Table 3. Extreme water levels with return periods (levels expressed in cm), which correspond to the relative flooded areas, expressed in terms of size (km²) and percentage value with respect to the built-up area of the Municipality of Grado of 0.96 km².

Return Period	Extreme Water Levels (cm)	Inhabited Area (km ²)	Flooded Area (%)
2	111	0.016	1.67
10	136	0.20	20.8
30	151	0.40	41.7
100	168	0.61	63.5

Below are the hazard maps drawn up on the basis of the episodic events considered. The hazard maps are realised by means of the water depth representation, i.e., the hypothetical maximum water elevation above the ground reached during flooding. The water depth is extrapolated as a function of the heights of the starting DTM and the flooded area.

4.3.1. The 2-Year Return Period Episodic Event

In the case of a meteomarine event with a RP of 2 years, the water level has a total elevation of approximately 111 cm. The flood hazard map is shown in Supplementary Materials (Figure S1). The downscaling analysis (scale 1:5000) enables detailed verification of the problems caused by flooding. On the map, it is possible to establish that the criticalities occur mostly around the Mandracchio Canal and the Brioni promenade. Both stretches correspond to the lowest urban areas that allow the water mass to advance inwards. The criticalities found mostly concern the propagation of the water mass into the

interior of the old town by means of the urban network. The nearby historic centre, located south of the Mandracchio Canal, does not exhibit any particular criticality.

4.3.2. The 10-Year Return Period Episodic Event

In the case of a meteomarine event with a RP of 10 years, the water level has a total elevation of 136 cm. The flood hazard map is shown in Figure 6.



Figure 6. Flood hazard map representing an event with a 10-year RP (136 cm). The blue colours represent the water depths as a function of the city's DTM elevations: (a) The inundation map of the 'Old Town' sector shows that this area is almost entirely affected by the extent of the flooding. Flooding also affects parts of the historic centre. (b) It depicts the slight expansion of flooding to the east as well, with some ingressions of the water mass toward the built-up area by the Mureri Canal. (c) Flooding in the western part of the historic centre during 27 October 2023 (photo credits: Cester E.). (d) Expansion of the water mass along the western docks of the Mandracchio Canal during 27 October 2023 (photo credits: Cester E.). (e) expansion flooding along A. Manzoni Street during 29 October 2018 (photo credits: Folla M.).

The 1:5000 downscaling analysis made it possible to observe more clearly the extended criticality along the lagoon promenade of Riva Brioni, the town's primary western encroachment area. We could also observe a generalised extension of the water mass

around the Mandracchio Canal through its perimetral docks. Compared to the previous simulation, the water mass extends both to the east and west of Mandracchio, almost completely affecting the old town and partially affecting the historic core to the south. There is also an eastern expansion of the water mass through two areal criticalities of the lagoon promenade along the Moreri Canal.

4.3.3. The 30-Year Return Period Episodic Event

Compared to the previous scenario, in the simulation of a storm surge event with a return time of 30 years and a total elevation of 151 cm, the urban flooding also extends along the eastern part of the town (Figure 7).

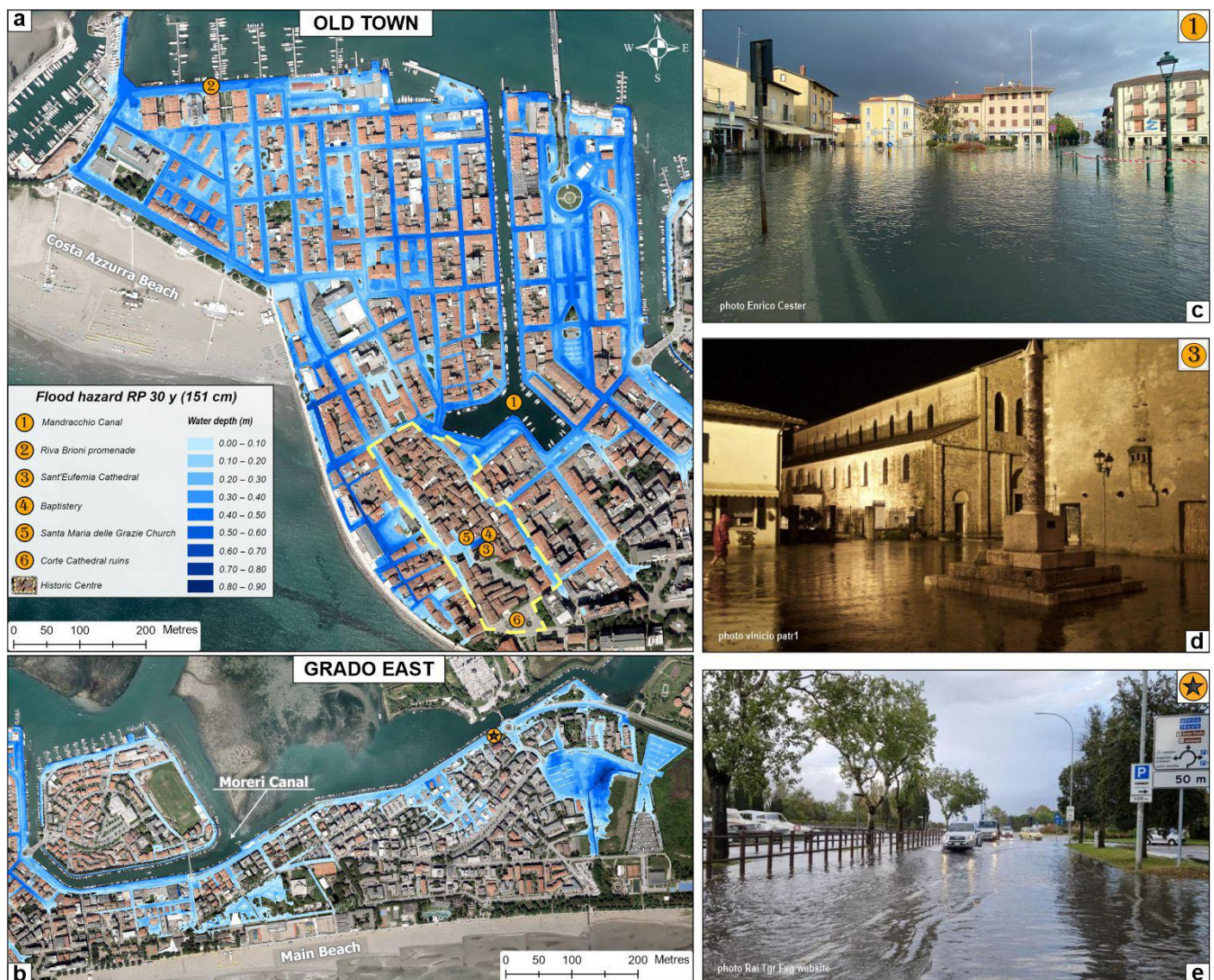


Figure 7. Flood hazard map representing an event with a 30-year RP (151 cm). The blue colours represent the water depths as a function of the city's DTMs elevations: (a) The inundation map of the 'Old Town' sector shows that this area is completely flooded. The extent of the flooding also affects much of the historic centre. (b) The widespread flooding in the city's 'Grado East' area. Water flows inland through the Moreri Canal's embankment at several places. (c) Flooding near the southwest dock of the Mandracchio Canal during 27 October 2023 (photo credits: Cester E.). (d) Flooding in front of the St. Eufemia Cathedral during 12 November 2019 (photo credits: Patruno V.). (e) Extensive flooding along the end of the Moreri Canal embankment, Monfalcone Street during 27 October 2023 (photo credits: Rai Tgr Fvg website).

The flooding affects the entire old town, particularly the historic core surrounding the St. Eufemia Cathedral and the Baptistery. It extends approximately 2000 metres along the lagoon promenade of the Moreri Canal, impacting many areas in the eastern part of the city. The additional 15 centimetres, compared to the 10-year RP scenario, clearly illustrate how a meteomarine event of this magnitude can lead to an expansion of the water mass covering a significant portion of the urban fabric.

4.3.4. The 100-Year Return Period Episodic Event

This statistically rare event is characterized by a water mass elevation of 168 cm, thus representing a real calamity for the town of Grado. The event is responsible for a large inundation effect, which extends throughout the old town. Some of these areas are affected by a very high water depth. Compared to the 30-year return time event, the water mass penetrates the lagoon promenade of Moreri Canal for its entirety, generating flooding that affects almost the entire eastern urban fabric, spreading the water mass into areas close to the Main Beach. The flood hazard map is shown in Supplementary Materials (Figure S2).

4.3.5. Lagoon Promenade Downscaling Analysis

We performed the promenade elevation analysis along the complete boundary that divides the town from the lagoon. The assessment encompasses the full perimeter embankment stretching from Riva Brioni to the easternmost part of the Moreri Canal, divided into four macro-sectors. This approach enabled a more thorough examination of the embankments, assessing both specific and broader critical issues. Table 4 presents the analysed promenade/embankment sectors along with their respective lengths, the total length of the embankments, and the percentage of each section in relation to the total length.

Table 4. Lagoon promenade/embankment sectors analysed for elevation analysis aimed at the flooding assessment.

Promenade/Embankment Sector	Length (m)	Percent (%) of Total Length
Riva Brioni-Mandracchio C.	573	9
Mandracchio C.	1392	22
Schiusa Island	1681	27
Mandracchio C.–Moreri C.	2685	42
Total embankment	6334	100

The two lagoon promenade and docks sectors most vulnerable to marine ingressions are described below. The first stretch considered concerns the Riva Brioni—Mandracchio sector. The second section concerns the Mandracchio Canal. The other two sectors, Moreri Canal and Schiusa Island, are shown and described in the Supplementary Materials (Figure S3 and Figure S4, respectively).

Riva Brioni—Mandracchio C.

The section considered has a total length of 260 m. Figure 8 displays the analysis of the promenade's heights along the entire Riva Brioni. The survey covered a total of 6188 measured points within an elevation range of 70 to 125 cm. Hence, approximately 85% of the height of the promenade section considered is below 111 cm (Figure 8b). This means that, already with a meteomarine event with a high probability of occurrence, having a RP of 2 years, the perimeter promenade is not in a safe condition. On the other hand, considering an episodic event with a RP of about 5 years and approximately 125 cm of water level, the entirety of the promenade is not in a safe condition, causing the expansion of the water mass in the western area of the urban centre.

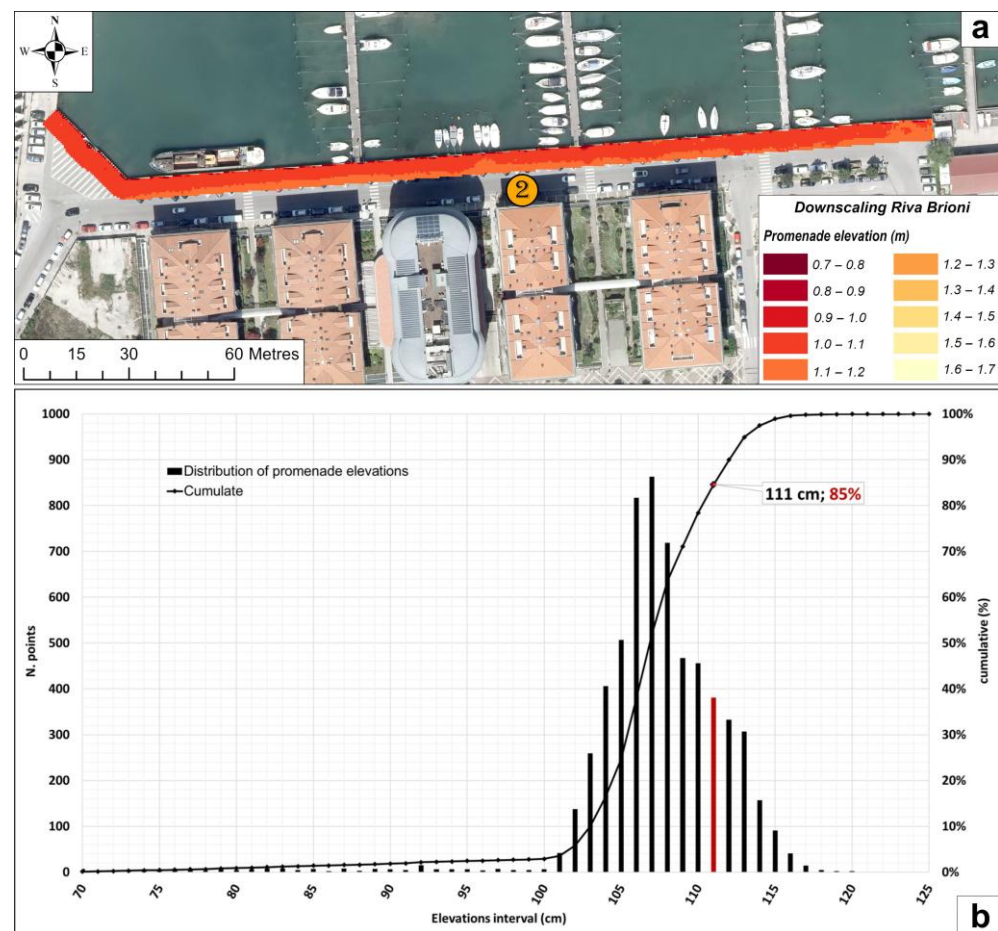


Figure 8. Critical sector promenade of Riva Brioni (see Figure 6a, number 2 for the position): (a) represents the elevations extracted from the 6-m buffer of the promenade. The elevation values of the promenade range from 70 to 125 cm. (b) represents the statistical distribution of the elevations extracted from the promenade of Riva Brioni. Shown in red is the 111-cm elevation column, which represents about 85% of the cumulative statistics. The promenade is then flooded with an event with a very high probability of occurrence (RP = 2 years).

Mandracchio C.

The Mandracchio Canal has a total length of 1392 m, corresponding to 22% of the total lagoon promenade. The analyses of the canal's banks covered a total of 31,782 measured points within an elevation range of 70 to 155 cm. Historically, the main flooding within the built-up area of Grado occurs through the docks of the Mandracchio Canal, the preferential route of water ingress within the ancient centre. In fact, as described in Section 4.2, the 110 cm threshold has been exceeded for 3 h in a year almost 9 times in the last 15 years (2008–2023). This statistic is corroborated by the graph in Figure 9b, which shows that 50% of the Mandracchio docks are not in a safe condition for an event with a RP-2 year. It follows that even with a very low elevation threshold, the historic centre is experiencing significant flooding. On the other hand, considering a RP of 10 years, with a medium-high frequency of occurrence and a level of 136 cm, the entire docks of the Canal do not guarantee any safety, entailing extensive flooding both to the west and east of the Mandracchio itself, also affecting the portion of the historic core post south of the Canal (Figure 6a,c).

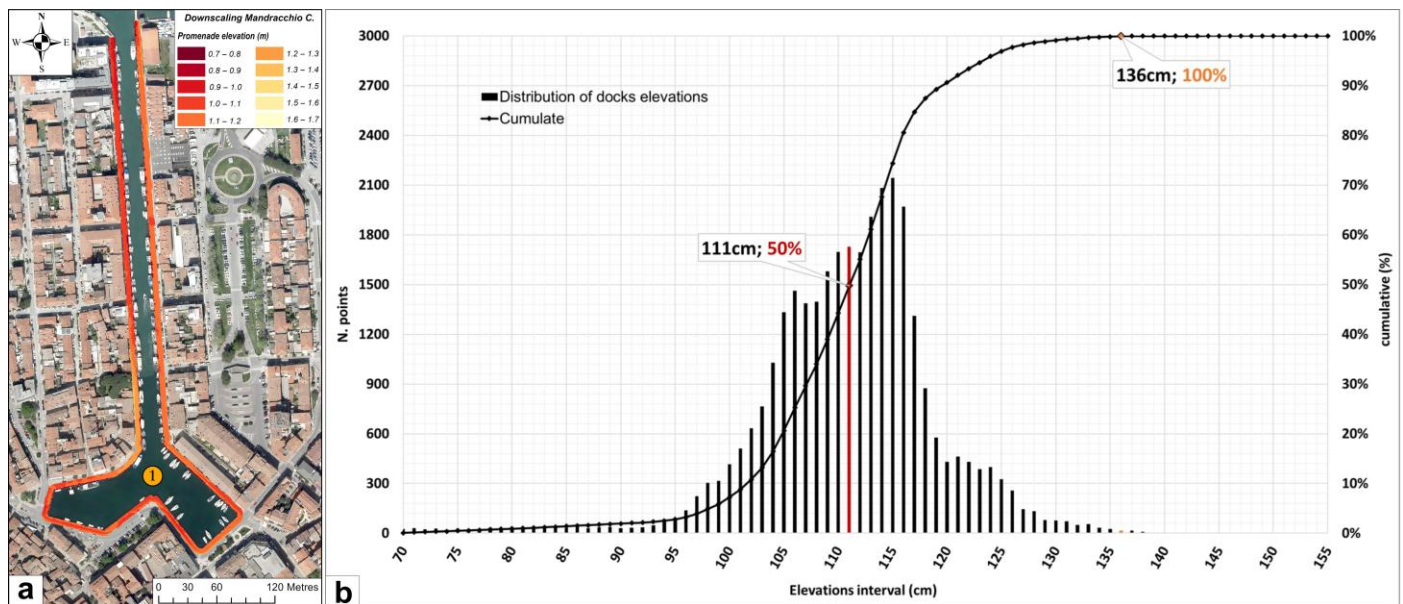


Figure 9. Critical sector of Mandracchio Canal docks (see Figure 6a, number 1 for the position): (a) represents the elevations extracted from a 6-m buffer of the docks. The elevation values of the canal docks range from 70 to 155 cm. (b) represents the statistical distribution of the elevations extracted from the Mandracchio Canal docks. Shown in red is the 111 cm elevation column, which represents about 50% of the cumulative statistics. Shown in orange is the elevation of 136 cm, the level of an event with a medium to high probability of occurrence (RP = 10 years), resulting in complete submergence of the canal docks.

4.4. Downscaling Analysis of Long-Term Flooding

Considering the last 30 years, from 1991 to 2023, the SLR trend of Grado falls back to values of 4.8 mm/y (Figure 10). Reducing the reference time interval tends to increase the trend. The level fluctuations can reach up to 10 cm from one year to the next, as demonstrated in the year 2010.

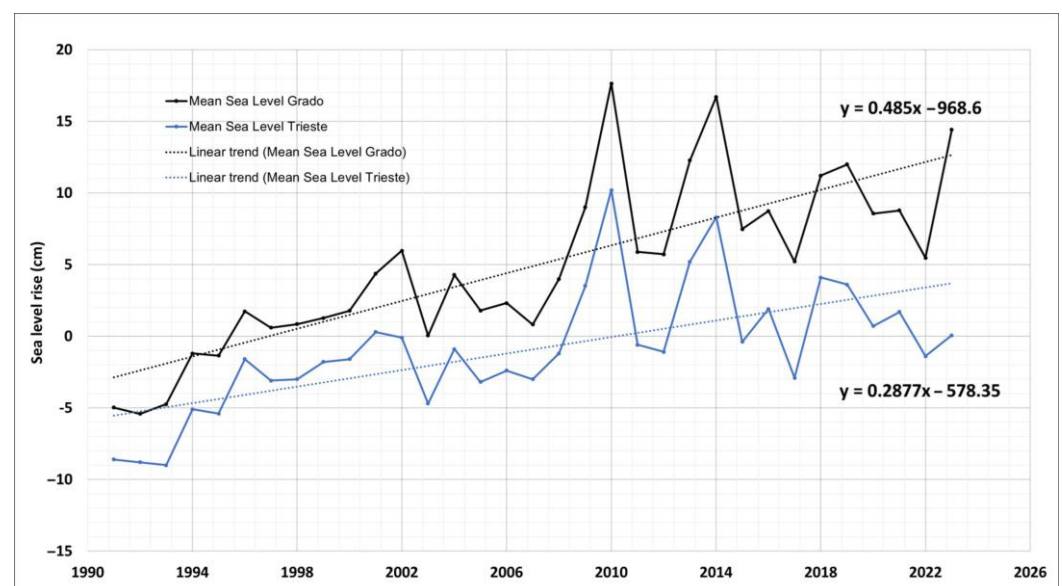


Figure 10. The 30-year trend of sea level change in Grado (black line) and Trieste (blue line) with IGM42 reference. Elevation in ordinate has been kept to scale for each series. Trends can be calculated on the basis of linear regression.

The sea level trends in Grado and Trieste exhibit notable similarities. The difference in rates, specifically 4.8 and 2.8 mm/year, can be attributed to the subsidence component (vertical land motion, VLM). Trieste is the only location where subsidence is minimal relative to the rest of the northern Adriatic [100,101]. The VLM inferred from sea level trend comparison and the literature data [94,95] falls within the interval 1–2 mm/year. Accordingly, we chose to apply a mean subsidence rate of 1.5 ± 0.5 mm/year for Grado, which is pertinent for formulating RSLR projections for 2050 and 2100. Using the nearest sea level data from Trieste, sourced from the NASA Sea Level Projection Tool [96], an increase of 1.5 mm/year should be calculated by multiplying this rate by the number of years since the barycentre of 2006. Specifically, this results in 44 years if the projection is extended to 2050 and 94 years if extended to 2100. The values for VLM to incorporate into the SLR scenarios are 6.6 ± 2.2 cm for 2050 and 14.1 ± 4.7 cm for 2100, respectively.

Table 5 summarises the sea levels projected to 2050 and 2100 according to the calculations made above.

Table 5. Projection of sea level in 2050 and 2100 according to IPCC AR-6, as reported in the NASA Sea Level Projection Tool [96]. Sea level projections refer to the city of Trieste. Vertical land motion (VLM) for Grado is assumed at a rate of 1.5 ± 0.5 mm/year (see text for explanation). The total sea level for Grado is calculated by adding the two components.

Year	SLR Scenario Reference 2006 Baseline (1995–2014)	Trieste Sea Level (cm)	Total VLM (cm) for Grado (Average Rate)	Total Sea Level for Grado (cm)
2050	SSP1-2.6 (median)	17	6.6	23.6
	SSP5-8.5 (median)	21	6.6	27.6
2100	SSP1-2.6 (median)	39	14.1	53.1
	SSP5-8.5 (median)	67	14.1	81.1

At this stage, by looking at the most important rare events and taking into account city planning and the expected RPs of 10, 30, and 100 years, we can figure out how much the RPs change by examining the expected sea level rise for 2050 and 2100 under the best- or worst-case scenario.

In the context of an extreme episodic event that has a low probability of occurrence and is linked to a RP of 100 years, along with projected sea level rises for both 2050 and 2100 under a pessimistic SSP5-8.5 scenario, we can anticipate a potential situation as follows:

critical threshold to 2050 = current RP 100 y – RSLR 2050 = 168 cm – 28 cm = 140 cm.

Considering a pessimistic scenario, the value of 168 cm at 2050 becomes, after subtracting the 28 cm SLR, approximately 140 cm. The latter value corresponds to a threshold reached by an episodic event with a RP of about 14/15 years. On a probabilistic level, exceeding the 168 cm threshold in 2050 could occur almost seven times more frequently. For this reason, the frequency of extreme events is bound to increase significantly in the near future. We can apply the same reasoning to a 100-year episodic event with an optimistic projection to 2100. In this case, 53 cm will have to be subtracted. At 2100, the value of 168 cm will become approximately 115 cm. The latter corresponds to an episodic event with a return time of about two to three years. On a probabilistic level, exceeding the 168 cm threshold in 2100 may occur 33 times more frequently. The values found, typical for the eastern part of the northern Adriatic, are quite similar to those reported by Lionello et al. [102], which looks at how RPs change based on sea level rise rates expected for 2050 and 2100 in the western part of the northern Adriatic. The application of SLR's worst-case scenario for 2100 is now rendered pointless.

4.5. Adaptation Plans

Grado, like other coastal resorts in the northern Adriatic that rise in contexts characterised by low and sandy coasts, is subject to the effects of sea level rise in a much more evident way than other territories [103]. Similarly to the safety measures adopted for the city of Venice through the activation of the Mo.S.E barrier in 2020 [104], the need to adopt adaptation and mitigation strategies to address the rising frequency of extreme events has also emerged for the town of Grado. In addition, the impacts of coastal flooding are expected to increase due to ageing defence infrastructures [105]. For this reason, urban embankments need to be structurally verified, and their heights carefully checked and adapted (and thus raised, [106]) to a safe level.

Consequently, plans to raise embankments and promenades need to be adjusted based on how much the sea levels are expected to rise [107] during extreme weather events. The types of actions to take depend on how uncertain we are about the extreme value statistics and future sea level rise predictions [108–110]. Therefore, the updated extreme level thresholds, based on the case histories of the past decades, made it possible to formulate hypotheses for adaptation and urban planning in the most vulnerable promenade sectors. Indeed, strategising for the medium- to long-term future would enable a decisive solution to site-specific flooding for many decades to come. However, the most reliable future projections focus on short-to-medium-term scenarios and the pessimistic SSP5-8.5 projections, which also depend on the potential increase in extreme events.

Starting from the data of the scenarios and the RP of the events, the embankment sealing hypothesis starts from the evidence that one must proceed by considering, in a modular way, interventions that, in order of priority, start from the most critical sections. The entire urban stretch facing the lagoon has docks whose elevation cannot guarantee sealing for events with very frequent return times. Consequently, based on the study conducted, a safety threshold level of 180 cm can be chosen. This figure roughly corresponds to a meteomarine event, which statistically occurs with a RP of approximately 250 years. Thus, considering a pessimistic sea level rise to 2050 calibrated on the city of Grado, equal to an increase of approx. 28 cm, on a probabilistic level, a lowering of the threshold level to 152 cm would occur. The value in question corresponds to an event with a RP of ca. 30 years, defined as having a medium probability of occurrence. At present, this type of intervention secures the territory and, in the future forecast, will allow sufficient time to prepare—should it be deemed necessary—appropriate modifications or additions. The value of 180 cm, therefore, allows us to have a certain margin of coverage that is much more reliable than a safety value that, correlated with a less reliable projection, would have a greater degree of uncertainty.

Once the threshold level of security and the most vulnerable sectors to be safeguarded have been ascertained, based on downscaling simulations and elevation analysis, the next step concerns which adaptation strategies to put in place. The provision of defensive measures depends on various factors, such as political, regional and local decision-making wills. An example of this approach is the SECAP project, undertaken to incorporate adaptation measures and climate mitigation strategies at the municipal level for the city of Trieste [58]. Nevertheless, additional factors will be closely related to the layout of the urban fabric [111] and therefore directly controlled by anthropogenic elements, such as urbanisation, accommodation space, adaptability, land-use change, as well as the configuration and size of the road network [112].

The first two stretches in need of timely intervention concern the perimeters that extend over two sectors, from Riva Brioni to the Mandracchio Canal inclusive, for a total of 1919 m. Within this section, the two perimeters requiring timely intervention are Riva Brioni (260 m) and the Mandracchio Canal (1392 m). Riva Brioni is characterised by a promenade that, throughout its entire extension, has heights ranging from 70 to 115 cm.

The road surface width, measured from the outer edge of the promenade to the pavement on the opposite side, is approximately 14 m (Figure 8). Of this, the space relating to the urban road is approx. 5 m. The area where changes will be made for raising the shoreline or changing the lagoon promenade is about 7 m wide: 3 m for the lagoon promenade and 4 m for parking spaces, which could be adjusted if needed. These characteristics make Riva Brioni one of the few city areas that are most exposed to flooding, where it is possible to implement a significant change in the urban fabric. One possibility concerns the application of bulkhead planter systems or of a bank (see Toledo et al., [113]) extended along the entire promenade. A further hypothesis is the application of a seawall-walk barrier system that transforms the Riva Brioni promenade into a fully-fledged barrier that maintains the existing pedestrian section connected to the waterfront.



Figure 11. The Riva Brioni promenade. (a) Photo of a promenade section, taken at coordinates 45°68'28.63" N, 13°38'06.56" E (photo credits: Spadotto S.). (b) Design of a bulkhead planter system, built along the entire promenade. Toward the lagoon, the promenade is maintained. Toward the street, parking spaces are created parallel to the bulkhead planter, and the roadway is maintained. (c) Rendering of what Riva Brioni might look like. For the sake of clarity, possible regulated openings needed between the planters for pedestrian transit and dock access are not depicted here.

The situation is different for the Mandracchio Canal. The docks surrounding the canal are characterised by a higher elevation than those at Riva Brioni. However, these fail to provide adequate defence, resulting in a general ingression of the water mass into the built-up area, affecting the historic centre to a certain extent, even with water levels that are not particularly critical, slightly higher than 110 cm. The layout of the streets and buildings surrounding the canal, for nearly their entire length, does not permit significant modifications to the urban fabric. The space available from the docks, where there are boat moorings, to the walls of the buildings on the opposite side is approximately 6 m. It follows that the usable space for a possible intervention is completely absent. For this reason, a possible proposal concerns the design of mobile defence systems at the Mandracchio lagoon entrance (Figure 12), similar conceptually to those already widely used in Northern Europe, especially in the Netherlands with the Maeslant Barrier in Rotterdam [114], designed for protection against very extreme flood events [115]. In Cesenatico, Emilia Romagna, Italy, there exist mobile defence systems known as Porte Vinciane (Da Vinci's gates), a Project by Binini Partners [116] (Figure 12c).

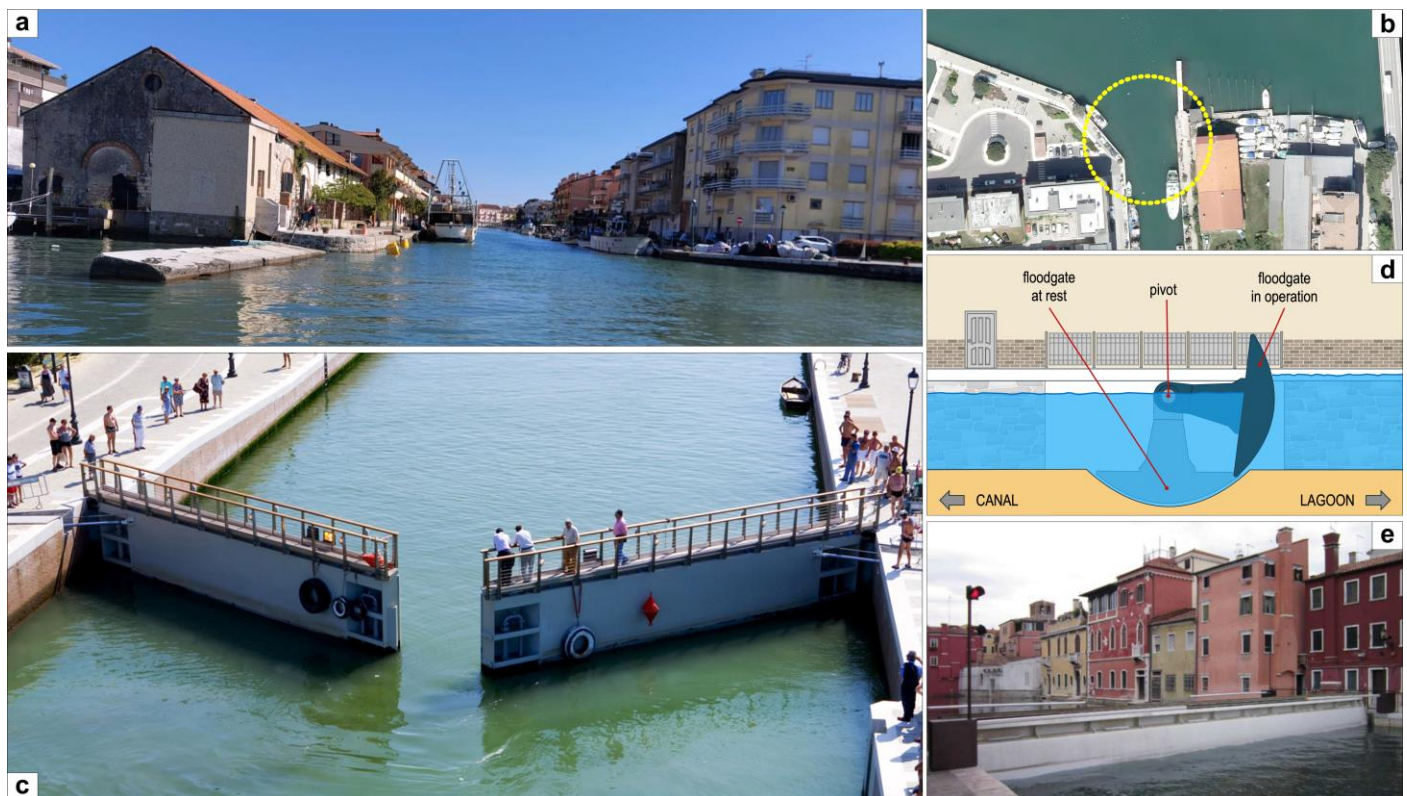


Figure 12. The Mandracchio Canal docks. (a) View of the Mandracchio C. lagoon entrance (Photo credits: Fontolan G.). (b) Plan view of the Canal opening. (c) Example of Porte Vinciane (Da Vinci's gates) mobile system for flood defence in Cesenatico, a Project by Binini Partners (after [116]). (d) Functional design of Baby Mo.SE floodgates in Chioggia (after [117], modified). (e) Example of mobile floodgate in operation in Chioggia (after [117]).

Another possible solution could be a mobile system like the Mo.S.E [118] designed in Chioggia, called Baby Mo.SE [117] (Figure 12d,e). Constructing these weirs directly in the upper opening part of the Mandracchio, approximately 20 m wide, can guarantee a safe condition in the city surroundings. Additionally, from an economic perspective, the intervention would be less costly than designing an extended dock elevation for the entire Mandracchio Canal.

5. Conclusions

In evaluating sea level estimates, the issue of flooding in coastal regions and towns vulnerable to marine intrusions emerges as a critical priority for spatial planning. In this paper, we presented an exhaustive investigation of the reality of Grado, an Adriatic coastal town that has experienced significant marine flooding, especially during the last decade. The objective of the study is to assess, identify, and delineate urban regions susceptible to flooding, based on current episodic occurrences and projections of future sea level rise that may exacerbate extreme events.

A statistical update of extreme water levels, analysing trends in maximum levels and the hourly duration of their exceedance, and evaluating medium and long-term sea rise projections, revealed the need for the town to verify the elevations of the perimeter embankments and promenades that separate the lagoon from the urban centre. As a result of the current defensive status, which does not provide adequate assurances during even minor surge events, some preliminary intervention hypotheses have been developed to improve the condition of the lagoon promenade, particularly in the most problematic

locations. These options can be considered in future adaptation plans, thus contributing to urban planning procedures.

A downscaling analysis found that the most important challenges are concentrated near the town's western lagoon edge. Even with very high recurrence times (i.e., a 2-year RP), equivalent to water levels of 111 cm, significant challenges were identified in two adjacent urban sectors that are crucial for the propagation of seawater into the historic centre.

Increasing the RP of the events, criticalities also spread toward the eastern lagoon edge. Accordingly, urban criticalities extend outward along the eastern perimeter, and the area of the regions impacted by the water mass expands significantly. An episode with a 10-year RP affects 21% of the whole municipality but entirely impacts the western historic centre, causing significant issues for both the people and the road network.

Sea level rise would cause floods to occur more frequently and with greater severity in the future, which will eventually result in shorter RPs. Between 2008 and 2023, ten flooding events occurred, exceeding the 110 cm water threshold for almost 3 h. Therefore, the trend to date is 1.5 events per year, with a greater size during the previous two years taken into consideration. Even with an optimistic sea rise forecasting for 2050 (short-medium projection period), it is possible to heavily reduce even very extreme events that have RP longer than 200 years.

These simulations demonstrate how crucial it is to downscale coastal urban locations in order to promptly define critical situations involving the existence of ingress points, presently insufficient perimeter embankments and promenades, and/or depressions in the urban fabric that allow water to easily enter and cause damage and inconvenience to the population.

With respect to the predisposition of climate change adaptation strategies by prompt evaluation of the phenomenon's incidence at the municipal level, the analyses suggested in this paper are crucial. Extreme events and return times aid in forecasting the future development of the phenomena, encouraging the first meaningful conversations regarding adaptation measures required to create comprehensive urban planning procedures for the town of Grado. Relying on defensive systems that are planned and constructed using a modular approach, considering the rates of sea rise and the potential for an increase in severe events, and that can be adjusted based on the configuration of the urban fabric, will be the issue and the challenge for the near future.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/w17131991/s1>, Figure S1: Flood hazard RP 2 y (111 cm); Figure S2: Flood hazard RP 100 y (168 cm); Figure S3: Statistics of elevation and flooding occurrence of Schiusa Island promenade; Figure S4: Statistics of elevation and flooding occurrence of Moreri Canal promenade.

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Abbreviations

The following abbreviations are used in this manuscript:

SLR	Sea Level Rise
RSLR	Relative Sea Level Rise
VLM	Vertical Land Motion
RP	Return Period
DTM	Digital Terrain Model

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