A multi-disciplinary approach to evaluate pluvial floods risk under changing climate: the case study of the municipality of Venice (Italy).

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Abstract

Global climate change is likely to pose increasing threats in nearly all sectors and across all sub-regions worldwide. Particularly, extreme weather events (e.g. heavy precipitations), together with changing exposure and vulnerability patterns, are expected to increase the damaging effect of storms, pluvial floods and coastal flooding. Developing climate and adaptation services for local planners and decision makers is becoming essential to transfer and communicate sound scientific knowledge about climate related risks and foster the development of national, regional and local adaptation strategies. In order to analyze the effect of climate change on pluvial flood risk and advice adaptation planning, a Regional Risk Assessment (RRA) methodology was developed and applied to the urban territory of the municipality of Venice. Based on the integrated analysis of hazard, exposure, vulnerability and risk, RRA allows identifying and prioritizing targets and sub-areas that are more likely to be affected by pluvial flood risk due to heavy precipitation events in the future scenario 2041-2050. From the early stages of its development and application, the RRA followed a bottom-up approach taking into account the requests, knowledge and perspectives of local stakeholders of the North Adriatic region by means of interactive workshops, surveys and discussions. Results of the analysis showed that all targets (i.e. residential, commercial-industrial areas and infrastructures) are vulnerable to pluvial floods due to the high impermeability and low slope of the topography. The spatial pattern of risk mostly reflects the distribution of the hazard and the districts with the higher percentage of receptors' surface in the higher risk classes (i.e. very high, high and medium) are Lido-Pellestrina and Marghera. The paper discusses how risk-based maps and statistics integrate scientific and local knowledge with the final aim to mainstream climate adaptation in the development of risk mitigation and urban plans.

Keywords: pluvial floods, risk assessment, climate change, urban areas, GIS maps.

1. Introduction

According to the Fifth Assessment Report of the IPCC (AR5, 2014), climate change is expected to increase extreme precipitations over many countries of Europe and, consequently, the incidence and severity of damaging events such as pluvial flooding and sewer surcharging (NERC, 2010; Larsen et al., 2009). Pluvial floods are defined as rain-related floods which occur when intense rainfall cannot be drained away quickly enough through sewage or rivers. They are usually associated with high intensity pluvial events (typically>30mm/h) but can also occur with lower intensity rainfall where ground is saturated, urbanized or has low permeability (NERC, 2009; Falconer et al., 2008). In this case drainage systems and surface watercourses may be completely overwhelmed leading to overland flows and pooling, causing damage to buildings, infrastructure and inconvenience to people (Spekkers, 2011). In urban areas the probability of pluvial flood events is particularly high and damages are significant - both in economic and social terms - due to the presence of many residential and productive activities (Houston et al., 2011). In fact, urbanization reduces soil infiltration and facilitates the establishment of micro-climates impacting extreme rainfall rates (Shepherd et al., 2002; Mote et al., 2007, WMO, 2008). Moreover, besides the influence of climate change, other social and economic factors, such as population growing and land use changes, can exacerbate the adverse consequences associated to extreme precipitation events in the future (Barredo 2009; Mitchell 2003).

Despite over the last years the interest in urban flood risk has been growing steadily as response to pluvial flood events occurred around Northern and Central Europe (e.g. United Kingdom, Ireland, Italy, France, Germany), knowledge on impacts that climate change is likely to have on the extent and pattern of pluvial floods and on the associated risks for human activities is still poor. At the current state of the art, in fact, very few methodologies have been specifically developed for the study of pluvial flood risk while most approaches consider the issue together with others typology of flood (i.e. river and coastal inundation) (Escuder Bueno et al., 2012). Moreover, available pluvial flood risk methods are fragmented across different scientific research areas (e.g. engineering, environmental sciences, economics and social sciences) and most are developed for single receptors (i.e. people, cultural heritage, buildings) without considering the possible presence of multiple targets in the same territory (Zhou et all., 2012, Scheid et al, 2013). Most of them require a huge amount of high resolution site-specific data (e.g. LIDAR, hydraulic models simulations, capacity and localization of drainage systems) resulting scarcely applicable for screening and routine analysis. Finally, the majority of the approaches tackle the assessment of pluvial flood risk neglecting the effect of future climate changes (Escuder Bueno et al., 2012, Zhou et all., 2012).

This paper presents the application of a spatially resolved risk assessment methodology integrating information about future climate change scenarios in the appraisal of pluvial flood risk in urban areas. The overall aim of the study is to produce a suite of risk and vulnerability indicators useful for local planners and decision makers to take action against pluvial floods in view of expected climate change. Being based on the overall Regional Risk Assessment (RRA) paradigms (Landis, 2005), the methodology considers multiple elements at risk (e.g. residential and commercial areas), allowing the identification of relatively higher risk areas, for future precipitation scenarios in the 2041-2050 timeframe, under the RCP 8.5 emission scenario. Moreover, it follows the bottom-up protocol developed within the FP7 European Project CLIM-RUN (Rousset et al., 2014) in order to deliver climate and adaptation services based on continuous and iterative stakeholders' involvement (Goosen et al, 2013).The main output of the methodology are user-oriented risk maps developed through the use of GIS based tools in order to provide an efficient visualization of areas and receptors more vulnerable to pluvial flood risk and requiring priority actions for adaptation and risk mitigation.

After a brief introduction to the case study area, the participative processes and available input data (Section 2) the paper describes the risk-based methodology developed to address pluvial flood risks in urban areas under changing climate (Section 3) and finally, discusses the risk maps and statistics obtained for the urban territory of the municipality of Venice (Section 4).

2. Background

2.1 Case study area

The study area selected for the pluvial flood risk assessment is represented by the urban territory of the municipality of Venice, the capital of the Veneto region in the North East coast of the Adriatic Sea (Figure 1). The municipality of Venice is located in the Venetian Plane on the Northern part of the Venice Lagoon and has an overall extension of about 416 km^2 and a population of 226.856 inhabitants (ISTAT,2012) mainly concentrated around the two major urban areas of Mestre and Venice. The urban territory is located both in small islands within and around the Venice Lagoon (e.g. Venice historical centre, Burano, Murano, Lido, Pellestrina) and in the mainland (e.g. Mestre and Marghera) which host about 2/3 of total resident inhabitants of the entire municipality. Moreover, Venice is divided into six administrative districts: Venezia-Murano-Burano, Lido-Pellestrina, Favaro Veneto, Mestre-Carpenedo, Chirignago-Zelarino, Marghera. Numerous economic activities take place in the study area ranging from petrochemical industry (i.e. Mestre and Marghera districts) to tourism, sea port activities, shipping and fishing in island such as Venice-Burano-Murano and Lido districts. The study area, especially with regard to urban centers of Mestre and Marghera, have a very high percentage of urbanization which started after the World War II when large numbers of people from the countryside and from Venice's historic center moved to urban areas on the coast following the development of the petrochemical plant of Porto Marghera. In a few years Mestre, turned from a small village of 20,000 inhabitants in the 1950, into a city of about 200,000 inhabitants in the 1970 (Municipality of Venice, 2013). The rapid development led to a growing demand of residential spaces and infrastructure in a restricted coastal area which were built in absence of planning and consequently radical changes of entire areas of the city occurred with the conversion of green areas in to urban zones. Despite of the chemical industry crisis in the late eighties and nineties have caused a considerable decline in residents due to emigration, Mestre and its suburbs, with more than 200.000 inhabitants, remain one of the most urbanized districts counting more than 66% of the population of the entire municipality (Municipality of Venice, 2013). Although in recent years many environmental restorations have occurred with the creation of green areas such as Via Bissuola Park, St. Giuliano Park and Mestre Wood, the study area has still numerous structural criticalities caused by the excessive urbanization and the inappropriateness of drainage and sewer systems. These criticalities have become more visible in the past decade when, in conjunction with heavy rainfall concentrated in a short period, different areas of the municipality have been flooded. The most evident example for intensity and damages was the flooding event occurred in September 26th 2007 in the city center of Mestre with 260 mm of precipitation in 24 hours (Barbi et al., 2007); however others similar events have occurred from 2000 and 2009 in the same areas. According to Sartori (2012), these pluvial floods events can be attributed to extreme rainfall events which are increasing in the whole Veneto region. However, the social and structural components (e.g. percentage of urbanization, growing population and lack of appropriately localized and dimensioned drainage systems) play a crucial role in increasing the vulnerability to pluvial floods events reducing the soil absorption rate and increasing the water runoff (Huong, 2013). As result, a comprehensive and integrated approach able to incorporate climate change scenarios with exposure and vulnerability assessment to pluvial flood risk evaluation is essential to aid decision making and adaptation planning in a medium and long term prospective.

2.2 The bottom-up approach for the involvement of North Adriatic stakeholders.

The risk-based methodology presented in this paper took advantage from a bottom-up approach developed with local stakeholders of the North Adriatic (NA) coast in order to identify their information needs for climate adaptation and to deliver risk-based products that can be practically used within urban planning and coastal zone management (Torresan et al., 2014). The bottom-up process followed the protocol established in the frame of the CLIM-RUN project for the development of climate services in the Mediterranean region (Rousset et al., 2014). Particularly, within the NA case study the protocol was applied by a multi-disciplinary group of experts, including: 1. the Stakeholders Expert Team (SET), supporting the involvement of local stakeholders by means of targeted workshops, questionnaires and thematic groups with the aim to identify their needs and requests in terms of climate services and information; 2. the Climate Expert Team (CET), providing climate information and products (e.g. analysis of climate observations, improved modeling and downscaling techniques); 3. the Risk Expert Team (RET), integrating basic climate information produced by CET with the assessment of exposure and vulnerability in order to evaluate climate-related risks for different natural and human systems (Torresan et al., 2014). Stakeholders to be involved in the process were selected among a list of public authorities with a mandate for Integrated Coastal Zone Management (e.g. regional meteorological offices, civil protection, environmental protection agencies, municipalities and regions) (Giannini et al., 2011). Two workshops were organized, during different stages of the project (Figure S1, supplementary material): the first workshop (and the initial perception questionnaire) allowed to identify stakeholders preferences concerning input data for climate and risk products (e.g. key climate variables, priority receptors and impacts, temporal horizon, spatial resolution); the second one (accompanied by the feedback questionnaire) allowed to discuss a suite of preliminary products produced by climate and risk experts and to define the best way to apply (and represent) them in specific testing areas (e.g. by defining local thresholds, the layout of maps, and the type of statistics). Finally, a focus group organized at the end of the project, allowed to present the final products developed and to get final feedbacks from local stakeholders about their usefulness and recommendations for further developments.

2.3 Climate scenarios

Climate scenarios more suitable to study pluvial flood risks were selected by the CET among the climate products specifically developed for the NA case study in the CLIM-RUN Project (Branković et al, 2011, Torresan et al., 2014). Specifically, future precipitation scenarios were provided by the Regional Climate Model (RegCM4) (Giorgi et al., 2012) developed by ICTP (International Centre for Theoretical Physics*)*. Figure 2

Two RegCM4 simulations were completed over the Med-CORDEX domain (Ruti et al.,2014) that covers the whole Mediterranean region at 50km and 12km resolution. The 12km simulation has been used in this study. This scenario simulation covers the period 1970-2100 and uses the RCP 8.5 scenario from the latest AR5 IPCC report (IPCC, 2013).

In Figure 2A the percentage of extreme precipitation is reported for the ERO4M precipitation dataset (Isotta et al, 2014) and for the RegCM 12km simulation for the present day period (1975-2004) Figure 2B. The extreme precipitation is defined as the precipitation greater of the 95th percentile and this is representative of the extreme precipitation events that we deal with in the present study. From Figure 2 the model and observation are showing a similar spatial distribution of the precipitation and the precipitation amount are also in agreement. In Figure 2C the change of extreme precipitation is shown for the period 2041-2050 compared to the present day. The increase of extreme precipitation events is evident everywhere in the domain, but in particular we notice a maximum of increase of 10% in the Venice Lagoon area.

3. Methods

The risk-based methodology proposed for the assessment of pluvial flood risk in urban areas according to future climate projections was developed upon the three main pillars of risk defined by UNISDR (2009) and IPCC (2012) (i.e. hazard, exposure, and vulnerability) and following the general steps of the Regional Risk Assessment already adopted by Ronco et al. (2014) for the assessment of flood risk in river basins (Figure 3). The following paragraphs describe the step by step procedure applied in the specific case study of the municipality of Venice, focusing on the input parameters and mathematical equations.

3.1 Hazard Assessment

The hazard assessment phase is aimed at identifying and ranking areas that could be affected by pluvial flood events in relation with future climate change scenarios. The final goal of the hazard assessment is to estimate the number of precipitation events exceeding a local threshold of ordinary hydraulic emergency. Emergencies are defined as hydraulic phenomena which involve the secondary hydraulic system (i.e. drainage and sewage system) causing difficulties in the water drainage with consequent localized flooding of infrastructures, urban surface and discomfort to people (Civil Protection, 2007). The assessment was performed considering the intensity of precipitation (mm/day), representing the volume of precipitation falling over time in a specific area, as relevant hazard metric. According to the IPCC (2012), the intensity is the parameter of a rainfall which is likely to be mostly altered in future by climate change and therefore it is an essential metric to be considered for the study of climate change impacts on pluvial floods' occurrence.

As described in Paragraph 2.3, the intensity of precipitation (mm/day) was provided by the RegCM4 model on daily basis for a ten years horizon (i.e. 2041-2050) according to the RCP8.5 emission scenario. The decade 2041-2050 was chosen as temporal period for the analysis since it represented a compromise between stakeholder's requests - asking for a short term period of analysis (i.e. 20, 30, 50 years) - and the significant period in which the climate change signal is observed from regional climate models. Rainfall projections for the case study area were obtained from 13 selected model grid cells (12 km of resolution) around the case study area. In order to make the data coming from the model suitable to be used in the risk assessment, they were processed and converted to GIS-based files, representing the center point of each model grid through some geographical attributes (i.e. longitude, latitude) and attributing to each of them the respective total daily intensity of precipitation. Accordingly, the hazard scenario was developed comparing future precipitation scenarios with Maximum Pluvial Thresholds (MPT) representing local critical rainfall values over which negative effects to the systems are expected (e.g. traffic line interruptions, flash floods due to failure of the drainage system). The estimate of the total number of hydraulic emergencies was performed following the procedure proposed by ARPA (2004) for the early warning pluvial flood system of the Veneto Region. Specifically the procedure is composed of four main steps:

1. Identification of the total daily precipitation for each day of the analyzed timeframe;
2. Identification of the state of the soil (WET/DRY) for each day of the analyzed timeframe;
3. Identification of the local MPT;
4. Comparison of the total daily precipitation with the MPT in order to estimate the number of potential ordinary hydraulic emergencies in the analyzed timeframe.

The total daily precipitation P_i (mm/day) for each day i of the analyzed period was provided as future climate projection by the RegCM4 model (Section 2.3.1). Then, in order to identify the previous state of the soil (i.e. WET or DRY conditions) the cumulative precipitation (Ci) for each of the 15 days before the day of concern (i.e. each day of 2041-2050 decade), was calculated according with Equation 1:

$$C_i = \sum_{j=i-15}^{i} P_j$$

Equation 1

Where:

i = the day of concern, must be greater than 15

C_i= cumulative precipitation of the day i;

P_j= total daily precipitation of the day j

The 15 cumulative precipitation values calculated as above were then compared, cell by cell, with the correspondent soil humidity thresholds proposed in Table S2 (supplementary material). According to the procedure proposed by ARPA (2004), if just one of the 15 cumulated values calculated in any center point of the RegCM4 model grid cell within the case study area exceeds the correspondent soil humidity threshold, the soil was considered wet in all the study area, otherwise the soil was considered dry in the whole area. Once the state of the soil was identified, the appropriate ordinary MPT for the selected area was chosen among those proposed by Civil Protection (2007) and compared with the total daily precipitation (Pi) of the day to study: the lowest threshold (58,4 mm of precipitation) was applied in case of wet soil while the highest (76 mm of precipitation) in case of dry soil. The procedure was performed for each day of the analyzed timeframe identifying the number of events of ordinary emergency in the 2041-2050 for each day and geographical site (i.e. center point associated with each model grid cell).

The total number of ordinary emergency events was then normalized according with Equation 2 and a final hazard score (Hs) ranging from 0 (meaning that there are no emergency events and therefore no hazard) to 1 (representing the class with the higher hazard and therefore the higher number of emergency events in the case study area) was obtained.

$$Hs = \frac{tot\ PotOE\mathrm{i}}{maxPotOE} \qquad \text{Equation 2}$$

Where:

Hs = pluvial flood hazard score;

$\mathrm{tot\ PotOE_i}$ = total number of ordinary emergency events in the cell i in the decade 2041-2050;

$\mathrm{maxPotOE}$ = maximum number of potential ordinary emergencies in the case study area in the decade 2041-2050.

The hazard score associated with each center point of the model grid (12 km spatial resolution) were then interpolated applying an Inverse Distance Weighted (IDW) technique in order to obtain an hazard map reflecting, as much as possible, the natural pattern of precipitations and providing a representation of the spatial distribution of potential ordinary emergencies.

3.2 Exposure Assessment

The second step of the RRA procedure (i.e. the exposure assessment) is aimed at identifying, selecting and localizing receptors (i.e. elements potentially at risk) that could be potentially subject to pluvial floods and therefore exposed to adverse consequences (e.g. damages of buildings and infrastructures) in flooded zones. Receptors can be chosen in relation with the objectives of the study, the spatial scale and the available dataset. In the present case study, receptors were selected through an interactive discussion with local stakeholders interviewed by means of workshops and surveys (Section 2.2). Three receptors were finally identified and included in the analysis: residential areas, commercial and industrial areas, infrastructures. As described in Table 1, the receptors were mainly localized using the land cover map for the Veneto region (1:10.000) (Veneto, 2012) as it represents the most homogenous and detailed dataset of land use available for the case study. In order to keep the highest feasible detail determined by the available dataset for exposure and vulnerability assessment, all the geographical information used for the exposure assessment was converted in raster format (i.e. grid cells) with a spatial resolution of 5 m. Finally, an exposure score equal to 1 was assigned to the cells where the receptor is present and equal to 0 in case of absence of the receptor.

3.3 Physical and environmental vulnerability assessment

The physical and environmental vulnerability assessment aims to evaluate the predisposition of a receptor to be adversely affected by a pluvial flood hazard based on site-specific information and vulnerability factors (e.g. land use, slope, soil type, percentage of urbanization) (Ronco et al., 2014).The choice of relevant vulnerability factors for the case study area (Table 2 was performed by the RET involved in the CLIM-RUN project (Torresan et al., 2014) according with the dataset availability for the municipality of Venice (Table 1) and approved by the local stakeholders who participated at workshops (e.g. regional environmental protection agencies, regional civil protection, regional met offices) (Section 2.2). In order to make relative rankings of areas more sensitive to pluvial floods, the vulnerability factors were classified and scored by the RET in the normalized range 0 to 1, following the qualitative linguistic evaluations reported in Table S3 (supplementary material) . The results of this process, summarized in Table 2, were presented and discussed with local stakeholders to obtain their positive feedback and proceed with the application. The slope factor was subdivided in classes using the Natural breaks classification method (Zald et al., 2006), which allows to reduce the variance within classes maximizing the variance between classes. Lower slope values (i.e. 0°-2.7°) were assigned the higher vulnerability score (i.e. 0.8) due their higher potential for water stagnation (Preston et al., 2008). The lower score (i.e. 0.2) was instead assigned to steeper lands (i.e. 10.4°-49.2°). Moreover, permeability classes, identified according with the classification proposed in the permeability map of the province of Venice (Province of Venice, 2011), were scored considering that the vulnerability to pluvial floods increases if the soil is characterized by low permeability (Abhas et al.,2012; Pan, 2012): the higher score (i.e. 1) was assigned to the impermeable areas (areas occupied by buildings and infrastructures) while the lower score (i.e. 0.2) was assigned to areas characterized by the presence of clear sands and gravel which are highly permeable. Intermediate scores (i.e. 0.8-0.3) were assigned to intermediate permeability classes (i.e. sand with silts, very fine sands). Finally, areas where pluvial floods have occurred in the recent past, were assumed as proxy indicators to detect the actual criticalities of drainage systems' that could make them more susceptible to pluvial floods events also in the future (Cheong et al.,2013). Therefore, a score equal to 0.8 was assigned to recently flooded areas while a score equal to 0.2 was assigned to areas were recent floods were not observed. According with the approach applied by Ronco et al. (2014) for the assessment of water-related hazards, after the normalization, vulnerability factors were aggregated through a Multi-Criteria Decision Analysis (MCDA) function named "probabilistic or" (Kalbfleisch J. G., 1985), in order to provide a single normalized score of physical and environmental vulnerability for each cell of the study area, following the Equation 3:

$$V_{pe} = \otimes_{i}^{n} [vf_i] \qquad \text{Equation 3}$$

where:

V_{pe}= physical and environmental vulnerability score, representing the predisposition of the territory to be affected by pluvial flood;

$\otimes$= "probabilistic or" function (see Table S4, supplementary material);

vf_i = i^{th} physical and environmental vulnerability factor.

The vulnerability score ranges from 0 (i.e. no vulnerability) to 1 (i.e. higher vulnerability in the case study area) and is calculated cell by cell aggregating information from overlaid vulnerability factors, already normalized in the range [0,1]. Applying the "probabilistic or" function (Equation 3), if just a vulnerability factor (vf) assumes the higher value (i.e. 1) then the vulnerability score will be 1. On the other side, different vf with lower scores contribute in increasing the final vulnerability score: the more is the number of low vulnerability factor scores, the greater is the final vulnerability (Gallina et al, 2014).

3.4 Relative Risk Assessment

The risk assessment phase is aimed at integrating information about the pluvial flood hazard related to a given climate change scenario, with the receptors' exposure and the territorial vulnerability in order to identify targets and areas at higher risk of flooding in the investigated area. The general function for the estimation of the pluvial flood risk (R) is the following (UNISDR, 2009; IPCC, 2012):

$$R_j = H_s \times E_j \times V_{pe} \qquad \text{Equation 4}$$

where:

R_j = risk score related to pluvial flood for the receptor j;

H_s = pluvial flood hazard score (Equation 2);

$E_{,j}$=exposure score determining the presence/absence of the receptor j (section 3.2);

V_{pe}= physical and environmental vulnerability score (Equation 3).

Risk score varies from 0 to 1, in which 0 means that in the area the risk is null (i.e. there is no hazard, no receptors or no physical and environmental vulnerability) and 1 means the higher risk in the case study area. Accordingly, the risk score provides a relative classification about areas and targets that are likely to be affected by pluvial floods more severely than others in the same region.

Hazard, vulnerability and risk scores ranging from 0 to 1 in a continuous scale were classified in 5 classes (i.e. very low, low, medium, high, very high) using the Natural breaks method (Zald et. Al., 2006) and represented in maps described in Section 4. The Natural breaks method was selected since it determines the best arrangement of values into different classes, reducing the variance within classes and maximizing the variance among classes in order to provide a more effective visualization of maps.

4. Results and discussion

The results of the RRA procedure described in Section 3 were classified and processed in GIS in order to obtain maps representing the spatial variability of hazard, exposure, vulnerability and risk to pluvial flood in the investigated area. Moreover, through GIS tools, several statistics (e.g. percentage and surface of each receptor associated to each hazard, vulnerability, risk class; percentage and surface of receptors at risk for each administrative unit) were calculated in order to synthesize relevant information coming from the RRA outputs. As discussed in the following paragraphs, the produced maps represent risk-based products useful to underpin best practices for risk management and novel solutions for climate change adaptation .

4.1 Hazard map

The hazard assessment applied to the case study area (Section 3.1) produced useful maps to spatially localize the number of potential hydraulic emergencies occurring in the future timeframe 2041-2050 and therefore to identify areas where drainage and storage systems should be reinforced and improved. Figure 4A shows that all the territory is interested by potential ordinary emergencies and that the hazard increases moving from north to south-east: higher hazard classes are located near Pellestrina with a number of potential emergencies ranging from 40 to 49 in the 2041-2050 period while decreasing classes are located in the area of Mestre - Carpenedo where the number of potential emergencies ranges from 12 to 19. Based on the hazard map, a statistic was calculated in order to provide stakeholders with information about the seasonal distribution of the potential future hydraulic emergencies. Figure 4B represents the total number of potential hydraulic emergencies in each cell of the case study area for each month of the 2041-2050 decade. The graph shows that the higher number of emergencies is concentrated in autumn with a maximum peak in October (70 potential emergencies). This result is in line with the trend observed by Sartori (2012) where the occurrence of extreme precipitations from 1992-2009 in the Veneto region is mainly concentrated in autumn (i.e. September) when a strong thermic contrast between land and sea is established in the North Adriatic coastal zone. In the other months, the hazard is homogeneously distributed with emergencies ranging from 7 to 19 with the exception of July where no emergencies occur.

5.2 Exposure map

The exposure map produced by the RRA procedure (Section 3.2) allows the identification and spatial localization of the receptors (i.e. elements at risk) that can be subject to potential losses due to pluvial floods events in the case study area. Figure 5 presents the exposure map for the municipality of Venice considering residential areas (red spots), commercial and industrial areas (violet spots) and infrastructures (grey segments) as main elements at risk for pluvial floods. Residential areas and infrastructure are spread on all the territory of the case study with an higher density in Mestre, Marghera and Lido. Whereas, commercial and industrial areas are mainly localized in correspondence of the industrial plant of Porto Marghera and in the north-east part of the case study area in correspondence of the Marco Polo airport. The zoom (Figure 5B) highlights the merging of the three receptors and specifically the localization of the most important infrastructures, including the railway station, of the city of Mestre.

5.3 Vulnerability maps

Vulnerability maps represent the spatial distribution of physical and environmental vulnerability factors (e.g. slope, permeability) for each element at risk, aggregated according to Equation 3. Specifically, vulnerability maps allow identifying which are the environmental factors that mainly contribute to increase the vulnerability of a specific area to pluvial flood events and therefore they are useful to identify which kind of intervention could be needed in order to reinforce the resilience of the territory, including for instance, the development of green areas and green roofs or the creation of blue infrastructures for the controlled drainage and storage of rainfall waters.

The map (Figure 6A and 6B) and the statistic (Figure 6C and 6D) shows the vulnerability for commercial and industrial areas depicting that the 41% (about 10,82 km^2) of the commercial and industrial areas is interested by very high vulnerability and 27% (about 7,24 km^2) by high vulnerability. These areas (i.e. very high and high vulnerability) are mainly located in the north-west of the case study area in correspondence with the industrial area of Porto Marghera (Figure 6A) and the Mestre railway station (Figure 6B).

The industrial area of Porto Marghera, the most influent industrial district of the Veneto region for what concern petrochemical and metallurgic industries, results highly vulnerable to pluvial flood due to the presence of territories composed by medium permeable soils (i.e. mixture of sand, silts and clay) that have an intermediate vulnerability score (i.e. 0.6). The transition to the very high vulnerability class (Figure 6A) occurs moving to areas interested by recent floods (i.e. Via dell'industria, Via dell'elettricità) characterized by the higher vulnerability score (i.e. 1). Moreover, The Mestre railway station (Figure 6B) one of the most important railway yard of the whole region, is associated to the very high vulnerability class because of the high impermeability of the surface due to urbanization and because of its localization in an area which, in recent years, has been affected by several pluvial flood events causing the flooding of the underpass and consequently discomfort to passengers and users of the station.By contrast, another significant and strategic commercial area, the Marco Polo airport of Venice, laying on soils characterized by medium permeability (i.e. sands with silts) with an intermediate vulnerability score (i.e. 0.4) results located in an area at moderate vulnerability where no pluvial flood events have been registered in recent years.

Figure S5 (supplementary material) describe the distribution of the vulnerability for residential areas within the municipality of Venice and highlights that 90 % of the residential areas (24,32 km^2) present very high, high and intermediate vulnerability scores (Figure 6C and 6D) mainly located in the northern part of the study area. Moreover, in Figure S5 it is possible to see that areas with the higher vulnerability scores are located in Mestre and Chirignago due to the high density of urbanization which confers low permeability to the soil. Another factor that increases the vulnerability in these areas is the occurrence, in the past, of pluvial flood events. Lido and Pellestrina (Figure S5) are mainly associated with lower vulnerability classes due to the presence of soil with moderate permeability (i.e. sand with silts and very fine sands) associated with lower vulnerability scores (i.e. 0.3, 0.4). However, also in this areas higher vulnerability classes are located in correspondence with totally impermeable surfaces, occupied by residential buildings extracted by the municipal technical map, where the vulnerability score is equal to 1 (Municipality of Venice, 2008).

Infrastructures are totally associated with very high vulnerability scores and therefore the whole receptor results highly vulnerable to pluvial flood events. This result can be attributed to the conservative assumption made in the scoring of vulnerability factors which assigned the higher vulnerability score equal to 1 to the presence of infrastructure, considered as totally impermeable to flood (Table 2). Due to this assumption, the others vulnerability factors (i.e. slope and recently flooded areas) not affect the final computation of vulnerability for this receptor.

5.4 Relative risk maps

Risk maps allow identifying the areas of the municipality of Venice at higher risk of flooding due to intense precipitation events, by considering the sito-specific physical and environmental vulnerability of the territory as well as future climate change scenarios.
The risk map for residential areas (Figure 7A and 7B) shows that the higher risk classes (i.e. very high and high) are represented in less than 1% of the territorial surface (0.54 km^2) (Figure 7C and 7D) and interest mainly the south-east part of the case study in correspondence with the insular areas of Lido- Pellestrina (Figure 7B) . In these areas the high risk is mainly due to the increasing pluvial hazard scores (e.g. 0.81 to 0.99) from north to south-west as the vulnerability is similar and generally low both for Pellestrina and Lido. By contrast, more than 80% of the residential areas, are located in areas at very low and low risk classes (Figure 7D) which can be attributed to the low and medium hazard classes (i.e. 12 to 28 number of potentially ordinary emergencies in the 2041-2050) and the presence of moderate permeable soils (i.e. sand, mixture of sand, silts and clays). Specifically, in the residential south part of the district of Marghera (Figure 7A) the transition between low risk class to intermediate risk class follows the main increase of hazard classes from low to medium (e.g. 19 to 28 number of potentially ordinary emergencies in the 2041-2050) while in the northern part of the Mestre city centre, the increase of the risk from very low to low is also due to the increase of vulnerability associated with the presence of recently flooded zones.

The results are quite similar for what concern commercial and industrial areas (Figure S6, supplementary material). The higher risk classes (i.e. very high and high) interest the south-east part of the case study area and mainly the littoral zones of Lido-Pellestrina with percentage of the territory at high and very high risk classes which is less than 1% (0.24 km^2) (Figure 7C and 7D). This relative high risk class is in accordance with the very high hazard class (i.e. 40 to 49 ordinary potential emergency in 2041-2050) associated with the area while the vulnerability, being relative low, doesn’t contributed significantly in increasing the risk. Lower risk classes (i.e. low and very low), including the 65% of the territorial surface (Figure 7C and 7D), are associated with the Marco Polo airport and the Mestre railway station. Although these areas represent vulnerable hotspots (Figure4) the low hazards score present in these areas classified them at low and very low risk of pluvial flood. Alternatively Figure S6 (supplementary material) highlights as, the industrial plan of Porto Marghera, a strategical industrial and product hotspot, is located in an area classified at medium risk. This risk score can be attributed both to the increase of the hazard score (i.e. 12 to 29 ordinary potential emergency in 2041-2050) and to the increase of vulnerability due to the presence of recently flooded areas and impermeable soils.

For what concern infrastructures generally we can see that, being the vulnerability very high for all the infrastructures, increasing risk classes are due to the increase of the hazard score which increase moving from north-west (0.2-0.4) to south-east (0.8-1). Only the infrastructures of the littoral zones of Pellestrina and Lido present very high and high risk mainly reflecting the hazard score which increase from 0.81 to 0.99. Infrastructures of Mestre, comprising the train station, are associated to the lower risk classes while in Marghera infrastructures are located in the intermediate risk class. This distribution is due to the hazard score that increases from 0.39 to 0.56 in Marghera.

In order to provide a more clear view of the distribution of risk classes at the administrative level a more specific statistic was calculated (Figure S7,supplementary material). It compares the risk distribution in the different administrative districts of the municipality of Venice for the three considered receptors (i.e. residential, commercial-industrial areas and infrastructures). Specifically, it allows to identify which districts present the higher percentage of surface at higher risk and therefore to provide support to prioritize administrative districts where adaptation and management strategies are mainly required. Lido-Pellestrina is the only district presenting very high and high risk classes for all the receptors considered. Here the residential areas have a quite relevant territorial surface at risk including 19 % in the very high and high classes and 45% in the medium class for a total surface of 1.77 km^2 of residential areas at risk. The district of Marghera, instead, presents more than 52% of the territory in the medium risk class for a total surface of 8.16 km^2 for commercial and industrial areas. The results is relevant considering that this district is located in the strategic industrial plan of Porto Marghera.

Risk maps developed can be used by local stakeholders and decision makers in order to set adaptation strategies and to plan the development of future human settlements and productive activities. Specifically, for what concern commercial and industrial areas, they are useful to identify which areas will be mainly interested by higher economic losses related to services interruption in case of flood and therefore can be used as a basis for a cost-benefit analysis aimed at evaluate the direct and indirect costs of climate change impacts on specific economic and productive sectors. In the case of infrastructures (i.e. road, highways, railways) risk maps can support decision makers to identify the areas presenting major criticalities in relation with future precipitation scenarios and, therefore, to set priorities for the allocation of public funds to the most affected districts for the improvement of the infrastructural systems.

6. Conclusions:

The Regional Risk Assessment (RRA) methodology applied in this work was useful to estimate areas and targets at risk (i.e. residential areas, commercial and industrial areas, infrastructures) from pluvial flood events in the urban area of the municipality of Venice, under future climate change scenarios. The bottom-up approach applied since the first phases of the procedure, allowed local stakeholders to actively participate in the development of risk-based adaptation products and the risk expert team to get the right questions for the development of products more tailored end-users' needs. Moreover, the multidisciplinary research approach integrating climate with socio-economic and environmental sciences allowed to incorporate science-based climate information and projections into a better assessment of impacts and risks and to provide a better quantification, communication and mapping of impacts, vulnerabilities and risks for end-users. The resulting risk-based products represent the first step toward the development climate and adaptation services (Goosen et al, 2013, WMO, 2011) paving the way to translate climate impacts information into real solutions to increase the adaptation capacity and resilience of ecosystems, societies and infrastructure to the anticipated climate change impacts .

The adopted RRA approach is flexible and therefore the methodology can be improved considering different hazard scenarios, extending the analysis to longer term timeframes (e.g. 2070-2100), considering other receptors of interest (e.g. people, cultural buildings, agricultural areas) and other vulnerability factors according with users' needs and aims.

Moreover, the analysis can be easily up-scaled to evaluate the consequences of pluvial flood impacts at a broader region/sub-national scale. On the whole, the methodology outputs (i.e. hazard, exposure, vulnerability and risk maps) and the related indicators can be considered as a first-screening product for the spatial identification of areas and targets at higher risk from pluvial flood impact which can be useful to support coastal authorities in examining possible risks associated with climate change and identifying areas where adaptation strategies are required. However, a more detailed analysis is necessary in order to respond to very specific needs of stakeholders (e.g. how to design future urban drainage systems). Further developments, in this sense, should consider a more detailed parameterization of local processes (e.g. by means of hydraulic models) and a more precise spatial dataset (e.g. high resolution data obtained by Light Detection and Ranging techniques (LIDAR)) and information about the capacity, structure and localization of the urban drainage system, in order to give a more precise assessment and localization of climate risks at the local scale. Specifically, in order to provide a more precise and detailed assessment of the pluvial flood risk for infrastructures, different vulnerability factors should be included in the analysis, considering for instance specific characteristics of the infrastructural system at the micro-scale (i.e. slope, presence and localization of depressed areas, typology of surfaces), their distance from the main drainage systems, the presence of specific adaptation structures aimed at avoiding floods. Moreover, in order to consider the influence of changes in land use and urbanization in the final estimate of future risk, the analysis should consider dynamic exposure and vulnerability (i.e. time-dependent) including different land use and socio-economic scenarios.

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Table 1 Available dataset for the assessment of pluvial flood impact in the municipality of Venice

Dataset	Spatial Domain	Source
Infrastructures map, 1:5000	Municipality of Venice	Municipality of Venice, 2008
Municipal tecnical map 1:5000	Municipality of Venice	Municipality of Venice, 2008
5 m Digital Elevation Model (DEM)	Veneto	Veneto, 2007
Permeability Map 1:100.000 extracted from Geologic Atlas of the Province of Venice	Province of Venice	Province of Venice, 2011
Recently flooded areas Map 1:100.000 extracted from Geologic Atlas of the Province of Venice	Province of Venice	Province of Venice, 2011
Land Cover Map for the Veneto region 1:10000	Veneto	Veneto, 2012
Administrative boundaries	Municipality of Venice	Municipality of Venice, 2011

Table 2 Classes, score and weight associated with vulnerability factors in the municipality of Venice

Factor	**Class**		**Score**
Slope (degrees)	0°-2.7°		0,8
	2.7°-10.4°		0,4
	10.4°-49.2°		0,2
Soil permeability	Areas occupied by building and infrastructure (Impermeable)		1
	Stratified clays	$<10e^{-8}$ (m/s)	0,8
	Mixture of sand, silts and clay	$10e^{-8}$ - $10e^{-7}$ (m/s)	0,6
	Sands with silts	$10e^{-7}$ - $10e^{-6}$ (m/s)	0,4
	Very fine sands	$10e^{-6}$ - $10e^{-5}$ (m/s)	0,3
	Clear sands and gravel	$>10e^{-5}$ (m/s) (permeable)	0,2
Flooded areas	Not flooded areas		0,2
	Flooded areas		0,8

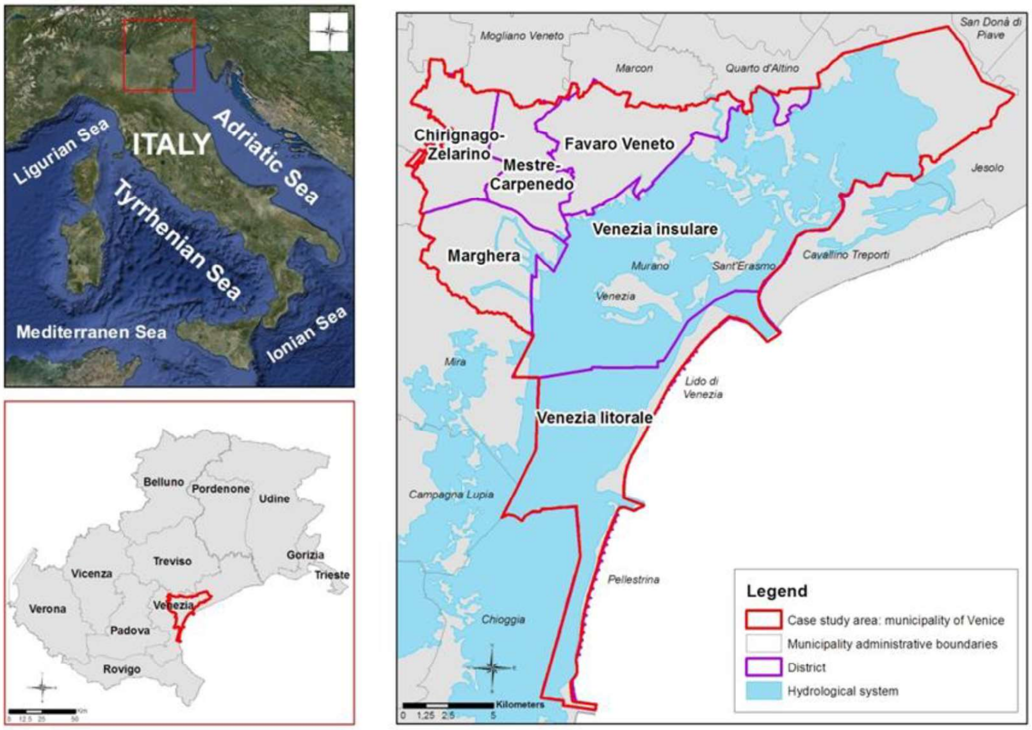


Figure 1 Case study area of the municipality of Venice.

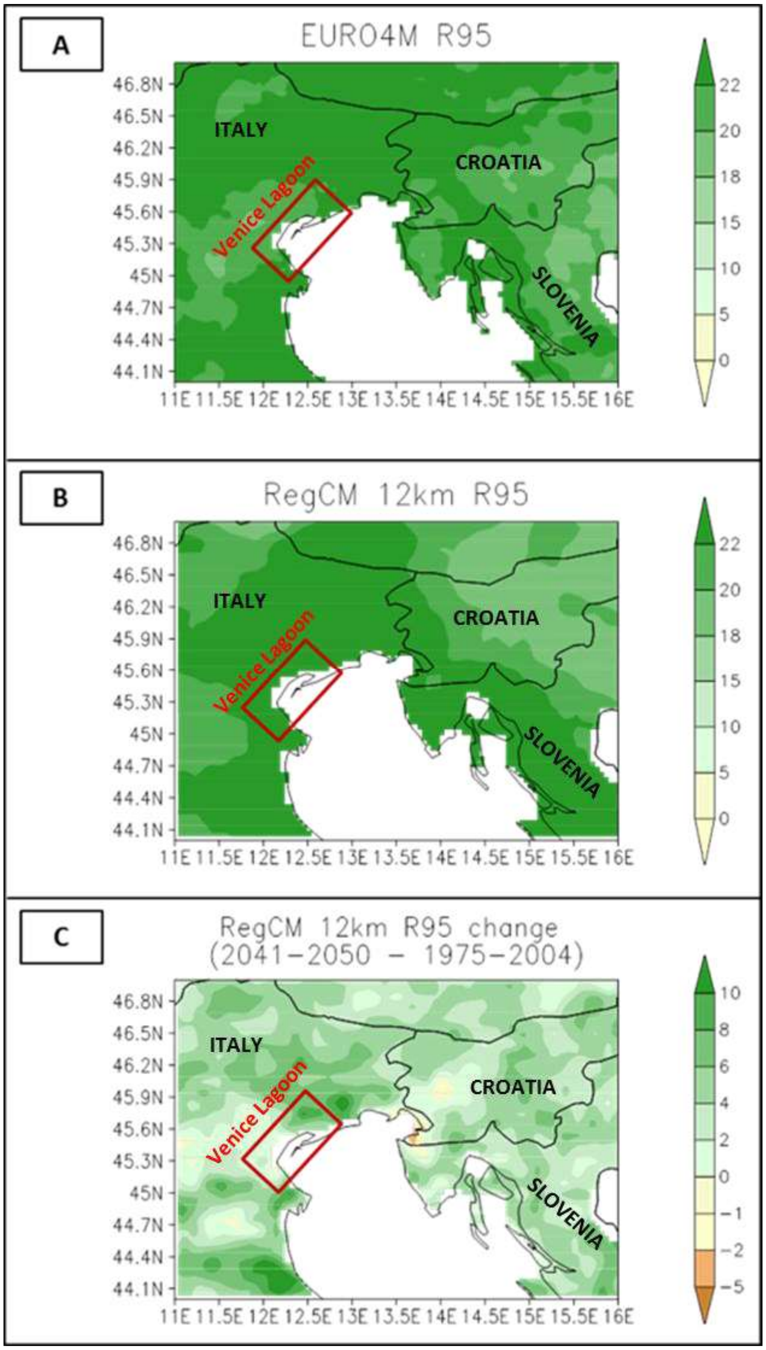


Figure 2 Percentage of precipitation due to events greater of the 95th percentile. Observation for the present day period (1975-2004) (A), model for the present day period (B) and change between future (2041-2050) and present period as shown by the model (C) above the Venice Lagoon.

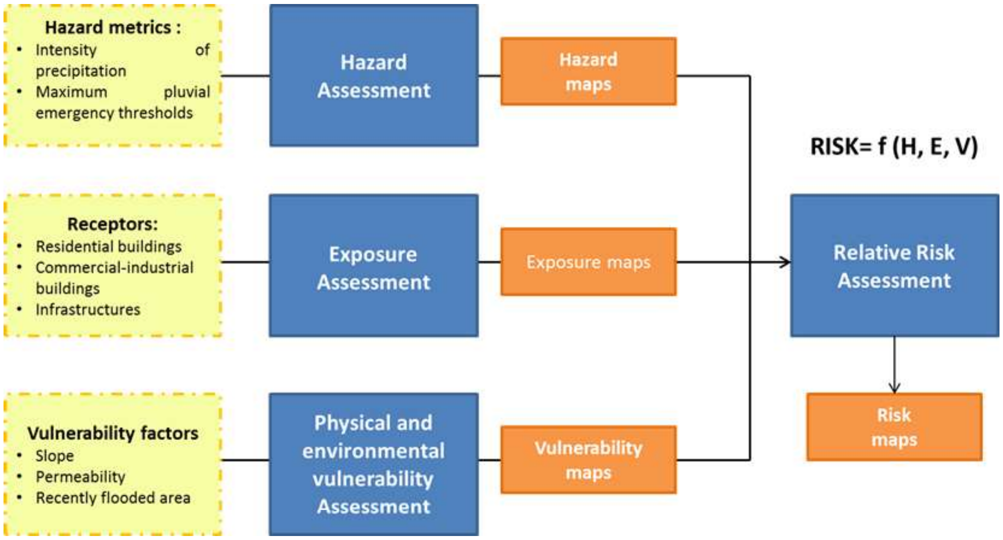
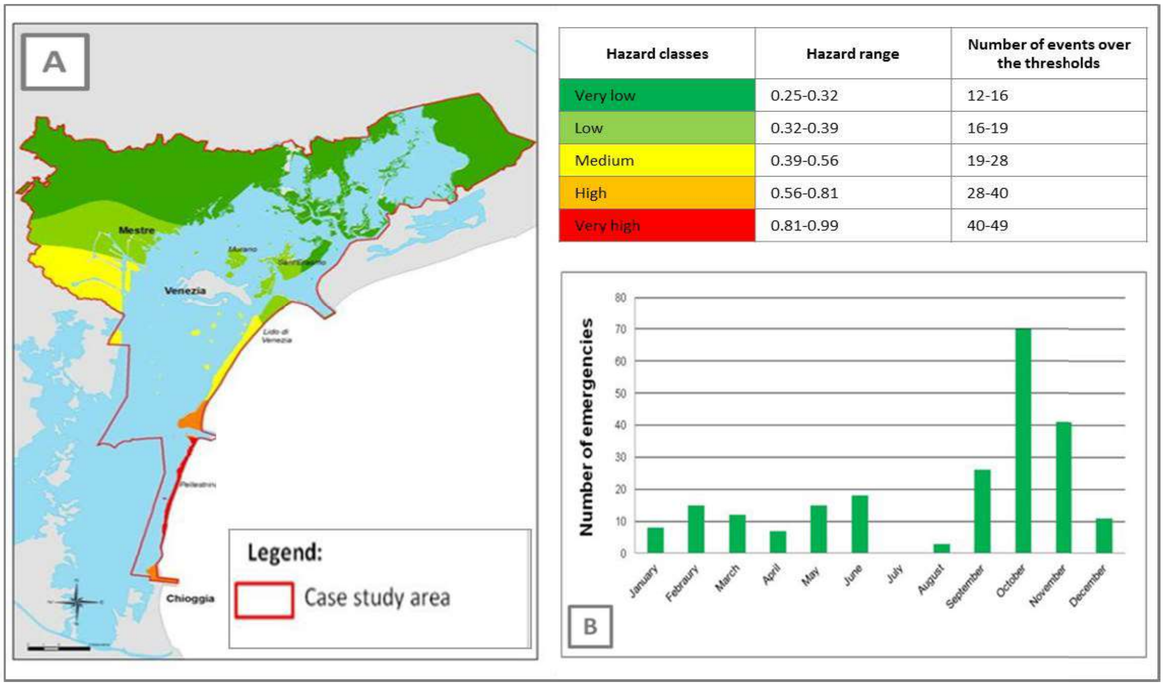


Figure 3 The Regional Risk Assessment conceptual framework.



Hazard classes	Hazard range	Number of events over the thresholds
Very low	0.25-0.32	12-16
Low	0.32-0.39	16-19
Medium	0.39-0.56	19-28
High	0.56-0.81	28-40
Very high	0.81-0.99	40-49

Figure 4 Hazard map for pluvial flood impact (A) and total number of potential ordinary emergency in the municipality of Venice for each month of the 2041-2050 decade (B).

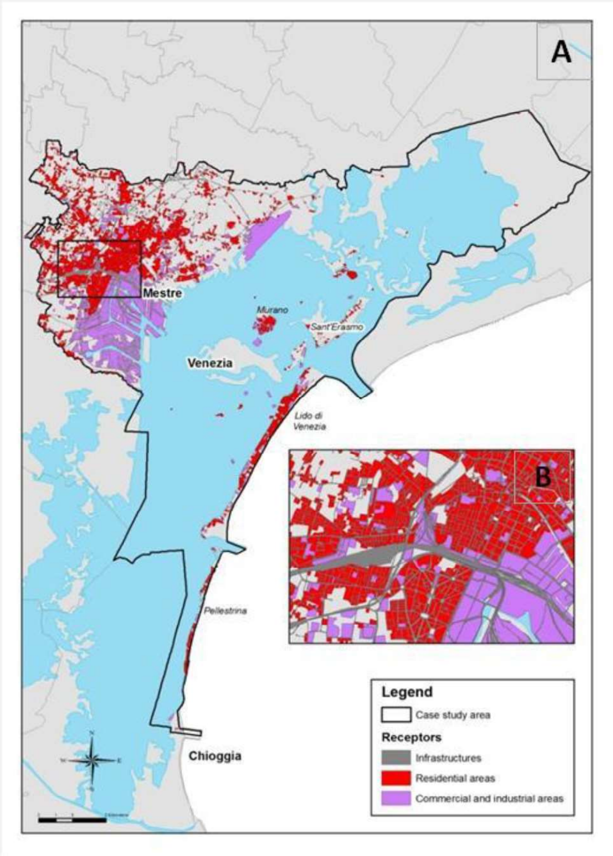
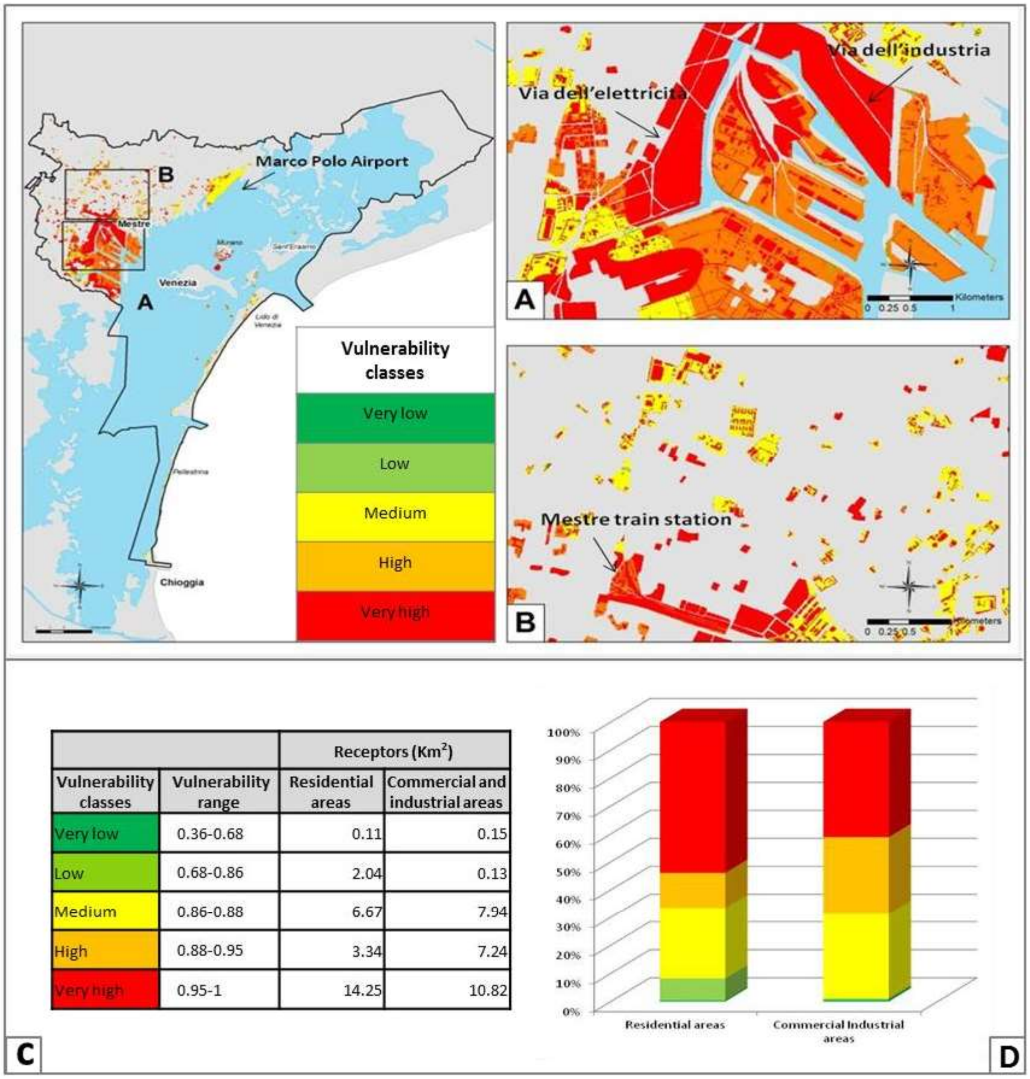
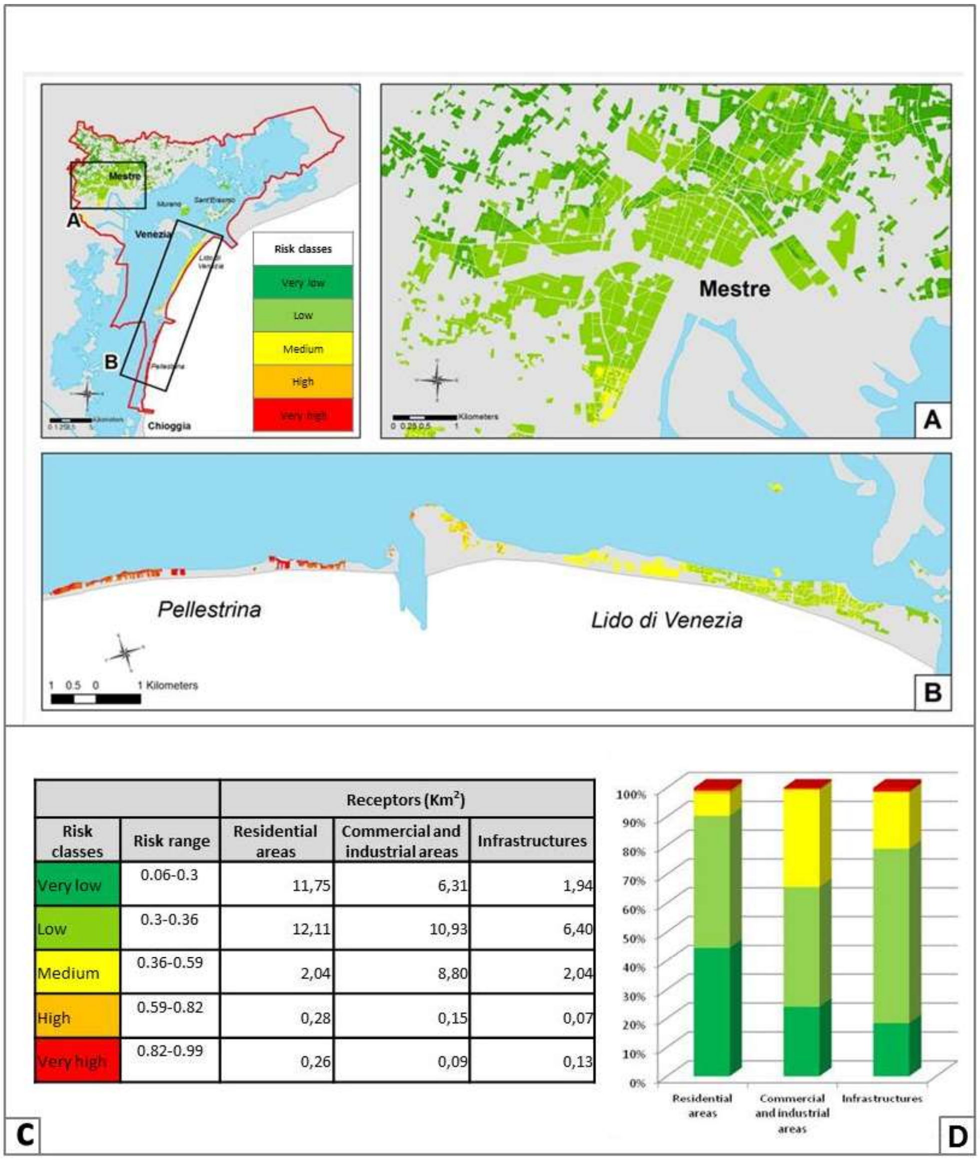


Figure 5 Exposure map for infrastructures, residential and commercial-industrial areas for the case study area (A) and for the area around Mestre (B).



		Receptors (Km^2)	
Vulnerability classes	Vulnerability range	Residential areas	Commercial and industrial areas
Very low	0.36-0.68	0.11	0.15
Low	0.68-0.86	2.04	0.13
Medium	0.86-0.88	6.67	7.94
High	0.88-0.95	3.34	7.24
Very high	0.95-1	14.25	10.82

Figure 6 Vulnerability map of commercial and industrial areas (A,B) and distribution of vulnerability classes considering the territorial surface (km2) (C) and percentage of surface (D) of each receptors in the municipality of Venice.



		Receptors (Km^2)		
Risk classes	Risk range	Residential areas	Commercial and industrial areas	Infrastructures
Very low	0.06-0.3	11,75	6,31	1,94
Low	0.3-0.36	12,11	10,93	6,40
Medium	0.36-0.59	2,04	8,80	2,04
High	0.59-0.82	0,28	0,15	0,07
Very high	0.82-0.99	0,26	0,09	0,13

Figure 7 Risk map for residential areas (A,B) and distribution of risk classes considering the territorial surface (km2) (C) and the percentage of surface (D) of each receptors in the municipality of Venice.