

Assessing storm surge risk under future sea-level rise scenarios: a case study in the North Adriatic coast

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Abstract Low-lying coastal areas are often prone to storm surge flooding that can render severe damages to properties, destruction of habitats, threat to human safety and the environment. The impacts of coastal flooding are also expected to increase in the future as a consequence of global climate change and sea-level rise. This paper presents a comprehensive assessment of the potential risks raised by storm surge and sea-level rise on multiple coastal targets (i.e., population, buildings, infrastructures, agriculture, natural and semi-natural environments and cultural heritage) in the Northern Adriatic coast in Italy. Through the assessment of hazard, exposure, vulnerability and risk, a Regional Risk Assessment (RRA) methodology allowed identifying and prioritizing hot-spot risk areas and targets requiring particular attention for the definition of adaptation strategies. Hazard scenarios were based on the analysis of tide gauge data (elaborated with the Joint Probability Method) and of different sea-level rise projections for the year 2100. Geographical-information analysis was then used to characterize vulnerability patterns of exposed natural and human systems and to make a spatial ranking of risks. Maps produced for the worst scenario showed that beaches are the target at higher risk (with more than 90% of the surface in the higher relative risk class) due to the low elevation and high proximity to the coastline.

Also cultural heritage (i.e., villas, historical buildings and roads) and wetlands are highly threatened by storm surge flooding. The relative risks will be lower (i.e., between 25% and 40% of their surface/length in the higher relative risk class) for most of the other receptors (i.e., local roads, railways, natural and semi-natural environments and agricultural areas), including population and buildings that are mostly classified in lower risk classes. The overall results of the assessment, including maps and risk metrics, can be useful to rise the attention of coastal managers about the need to adapt to climate change, developing climate-proof policies and programs for the sustainable management of coastal zones.

Keywords Storm surge · Climate change · Sea-level rise · Regional risk assessment · Joint probability method

Introduction

Recent studies showed that the rise in the mean sea level and regional climate variations led to an increase in the trend of extreme high water levels worldwide in the late twentieth century (IPCC, 2007a, b, 2012, 2013), generating widespread impacts in several European coastal areas such as damages to properties and infrastructures (Devoy 2008) or threatening coastal populations' safety (Hallegatte et al. 2013; Ciscar et al. 2011; Hinkel et al. 2010). Storm surge flooding, in particular, is one of the main natural disasters to be taken into account in the management and planning of coastal zones as it is one of the most costly hazard (EEA 2011). These regions host many human settlements (21% of the world's population live within 30 km of the coast and about 10% lives in coastal zones below 10 m elevation) and have a great environmental, economic, social, cultural and recreational importance, including many different natural and anthropic systems that should

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be protected to preserve their richness of resources (Gommes et al., 1997; Post and Lundin, 1996; Nicholls and Cazenave 2010).

The importance of coastal zones and the urgency of protecting them from flood was recognized also by the European Commission, who adopted the Flood Directive in 2007 (EC 2007). This directive aims at identifying the areas at significant risk through the production of flood hazard and risk maps, considering frequency, magnitude and consequences of river and coastal floods and the impacts of climate change on the occurrence of floods. For each river basin district, the implementation of the Flood Directive required the development of flood hazard and risk maps by June 2013 to be updated by December 2019 (de Moel et al. 2009; EC 2007). Hazard maps delineate areas that may be affected by floods with different probabilities of occurrence and different return periods; they are based on the estimation of water levels generating temporary (and extreme) coastal flooding and should take into account also the effect of gradual sea level rise. Flood hazard maps represent the basis to produce flood risk maps showing the potential adverse consequences associated to different elements at risk: population, buildings, infrastructures, agriculture, natural and semi-natural environments and cultural heritage (EC 2007).

In recent years, several projects defined new methodologies and approaches supporting the implementation of the flood directive and the production of hazard and risk maps. However, the majority of them focused on river floods (Ronco et al. 2014) and only few of them are specifically tailored to coastal floods. Among the latest, most focus on specific aspects (e.g., on the physical aspects of storm surges; Jiménez et al., 2009) or on specific targets, such as population (e.g., Crowell 2010) or ports (e.g., Hallegatte et al. 2013). Further, only some studies included the effects of climate change scenarios in the assessment of coastal flood risks (e.g., Nicholls and Klein 2005) and analysis are often performed at a coarse national scale resolution (e.g., Ramsbottom et al. 2012). The methodologies developed with a specific focus on the evaluation of flood risks, addressed the analysis using different scales, from the local/municipal one (Grünthal et al. 2006) to the regional (Ronco et al. 2015) and national/supra-national (i.e. European) one (Hall et al., 2003; Schmidt-Thomé et al. 2006). The consequences of storm surges can be highly influenced by local factors. In particular flooded areas highly depend on local topography, and extreme sea-level recorded along the coastline may be influenced by the beach slope, which can be very heterogeneous. Accordingly, among all, the regional and local scales appear the most suitable ones for the definition of flood hazard and risk plans, as the considered phenomena will not be uniform, but will assume specific regional or local characteristics (Ramieri et al. 2011).

Several studies have been conducted to understand physical processes related to storm surges in the North Adriatic

region, especially in local relevant sites (e.g. the Lagoon of Venice), and evaluate their potential impacts (Bondesan et al. 1995; Gonella et al. 1998; Gambolati and Teatini 2002; Lionello et al., 2008). Further, several studies (e.g., Lionello et al. 2012; Lionello 2012) focused on possible changes of magnitude and frequency of future storm surge events taking into account the possible effect of climate change. According to Lionello et al. (2012) the sea surface height in Venice shows a centennial trend of 0.3 m/year due to tectonic and isostatic adjustments, which is less than the global mean. Lionello et al. (2012) also address the strong inter-annual variability of storminess, which determines the occurrence of storm surges. They also consider the trends of severe high wave and surge events and various thresholds and show that time series of storminess show large inter-annual variability and very little overall tendencies on multi-decadal time scale, suggesting progressively milder storms during the second half of the twentieth century. They also forecast that extreme storms will be stronger in future scenarios, but differences with the current ones are not statistically significant. Moreover, a recent study of Vousdoukas et al. (2016) provided storm surge scenarios for all Europe, estimating that along the coast of the North Adriatic sea extreme storm surge level with a return period of 1000 years could be higher than 3.5 m. The high spread of storm surge estimates show the high level of uncertainty of the applied models, proving the importance of improving the studies even in a region that has already been deeply investigated. However, despite physical phenomena of the considered region are well known (even though uncertain), existing studies did not considered the impacts of storm surges on coastal zones and did not performed risk analysis including other important factors contributing to coastal vulnerability to climate change, such as distribution of coastal assets, inhabitants and ecosystems (Fontolan 2001; Seminara et al. 2005; Ferla et al. 2007; Simeoni et al. 2007). The complexity of the problems linked to climate change and the importance of natural and socioeconomic aspects in the study area ask instead for a broader integrated approach.

The Regional Risk Assessment (RRA) methodology described in this paper provides an integrated and quick scan method for assessing and mapping hazard, exposure, vulnerability and risk related to storm surge flooding and climate change, supporting the consequent implementation of risk management and adaptation plans.

It is based on a multidisciplinary framework operationalizing the main components of risk (i.e. hazard, exposure and vulnerability) by means of a set of physical/environmental, economic, social, geographic and cultural indicators (Balbi et al., 2010; Rizzi et al. 2015a,b) and support the implementation of the flood directive and the definition of risk management strategies.

After a brief introduction to the case study area (Section 2), the paper presents the RRA methodology adopted to evaluate

coastal floods in view of climate change (Section 3), and the results coming from its application to the coastal areas of the North Adriatic sea (i.e., Veneto and Friuli Venezia Giulia regions) (Section 4).

Background

Case study area

The case study area include the coastal zone of Veneto and Friuli Venezia Giulia regions, bordering the North Adriatic Sea with a coastline of about 286 km (Fig. 1), from the national border between Italy and Slovenia to the mouth of the southern tributary of the Po Delta system (i.e., Po di Goro). From north-east to south-west, between the Slovenian border and the Timavo river mouth, the coast is high and rocky with few narrow beaches. In the rocky coast can be found the gulf of Trieste and several bays (e.g., Sistiana bay). Moving southwards, from Monfalcone to the Po river delta the coast consists of low sedimentary shores. The overall continuity of the coast is interrupted by several river outlets (e.g., Tagliamento, Isonzo, Livenza, Piave, Brenta, Adige and Po) and lagoons (i.e., the Marano and Grado Lagoon and the Venice Lagoons and the lagoons of the Po river Delta). From a morphological point of view the sedimentary shores of the case study area

include straight littoral coasts, lagoon barrier islands, spits, river outlets and salt marshes.

The considered coastal zone is particularly vulnerable to flood as many areas, particularly around the Po river Delta, are located below the mean sea level and affected by natural or man-induced subsidence (Pirazzoli 2005). Further, the situation is worsened by the increasing mean sea-level. In the Mediterranean sea, rates of sea-level rise for the three longest tide-gauge stations ranged from 1.1 mm/yr. to 1.3 mm/yr. (Tsimplis and Spencer 1997). However, spatially the change is not uniform and in the North Adriatic sea the observed sea level rate can vary from 1.2 mm/year in Trieste to 2.5 mm/year in Venice (Antonioli and Silenzi 2007). Furthermore, the municipality of Venice has recorded an increased rate of high tides events with consequent flooding of the city: the decadal frequency of tides higher or equal to 110 cm was less than 10 events/decade up to 1949, around 30 events/decade from the '50s to the '80s and increased to more than 40 events/decade or even more than 50 events/decade after 1990 (<http://www.comune.venezia.it>). In order to protect the city of Venice and the surrounding lagoon from high tides, the Experimental Electromechanical Module (MOSE) is under construction. It consists of 79 mobile gates located at the three lagoon's inlets that will be closed when the tide heights threatens the city. This system is expected to protect the Lagoon of Venice but a debate is still ongoing and its construction will not solve the

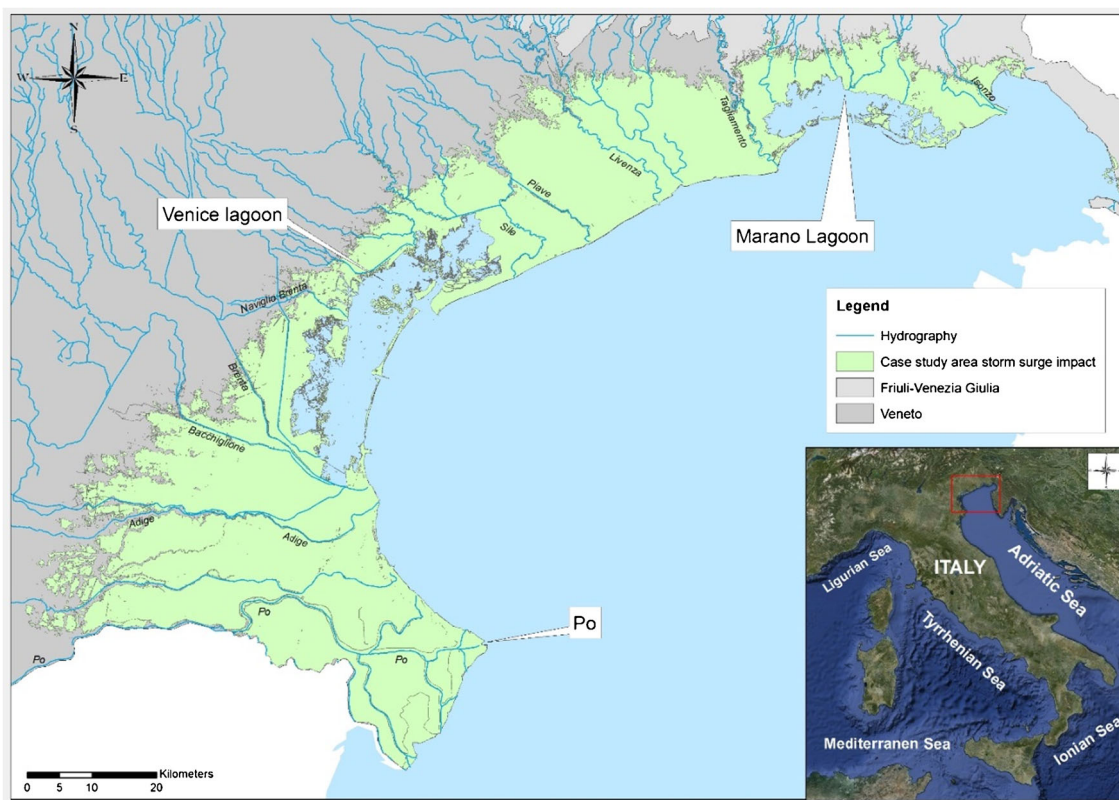


Fig. 1 The case study area

problem of high tide that affect not only the Lagoon of Venice but the whole coastline of Veneto and Friuli Venezia Giulia.

Climate change and sea-level rise could worsen the situation and thus represent a prominent issue for the case study area both considering the vulnerability of fragile ecosystems such as coastal lagoons, and the concentration of cultural and socio-economic values.

Data collection

In order to identify available data to perform the risk analysis, a survey regarding physical, socio-economic and ecological features of the case study area was performed. As a result, several data in graphic format or database were requested and retrieved by many public institutions. Table 1 shows the dataset used for the application and their spatial domain in the North Adriatic region.

Moreover, a dataset containing information from tide gauge stations located along the Adriatic coast (from Trieste to Ancona), inside the Lagoon of Venice and in the Lagoon of Marano and Grado was developed. Historical data from the year 1989 to the year 2012 coming from 28 tide gauge stations were collected, validated and organized within a geodatabase. The amount of data made available within the project was an average of 25 years for each station.

To ensure high quality information, raw data were verified through a series of quality checks using numerical filters within the same time series and comparing data collected in nearby stations. Doubtful data or low quality series were dismissed. Moreover, harmonic constants were calculated to obtain the astronomical tide, useful for additional quality checks. Among the 28 stations for which time series were prepared, 10 representative stations (5 in the Lagoon of Venice, 1 in the Lagoon

of Marano and Grado and 4 along the coastline) were selected in order to apply the Joint Probability Method. The 10 station were those with longer time series with a good quality and are homogeneously distributed over all the considered region (Fig. 2). Collected data were also referred to different reference, thus water levels were increased/decreased in order to use the IGM Genova 1942 as reference system for all data.

Materials and methods

Regional Risk Assessment (RRA) is a methodology generally used to analyse problems affecting large geographic areas (i.e., a region, a country) taking into account multiple stressors (e.g., climate change, contamination) and targets (e.g., beaches, wetlands, agricultural areas) considering their spatial relationships (Hunsaker et al. 1990; Landis 2005). The proposed approach is derived from a methodology already developed within the KULTURisk project (Ronco et al. 2014) where the risk is defined as a function of hazard, exposure and vulnerability. The method has the final aim of screening potential areas and targets at risk where deeper investigations are needed to prevent potential environmental or socio-economic damages. Final results (including detailed spatial maps and tabular metrics) are obtained through four steps (Fig. 3): 1) Hazard assessment; 2) Exposure assessment; 3) Physical and environmental vulnerability assessment; 4) Relative Risk assessment.

Hazard assessment

The hazard assessment phase aims at identifying areas that could be flooded by a storm surge along the coast integrating information about: *Hazard metrics* (e.g., sea-level rise, storm surge height) derived from climatic and hydrodynamic models or from time series analysis; *Pathway factors* (e.g., elevation, distance from coastline), which are used to determine the potential extent of coastal flooding; *Attenuation factors*, representing elements that can attenuate the intensity of the storm surge (e.g., the presence of dikes).

The hazard equation (Eq. 1) is therefore based on a simplified approach where the topography is used to evaluate potentially low-lying flooded areas, considering a hyperbolic function to progressively decrease the flood water level (and the inundated distance) going inland from the shoreline (Eq. 1).

$$H_{ssf,s} = \begin{cases} 0 & \text{if } pf_1 \geq b \\ \min \left[\max \left(\frac{((h_{ssf,jpm} + h_{slr,s})(1-af_1)) - pf_2}{s_1} d_1, 0 \right), 1 \right] & \text{otherwise} \end{cases} \quad (1)$$

Where:

Table 1 Available datasets in the case study area (i.e., the North Adriatic coasts) for the storm surge flooding impact

| Dataset | Spatial domain | Source |
|--------------------------------|---------------------------------|-----------------------|
| Digital Elevation Model (DEM) | FVG, 10 m VE, 5 m | FVG, 2006 VE, 2007 |
| Land Cover -Regional Scale- | FVG 1:25,000 VE, 1:10,000 | FVG, 2000 VE, 2009 |
| Protected Areas | VE, FVG, 1:150,000 | VE, 2008, FVG, 2007 |
| Soyl type, Geologic map | FVG, 1:150,000 VE, 1:100,000 | FVG, 2006 VE, 2009 |
| Administrative unit boundaries | FVG, 1:5000 VE, 1:10,000 | FVG, 2012 VE, 2012 |
| Population census data | VE, FVG | ISTAT, 2001 |
| Infrastructures | FVG, 1:5000 VE, 1:5000 | FVG, 2006 VE, 2011 |

FVG = Friuli Venezia Giulia Region; VE = Veneto Region.

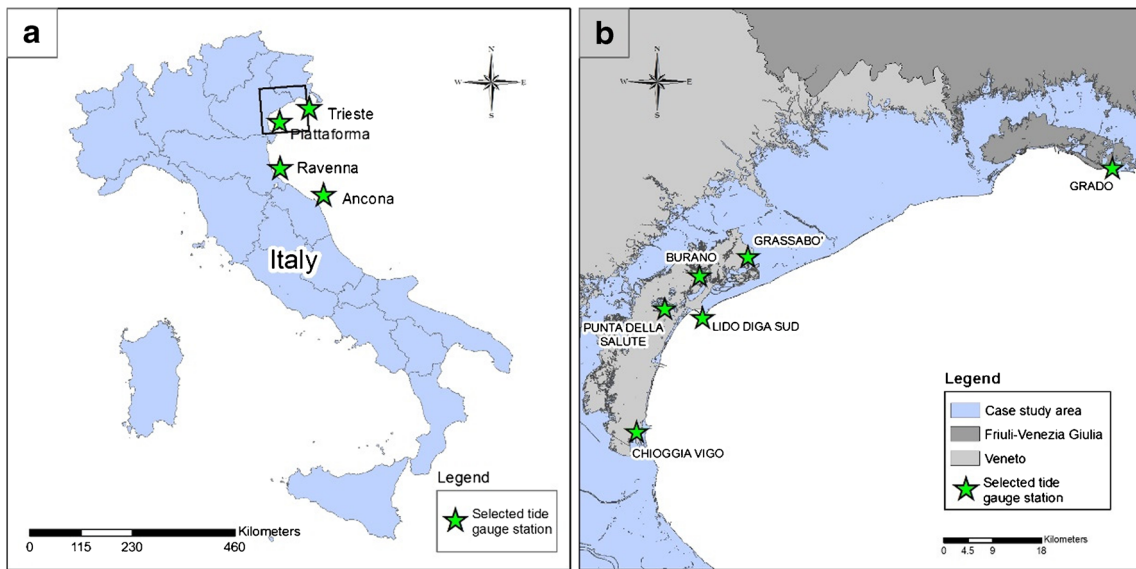
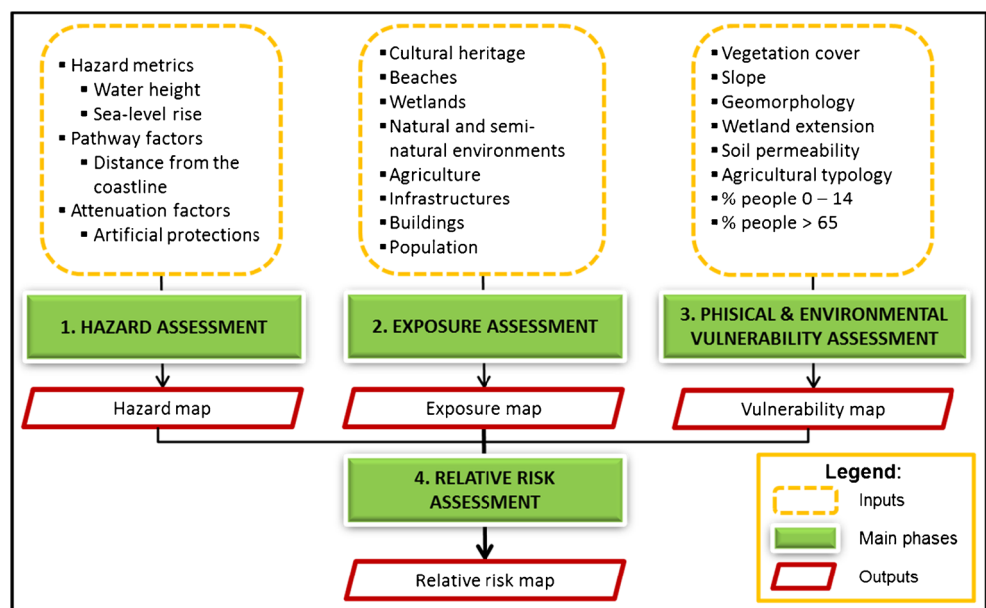


Fig. 2 The 10 tide gauge stations selected for the application of the JPM: 4 stations in the Adriatic sea (a); 6 in the Venice and Grado-Marano lagoons (b)

| | | | |
|-----------------------------|---|---------------|---|
| $H_{ssf, s}$ | <i>hazard score for the scenario s;</i> | l | <i>number of times the water level is reduced before being considered 0;</i> |
| $h_{ssf, jpm}$ | <i>projection of the water level of a storm surge based on JPM outputs;</i> | $b = s_1 t =$ | <i>distance from the sea representing the maximum distance of inundation;</i> |
| $h_{slr, s}$ | <i>projection of sea-level rise according to a scenario s (0 if climate change is not considered);</i> | s_1 | <i>amount of water above a cell which generates the maximum impact;</i> |
| af_1 | <i>attenuation factor resulting from artificial protections;</i> | t | <i>constant defining at which distance the water level is assumed equal to 0;</i> |
| pf_2 | <i>elevation of the cell according to the Digital Elevation Model DEM;</i> | | |
| $d_1 = D_{hip}(pf_3, l, b)$ | <i>factor decreasing the hazard with the increase of the distance from the coastline;</i> | | |
| pf_3 | <i>distance of the center of the cell from the sea (always ≥ 1).</i> | | |

The function estimates the water level above each cell starting from the pixel along the coastline. This value is increased considering sea-level rise projections for that pixel and can be reduced due to the presence of artificial protections (according to the factor af_1). Coastal parcels are inundated

Fig. 3 Steps for the application of the Regional Risk Assessment



with a quantity of water that is reduced with the increase of the distance from the shoreline following a hyperbolic function (d_1). The equation also requires the definition of three constants. The first (l) is the number of times the water level is reduced before being assumed equal to 0, moving away from the coastline; the second (s_1) is the amount of water above a cell generating the maximum impact; the last (t) is the maximum distance that can be reached by a flood from the coastline. These values are specifically defined for each case study based on historical events and on local specific characteristics and were defined by experts in the environmental sector and by a group of technicians working in the forecast and analysis service of flood events in the Municipality of Venice. Specifically, t was set equal to 9 km, representing the maximum distance flooded in an event with an intensity similar to the worst event presented in this study; s_1 was set to 1 m based on the opinion of experts working for different public authorities with competences on the coastal zones of Veneto and Friuli Venezia Giulia regions; finally l was set to 20 due to computational reasons, representing a good balance between obtained results and required computational resources.

An important factor in the estimation of the storm surge height that could lead to an increase/decrease of its extreme values is the presence of vertical movement such as subsidence or uplift of the coast (Wolff et al. 2016). However, information to apply these approaches is not always available, or is not available as future projection, such in the case of the North Adriatic sea. Specific studies have conducted, e.g., by Carbognin et al. (2009) who estimate a natural subsidence of 0.05 cm/year for the city of Venice. However, extrapolating subsidence values over last decades to evaluate the future could lead to big errors especially when the main causes are anthropogenic, such as in the North Adriatic coast.

Considering that detailed data about the height of artificial protections were missing for the North Adriatic coastal zones, a precautionary approach was assumed in the assessment of the attenuation factor (af_1), assuming no influence (i.e. protection) of existing artificial protections in the considered region.

The final hazard score ($H_{ssf,s}$) ranges from 0 (i.e., no flooding) to 1 (i.e. maximum hazard in the case study area), that is reached when the water level is higher or equal than the selected threshold s_1).

In order to assess the hazard in the North Adriatic coastal zone, it was required to define storm surge height scenarios and identify the possible values of sea-level rise, in order to evaluate possible consequences of climate change.

The value of the storm surge height ($h_{ssf,jpm}$), representing the temporary increase in sea level above the level of the astronomical tide caused by low atmospheric pressure and strong winds (Willows et al. 2003), is determined considering three main physical components: i) the mean sea-level, ii) the astronomical tide (i.e., the normal high tide), iii) the meteorological tide (i.e., the storm surge). Sea-level rise projections (i.e., the

permanent increase of the mean sea-level due to climate change) are also considered in the final estimate of ($h_{ssf,s}$), in order to evaluate a future scenario s where extreme water levels are exacerbated by climate change. The final components considered to estimate ($h_{ssf,jpm}$), are defined according to eq. 2:

$$h_{ssf,jpm} = AT + MT + MSL \quad (2)$$

Where.

| | |
|---------------|--|
| $h_{ssf,jpm}$ | <i>projection of the water height of a storm surge according to a scenario s;</i> |
| AT | <i>Astronomical Tide</i> |
| MT | <i>Meteorological tide</i> |
| MSL | <i>Mean Sea-Level</i> |

The values of $h_{ssf,jpm}$ to be used within the RRA application were estimated through the application of the Joint Probability Method (JPM, Pugh and Vassie, 1979) to the tide gauge stations' data. The JPM allowed estimating the intensity of extreme events with different return periods (e.g., 20, 50 and 100 years). It is a method where the separate action of tide and surges is considered. Astronomical tides and surges were tabulated to produce normalized frequency distributions in bands with a tabulating interval of 5 cm and the frequency distributions of the observations was assumed to be representative of the probability of future events. Briefly, the probability for the sea level to reach the value M is the joint probability (hence, a product) for the surge to be M and the tide to be zero, plus the probability for the surge to be $M - 1$ and the tide to be unitary. Obviously, also surge being $M + 1$ and tide being -1 were considered, and so on.

The calculations were based on hourly measurements. This choice is important because the focus of the present study is the North Adriatic Sea, where the separation of different surges is made almost impossible by seiches (Tomasin and Pirazzoli, 2007), the free oscillations of the basin after a storm, very persistent due to the shape of the local morphology.

The output of the JPM include: probability (%) and cumulated percentage of events associated to different water levels; expected number of hours/year of events equal to or higher than a defined level; average duration and return periods (years, months) of events of a defined level.

Based on these output, water levels related to the return periods defined by the Flood Directive and by the Italian law (i.e., D.Lgs. n.49 of the 23rd February 2010) were selected (i.e., 20, 50, 100, 200 and 500 years) categorized into floods with a high probability, floods with a medium probability and floods with a low probability (Table 2).

A rise in sea level is expected to increase the risk of coastal flooding due to storm surge, moving the hazard-prone areas upward. The magnitude of the rise in storm surge height as a

Table 2 JPM output for the considered tide gauge stations

| | Adriatic Sea | | | Venice Lagoon | | | | | Marano and Grado Lagoon | | |
|----------------------------------|-----------------------|---------------------------|----------------------------|--------------------------------|----------------------------|-----------------------------|----------------------------------|---------------------------------------|---------------------------|-----------------------------|--------------------------|
| | Return period (years) | Ancona (water levels, cm) | Ravenna (water levels, cm) | Piattaforma (water levels, cm) | Trieste (water levels, cm) | Chioggia (water levels, cm) | Lido Diga Sud (water levels, cm) | Punta della Salute (water levels, cm) | Burano (water levels, cm) | Grassabò (water levels, cm) | Grado (water levels, cm) |
| Floods with a high probability | 20 | 89 | 124 | 150 | 155 | 165 | 154 | 153 | 147 | 145 | 155 |
| Floods with a medium probability | 50 | 92 | 129 | 156 | 173 | 172 | 159 | 157 | 154 | 150 | 161 |
| Floods with a low probability | 100 | 93 | 132 | 159 | 185 | 177 | 163 | 161 | 159 | 153 | 164 |
| | 200 | 94 | 134 | 162 | 196 | 181 | 165 | 163 | 163 | 156 | 167 |
| | 500 | 96 | 138 | 166 | 207 | 185 | 168 | 166 | 167 | 159 | 171 |

consequence of sea-level rise is usually taken as the amount of the expected rise in sea level (Holman and Loveland 2001). Accordingly, for the identification of sea-level rise scenarios to be used within the application, several numerical climate models were evaluated and compared (e.g., IPCC 2007a, 2013; Vermeer and Rahmstorf 2009), but projections available for some areas, such as the North Adriatic basin, do not completely agree in the estimate. In fact, the uncertainty associated to climate projections is connected to the complexity and quantity of information to be considered in the computation of sea level change scenarios (e.g., the thermohaline and the halohaline effects, the mass addition, the dynamical effects related to circulation patterns). The sea-level rise scenarios selected for this study are the ones estimated by CMCC and CNR-ISMAR by the application of a multi-model chain including coastal hydrodynamic models for the North Adriatic region (Torresan et al. 2009) for the future scenario 2070–2100. Results include two sea-level rise scenarios: i) a low sea-level rise returning an average rise of 17 cm and a high sea-level rise returning an average rise of 42 cm.

The final water levels considered for the hazard assessment were defined combining the output provided by the JPM (i.e., astronomical tide, meteorological tide and mean sea-level, Table 2) and high and low Sea Level Rise (SLR) scenarios (i.e., 17 and 42 cm).

In order to evaluate the water height along the shoreline from point data calculated in each tide gauge stations, the Inverse Distance Weighted (IDW) method was used in GIS to interpolate data assigning to each 10×10 m pixel of the coastline the water level of the closest cell of the sea. This method was considered appropriate as the considered phenomenon (i.e., the water level) increase/decrease linearly between tide gauge stations if they are close to each other (such as in the considered region). The output of this phase (presented in section 4.1) are maps showing the storm surge height along the coastline for events with different return periods and considering several climate change scenarios.

Exposure assessment

The exposure assessment is aimed at identifying and localizing receptors (i.e., elements at risk) that could be adversely affected by the storm surge flooding (UNISDR 2009; IPCC 2012). According to the requirements of the Flood Directive, people, economic activities, cultural heritages and the environment were considered as major targets of the analysis. Economic activities were divided into infrastructures, buildings and agricultural areas; the environment was split into natural and semi-natural systems (including forests), beaches and wetlands. Receptors were localised in the case study area using regional land cover data detailed in Table 1.

For six receptors (i.e., infrastructures, beaches, wetlands, natural and semi-natural environments, agricultural areas and

cultural heritage) the assessment considered only the presence (with a score of 0) or the absence (with a score of 1). For the receptors population and buildings, land cover data were integrated with the census data of the year 2001 in order to calculate the number of residents or of buildings per census zone. The value was successively normalized between 0 and 1, where 1 represent the maximum number of residents or buildings in the region under investigation. The product of this phase (described in more detail in section 4.2) is an accurate and comprehensive GIS inventory of natural systems and human assets at risk that can be displayed on maps.

Physical and environmental vulnerability assessment

The physical and environmental vulnerability assessment is used within the RRA to evaluate the degree to which coastal receptors could be affected by storm surge flooding and is determined through the identification, classification and aggregation of a subset of *Vulnerability factors* for selected receptors (Table 3). Classes and scores for each vulnerability factor (Table 4) were defined by a group of experts in environmental risk assessment assigning values ranging from 0 to 1, where: 0 represents no vulnerability in relation to the specific factor; 1 represents the higher vulnerability class for that factor. The use of expert judgement, especially in situations where quantitative estimations are not achievable due to lack of resources or data, has been considered a valid approach to risk assessment (Crozier and Glade 2005). However it can contribute to limit the rigor of the process. Higher objectivity can be obtained by using a common scoring methodology based on qualitative descriptions used by the experts to compare and rank the classes during the course of the assessment. This approach allows reducing the subjectivity by using the same qualitative criteria for the scoring system. Furthermore, the proposed scores must be supported by literature references or statements of significance to add credibility to the assessment process.

For three receptors (i.e., infrastructures, cultural heritage and buildings) no vulnerability factors were identified and the vulnerability score was considered as the maximum (i.e., 1). As far as infrastructures are concerned, it was not possible to evaluate their structural vulnerability due to lack of specific

Table 4 Vulnerability factors selected for the storm surge flooding impact applied to the North Adriatic coastal receptors and related scores

| Factor | Legend | Score |
|--------------------------------------|--|-------|
| % people 0–14 and >65 | 0% - 20% | 0.2 |
| | 20% - 40% | 0.4 |
| | 40% - 60% | 0.6 |
| | 60% - 80% | 0.8 |
| | 80% - 100% | 1 |
| Agricultural typology | Permanent crops | 0.2 |
| | Stable meadow-Pastures | 0.6 |
| | Arable land | 1 |
| Slope (degrees) | Plains: 0°-6° | 1 |
| | Gentle to moderate slope terrain: 6°- 20° | 0.6 |
| | Steep slope terrain: 20°- 37.7° | 0.2 |
| Soil permeability | Low permeability | 1 |
| | Moderate permeability | 0.5 |
| | High permeability | 0.2 |
| Vegetation cover | Natural grassland and meadow | 1 |
| | Vegetation with shrubbery | 0.6 |
| | Forest | 0.2 |
| Wetland extension (Km ²) | 0–5.96 | 1 |
| | 5.97–11.93 | 0.8 |
| | 11.94–17.89 | 0.6 |
| | 17.90–23.86 | 0.4 |
| | 23.87–29.83 | 0.2 |
| Geomorphology | Muddy coast | 1 |
| | Sandy coast | 0.5 |
| | Rocky coast | 0.2 |
| Wetland typology | Inland wetlands (marshes, peatbogs) | 1 |
| | Coastal wetlands (salt marshes, salines, intertidal flats) | 0.5 |

data (e.g. data about the structural characteristics of the streets) at the regional scale. Consequently, it was decided to consider only the possibility of temporary inundation of infrastructures, causing potential interruption of service, as assessment endpoint. Similarly, no data were available at the regional scale to evaluate physical vulnerability of cultural heritage and buildings (e.g., height of buildings, state of conservation). In all

Table 3 Vulnerability factors selected for the storm surge flooding impact applied to the North Adriatic coastal zones

| Population | Agriculture | Natural and seminatural environments | Wetlands | Beaches |
|-------------------------|-------------------------|--------------------------------------|---------------------|--------------------|
| - % people 0–14 and >65 | - Agricultural typology | - Vegetation cover | - Vegetation cover | - Vegetation cover |
| | - Slope | - Slope | - Slope | - Slope |
| | - Soil permeability | - Soil permeability | - Wetland extension | - Geomorphology |
| | | | - Wetland typology | |

these cases, following a precautionary approach, it was considered that the presence of water over the receptor (e.g. a historical church or residential building) is the driving risk factor.

For the receptor population, the considered factor is the percentage of people older than 65 years and between 0 and 14 years who are considered more vulnerable to possible impacts of climate change and natural hazards (Ford et al. 2006; Granger 2003; McCann 2011). The higher is the percentage of people in these classes, the higher is the vulnerability of the population receptor (i.e., 100% of aged or young population correspond to a vulnerability score of 1). For the receptor agriculture, three factors were considered. The first is the agricultural typology: arable lands have lower protective cover (and therefore higher vulnerability scores) than other types of crops (French 2001). The second factor for agricultural areas (also used for the others environmental receptors) is the slope. It determines the energy of the impact of water on the land and how easily a storm surge flooding can move inland from the coastline; accordingly, the lower is the slope, the higher is the vulnerability (Sharples 2006). Another important factor (used both for agriculture and for natural and semi-natural environments) is the soil permeability, related to the permeability which can reduce the duration of a flooding event (i.e. soils with high permeability can drain water more rapidly). Urbanised areas (always considered with low permeability due to the high density of impermeable surfaces) and other areas with low permeable soils (e.g., clay soils), instead, remain flooded for a longer time and are characterised by a higher vulnerability. For the environmental receptors (i.e. natural and semi-natural environment, wetlands and beaches) the vegetation cover typology was used to indicate whether these systems can support a temporary flood generated by storm surges: forests will be more resistant and less affected by a temporary flood, while other typologies (e.g. grassland and meadows) are considered more susceptible to the impact of flood and therefore gained higher vulnerability scores (Preston et al., 2008; McLaughlin and Cooper 2010; Torresan et al., 2008). For the wetlands, two additional factors were considered: extension and typology. In this case it was assumed that a smaller wetland has a lower recovery potential and thus can be affected more severely by storm surge flooding if its extension is smaller. Accordingly, the larger is the extension, the lower is the vulnerability score and vice versa (Torresan et al. 2008 and 2012). As far as the typology is concerned, coastal wetlands, which are already in contact with marine water, are less vulnerable to floods than inland wetlands, which are usually living in freshwater environments. Finally, the geomorphology was considered a key factor to evaluate the vulnerability of beaches. They are classified as muddy, sandy or rocky, with muddy beaches characterised by a higher vulnerability to the considered impact (Sharples 2006).

The final vulnerability score for each receptor was obtained by the aggregation of vulnerability factors using the *probabilistic or operator* (Kalbfleisch 1985) according to the following equation.

$$V_{ssf,k} = \otimes v_{ssf} \quad (3)$$

Where:

$$\begin{aligned} V_{ssf,k} & \text{ vulnerability score for the receptor } k; \\ \otimes & \text{ probabilistic or operator;} \\ v_{ssf} & \text{ vulnerability factors.} \end{aligned}$$

By using the probabilistic or operator, if just a vulnerability factor v_{ssf} assumes the maximum value (i.e. 1) then the result will be 1. Vulnerability scores were finally classified in 5 qualitative classes (from Very low to Very High) using the equal interval. Results can be displayed on maps and tables showing the distribution and ranking of vulnerable targets based on their physical-environmental characteristics. As described in section 4.3, vulnerability maps and statistics can support decision makers in the definition of measures aimed at boosting the resilience of receptors in the considered region (e.g., change of land use and agricultural typologies).

Risk assessment

The Risk assessment phase aims at integrating hazard scenarios with exposure and vulnerability assessment in order to estimate and spatially rank risk levels in the considered region. Based on the widely accepted definitions of UNISDR (2009) and IPCC-AR5 (2014), the risk score is calculated according to the following function:

$$R_{ssf,k,s} = H_{ssf,s} \cdot E_{ssf,k} \cdot V_{ssf,k} \quad (4)$$

Where:

$$\begin{aligned} R_{ssf,k,s} & \text{ risk score related to the scenario } s \text{ and the receptor } k; \\ H_{ssf,s} & \text{ hazard score for the scenario } s; \\ E_{ssf,k} & \text{ exposure score or the receptor } k; \\ V_{ssf,k} & \text{ vulnerability score for the receptor } k. \end{aligned}$$

Risk scores calculated for each receptor range between 0 and 1, where: 0 means no risk (i.e., there is no hazard, exposure or vulnerability) and 1 means maximum risk for the considered scenario and target/area in the considered region.

According to the RRA paradigm (Landis, 2005), regional risk scores are not absolute predictions about climate change related risks, but provide relative classifications about areas and targets that are likely to be affected by climate change impacts more severely than others within a defined region.

The output of this step is represented by relative risk maps showing the distribution of the relative risk scores, for each

considered scenario and receptor. As described in more detail in the next Section, they are useful tools supporting decision makers in the definition of areas where further investigations should be needed in order to define suitable adaptation measures (e.g., coastal zoning and land use planning, construction of sea defence structures) aimed at mitigating environmental and socio-economic damages.

Results and discussion

The results of the RRA applied in the coastal zone of the North Adriatic sea are basically represented by GIS-based maps showing the spatial variability of hazard, exposure, vulnerability and risk for each considered scenario. Moreover, tabular statistics summarising key risk metrics (e.g., percentage and surface of receptors at risk in different districts) were calculated in order to easily compare results for different receptors and scenarios.

Hazard maps

Hazard maps show how the considered region can be affected by coastal floods of different probabilities in the baseline scenario and considering high/low sea-level rise projections at 2100. The total surface that has a hazard score higher than 0 is represented by a quite homogenous coastal strip that can reach 8/9 km of width. The surface of coastal area prone to hazard ranged from around 1.640 km² in the best scenario (i.e. return period of 20 years and no sea-level rise projection) to almost 1.775 km² in the worst scenario (i.e., return period of 500 years and a sea-level rise projection of 42 cm). The difference between the best and the worst scenarios indicates that there are not significant differences among the considered scenarios. Within these areas, more than 1/3 of the surface is characterized by a very high hazard (i.e., between 510 km² and more than 690 km²).

The analysis of the maps highlights a strong correlation of the hazard score with the elevation and the distance from the coastline: hazard is maximum in low elevation areas close to the coastline and decreases in areas characterized by higher elevation and more distant from the shoreline. It is important to consider that produced maps consider only storm surge flooding coming from the sea, and do not include the contribution from a potential floods coming from rivers. Accordingly, inundated areas close to rivers can be exposed to higher coastal inundation hazard if a river flood occurs at the same time. Moreover, hazard maps do not take into account the presence of artificial protection (as the information about their height and effectiveness was not available) and the effects of the barriers under construction at the three inlets of the Lagoon of Venice (MOSE), which are expected to contrast storm surges with a height of more than 110 cm that usually

flood the historical center of Venice. Therefore, results could be improved by integrating information about artificial protections, allowing the evaluation of their contribution in the hazard's reduction. However, the validity of the hazard maps has been tested by comparing with the map of the historical flood of the year 1966, when the water level reached 194 cm. The map of the inundated areas with an event of similar height is quite similar, showing consistent results, especially for some regions bordering the central and northern parts of the lagoon of Venice where the effect of concomitant river floods can be neglected.

Figures 4 allows the hazard comparison between storm surge heights with different return periods and different values of SLR. According to the proposed methodology (paragraph 3.2), each hazard scenario indicate the severity of inundation level above each considered coastal parcel (i.e. grid cell of 25 m). The extension of flooded areas and the percentage of surface within each hazard class do not significantly change for extreme events with different return periods (i.e., 20, 50, 100, 200 and 500 years), within the same SLR scenario. Histograms of Figs. 4 confirms that the differences among scenarios are not big and slightly increase as the return period and SLR increase.

Hazard maps provide useful information about areas characterized by low, medium or high hazard and can support decision makers in the identification of coastal zones that can be inundated more heavily than others by a storm surge event, giving useful indications for the definition of regional plans and the implementation of the Flood Directive. As an example, areas with higher hazard scores should not be considered suitable for new urbanizations without previous intervention aimed at reducing the hazard (e.g., construction of artificial protection against temporary floods or seawalls).

Exposure maps

Exposure maps show the distribution of receptors at risk, including human-made settlements and assets, sites of cultural heritage, crops or other natural systems which have a high environmental or socio-economic value (e.g. beaches, wetlands). Figure 5 shows an example of exposure map for population and buildings. The exposure is quite low over all the entire region for both the receptors and only few areas have scores ranging from the Medium to the Very high class. Being based on land use and census data, exposure maps allow an easy visualization of areas where touristic activities are concentrated (i.e., areas with several buildings but no residents along the coastline in the municipality of Cavallino-Treporti; Fig. 9A), the localization of industrial settlements (e.g., areas with several buildings but few residents North-East of the centre of Jesolo; Fig. 5B) or of major residential zones (e.g., the centres of Jesolo and Chioggia; Fig. 9C).

Fig. 4 Percentage of the case study area in different hazard classes according to different sea-level rise scenarios

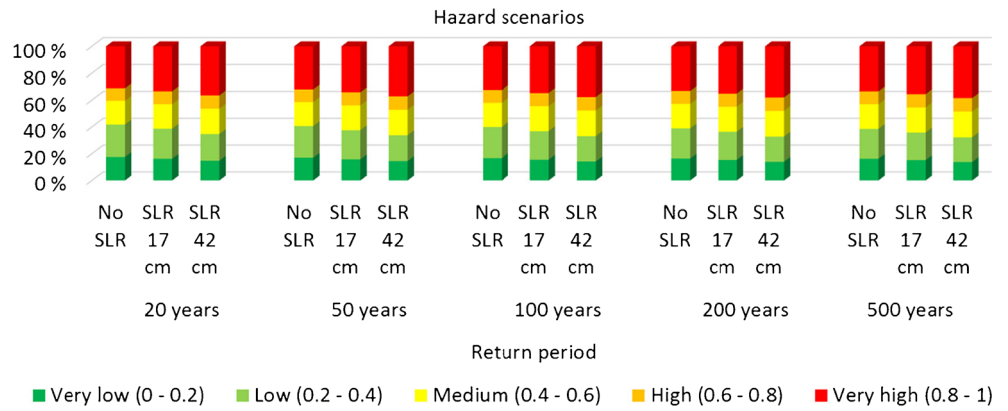


Figure 6 shows the localization of the environmental receptors (beaches, wetlands, natural and semi-natural environments) and agricultural areas for the whole case study area and for some specific areas. Agricultural areas occupy most of the surface (around 1.200 km²), while beaches and natural and semi-natural environments have a lower surface (around

10 Km² and 30 km² respectively). Wetlands have a relevant surface (almost 300 Km²) especially along the coastline of the Veneto region and over the Lagoon of Venice. It is important to note that the environmental receptors includes also several protected areas, represented by Sites of Community Interest (SIC) and Zones of Special Protection (ZPS) identified by the

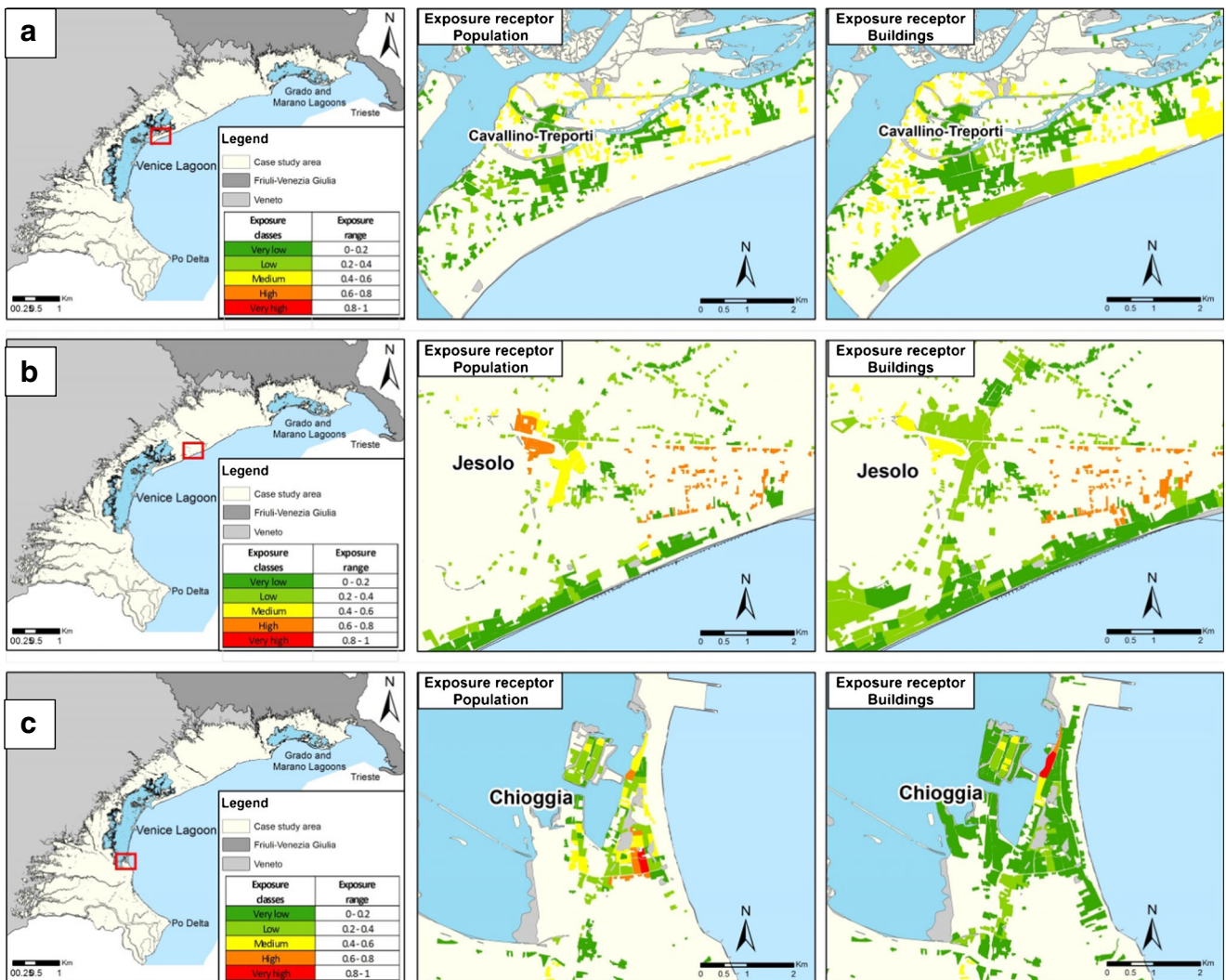


Fig. 5 Exposure map of population and buildings

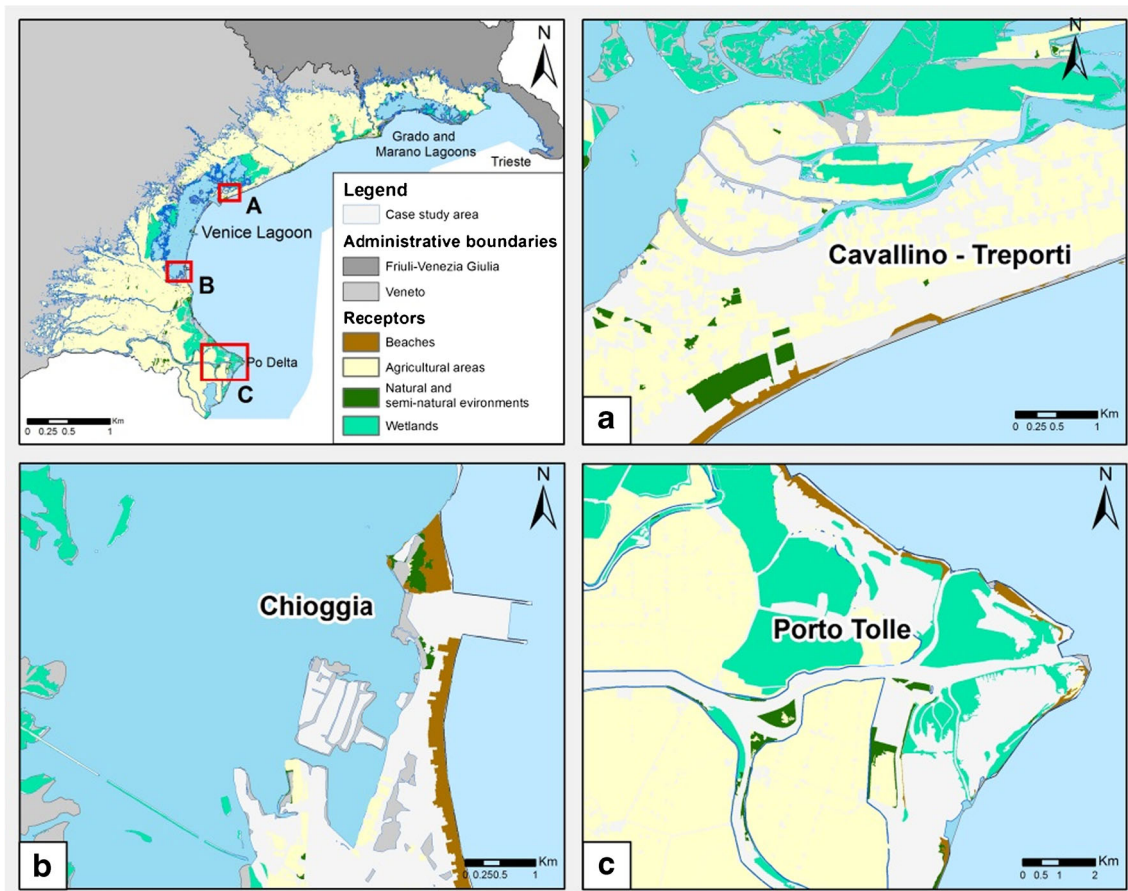


Fig. 6 Exposure map of the considered environmental receptors and agricultural areas with a focus on the municipalities of Cavallino Treporti (a), Chioggia (b) and Porto Tolle (c)

European Commission (especially beaches, wetlands and natural and semi-natural environments).

Physical and environmental vulnerability maps

Physical and Environmental Vulnerability maps represent the sensitivity of receptors against storm surge and highlight the ones that could be affected more severely than others by extreme inundation events. Based on the methodology presented in paragraph 3.4, physical and environmental vulnerability maps were produced for each analysed receptor. As far as population, beaches, wetlands, natural and semi-natural environments and agricultural areas are concerned, vulnerability was calculated integrating factors and scores reported in Table 4. For the other three receptors (i.e. infrastructures, buildings and cultural heritage) vulnerability was set equal to 1. This choice, agreed with the experts involved in the definition of scores and weights, implicitly assumes that, at the mesoscale level, buildings, infrastructure and cultural heritage are characterized by the same susceptibility. Even though this choice leads to an increase of the final risk score, being a relative – and not absolute – assessment, these results do not affect the final ranking.

Results showed that the vulnerability is very high (i.e. equal to 1) almost for all the considered receptors, except for population. This is basically due to the low slope of the case study area that corresponds to the higher vulnerability class for this factor. Fig. 7 shows an example of vulnerability map for the beaches of Veneto and Friuli Venezia Giulia but similar results were obtained also for all the other environmental receptors (i.e., wetlands, natural and semi-natural environments) and agricultural areas. An analysis of the contribution of the different vulnerability factors showed that beyond slope, geomorphology is the factor mainly contributing to the definition of the vulnerability of beaches. Wetlands show high vulnerability even without slope, suggesting that vegetation cover, wetlands extension and wetlands typology already characterize them with high scores. The vulnerability of natural and semi-natural environments, besides slope, is mainly influenced by the soil permeability which has higher influence than the vegetation cover. Finally, the high vulnerability of agricultural areas is due also to the crop typology, mainly represented by arable lands.

Figure 8 shows the vulnerability of Population over the considered region and for some specific municipalities. Differently from the other receptors, the vulnerability is

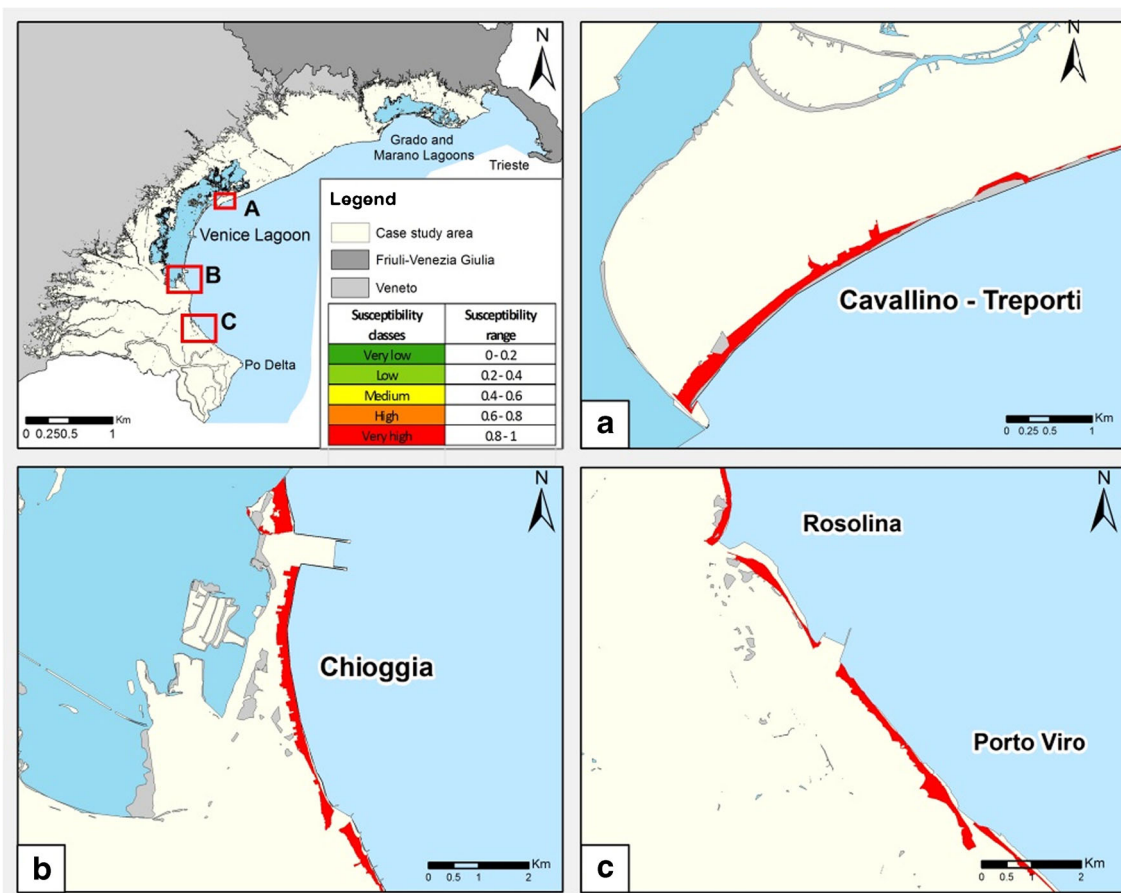


Fig. 7 Vulnerability map of beaches in the municipalities of Cavallino-treporti (a), Chioggia (b), Porto Viro and Rosolina (c)

generally quite low over the entire considered region except in census zones where there is a concentration of children and old people (e.g., census zones where there are hospices).

Based on the obtained results, several actions could be undertaken to reduce the vulnerability, such as the reconstruction of dunes that could boost beaches’ resilience and reduce their vulnerability; the reinforcement or reconstruction of wetlands’ where the boundaries are damaged or destroyed, in order to make them more resistant to floods. Wetlands are particularly important because they represent also a natural protection against storm surge events. Thus their maintenance could be particularly useful to reduce the intensity of future events and reduce the risk of areas located beyond them. Further, wetlands are protected areas under several laws and directives (e.g. the habitat directive, 92/43/EEC, or the birds directive, 2009/147/EC), thus it is desirable to reduce their vulnerability in order to prevent potential climate change impacts. The reduction of the vulnerability for natural and semi-natural environments and for agricultural areas could be achieved by changing crops and introducing species more resistant to temporary floods.

Risk maps

Based on hazard, exposure and vulnerability maps previously described, risk maps were produced for each considered receptor and scenario and some statistics were calculated in order to better understand the results. Risk maps provide a relative estimate of the potential negative consequences caused by the combination of extreme storm surges and sea-level rise scenarios. Risk was calculated for each receptor for the best scenario (i.e., return period of 20 years without SLR) and the worst scenario (i.e., return period of 500 years with a SLR of 42 cm). The risk over the entire considered region is very high close to the coastline and decreases moving inland. Environmental receptors have a relevant surface classified within the higher risk classes, while almost all buildings and population are in the lowest risk classes. This difference is due to the fact that the environmental receptors have generally a higher vulnerability score.

The two maps in Fig. 9 show the spatial distribution of the risk for wetlands and agricultural areas, which are the most extended receptors. By the maps it emerges that the areas classified within the very high relative risk class are usually within the first 3 km. Coastal wetlands (Fig. 9A), and

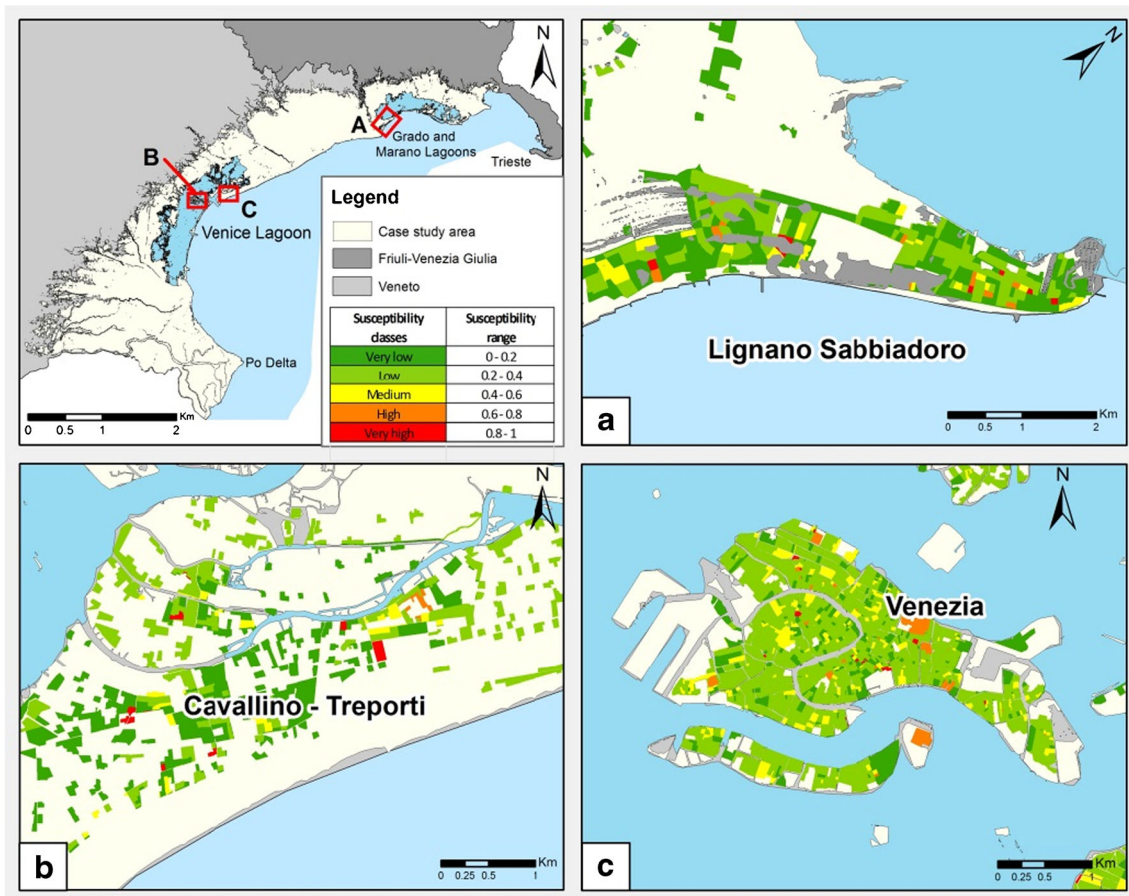


Fig. 8 Vulnerability map of population for the municipalities of Lignano Sabbiadoro (a), Cavallino Treporti (b), Venice (c)

especially those around the Lagoon of Venice and the Lagoon of Marano and Grado, are classified within the highest risk class, while wetlands classified with lower risk classes are those who are more far from the coastline, in the Po river delta. Wetlands of the North Adriatic region are protected areas included within the Natura 2000 network as particularly important habitat for several species of birds, including migratory birds that transit over the lagoons of the North Adriatic sea.

Accordingly it will be important to preserve them not only because they are a natural systems contributing to the reduction of the intensity of storm surge events, but also because they represent fragile and important natural habitats. Agricultural areas (Fig. 9B) show very high relative risk scores along all the case study coastline, with a level of risk decreasing moving inland from the coastline. The result is mainly related to the hazard score, as the vulnerability score

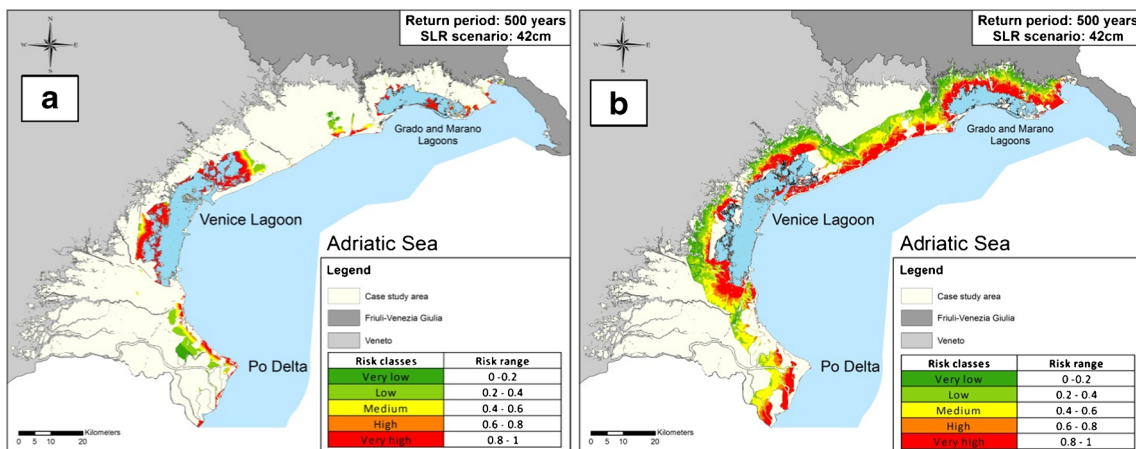


Fig. 9 Risk maps of wetlands (a) and agricultural areas (b)

and the exposure score are the maximum (i.e., 1) almost everywhere, thus they do not significantly change the original hazard score. Almost all the areas at risk are used as arable lands, with crops – mainly cereals – rotating each year. There are two main potential impacts that could threaten such areas: damages of the plant related to the impact of the water, if the storm surge is in a period where the plant are fragile, and salinization of the soil, if the events have a long duration with salt water stagnates over the fields for days. In order to reduce the risk it could be decided to plant species more resistant if such impacts occur.

Some additional information related to all the environmental receptors are provided by the statistics calculated for the best and worst scenarios (Fig. 10) showing the percentage of the surface within each risk class. Almost all beaches are classified within the highest relative risk class. This is mainly due to their proximity to the coastline and to their high vulnerability. Wetlands are classified within the higher risk class for around the 50% of their surface. The environmental receptor with the lower percentage of surface within the higher risk class is agricultural areas (i.e., less than 25% in the worst scenario). Finally, natural and semi-natural environments are characterised by very high risk for more than 25% of their surface in the best scenario and 40% in the worst one. No clear pattern or trends were identified for this receptor and the vegetation typology, mainly contributing to the final risk value, is quite heterogeneous (e.g., close to the coastline, where there are the higher hazard scores, there could be some areas with pine tree that have a very low vulnerability alternated with areas with low vegetation or grass, characterized by a higher susceptibility). However, in most cases the main common driver of risk is represented by the distance from the coastline considered during the hazard assessment phase.

Relative risk scores and statistics produced for population and buildings are quite low all over the considered region, even for the worst scenario (i.e., return period of 500 years with a SLR of 42 cm; Fig. 11). Population is almost always classified in the lower risk classes (i.e., Low and Very low) and buildings in the classes from Medium to Very low. The

comparison between the best and worst scenarios shows that there is an increase of population and buildings at risk especially in the province of Venice, (e.g., increase of 50,000 people and 7000 buildings at risk in the worst scenario). However, in all scenarios, including the worst one, the highest percentage of population and buildings at risk are in the lowest risk classes, as shown in Fig. 11. This estimate is a precautionary evaluation of buildings and people that could be exposed to the flood hazard. A more detailed analysis at the local scale focusing on hot spots should take into account also other elements, such as the number of floors of the building, the typology of construction, and the fluxes of people (e.g. the workers in industrial zones, or the tourists in the main touristic spot such as Venice).

Adaptation measures will play a key role in the reduction of the hazard and many public authorities are taking initiative in such direction. The most relevant example is represented by the MOSE project: when the construction of the barriers will be completed, the hazard related to floods coming from the sea should be eliminated or reduced for receptors in areas located within the Lagoon of Venice. The produced maps could also support the definition of new urban plans in order to identify areas more suitable for new human settlements and zones more prone to floods that require particular adaptation measures or specific building restrictions.

As far as infrastructure are concerned, Local roads will be the most impacted infrastructures both in absolute terms (i.e., the length in km) and in percentage (Fig. 12) of roads in the highest risk class (40% in the worst scenario). As far as railways are concerned, around the 35% will be classified in the higher risk class; moreover the total length in the worst scenario will be almost the double of the best scenario (i.e., 95 km and 55 km respectively). As far as highways are concerned, the decrease of percentage in the higher risk class is due to a very high increment of highway at risk in the worst scenario compared to the best scenario; highway at risk mainly in the worst scenario are almost all classified within the lowest risk class. In case of an extreme storm surge event, flooded infrastructures will not be available, so it is important to identify

Fig. 10 Risk statistics for the environmental receptors

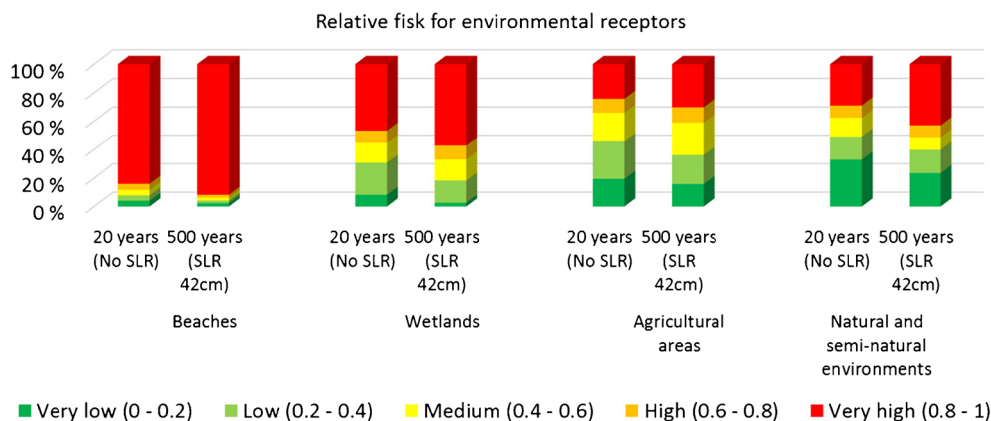
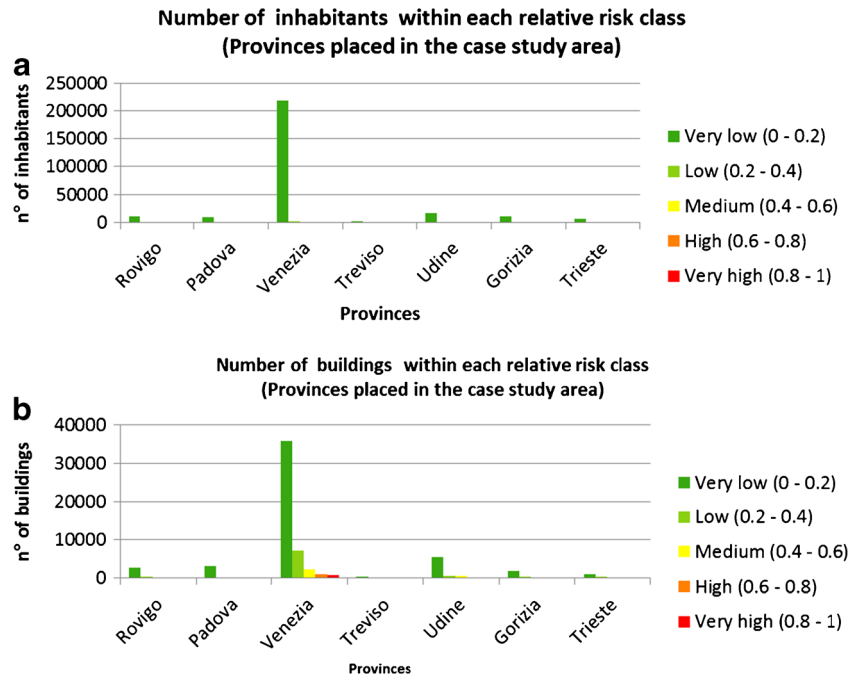


Fig. 11 Risk statistics showing the number of people (a) and buildings (b) in different risk classes for the worst scenario



areas that should not be flooded in order to locate strategic infrastructures in these regions or build protection for already existing strategic infrastructures.

Finally, as far as cultural heritage are concerned (i.e., villas, historical buildings and roads), it appears that almost the 70% of their surface will be characterized with the very high risk

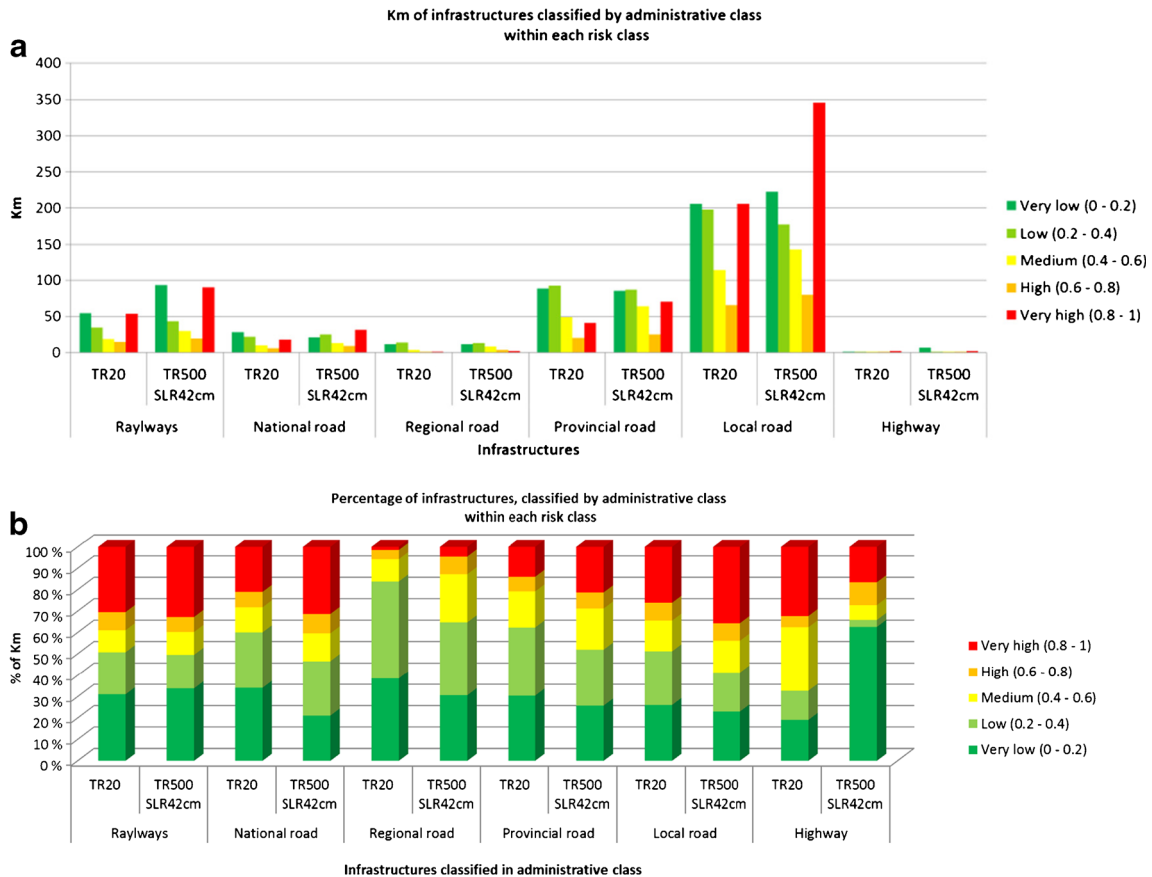


Fig. 12 Comparison of the length of infrastructure in the different relative risk classes for the 2 extreme scenarios in absolute values (a) and percentages (b)

class, and even in the best scenario more than 50% of the surface will be in the higher risk class. Protection of cultural heritage is particularly important within the Veneto region as attract many tourists from all over the world.

The proposed approach is the only example of regional scale analysis of climate change impact on storm surge floods in the coastal areas of the North Adriatic Sea. Another analysis has been performed by the water management authority of eastern Alps at the local scale, based on datasets partially not publicly available, which has then been integrated into the national plan required by the European Commission. However, their method is mainly focused on river floods (the storm surge levels are based on a smaller dataset) and do not include the potential impacts of climate change, performing the analysis with slightly different return periods. Due to these differences, it is not possible to make a direct quantitative comparison of the risk maps. Nevertheless, a qualitative comparison of the results shows that the extension of areas potentially flooded by similar events is not in total disagreement.

The produced risk maps, as highlighted in the previous paragraphs, can support stakeholders and decision makers, through a preliminary screening, in the identification of areas where adaptation measures should be implemented and in the definition of regional adaptation plans aimed at prioritizing areas that could experience more severe effect from coastal floods under future climate change scenarios. The output of the proposed RRA approach are consistent with the requirement of the flood directive and can be used as a basis for the definition and the periodic update of management plans. Final results showed that all the coastal zone of the case study area should be protected due to the low elevation and low slope, but specific interventions should be planned on the basis of further quantitative analysis performed at the local scale. Such interventions could be aimed at reducing one or both the components that contribute to the definition of the risk, i.e., the hazard or the vulnerability, as highlighted in the previous paragraphs. Several barriers are already in place (e.g., in the area of the Po' delta) or are under construction (e.g., the MOSE, floating dams located in the three inlets to protect the whole Lagoon of Venice), but a general integrated strategy for the whole region would be useful to better address possible climate change impacts in an effective way.

Conclusion

The described RRA outputs (i.e., exposure, vulnerability and risk maps) and the related statistics represent a first-pass assessment for the spatial identification of areas and targets at higher risk from storm surge flooding, in view of future climate change scenarios. These products are useful to communicate information about potential environmental and socio-

economic impacts and losses to stakeholders and regional public administrations (e.g., planning offices of provinces and regions). Produced maps can provide suitable information for setting priorities for further investigations (quantitative risk assessment based on dynamic numerical models) and can be used to pave the way for future adaptation pathways, including the development of climate-proof land use planning and management. Moreover, the final results can support the implementation of the European Flood Directive (2007/60/EC), establishing a framework for the assessment and management of flood risk considering frequency, magnitude and consequences of floods in coastal areas. The proposed approach is applicable to any coastal region by replacing input data and customizing scores and weights.

In order to properly use the RRA results it is important to underline that the rankings produced by the methodology are unitless numbers, expressed in qualitative classes (i.e., very high, high, medium, low, very low), which provide information about the sub-areas and targets within a region that are more likely to be affected by climate change impacts than others.

The novelty of the proposed approach consist in the spatial scale of analysis (i.e. meso-scale assessment performed for the subnational coastal area of the North Adriatic Sea), and in the multi-disciplinary approach that takes into account downscaled climate change processes (e.g., sea-level rise) to characterize climate change hazards at the regional scale with physical, environmental and socio-economic vulnerability factors (e.g., altimetry, geomorphology, land use and vegetation cover).

An improvement of the vulnerability assessment can be represented by the evaluation of the territorial vulnerability, aggregating the vulnerability of the different considered receptors into a unique value. Another development of the presented work (going beyond the simplified approach used to estimate hazard-prone areas) would be represented by the use of dynamic coastal flood models, simulating the propagation of extreme storm surge events inland, and providing information about water velocity and direction. In addition, the potential effect of other related hazards (e.g., river floods, coastal erosion) should be included in the analysis in order to perform a multi-risks assessment taking into account cumulative hazards. The hazard estimation could be improved also by using probabilistic methods for evaluating levels of extreme marine flooding (e.g. Le Cozannet et al. 2015, Purvis et al., 2008). Further, it is important to consider all the components contributing the increase/decrease storm surge extreme events, including vertical movement such as subsidence or uplift of the cost (e.g., Wolff et al. 2016). However information to apply these approaches is not always available, or is not available as future projection. Specific studies have conducted, e.g., over the Lagoon of Venice by Carbognin et al. (2009), but extrapolating subsidence values over last decades to evaluate the future could lead to big errors especially when the main causes are anthropogenic, such as in the North Adriatic

coast. The exclusion of subsidence can lead to an underestimation of the hazard, and, as a consequence, of the risk. It is therefore important to carefully evaluate the results provided by the application. Further, the analysis is based on the use of a DTM generated by interpolation of elevations points and elevation contour lines, with a vertical accuracy that can be up to also to 50/60 cm and less in flat areas. In order to obtain more robust results it would be recommended the use of high resolution elevation data, such as LIDAR. In addition, a better hazard estimation could be obtained by using climate models with a higher resolution. Another interesting development would be the integration of the proposed approach with the approach at the local scale.

Finally, future improvements of the methodology can be obtained by eliciting more elements at risk and extending the subset of vulnerability factors, by including indicators representing potential direct economic losses and social adaptive capacity.

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