# The Value of Citizen Science for Flood Risk Reduction: Cost-benefit Analysis of a Citizen Observatory in the Brenta-Bacchiglione Catchment

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**Abstract.** ~~Citizen observatories are a relatively recent form of citizen science, which involve citizens in making environmental observations over a period of time. These observations can help to inform the decision making of local authorities and other stakeholders, creating a platform for two-way interaction between citizens and public agencies. Although citizen observatories can clearly generate many different benefits, they also have an associated cost. There are currently no examples of quantifying the costs and benefits of citizen observatories in the literature, yet this type of analysis is critical if there is to be real uptake of citizen observatories by public agencies more generally. This paper presents and applies a generic methodology for capturing the value of a citizen observatory for flood risk reduction in the Brenta-Bacchiglione catchment using a cost-benefit analysis. The results show that the benefits of implementing a citizen observatory approach outweigh the costs by approximately 2 to 1 and can reduce the annual expected damage to a greater degree than a much more costly structural approach~~Citizen observatories are a relatively recent form of citizen science. As part of the flood risk management strategy of the Brenta-Bacchiglione catchment, a citizen observatory for flood risk management has been proposed and is currently being implemented. Citizens are involved through monitoring water levels and obstructions and providing other relevant information through mobile apps, where the data are assimilated with other sensor data in a hydrological-hydraulic model used in early warning. A cost benefit analysis of the citizen observatory was undertaken to demonstrate the value of this approach in monetary terms. Although not yet fully operational, the citizen observatory is assumed to decrease the social vulnerability of the flood risk. By calculating the hazard, exposure and vulnerability of three flood scenarios (required for flood risk management planning by the EU Directive on Flood Risk Management) with and without the proposed citizen observatory, it is possible to evaluate the benefits in terms of the average annual avoided damage costs. Although currently a hypothetical exercise, the results showed a reduction in avoided damage of 45% compared to a business as usual scenario. Thus, linking citizen science with hydrological modelling, and to raise awareness of flood hazards, has great potential in reducing flood risk in the Brenta-Bacchiglione catchment in the future. Moreover, such approaches are easily transferable to other catchments.

## 1 Introduction

In 2018, flooding affected the highest number of people of any natural disaster globally and caused major damage worldwide (CRED, 2019). With climate change, the frequency and magnitude of extreme events will increase, leading to a higher risk of flooding (Schiermeier, 2011). This risk will be further exacerbated by future economic and population growth (Tanoue et al., 2016). Thus, managing flood risk is critical for reducing future negative impacts. Flood risk assessments are undertaken by the insurance industry for determining properties at high risk (Hsu et al., 2011), but they are also a national requirement in the European Union as set out in the EU Flood Risk Management Directive, which requires that flood risk management plans are produced for each river basin (EU, 2007; Müller, 2013). The assessment of flood risk involves quantifying three main drivers (National Research Council, 2015): (a) flood hazard, which is the probability that a flood of a certain magnitude will occur in a certain period of time in a given area; (b) exposure, which is the economic value of the human lives and assets affected by the flood hazard; and (c) vulnerability, which is the degree to which different elements (i.e., people, buildings, infrastructure, economic activities, etc.) will suffer damage associated with the flood hazard. In addition, flood risk can be mitigated through hard engineering strategies such as implementation of structural flood protection schemes, soft engineering approaches comprising more natural methods of flood management (Levy and Hall, 2005), and community-based flood risk management (Smith et al., 2017). As part of requirements in the EU Flood Risk Management Directive, any mitigation actions must be accompanied by a cost-benefit analysis.

Flood hazard is generally determined through hydrological and hydraulic modelling. Hence accurate predictions are critical for effective flood risk management, particularly in densely populated urban areas (Mazzoleni et al., 2017). The input data required for modelling are often incomplete in terms of resolution and density (Lanfranchi et al., 2014), which translates into variable accuracy in flood predictions (Werner et al., 2005). New sources of data are becoming available to support flood risk management. For example, the rise of citizen science and crowdsourcing (Howe, 2006; Sheldon and Ashcroft, 2016), accelerated by the rapid diffusion of information and communication technologies, is providing additional, complementary sources of data for hydrological monitoring (Njue et al., 2019). Citizen science refers to the involvement of the public in any step of the scientific method (Shirk et al., 2012). However, one of the most common forms of participation is in data collection (Njue et al., 2019). Citizen observatories (CO) are a particular form of citizen science in so far as they constitute the means not just for new knowledge creation but also for its application, which is why they are typically set up with linkages to specific policy domains (Wehn et al., 2019). COs must therefore include a public authority (e.g., a local, regional or national body) to enable two-way communication between citizens and the authorities to create a new source of high quality, authoritative data for decision making and for the benefit of society. Moreover, COs involve citizens in environmental observations over an extended period of time of typically months and years (rather than one-off exercises such as data collection 'Blitzes'), and hence contribute to improved temporal resolution of the data, using dedicated apps, easy-to-use physical sensors and other monitoring technologies linked to a dedicated platform (Liu et al., 2014; Mazumdar et al., 2016). COs are increasingly being used in hydrology/water sciences and management and in various stages of the flood risk management cycle, as reviewed and reported by Assumpção (2018), Etter et al. (2018), Mazzoleni et al. (2017), Buytaert et al. (2014), Wehn and Evers (2015) and Wehn et al. (2015). These studies found that the characteristic links of COs to authorities and policy do not automatically translate into higher levels of participation in flood risk management, nor that communication between stakeholders improves; rather, changes towards fundamentally more involved citizen roles with higher impact in flood risk management take years to evolve (Wehn et al., 2015).

The promising potential of the contribution of COs to improved flood risk management is paralleled by limited evidence of their actual impacts and added value. Efforts are ongoing such as the consolidation of evaluation methods and empirical evidence by the H2020 project WeObserve[1] Community of Practice on the value and impact of citizen science and COs, and the development and application of methods for measuring the impacts of citizen science by the H2020 project MICS[2]. To date, the societal and science-related impacts have received most attention, while the focus on economic impacts, costs and benefits has been both more limited and more recent (Wehn et al., 2020a). The studies that do focus on economic impacts related to citizen science (rather than citizen observatories) propose to consider the time invested by researchers in engaging and training citizens (Thornhill et al., 2016); to relate cost and participant performance for hydrometric observations in order to estimate the cost per observation (Davids et al., 2019); to estimate the costs as data-related costs, staff costs and other costs; and the benefits in terms of scientific benefits, public engagement benefits and the benefits of strengthened capacity of participants (Blaney et al., 2016); and to compare citizen science data and in-situ data (Goldstein et al., 2014; Hadj-Hammou et al., 2017). Wehn et al. (2020b) assessed the value of COs from a data perspective and a cost perspective, respectively, to

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[1] https://www.weobserve.eu/

[2] https://mics.tools/

qualify the degree of complementarity that the data collected by citizens offers to in-situ networks and to quantify the relation between the investments required to set up a CO and the actual amount of data collected. Based on a comparison of four COs, they suggest that setting up a CO for the sole purpose of data collection appears to be an expensive undertaking (for the public sector organization(s) benefitting from the respective CO) since, depending on the process of (co)designing the CO, it may not necessarily complement the existing in-situ monitoring network (with the likely exception of infrastructure-weak areas in developing countries).

Overall, there is a lack of available, appropriate and peer-reviewed evaluation methods and of evidence of the added value of COs, which is holding back the uptake and adoption of COs by policy makers and practitioners. In this paper, we take a different approach to previous studies by using a more conventional cost-benefit analysis framework to assess the implementation of a citizen observatory on flood risk management in the Brenta-Bacchiglione catchment in northern Italy. The purpose of a cost-benefit analysis is to compare the effectiveness of different alternative actions, where these actions can be public policies, projects or regulations that can be used to solve a specific problem. We treat the citizen observatory in the same way as any other flood mitigation action for which a cost-benefit analysis would be undertaken in this catchment. Although the citizen observatory is still being implemented, the assumptions for the cost-benefit analysis are based on primary empirical evidence from a CO pilot that was undertaken by the WeSenseIt project in the town of Vicenza, Italy, described in more detail in section 2.1 and now extended to the wider catchment (sections 2.2 and 2.3). In section 3 we present the flood risk and cost benefit methodology followed by the results in section 4. Conclusions, limitations of the methodology and case-specific insights are provided in section 5.

## 2 The Development of a Citizen Observatory for Flood Risk Management

### 2.1 The WeSenseIt Project

Through the WeSenseIt research project (www.wesenseit.eu), funded under the 7th framework program (FP7-ENV-2012 n° 308429), a CO for flood risk was developed with the Upper Adriatic Basin Authority in northern Italy. The objective of this CO was to collect citizen observations from the field, and to obtain a broader and more rapid picture of developments before and during a flood event. The CO involved many stakeholders concerned with the management and use of the water resources, and with water-related hazards in the Bacchiglione River basin. The main actors included the local municipalities, the regional and local civil protection agencies, environment agencies and the irrigation authorities. The Alto Adriatico Water Authority (AAWA) facilitated access to a highly trained group of citizen observers, namely civil protection volunteers, who undertook the observations (i.e., using staff gauges with a QR code to measure the water level and reporting water way obstructions) as part of their volunteer activities. Additional volunteers were also recruited during the project from the Italian Red Cross, the National Alpine Trooper Association, the Italian Army Police and other civil protection groups, with more than 200 volunteers taking part in the CO pilot. Training courses for the volunteers were organized to disseminate and explain the use of a smartphone application and an e-collaboration platform, which were developed as part of the WeSenseIt project. In addition to the low cost sensing equipment, the CO also used data from physical sensors: 3 sonar sensors (river water level), 4 weather stations (wind velocity and direction, precipitation, air temperature and humidity) and 5 soil moisture sensors. The combined visualization of the sensors (including existing sensors from the Venice Environment Agency) was available in the online e-collaboration platform. During the WeSenseIt project, research into the value of crowdsourced data for hydrological modelling was investigated (Mazzoleni et al., 2017, 2018) and found to complement traditional sensor networks.

This pilot was later adopted by the European Community as a "good practice" example of the application of Directive 2007/60/EC. After the positive experience in WeSenseIt, funds were made available to develop a CO for flood risk management at the district scale, covering the larger Brenta-Bacchiglione catchment. At this stage, a cost-benefit analysis was undertaken, which is reported in this paper. The next section provides details of the Brenta-Bacchiglione catchment followed by ongoing developments in the CO for flood risk management.

### 2.2 The Brenta-Bacchiglione Catchment

The Brenta-Bacchiglione River catchment includes the Retrone and Astichiello Rivers, and falls within the Veneto Region in Northern Italy, which includes the cities of Padua and Vicenza (Figure 1). The catchment is surrounded by the Beric hills in the south and the Prealpi in the northwest. In this mountainous area, rapid or flash floods occur regularly and are difficult to predict. ~~For the past three years, extreme weather events (including flooding) are the top risk in terms of likelihood and among the top three risks in terms of impact, where this combination makes it the top risk in 2019 (WEF, 2017, 2018, 2019). Between 1995-2015, flooding alone accounted for 47% of all weather-related disasters, affecting 2.3 billion people globally (CRED and UNISDR, 2015). Continuing an upward trend, financial losses in 2017 due to global weather-related disasters exceeded US$300 billion (Swiss Re, 2017). Hurricane Harvey, in particular, caused US$125 billion damage in 2017, led to the death of 88 people, destroyed more than 12,700 homes and resulted in a rise in gas prices due to the impacts on oil production (Amadeo, 2019). However, economic losses can go well beyond damage to infrastructure and assets, e.g., disruption to businesses and supply chains can equal or exceed the costs of infrastructure damage (Hallegatte, 2008; Jongman, 2018). Moreover, developing countries and small island states affected by tropical storms are likely to suffer greater losses. In 2017, Hurricane Maria caused an estimated total damage and loss of US$1.3 billion to Dominica while US$5.4 billion in damage and loss was estimated for other islands due to the combined effects of Hurricanes Maria and Irma (Asariotis, 2018).~~

~~Accurate predictions are crucial for flood risk management (FRM), e.g., to control river structures and water levels, in order to reduce risks and damages from flooding, particularly in densely populated urban areas (Mazzoleni et al., 2017b). However, weather patterns are local in nature, not easily captured or predicted by existing in-situ and remote sensing-based modelling approaches, and are likely to be intensified by climate change (Pachauri et al., 2014; Tol, 2014). The data acquired using these methods are often incomplete in terms of resolution and density (Lanfranchi et al., 2014). This translates into variable accuracy in flood predictions (Werner et al., 2005).~~

~~**The recent exponential growth in citizen science and crowdsourcing approaches, accelerated by the rapid diffusion of information and communication technologies, is providing additional, complementary sources of data for hydrological and hydraulic models. Citizen science refers to the involvement of the public in any step of the scientific method (Shirk et al., 2012). Among the various forms of citizen science (Cooper et al., 2007; Bonney et al., 2009; Shirk et al., 2012), contributory forms are of particular interest here, focusing on the observations that citizens can contribute (as opposed to their collaboration in the entire research process or the co-design of the research). Citizen observatories (CO) are a particular form of citizen science in so far as they involve citizens in environmental observations over an extended period of time (rather than one-off exercises such as data collection ‘Blitzes’), and hence contribute to improved temporal resolution of the data, using dedicated apps, easy-to-use physical sensors and other monitoring technologies linked to a dedicated platform (Liu et al., 2014; Mazumdar et al., 2016). COs must also**~~Rapid floods generally affect the towns of Torri di Quartesolo, Longare and Montegaldella, although there is also widespread flooding in the cities of Vicenza and Padua, which includes industrial areas and areas of cultural heritage. For example, in 2010, a major flood affected 130 communities and 20,000 individuals in the Veneto region. The city of Vicenza was one of the most affected municipalities, with 20% of the metropolitan area flooded.

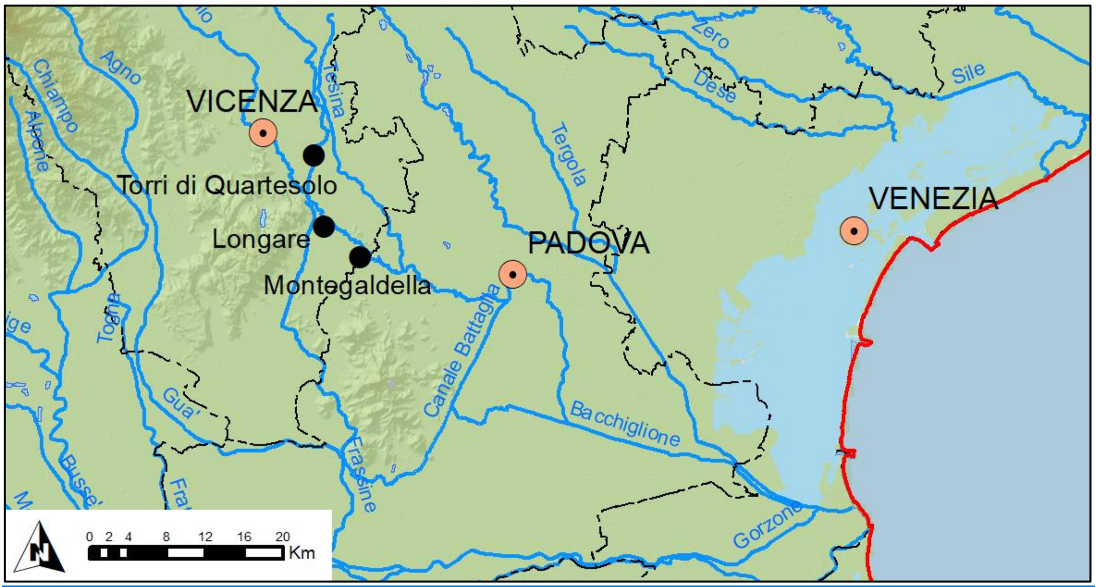

Figure 1: Location of the Brenta-Bacchiglione catchment and its urban communities.

### 2.3 The Citizen Observatory for Flood Risk Management for the Brenta-Bacchiglione Catchment

The CO for flood risk management, which is currently being implemented, was included in the prevention measures of the Flood Risk Management Plan (PGRA) for the Brenta-Bacchiglione catchment. The purpose of the CO is to strengthen communication channels before and during flood events in accordance with the EU Flood Directive on Flood Risk Management, to increase the resilience of the local communities and to address residual risk. Building on the WeSenseIt experience, an IT platform to aid decision support during the emergency phases of a flood event is being implemented. This platform will integrate information from the hydrological model, which is equipped with a data assimilation module that integrates the crowdsourced data collected by citizens and trained experts with official sensor data. A mobile app for data collection based on the WeSenseIt project is under development. The platform and mobile technology will guarantee user traceability and facilitate two-way communication between the authorities, the citizens and the operators in the field, thereby significantly increasing the effectiveness of civil protection operations during all phases of an emergency. The fully operational CO will include 64 additional staff gauges equipped with a QR code (58 to measure water level and 6 for snow height), 12 sonar sensors and 8 weather stations.

To engage and maintain the involvement of “expert” CO participants (i.e., civil protection volunteers, technicians belonging to professional associations, members of environmental associations), a set of training courses will be run. The involvement of technicians (formalized in November 2018 with an agreement between the respective associations and AAWA) offers an important opportunity to use the specific knowledge and expertise of these technicians to better understand the dynamics of flood events and to acquire high quality data to feed the models and databases. When an extreme event (i.e., heavy rain) is forecast, AAWA will call upon any available technicians in providing data (with a reimbursement of 75 €/day (including insurance costs) and a minimum activity per day of 3 hours). There are currently 41 technicians involved in the CO, which includes civil/hydraulic/geotechnical engineers, agronomists and forestry graduates. Participants must attend two training sessions followed by a final examination. To give an example of the valuable information that the expert CO participants can provide, AAWA called upon technicians during two heavy rainfall events (November 2019; 5 days). These technicians collected relevant data on the status of the rivers including the vegetation, the water levels, the status of bridges and levees, collecting 1660 images and completing 700 status reports.

To engage citizens, a different approach is being taken. Within the 120 municipalities currently in high flood risk zones, engagement of schools is currently ongoing, including the development of educational programs for teachers. The aim is to raise student awareness of existing flood risks in their own area, and to help students recognize the value of the CO (and the mobile technology) in protecting their families, e.g., using the app to send important information about flooding, which then contributes to everyone's safety. This component of the CO involves 348 primary schools and 340 middle and secondary schools. The three universities in the area will also be involved through conferences and webinars. Communication through the CO website, via social media campaigns, radio broadcasts and regional newspapers will be used to engage and maintain citizen involvement in the CO. This communication plan, which will continue over the next five years, has the ambitious goal of involving 75,000 people in the CO to download the app and contribute observations.

## 3 Methodology

The methodology consists of three steps: (i) mapping of the flood risk (section 3.1); (ii) quantification of the flood risk reduction (section 3.2); and (iii) calculation of the damage from flooding under three flood scenarios (section 3.3), all of which consider the flood risk with and without the implementation of the CO on flood risk management.

### 3.1 Flood risk mapping

Figure 2 provides an overview of the flood risk methodology employed in the paper, which uses input data outlined in section 3.1.1. As mentioned in the introduction, risk is evaluated from three different components. The first is the flood hazard, which~~ include a public authority (e.g., a local, regional or national body) to enable two-way communication between citizens and the authorities to create a new source of high quality, authoritative data for decision making and for the benefit of society. This approach is increasingly being used in hydrology/water sciences and management and in various stages of the FRM cycle, as reviewed and reported by e.g., Assumpção (2018), Etter et al. (2018), Mazzoleni et al. (2017a), Buytaert et al. (2014), Wehn and Evers (2015) and Wehn et al. (2015).~~

~~The promising potential of the contribution of COs to improved FRM is paralleled by limited evidence of their actual impacts and added value. Efforts are ongoing such as the consolidation of evaluation methods and empirical evidence by the H2020 project WeObserve[3] Community of Practice on the value and impact of citizen science and COs and the development, and the application of methods for measuring the impacts of citizen science by the H2020 project MICS[4]. However, the lack of available, appropriate and peer-reviewed evaluation methods and of evidence of the added value of COs is holding back the uptake and adoption of COs by policy makers and practitioners. The aim of this paper is to fill this gap by presenting and applying a generic methodology for capturing the value of COs by means of a tailored, detailed cost-benefit analysis (CBA), the COCBA. The proposed methodology is applied using primary empirical evidence from a CO pilot that was undertaken by the WeSenseIt project in the town of Vicenza, Italy, and now extended to the wider catchment.~~

~~The paper is structured as follows. Section 2 presents the conceptual details of the COCBA as well as information about the Brenta-Bacchiglione catchment and the WeSenseIt CO pilot while section 3 presents the results from the analysis. Conclusions and limitations of the methodology as well as case-specific insights are provided in section 4.~~

## ~~2 Methodology~~

~~Starting with a description of the input data used (section 2.1), the proposed methodology is presented in terms of the calculation of risk (section 2.2) and the steps involved in evaluating the costs and benefits of COs for FRM (section 2.3). This is followed by the justification of the selected case study to which this methodology has been applied, i.e., the WeSenseIt CO in the Brenta-Bacchiglione catchment, together with information about the case study (section 2.4).~~

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~~[3] https://www.weobserve.eu/~~
~~[4] https://mics.tools/~~

## ~~2.1 Input data~~

~~There are four main data sets used in the COCBA methodology. The first is Corine Land Cover 2006[5] produced by the European Environment Agency (Steemans, 2008). The second is the population of the catchment, which was obtained from ISTAT 2001[6]. The third data set is the pollutants affecting the basin[7] while the protected areas and cultural heritage is the final data set, obtained from the Italian Ministry of Property and Cultural Activities[8].~~

## ~~2.2 Calculation of risk~~

~~In this context, risk is the probability that a damaging event will occur from a natural phenomenon or due to human activities that can cause harmful effects to the surrounding population, assets and/or infrastructure, within a particular area and over a given period of time. Specifically, *Risk*~~ is calculated ~~as the combination of three components (Cutter, 1996):~~

~~$Risk = Hazard * Vulnerability * Exposure$ (1)~~

~~where *Hazard* is the probability that a phenomenon of a certain intensity will occur in a certain period of time in a given area; *Vulnerability* is the degree to which different elements (i.e., people, buildings, infrastructure, economic activities, etc.) will suffer damage as a consequence of the stresses induced by an event of a certain intensity; and *Exposure* is the number of units (or the "value") of each of these elements at risk present in a given area, such as human lives or assets. The potential damage can then be~~ using a hydrological-hydraulic model to generate flood hazard maps and is described in section 3.1.2. The second is exposure, outlined in section 3.1.3, which is calculated ~~as the combination of the value of the exposed elements with the value of these elements with respect to an event of given intensity. If the impact of floods is assessed at a mesoscale, risk can be quantified in relative terms, i.e., a value between 0 and 1, where 0 represents the absence of risk and 1 is the maximum risk. Figure 1 depicts the different steps in calculating risk for the purpose of undertaking an integrated flood risk assessment. Each of the components of risk are described in more detail in the sections that follow.~~

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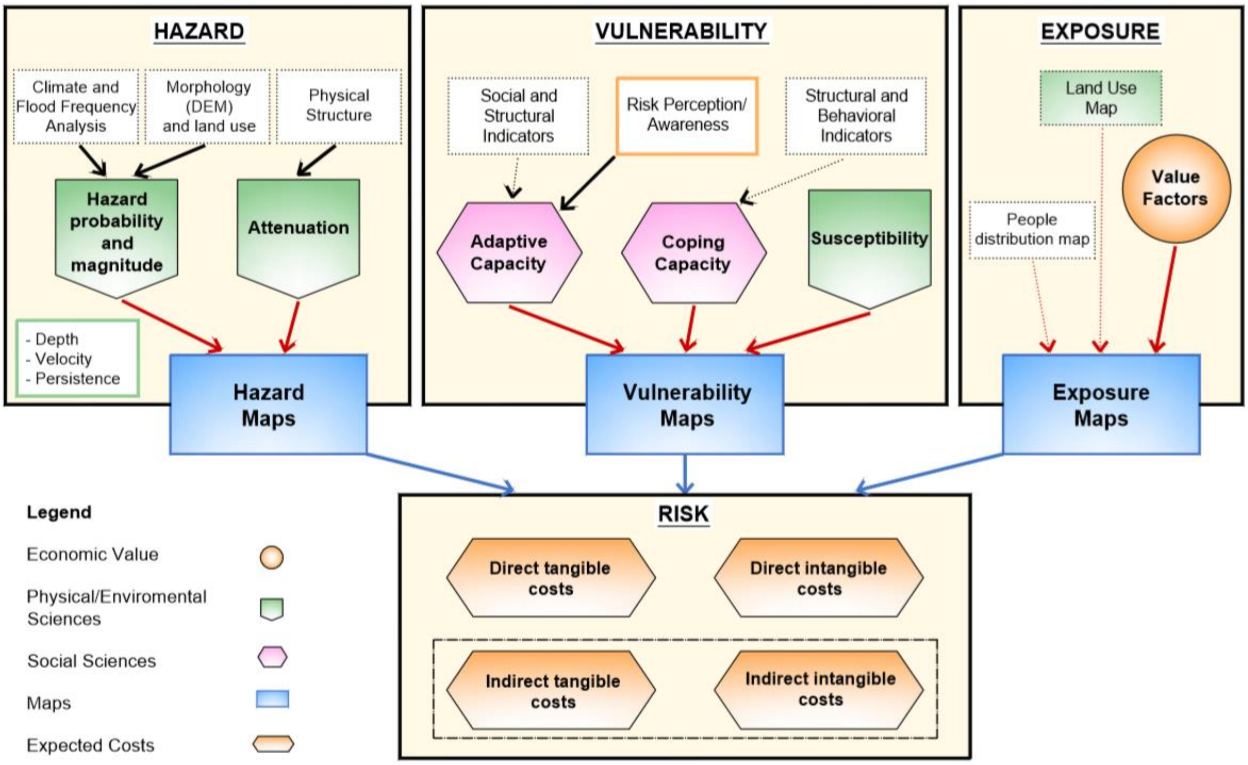
[5] ~~http://www.centrointerregionale-gis.it/script/corinedownload.asp~~

[6] ~~http://www.istat.it/it/archivio/44523~~

[7] ~~https://prtr.eea.europa.eu/#/home~~

[8] ~~http://vincoliinrete.beniculturali.it~~



~~**Figure 1: Flowchart outlining the determination of risk in a flood risk assessment context.**~~

~~The exposed elements must be expressed in terms of the following~~for three macro-categories~~, which are~~ as set out in the EU 2007/60/CE Flood Directive (EU, 2007)~~; these include:~~: the population affected (art.6-5.a); the types of economic activities affected (art.6-5.b); and the environmental and cultural-archaeological assets affected (art.6.5.c).~~ These three macro-categories can be characterized by the land use classes shown in Table 1, which are taken from the Corine Land Cover map 2006. The next three sections describe how the individual components of risk (Figure 1) are calculated in the context of this case study.~~

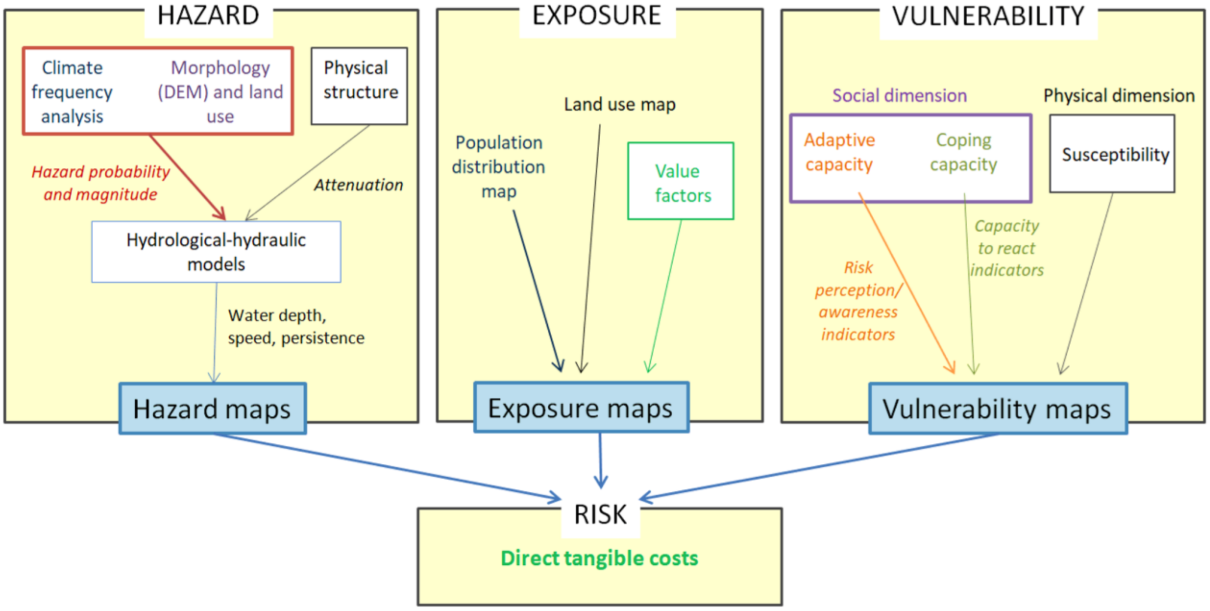


**Figure 2: Flowchart outlining the determination of risk in a flood risk assessment context.**

The final component is vulnerability, which has a physical and social dimension. Physical vulnerability is defined as the susceptibility of an exposed element such as people or buildings to flooding (Balbi et al., 2012) and is calculated using the same three macro-categories as that of exposure, i.e., the population affected, the economic activities affected, and the environmental and cultural-archaeological assets affected. Within the people affected category, we also consider social vulnerability. This refers to the perception or awareness that an adverse event may occur. Some studies have found that if citizens have directly experienced a flood, their perception of flood risk is higher (e.g., Thistlethwaite et al., 2018) although the factors that determine flood risk perception are varied. Moreover, the results from different studies can be ambiguous and/or contradictory (Lechowska, 2018). Social vulnerability can be divided into: (i) adaptive capacity, which is the capacity of an individual, community, society or organization to prepare for and respond to the consequences of a flood event (IPCC, 2012; Torresan et al., 2012); and (ii) coping capacity, which is the ability of an individual, community, society or organization to cope with adverse conditions resulting from a flood event using existing resources (IPCC, 2012; Torresan et al., 2012). The calculation of vulnerability is described in section 3.1.4. Risk is then calculated as the product of hazard, exposure and vulnerability as described in more detail in section 3.1.5, from which the direct tangible costs associated with the flood risk can be calculated (outlined in section 3.2).

### 3.1.1 Input data

There are several data sets used as inputs to the assessment of flood risk as outlined in Table 1. For the evaluation of flood hazard, the water height, flow velocity and flooded areas are provided by AAWA using the methodology described in the Supplementary Materials. Several data sets are used to evaluate flood exposure and vulnerability, but a key data set is Corine Land Cover (CLC) 2006 produced by the European Environment Agency (Steemans, 2008). Other data sets used to determine exposure include layers on population, infrastructure and buildings, areas of cultural heritage, protected areas and sources of pollution, where these data sets were obtained from different Italian ministries to complement the CLC. Data from OpenStreetMap on infrastructure and buildings were also used.

**Table ~~2.2.1 Hazard~~**

**1: Input data used to calculate risk.**

| **Component of risk** | **Data** | **Source** |
|---|---|---|
| Flood Hazard<br>(low, medium, high hazard scenarios) | Water height (m) | AAWA; see Supplementary Materials for model details |
| | Water speed (m/s) | |
| | Flooded area (km$^2$) | |
| Flood Exposure | Population in residential areas | ISTAT, census data, 2001 |
| | Infrastructure and buildings | Corine Land Cover 2006, OpenStreetMap |
| | Types of agriculture | Corine Land Cover 2006 |
| | Natural and semi-natural systems | Corine Land Cover 2006 |
| | Areas of cultural heritage | Corine Land Cover 2006, MiBACT-Italian Ministry for cultural heritage |
| | Protected areas | Corine Land Cover 2006, MATTM-Italian Ministry for Environment, Veneto Region |
| | Point and widespread sources of pollution (Directives 82/501/EC, 2008/1/EC) | ISTAT, https://prtr.eea.europa.eu |
| Flood Vulnerability (Susceptibility) | Vegetation cover | Corine Land Cover 2006 |
| | Soil type | Corine Land Cover 2006 |

### 3.1.2 Flood Hazard Mapping

According to Article 6 of the 2007/60/CE Flood Directive (EU, 2007), when local authorities implement a Flood Risk Management Plan, three hazard scenarios must be ~~addressed, which can be calculated using a hydrological and hydraulic model~~considered:

1. A flood with a low probability, which is 300-year return period in ~~this~~the study area;
2. A flood with a medium probability, which is a 100-year return period in the study area; and
3. A flood with a high probability, which is a 30-year return period in the study area.

These have been calculated using a two-dimensional hydrological and hydraulic model to generate the water levels and the water speeds at a spatial resolution of 10 m (Ferri et al., 2010). Details of the model can be found in the Supplementary Materials. The hazard associated with these scenarios was calculated in relative terms as a value between 0 and 1.

### 3.1.3 Flood Exposure Mapping

The 2006 CLC map provides the underlying spatial information to calculate exposure; the land use classes used here are shown

~~**Table 1: List of the land use classes used to characterize the three macro-categories from the EU 2007/60/CE Flood Directive.**~~

| ~~**ID**~~ | ~~**Description**~~ |
|---|---|
| ~~1~~ | ~~Residential~~ |
| ~~2~~ | ~~Hospital facilities, health care, social assistance~~ |
| ~~3~~ | ~~Buildings for public services~~ |
| ~~4~~ | ~~Commercial and artisan~~ |
| ~~5~~ | ~~Industrial~~ |
| ~~6~~ | ~~Specialized agricultural~~ |
| ~~7~~ | ~~Woods, meadows, pastures, cemeteries, urban parks, hobby agriculture~~ |
| ~~8~~ | ~~Tourist-Recreation~~ |
| ~~9~~ | ~~Unproductive~~ |
| ~~10~~ | ~~Ski areas, Golf course, Horse riding~~ |
| ~~11~~ | ~~Campsites~~ |
| ~~12~~ | ~~Communication and transportation networks: roads of primary importance~~ |
| ~~13~~ | ~~Communication and transportation networks: roads of secondary importance~~ |
| ~~14~~ | ~~Railway area~~ |
| ~~15~~ | ~~Area for tourist facilities, Zone for collective equipment (supra-municipal, subsoil)~~ |
| ~~16~~ | ~~Technological and service networks~~ |
| ~~17~~ | ~~Facilities supporting communication/transportation networks (airports, ports, service areas, parking lots)~~ |
| ~~18~~ | ~~Area for energy production~~ |
| ~~19~~ | ~~Landfills, Waste treatment plants, Mining areas, Purifiers~~ |
| ~~20~~ | ~~Areas on which plants are installed as per Annex I of Legislative Decree 18 February 2005, n. 59~~ |
| ~~21~~ | ~~Areas of historical, cultural and archaeological importance; cultural heritage~~ |
| ~~22~~ | ~~Environmental goods~~ |
| ~~23~~ | ~~Military zone~~ |

~~The hazard associated with these scenarios was calculated in relative terms as a value between 0 and 1. A two-dimensional hydraulic model was used to generate the water levels and the water speeds at a resolution of 10 m (Ferri et al., 2010) for these hazard scenarios. These model outputs were also used to calculate the vulnerability in this area (see section 2.2.3).~~

### ~~2.2.2 Exposure~~

~~Exposure is calculated for each of the macro-categories~~ in Table S1 in the Supplementary Materials. As mentioned above, the ~~EU Flood Directive, i.e., based on~~ first macro-category is the people~~, economic activities and environmental/cultural-archaeological assets~~ affected~~, as described in more detail below.~~

#### ~~(i) People affected~~

~~The~~ by the flooding, or the exposure of the population ~~is a function of two factors. The first is the number of people living in an area expressed by a four-class density factor ($F_d$) as outlined in Table 2. The second is the duration factor ($F_t$~~($E_P$), which is calculated as follows:

$$E_p = F_d * F_t \tag{2}$$

where $F_d$ is a factor characterizing the density of the population in relation to the number of people present (Table 2), which uses gridded population from the census (Table 1), and $F_t$, which is the proportion of time spent in ~~certain~~different locations (e.g., houses, schools, etc~~. – see~~., using the land use types listed in Table ~~1~~S1) over a 24 hour ~~day~~period (Provincia Autonoma di Trento, 2006). ~~The exposure of the population ($E_P$) is then calculated as:~~The four classes in Table 2 reflect a very slight decrease in exposure as population density decreases, and were defined by stakeholders in the AAWA based on guidance from ISPRA (2012).

~~$E_p = F_d * F_t$ (2)~~

**Table ~~2:~~2: A factor characterizing the density of people ($F_d$) in relation to the number of people present.**

| **Number of people** | $F_d$ |
|---|---|
| 1 ~~÷~~– 50 | 0.90 |
| 51 ~~÷~~– 100 | 0.95 |
| 101 ~~÷~~– 500 | 0.98 |
| > 500 | 1 |

### ~~(ii) Economic activities affected~~

~~The spatial distribution and types of economic activities in flood risk areas must be determined in order to assess the potential negative impacts from flooding.~~ The exposure or impact on economic activities ($E_E$~~)~~), which is the second macro-category, is calculated from the restoration costs, and the costs resulting from losses in production and services. ~~These are calculated for each of the land use categories provided in Table 1.~~

### ~~(iii) Environmental and cultural heritage assets affected~~

~~The~~The final macro-category, i.e., the exposure of assets in the environmental and cultural heritage category ($E_{ECH}$) is calculated ~~by land use type (Table 1), by considering the degree~~from estimates of potential damage caused by an adverse flood event ~~(Provincia Autonoma di Trento, 2006). The relative values of exposure for each of the three macro-categories ($E_P$, $E_E$ and $E_{ECH}$) are provided in Table 3, listed by land use type~~. These various costs were obtained from the Provincia Autonoma di Treno (2006) and have been calculated for each of the land use classes in Table S1.

### ~~2.2.3 Vulnerability~~

~~Vulnerability results from the interaction between physical-environmental and social components. To define vulnerability from a physical point of view, we use the concept of the susceptibility of an exposed element such as people or buildings, as outlined above (Balbi et al., 2012). Susceptibility is related to the context in which the event occurs and refers to a quantitative (or qualitative) assessment of the event type, the causal factors and the characteristics of the event. Social vulnerability refers to the perception or awareness that an adverse event may occur. Greater awareness tends to correspond to greater preparation if an event takes place. Social vulnerability can be divided into:~~

- ~~Adaptive Capacity: the combination of strengths, attributes and resources available to an individual, community, society or organization (ex-ante hazard) that can be used to prepare and/or implement actions aimed at reducing impacts or exploiting beneficial opportunities (IPCC, 2012; Torresan et al., 2012).~~

~~**Table 3:**~~

The relative values of exposure by land use type for each of the three macro-categories ($E_P$, $E_E$ and $E_{ECH}$) are provided in Table 3. These values have been derived by the Provincia Autonoma di Treno (2006) from decades of experience with understanding exposure related to flood risk. Moreover, they have been tested over time and shown to be valid within AAWA.

Table 3: **The relative values of exposure for people, economic activities, and environmental/cultural assets by land use type.**

| ID | Description | $E_P$ | $E_E$ | $E_{ECH}$ |
|---|---|---|---|---|
| 1 | Residential | 1 | 1 | 1 |
| 2 | Hospital facilities, health care, social assistance | 1 | 1 | 1 |
| 3 | Buildings for public services | 1 | 1 | 1 |
| 4 | Commercial and artisan | 0.5 ~~÷~~- 1 | 1 | 0.8 |
| 5 | Industrial | 0.5 ~~÷~~- 1 | 1 | 0.3 ~~÷~~- 1 |
| 6 | Specialized agricultural | 0.1 ~~÷~~- 0.5 | 0.3 ~~÷~~- 1 | 0.7 |
| 7 | Woods, meadows, pastures, cemeteries, urban parks | 0.1 ~~÷~~- 0.5 | 0.3 | 0.7 |
| 8 | Tourist recreation | 0.4 ~~÷~~- 0.5 | 0.5 | 0.1 |
| 9 | Unproductive | 0.1 | 0.1 | 0.3 |
| 10 | Ski areas, Golf course, Horse riding | 0.3 ~~÷~~- 0.5 | 0.3 ~~÷~~- 1 | 0.3 |
| 11 | Campsites | 1 | 0.5 | 0.1 |
| 12 | Roads of primary importance | 0.5 | 1 | 0.2 |
| 13 | Roads of secondary importance | 0.5 | 0.5 ~~÷~~- 1 | 0.1 |
| 14 | Railway area | 0.7 ~~÷~~- 1 | 1 | 0.7 |
| 15 | Area for tourist facilities, Zone for collective equipment (supra-municipal, subsoil) | 1 | 0.3 | 0.3 |
| 16 | Technological and service networks | 0.3 ~~÷~~- 0.5 | 1 | 0.1 |
| 17 | Facilities supporting communication and transportation networks (airports, ports, service areas, parking lots) | 0.7 ~~÷~~- 1 | 1 | 1 |
| 18 | Area for energy production | 0.4 | 1 | 1 |
| 19 | Landfill, Waste treatment plants, Mining areas, Purifiers | 0.3 | 0.5 | 1 |
| 20 | Areas on which plants are installed as per Annex I of Legislative Decree 18 February 2005, n. 59 | 0.9 | 1 | 1 |
| 21 | Areas of historical, cultural and archaeological importance | 0.5 ~~÷~~- 1 | 1 | 1 |
| 22 | Environmental goods | 0.5 ~~÷~~- 1 | 1 | 1 |
| 23 | Military zone | 0.1 ~~÷~~- 1 | 0.1 ~~÷~~- 1 | 0.1 ~~÷~~- 1 |

- ~~Coping Capacity (or ex-post adaptation capacity): the ability of people, organizations and systems to cope with adverse conditions using available skills, resources and opportunities (IPCC, 2012; Torresan et al., 2012).~~

### 3.1.4 Flood Vulnerability Mapping

Vulnerability is also quantified for each of the three macro-categories (i.e., people, economic activities and environmental/cultural-archaeological assets affected) as outlined below~~.~~ but we additionally differentiate between physical and social vulnerability as described in Section 3.1 and shown in Figure 3.

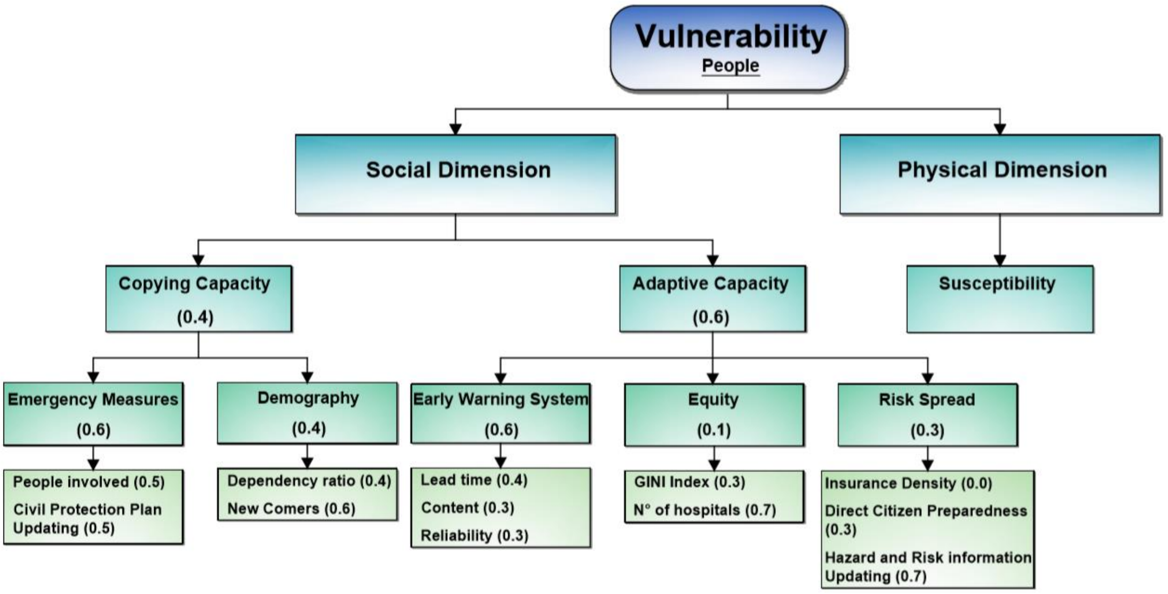


Figure 3: Hierarchical combination of indicators and relative weights (in brackets) to calculate the vulnerability of the population.

**(i) ~~People~~Physical vulnerability of people affected by flooding**

~~To characterize the~~The physical vulnerability associated with ~~human presence, we refer to~~people considers the values of flow velocity (*v*) and water ~~depth~~height (*h*)~~ values~~ that produce "instability" with respect to remaining in an upright position. Many authors have dealt with the instability of people in flowing water ~~(see e.g., Chanson and Brown, 2018)~~(see e.g., Chanson and Brown, 2018), and critical values have been derived from the product of *h* and *v*~~ have been proposed~~. For example, Ramsbottom et al. (2004) and Penning-Rowsell et al. ~~(2005)~~(2005) have proposed a semi-quantitative equation that links a flood hazard index, referred to as the Flood Hazard Rating (FHR), to *h*, *v* and a factor related to the amount of transported debris, i.e., the Debris Factor (*DF*), as follows:

$$FHR = h * (v + 0.5) + DF \qquad (3)$$

~~The values of *DF* related to different ranges of *h*, *v* and land use are reported in Table 4.~~

The values of the *DF* related to different ranges of *h*, *v* and land use are reported in Table 4, which were taken from a study by the UK Department for Environment, Food and Rural Affairs (DEFRA) and the UK Environment Agency (2006) as reported in ISPRA (2012).

**Table ~~4:~~4: The Debris Factor (*DF*) for different water depths (*h*), flow velocities (*v*) and land uses.**

| Values of $h$ and $v$ | Grazing/Agricultural land | Forest | Urban |
|---|---|---|---|
| 0 m < $h \leq$ 0.25 m | 0 | 0 | 0 |
| 0.25 m < $h \leq$ 0.75 m | 0 | 0.5 | 1 |

| | | | |
|---|---|---|---|
| *h* > 0.75 OR *v* > 2 m/s | 0.5 | 1 | 1 |

~~Based on~~Using the FHR, the physical vulnerability of the population~~, $V_P$,~~ can be calculated~~. One assumption~~, which is ~~that people are vulnerable at water heights greater than 0.25m. People located in "hospital and social assistance structures", whose~~summarized in Figure 4.

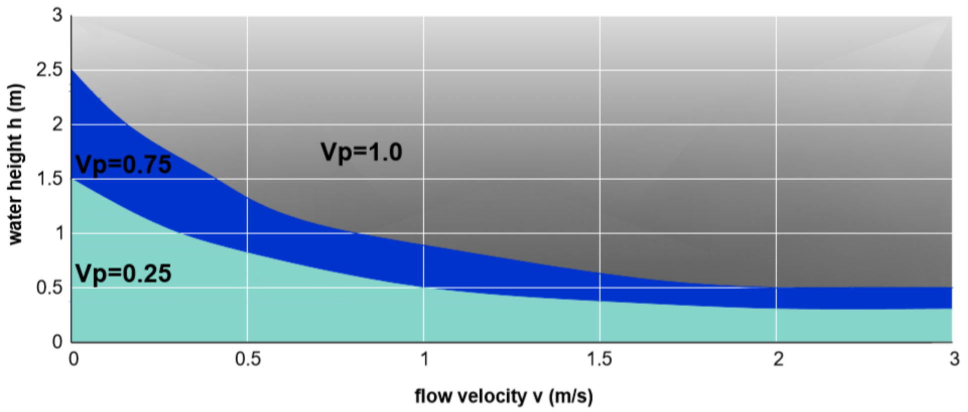
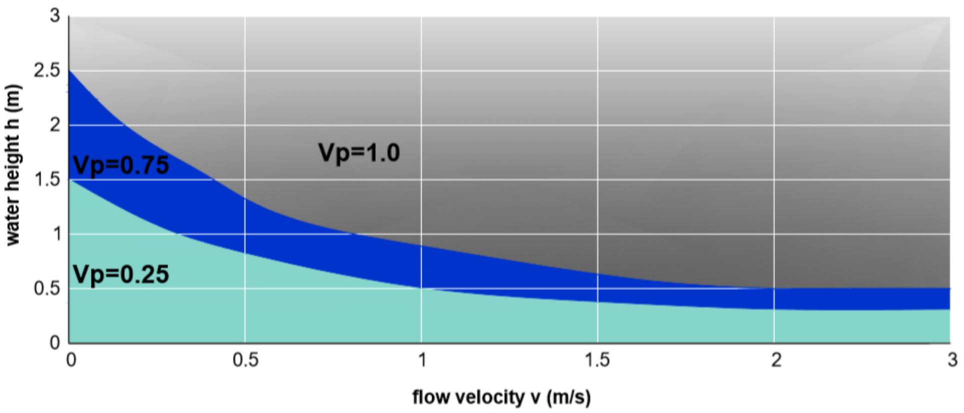


Figure 4: Physical vulnerability ~~is considered as 1 for an FHR > 0.75, represent an exception because the physical condition of people living in such structures makes them more vulnerable. These relationships are summarized in Figure 2.~~

~~The method to evaluate the adaptive and coping capacities is based on the hierarchical combination of indicators as shown in Figure 3, where the weights used in the calculation are reported in brackets. The data related to the social indicators have different units of measurement. Therefore, it is necessary to adopt a normalization procedure using value functions (Mojtahed et al., 2013).~~



**~~Figure 2: Vulnerability~~ values for the population ~~($V_p$)~~ as a function of water ~~depth~~height (*h*) and flow velocity (*v*).**

~~To evaluate the Coping Capacity, four different variables are included (shown in Figure 4 along with their normalized functions):~~

### (ii) Social vulnerability of people affected by flooding

Figure 3 shows the components of social vulnerability, i.e., the adaptive and coping capacity and their respective indicators, along with the weights associated with each of them. The weights and values assigned to each of these indicators have been determined through an expert consultation process carried out by AAWA. Because the different indicators have varying units of measurement, they were first normalized so that they could be combined. Several normalization techniques exist in the literature (Biausque, 2012) but the 'value function' was chosen because it represents a mathematical expression of a human judgement that can be compared in a systematic and explicit way (Beinat, 1997; Mojtahed, et al., 2013). The coping capacity is comprised of the following demographic and emergency measure indicators, where the corresponding value functions are shown in Figure S1:

- Dependency ratio: the number of citizens aged under 14 and over 65 ~~compared to~~as a percentage of the total population. ~~A population with a~~A high value of this index implies a reduced ability to adapt to hazardous events.
- Foreigners: the number of foreigners as a percentage of the total population. ~~An area~~Due to language barriers and other cultural reasons, areas with a high number of immigrants may ~~react with more difficulty~~not cope as well after a flood event and during emergency situations~~, due to, e.g., language barriers and cultural habits~~.
- Number of people involved in emergency management: the number of operators who have been trained to manage an emergency in the region, expressed qualitatively as low, medium and high~~; and~~.
- ~~The frequency at which Civil Protection Plans~~How frequently civil protection plans are updated: Updating is measured in months to years and indicates how often new hydraulic, urban and technological information is ~~taken~~incorporated into ~~account in Civil Protection Plans~~civil protection plans.

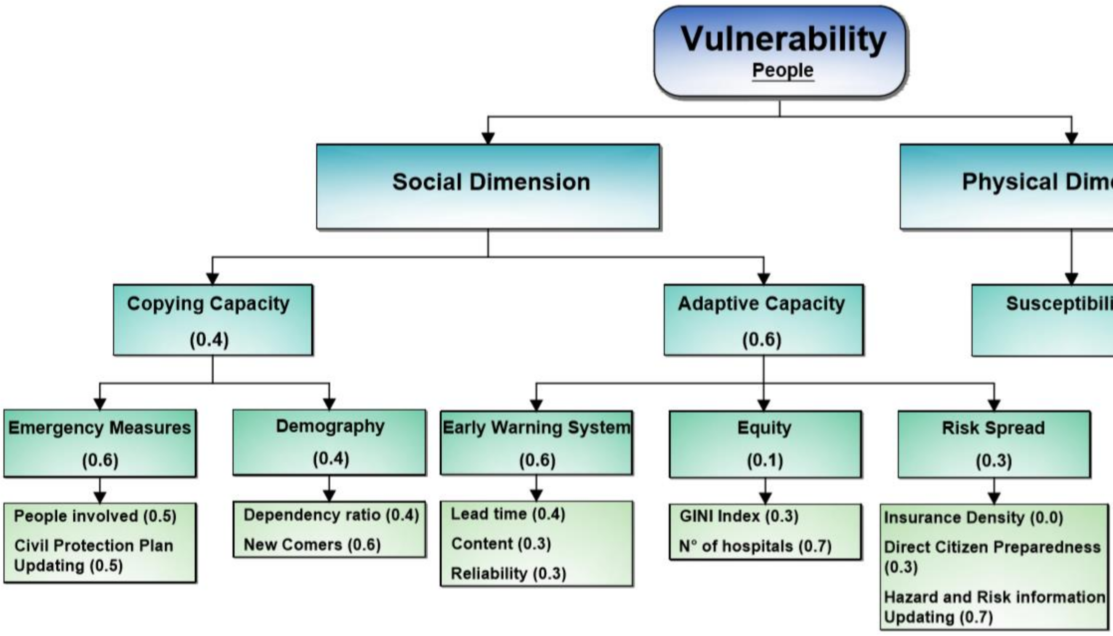
~~Similarly, for~~The adaptive capacity is comprised of three components: the ~~Adaptive Capacity, the variables~~early warning system, equity and ~~normalized~~risk spread. Early warning systems are evaluated according to three criteria, where the value functions ~~(~~are shown in Figure S2:

- Lead time (or warning time): the number of hours before an event occurs that was predicted by the early warning system.
- Content: the amount of information provided by the early warning system, such as the time and the peak of the flooding at several points across the catchment.
- Reliability: this is linked to the uncertainty of the results from the meteorological forecasts and the hydrological models (Schroter et al., 2008). ~~5) are described below~~False alarms can cause inconvenience to people, hinder economic activities, and people may be less likely to take warnings seriously in the future; therefore, they should be minimized.

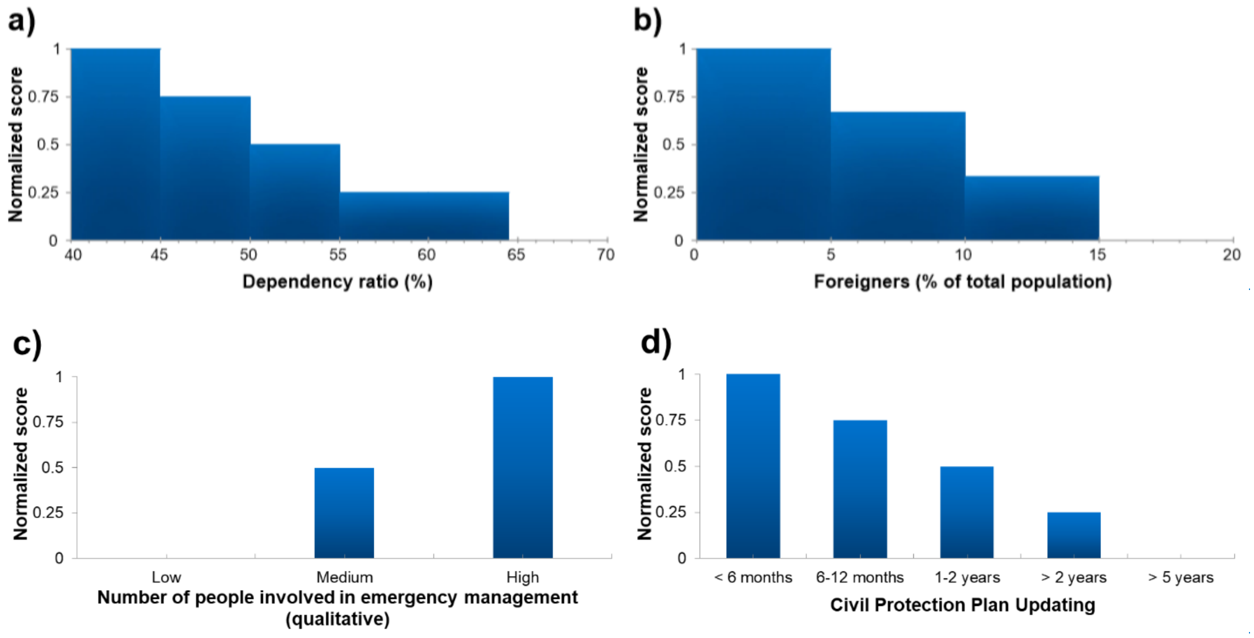
Finally, equity and spread (shown in Figure S3) are characterized by:

- Gini Index: a measure of the inequality of income distribution within the population. A value of 0 means perfect equality while 1 is complete inequality.
- Number of hospital beds: this is calculated per 1000 people.
- Insurance density: this is the ratio of total insurance premiums (in €) to the total population (Lenzi and Millo, 2005). Values with higher insurance density lead to increased adaptive capacity. However, the insurance density is set to zero because insurance companies in this part of Italy do not currently offer premiums to protect goods against flood damage.
- The frequency at which information on hazard and risk are updated: this is measured in months to years and indicates the ability of institutions to communicate the conditions of danger and risk to the population.
- Involvement of citizens: This is based on the number of students, associations such as farmers and professionals, and citizens that can be reached across large areas through social networks (WP7 WSI Team, 2013) to disseminate information. The values in Figure ~~5d~~S3d show the maximum achievable value in the three categories of citizen involvement.

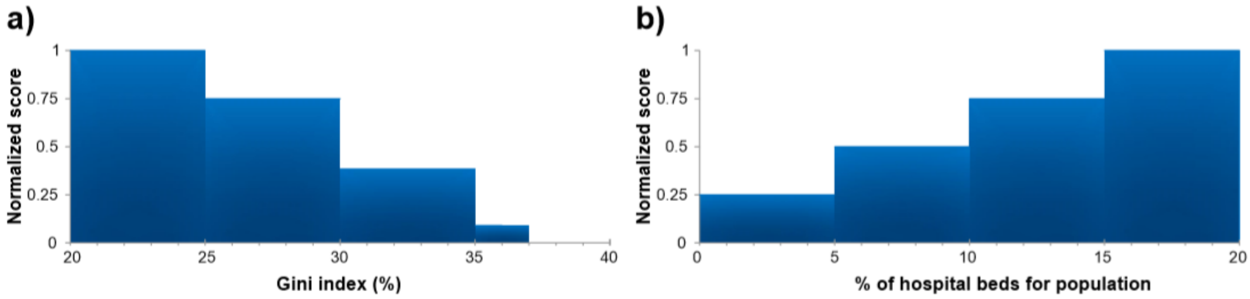
~~The normalized functions used in the calculation of these indices are shown in Figure 5.~~

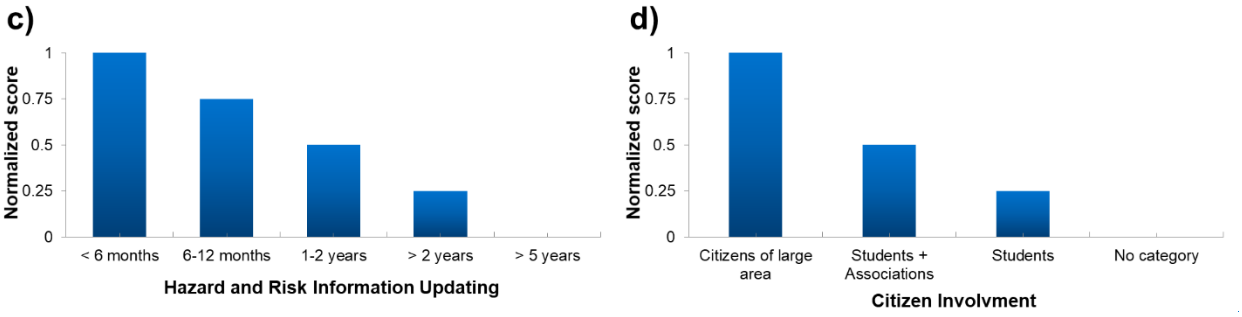


~~Figure 3: Hierarchical combination of indicators and relative weights (in brackets) to calculate the vulnerability of the population.~~



~~Figure 4: Variables as normalized index functions for evaluating the Coping Capacity (from De Luca, 2013).~~

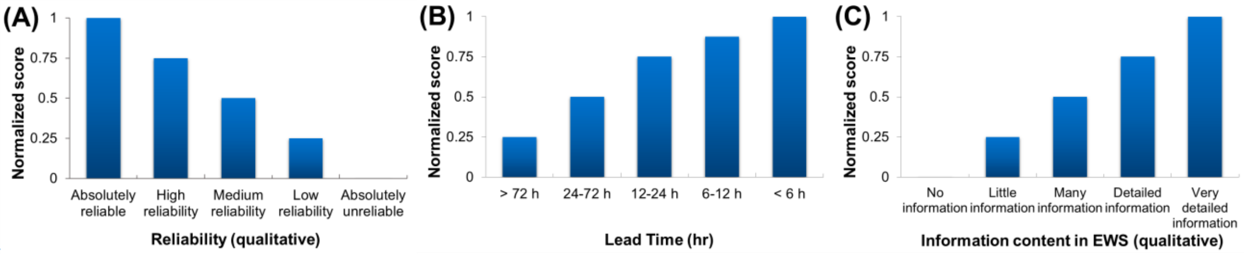




~~**Figure 5: Variables as normalized index functions for evaluating the Adaptive Capacity (from De Luca, 2013).**~~

~~Finally, forecasting systems are evaluated according to the three criteria, where the value functions are shown in Figure 6:~~

- ~~Reliability: this is linked to the uncertainty of the results from the meteorological forecasts and the hydrological models (Schroter et al., 2008). False alarms can inconvenience people and hinder economic activities and should, therefore, be minimized.~~
- ~~Lead time (or warning time): the number of hours before an event occurs that was predicted by the early warning system.~~
- ~~Information Content: the amount of information provided by the forecasting systems, such as the time and the peak of the flooding at several points across the catchment.~~



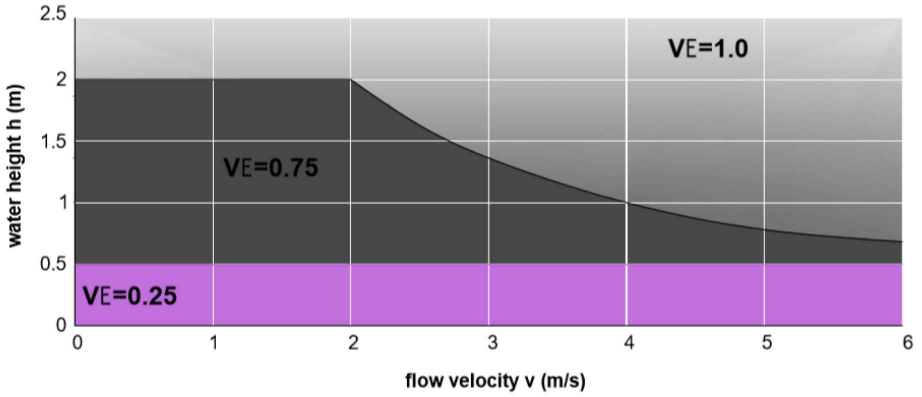
~~**Figure 6: Normalized function of the indices linked to the forecasting systems: A) reliability, B) lead time, and C) information content (from De Luca, 2013).**~~

~~**(ii) Economic activities affected**~~

The value for social vulnerability is the sum of the coping and adaptive capacities while the final value for the vulnerability of people is calculated by multiplying the physical and the social vulnerability together.

### (iii) Physical vulnerability of economic activities affected by flooding

The vulnerability associated with economic activities~~, $V_E$, is evaluated using the land use categories in Table 1. Three main aspects are considered:~~ considers buildings, network infrastructure and agricultural areas. For buildings, ~~which are found in land use types 1 to 5, 14 to 15, 17 to and 23 in Table 1,~~the effects from flooding include collapse due to water pressure and/or undermining of the foundations. Moreover, solid materials, such as debris and wood, can be carried by a flood and can cause additional damage to structures. A damage function for brick and masonry buildings has been formulated by Clausen and Clark ~~(1990)~~(1990). ~~Regarding losses to indoor goods, laboratory~~Laboratory results have shown that at a water height of 0.5m, the loss to indoor goods is around 50%, which is based on an evaluation made by Risk Frontiers, an independent research center sponsored by the insurance industry. The structural vulnerability of ~~the~~ buildings and losses of ~~the~~ associated indoor goods is shown in Figure ~~7~~S4 as a function of the height of the water ~~depth~~ and flow velocity~~.~~, which are applied to land use types containing buildings (Table S1). For the camping land use type 11 (Table ~~1~~S1), the values have been modified based on results from Majala (2001).

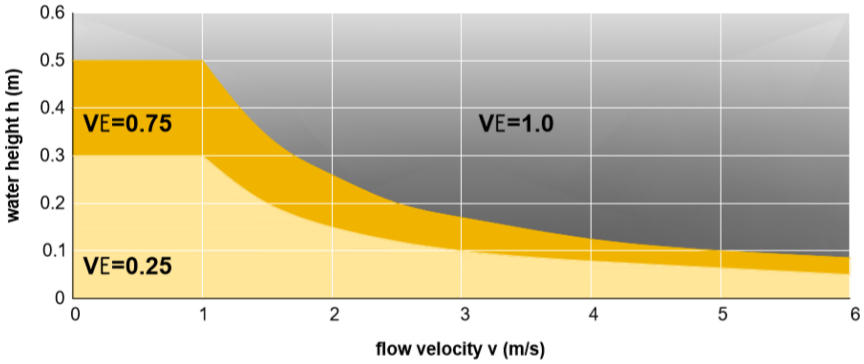


~~**Figure 7:**~~ Vulnerability ~~**values of buildings as a function of water depth (*h*) and flow velocity (*v*).**~~

~~Vulnerability to~~of the road network is evaluated for land use types 12 and 13 in Table ~~1. Vulnerability~~ S1, which occurs when it is not possible to use the road due to flooding. ~~This can occur with or without structural damage to the road (i.e., this could be a simple inundation or a destruction of the road infrastructure). Based on the~~This is based on an estimation of the water height and the critical velocity at which vehicles become unstable during a flood, which are derived from direct observation in laboratory experiments ~~(Reiter, 2000),~~and from a report on the literature in this area (Reiter, 2000; Shand et al., 2011); the vulnerability function for the road network is presented in Figure ~~8.~~

S5. Regarding technological and service networks (land use type 16, Table ~~1~~S1), we assume a vulnerability value equal to 1 if the water height and flow velocity ~~is~~are greater than 2 m and 2 m/s, respectively~~;~~, otherwise ~~it is~~ 0.

To assess the vulnerability in agricultural areas (land use types 6 and 7 in Table ~~1~~S1), we assume that the damage is related to harvest loss, and when considering higher flow ~~velocity~~velocities and water ~~depth values~~heights, to agricultural buildings and internal goods. ~~However, the highest tolerable height at which agricultural land can be submerged depends on the crop type and vegetation height.~~ Citeau (2003) provides ~~some examples~~relationships that take water ~~depth~~height and flow velocity into account, e.g., the maximum height is 1 m for orchards and 0.5 m for vineyards, and the maximum velocity varies from 0.25 m/s for vegetables and 0.5 m/s for orchards. Concerning cultivation in greenhouses, the maximum damage occurs at a height of 1 m. Finally, high velocities can cause direct damage to cultivated areas but can also lead to soil degradation due to erosion. The vulnerability values for four different types of land as a function of water ~~depth~~height and flow velocity are shown in Figure ~~9~~S6. In the case of unproductive land (land use type 9 in Table 1), the vulnerability is assumed to be 0.25, regardless of the *h* and *v* values.

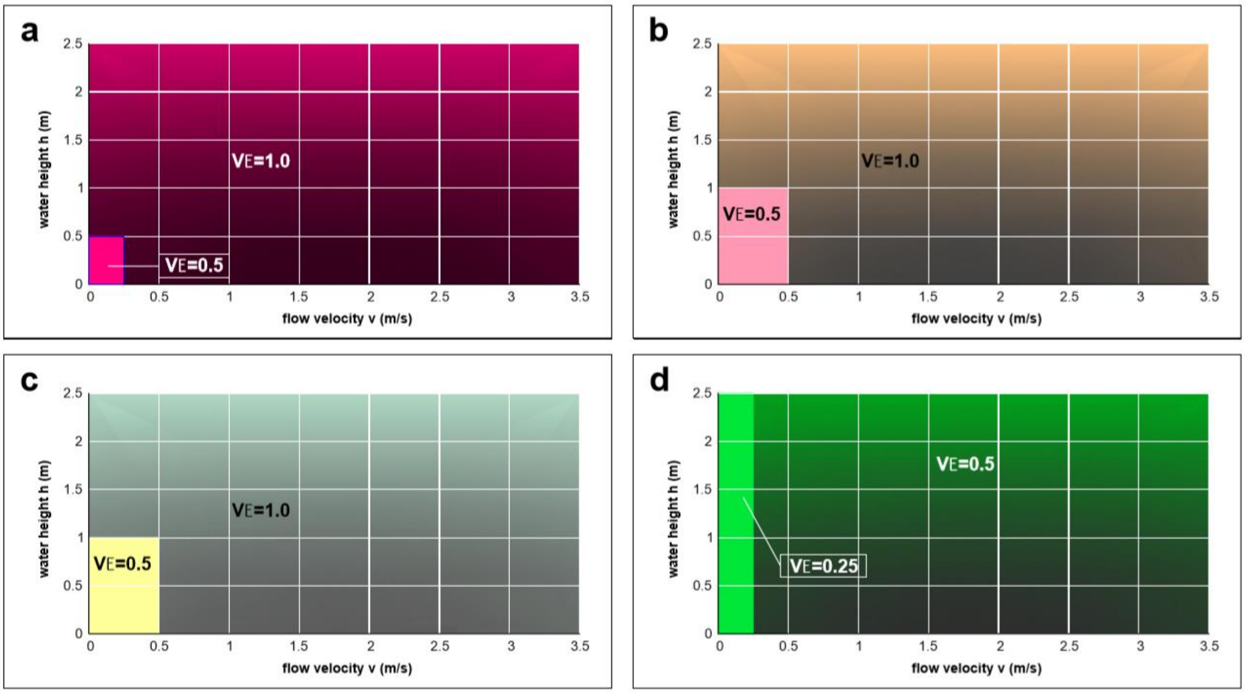


~~**Figure 8: Vulnerability values**~~Physical vulnerability of ~~**the network infrastructure as a function of water depth (*h*) and flow velocity (*v*).**~~

### ~~(iii)~~(iv) ~~Environmental~~ environmental and cultural heritage assets affected by flooding

~~Evers (2006) describes environmental flood susceptibility using three indicators: contamination/pollution, erosion and open space. Contamination is caused by industry, animal/human waste and the stagnation of flooded water.~~Environmental flood susceptibility is described using contamination/pollution and erosion as indicators. Contamination is caused by industry, animal/human waste and stagnant flooded waters. Erosion can produce disturbance to the land surface and to vegetation but can also damage infrastructure. ~~Open spaces are natural areas used for recreational activities, such as tourist attractions and natural protected areas.~~ The approach ~~proposed~~taken here ~~is~~was to identify protected areas that could potentially be damaged by a flood. For areas~~ that are~~ susceptible to nutrients, including those identified as vulnerable in Directive 91/676/CEE (Nitrate), and for those defined as susceptible in Directive 91/271/CEE (Urban Waste), we assume a value of 1 for vulnerability (land use type 20 in Table ~~1).~~ S1). Similarly, in~~ the~~ areas identified for habitat and species protection, i.e., sites belonging to the Natura 2000 network established in accordance with the Habitat Directive 92/43/CEE and Birds Directive 79/409/CEE (land use types 8 and 22 in Table ~~1~~S1), the presence of ~~Integrated Pollution Prevention and Control (IPPC) installations and/or other~~ relevant pollution sources ~~are~~was identified~~,~~ (Tables 1 and ~~the~~S1) and assigned a vulnerability ~~is~~of 1. ~~When~~In the absence of pollution sources ~~are not identified~~, the vulnerability ~~is~~was calculated as ~~follows. If~~0.25 if the flood velocity ~~is~~was less than or equal to 0.5 m/s and the water depth ~~is~~was less than or equal to 1 m~~, the vulnerability is 0.25~~; otherwise ~~the value is~~it was 0.5. Regarding cultural heritage (land use type 21 in Table S1), we assigned a vulnerability of 1 to these areas, taking a conservative approach.

~~Elements classified as "cultural heritage" are considered by the EC to be one of the potential adverse consequences of future flood events. As it is not currently possible to determine the vulnerability associated with different elements of cultural heritage (land use type 21 in Table 1), we assign a vulnerability of 1 to such elements in a conservative approach.~~



**~~Figure 9: Vulnerability values as a function of water depth (*h*) and flow velocity (*v*) for: (a) vineyards, (b) orchard and olive trees, (c) vegetables, and (d) natural and semi-natural environments.~~**

### ~~2.2.4 Calculation of total risk~~

~~The total risk, *R*, can be calculated as a single value based on the following formula:~~

~~$R = \frac{p_P \cdot R_P + p_E \cdot R_E + p_{ECH} \cdot R_{ECH}}{p_P + p_E + p_{ECH}}$, (4)~~

### ~~**where $R_P$, $R_E$ and $R_{ECH}$ represent the risk for the three macro-categories and $p_P$, $p_E$ and $p_{ECH}$**~~3.1.5 Mapping flood risk before and after implementation of a CO on flood risk management

Once the hazard, exposure and vulnerability are mapped, the flood risk, *R*, for the three flood hazard scenarios, *i*, can be mapped as follows:

$$R = \sum_{i=1}^{3} R_i = \frac{w_P\,(H_i \cdot E_P \cdot V_P) + w_E\,(H_i \cdot E_E \cdot V_E) + w_{ECH}\,(H_i \cdot E_{ECH} \cdot V_{ECH})}{w_P + w_E + w_{ECH}} \qquad (4)$$

where *H*, *E* and *V* are the hazard, exposure and vulnerability associated with the three macro-categories *P*, *E* and *ECH* which are the people, economic activities and environmental/cultural-archaeological assets affected, and $w_P$, $w_E$ and $w_{ECH}$ are weights applied to each macro-category, with values of 10, 1 and 1, respectively, which were defined based on stakeholder interviews~~. However, these weights can be adjusted based on the priorities of the community.~~ undertaken by AAWA. To establish the level of risk~~ (i.e., moderate, medium, high, very high),~~, four risk classes ~~are introduced, as provided in Table 5.~~were defined (Table 5).

~~The method described above produces total risk for every grid cell in the catchment that is analyzed, taking into account the three scenarios (section 2.2.1) defined in art. 6 of the EU Flood Directive.~~

**Table ~~5:~~5: Definition of risk classes.**

| Range of R | Description | Risk Category |
|---|---|---|
| 0.1 < R ≤ 0.2 | ~~Moderate~~Low risk where social, economic and environmental damage are negligible or zero | R1 |
| 0.2 < R ≤ 0.5 | Medium risk for which minor damage to buildings, infrastructure and environmental heritage is possible, which does not affect the safety of people, the usability of buildings and economic activities | R2 |
| 0.5 < R ≤ 9 | High risk in terms of safety of people, damage to buildings and infrastructure (and/or unavailability of infrastructure), interruption of socio-economic activities and damage related to the environmental heritage | R3 |
| 0.9 < R ≤ 1 | Very high risk including loss of human life and serious injuries to people, serious damage to buildings, infrastructure and environmental heritage, and total disruption of socio-economic activities | R4 |

## ~~2.3 Cost-benefit analysis~~

~~According to EU directive 2007/60/EC, the flood risk plan must contain an analysis of the costs and benefits (hereafter referred to as CBA) that would be generated from each planned intervention. The purpose of the CBA is to compare the efficiency and effectiveness of different alternatives in technological, economic, social and environmental terms. These interventions can be public policies, projects or regulations that can be used to solve a specific problem.~~

~~The economic and social aspects related to exposure are considered through the Value Factor, which refers to the economic value of life, the willingness to pay or accept a reward, and the number of direct and indirect users. These factors~~

~~are designed to support decision makers in assigning monetary value to damages and classifying them, as proposed by Merz et al. (2010). In this analysis, only the direct tangible costs due to damage resulting from a flood event are considered.~~

### ~~2.3.1 Determining the effectiveness of an action plan~~

These risk classes were then mapped with and without the implementation of the CO for flood risk management. The main change in the calculation of risk is in the social dimension of vulnerability. Before the CO is implemented, this component has a value close to 1. Based on the experience gained in the WeSenseIt project and the goals of the CO, the changes in social vulnerability with the implementation of the CO are shown in Table 6, which decreases the social vulnerability to a value of 0.63. For example, in the coping capacity, the number of people employed in emergency management does not change but as a result of the CO, they will work in a much more efficient manner due to the technology that allows for better emergency management. These tools will also lead to more frequent updating of civil protection plans as well as hazard and risk information updates. In addition, the early warning system will improve in terms of lead time, content and reliability through the greater involvement of trained volunteers and citizens.

**Table 6: Changes in the indicators of social vulnerability with and without implementation of the CO on flood risk management.**

| **Social vulnerability** | **Indicator** | **Value without CO** | **Value with CO** |
|---|---|---|---|
| Adaptive capacity | Number of people involved in emergency management | Medium | High |
| | Frequency of civil protection plan updating | > 5 years | > 2 years |
| Coping capacity | Lead time of EWS | < 6 hours | 24-72 hours |
| | Content of EWS | Little information | Very detailed information |
| | Reliability of EWS | None | High |
| | Citizen involvement | None | Citizens of large area |
| | Hazard and risk information updating | > 5 years | 1-2 years |

### 3.2. Quantifying the risk reduction after implementation of the CO for flood risk management

To determine the effectiveness (or benefit) of implementing the ~~action plan,~~CO for flood risk management, we consider the ~~modification~~changes to the risk class~~ as a result of the intervention must be determined. The~~, which has been mapped across the study area before and after implementation of the CO. To aggregate this change in risk after implementation of the CO, the Synthetic Index of Risk Reduction (ISRR~~), which represents the effectiveness of an intervention relative to the current situation, can then be~~ ) is calculated as~~ follows~~:

$$ISRR = \frac{\sum_{ij} k_{ij} \cdot A_j}{\sum_j A_j},$$ (~~5~~7)

~~where $A_j$ is the flooded area after an intervention and $k_{ij}$ are the weights listed in Table 6 for the risk class *i* before the intervention and *j* after the intervention. We then use the *ISRR* from equation (5) to calculate the CBA value:~~

~~$CBA = \frac{Costoopera}{ISRR \cdot 10^6}$, (6)~~

~~where *Costopera* is the cost of the intervention.~~

~~**Table 6:**~~where $A_j$ is the flooded area after the CO is implemented and $k_{ij}$ are the weights from Table 7 for the risk class *i* before the CO is implemented and *j* after the implementation. The weights in Table 7 have been determined through expert consultation within the AAWA, supported by the guidelines from ISPRA (2012). If the ISRR is positive, then the overall risk is reduced.

**Table 7: Weights (*k*) for the Synthetic Index of Risk Reduction (ISRR) for changes in risk ~~before and~~ after implementation of the ~~intervention~~CO for flood risk management**

| **Weights (*k*)** | | Risk class before the intervention | | | |
|---|---|---|---|---|---|
| | | R1 | R2 | R3 | R4 |
| Risk class after the intervention | R1 | 0.0 | 10.0 | 20.0 | 30.0 |
| | R2 | -10.0 | 0.0 | 10.0 | 20.0 |
| | R3 | -20.0 | -10.0 | 0.0 | 10.0 |
| | R4 | -30.0 | -20.0 | -10.0 | 0.0 |

### ~~2.~~3.~~2~~3 Financial quantification of the direct damage due to flooding

To estimate the direct ~~economic impact of the floods, the vulnerability and exposure functions presented in sections 2.2.2 and 2.2.3 are used to calculate the cost of the expected~~ tangible costs due to damage ~~for each square meter of different land uses. Maximum~~resulting from a flood event, we use the maximum damage functions related to the 44 land use classes in ~~CORINE were~~the CLC developed by Huizinga ~~(2007)~~(2007) for the 27 EU member states, which are based on replacement and productivity costs and their gross national products. The replacement costs for damage to buildings, soil and infrastructure assume complete rebuilding or restoration. Productivity costs are calculated based on the costs associated with an interruption in production activities inside the flooded area. The maximum flood damage values for the EU-27 and various EU countries are provided in Table ~~7.~~

~~**Table 7: Maximum flood damage values (€ / m2) per damage category (Huizinga, 2007).**~~

| ~~Region/country~~ | ~~Residential building~~ | ~~Commerce~~ | ~~Industry~~ | ~~Road~~ | ~~Agriculture~~ |
|---|---|---|---|---|---|
| ~~EU27~~ | ~~575~~ | ~~476~~ | ~~409~~ | ~~18~~ | ~~0.59~~ |
| ~~Italy~~ | ~~618~~ | ~~511~~ | ~~440~~ | ~~20~~ | ~~0.63~~ |
| ~~Luxembourg~~ | ~~1443~~ | ~~1195~~ | ~~1028~~ | ~~46~~ | ~~1.28~~ |
| ~~Germany~~ | ~~666~~ | ~~551~~ | ~~474~~ | ~~21~~ | ~~0.68~~ |
| ~~Netherlands~~ | ~~747~~ | ~~619~~ | ~~532~~ | ~~24~~ | ~~0.77~~ |
| ~~France~~ | ~~646~~ | ~~535~~ | ~~460~~ | ~~21~~ | ~~0.66~~ |
| ~~Bulgaria~~ | ~~191~~ | ~~158~~ | ~~136~~ | ~~6~~ | ~~0.20~~ |

S3. The direct economic impact of the flood is calculated by multiplying the maximum damage values per square meter (in each land use category) by the corresponding areas affected by the floods, i.e., the flood hazard (Section 3.1.2), weighted by the vulnerability value ~~attributed to~~associated with each ~~area calculated using the value functions described above~~grid cell. Since the land use map used in this study does not distinguish between industrial and commercial areas, the average of the respective costs per square meter (475.5 ~~€ /~~ €/m$^2$) has been applied. Moreover, in discontinuous urban areas, 50% of the value of the damage related to continuous urban areas (i.e., 309 ~~€ /~~ €/m$^2$) was applied, due to the lower density of buildings in these areas.

~~The benefits are monetized as the "avoided" damage (to people, real estate, economic activities, protected areas, etc.) following the intervention.~~ The average annual expected damage (*EAD*) can be calculated as follows, where *D* is the damage as a function of the probability of exceeding *P* for a return time *i* (Meyer et al., 2007):

$$EAD = \sum_{i=1}^{k} \frac{D(P_{i-1})+D(P_i)}{2} \cdot |P_i - P_{i-1}|$$ ~~(7~~(5)

$$D(P_i) = \sum_i \frac{\sum_j A_{Dj}^{i} * w_{Dj}}{\sum_j w_{Dj}} \cdot D^i$$ ~~,~~ ~~(8~~(6)

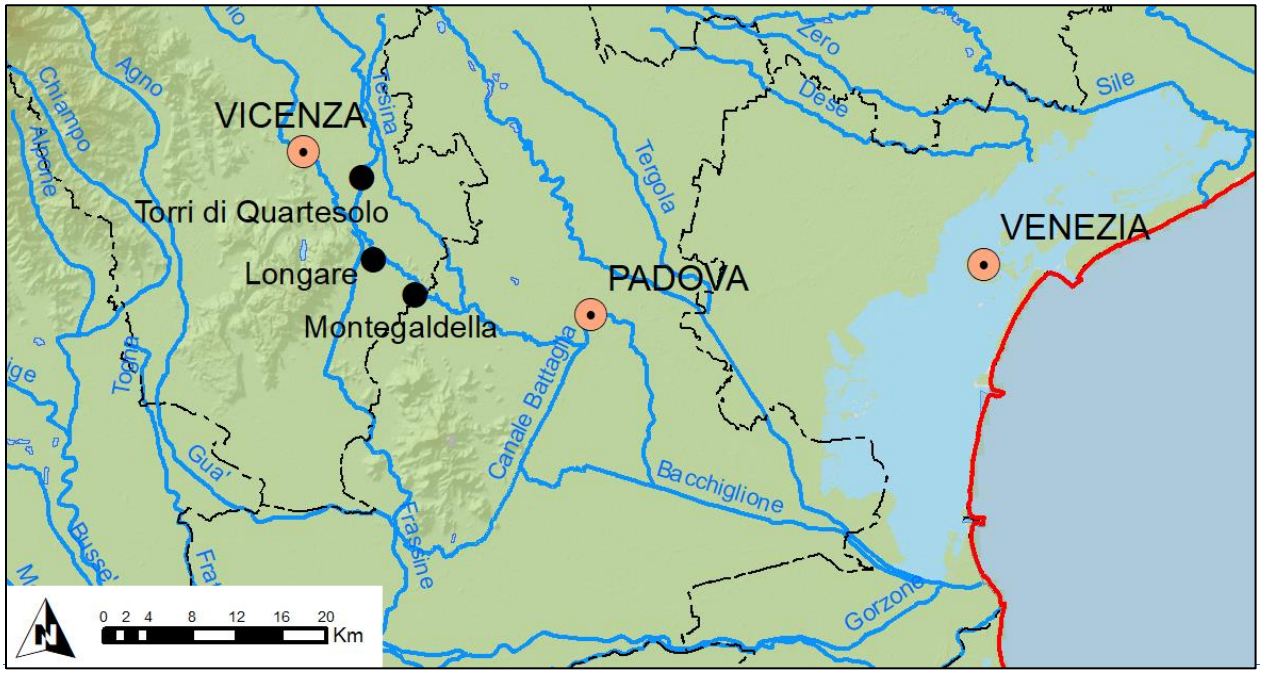
where ~~$w_{DJ}$~~ $w_{Dj}$ is the weight of the damage class, *j* is the damage category ~~(Table 7)~~ and *D* is the damage value shown in Table ~~7. In the CBA, this value allows the net benefit related to an intervention to be evaluated, which is expressed as the difference between the~~ S3. The EAD ~~value for the current situation compared to the *EAD* value after the intervention.~~

## ~~2.4 The Brenta-Bacchiglione catchment and the Citizen Observatory on Water~~

~~The EU Flood Directive requires that~~ **is calculated before and after implementing the CO for flood risk management** ~~plans~~**. The monetary benefits are** ~~produced for each unit of management. In this case, the Brenta-Bacchiglione River catchment coincides with one unit of management (Figure 10). It also includes the Retrone and Astichiello Rivers, and falls within the Veneto Region in Northern Italy, which includes the cities of Padua and Vicenza. The catchment is surrounded by the Beric hills in the south and the Prealpi in the northwest. In this mountainous area, rapid or flash floods occur regularly and are difficult to predict.~~

~~Rapid floods generally affect the towns of Torri di Quartesolo, Longare and Montegaldella, although there is also widespread flooding in the cities of Vicenza and Padua, which includes industrial areas and areas with cultural heritage. For example, in 2010, a major flood hit 130 communities and 20,000 individuals in the Veneto region, with Vicenza being one of the most affected municipalities with 20% of the metropolitan area flooded.~~

~~Because rapid floods are difficult to predict, early warning systems and prevention measures are of less use in this region. However, reducing~~the "avoided" damage~~, and therefore~~ costs (to people, buildings, economic activities, protected areas, etc.) if the CO for flood risk~~, is critical as flood events are frequent and affect several urban areas. In the past, the Upper Adriatic Basin Authority gained practical experience with a Citizen Observatory on Water through the WeSenseIt research project (www.wesenseit.eu), funded under the 7th framework program (FP7-ENV-2012 n° 308429). The objective of this CO, which covered a smaller part of the catchment, was to collect citizen observations from the field, and to obtain a broader and more rapid picture of developments before and during a flood event. As this is sensitive information that must be trustworthy enough to be acted upon directly, the Civil Protection Agency developed a separate e-collaboration platform for trained volunteers. The use of the platform resulted in new tasks for organized volunteering groups like Alpinists and the Red Cross.~~



~~**Figure 10: Location of the Brenta-Bacchiglione catchment and its urban communities.**~~

~~This pilot was later adopted by the European Community as a "good practice" example of the application of Directive 2007/60/EC. After the experience in WeSenseIt, the development of a Citizen Observatory on Water at the district scale was included in the prevention measures of the Flood Risk Management Plan (PGRA) for the Brenta-Bacchiglione catchment to strengthen communication channels before and during flood events in accordance with 2007/60/EC. The Citizen Observatory on Water is currently being~~ management is implemented~~ in the Brenta-Bacchiglione catchment under green infrastructure, with the objective of increasing resilience and addressing residual risk~~.

# ~~3~~4 Results

## ~~3.1 The situation before the intervention~~

## ~~3~~4.1 Flood risk estimation without implementation of a flood risk management CO

### 4.1.1 Hazard and risk

The results of the numerical simulations~~,~~ from the hydraulic model, which were carried out based on the methodology described in ~~section 2~~the Supplementary Materials, have shown that in some sections of the Bacchiglione River, the flow capacity will exceed that of the river channel. This will result in flooding, which will affect the towns of Torri di Quartesolo, Longare and Montegaldella. There will also be widespread flooding in the cities of Vicenza and Padua, including some industrial areas and others rich in cultural heritage. For a 30-year flood event, the potential flooding could extend to around 40,000 ha, where 25% of the area contains important urban areas with significant architectural assets. In the case of a 100-year flood event, the areas affected by the flood waters increase further, with more than 50,000 ha flooded, additionally affecting agricultural areas.

The results of the simulations are summarized in Tables 8 and 9 in terms of the areas affected in the catchment for different degrees of hazard and risk for 30-, 100- and 300-year flood events.

**Table 8: The hazard classes for each return period in terms of area flooded before implementation of the CO.**

| Hazard class | 30 year return period | 100 year return period | 300 year return period |
|---|---|---|---|
| | Area (km$^2$) | | |

~~In Figure 11, we provide a map showing~~

| | | | |
|---|---|---|---|
| Low | 185.12 | 294.77 | 370.07 |
| Medium | 118.87 | 161.82 | 225.67 |
| High | 54.18 | 74.55 | 104.61 |
| Total | 358.17 | 531.14 | 700.35 |

**Table 9: The risk classes for each return period in terms of area flooded before implementation of the CO.**

| Risk Class | 30 year return period | 100 year return period | 300 year return period |
|---|---|---|---|
| | Area (km$^2$) | | |
| Low (R1) | 160.29 | 254.29 | 318.80 |
| Medium (R2) | 137.26 | 191.89 | 262.03 |
| High (R3) | 56.70 | 79.23 | 110.29 |
| Very High (R4) | 3.92 | 5.73 | 9.23 |
| Total | 358.17 | 531.14 | 700.35 |

Figure 5 shows the areas at risk in the territory of Padua for a 100-year flood event. Risk classes R1 (low risk) and R2 (medium risk) have the highest areas for all flood event frequencies. Although areas in R3 (high risk) and R4 (very high risk) may comprise a relatively smaller area when compared to the total area at risk, these also coincide with areas of high concentrations of inhabitants in Vicenza and Padua.

~~**Table 8: The hazard classes for each return period of flooding in terms of area extension.**~~

| ~~Hazard class~~ | ~~30 year return period~~ | ~~100 year return period~~ | ~~300 year return period~~ |
|---|---|---|---|
| | ~~Area (km$^2$)~~ | | |
| ~~P1 (Low)~~ | ~~185.12~~ | ~~294.77~~ | ~~370.07~~ |
| ~~P2 (Medium)~~ | ~~118.87~~ | ~~161.82~~ | ~~225.67~~ |
| ~~P3 (High)~~ | ~~54.18~~ | ~~74.55~~ | ~~104.61~~ |
| ~~Total~~ | ~~358.17~~ | ~~531.14~~ | ~~700.35~~ |

~~**Table 9: The risk classes for each return period of flooding in terms of area extension.**~~

| ~~Risk class~~ | ~~30 year return period~~ | ~~100 year return period~~ | ~~300 year return period~~ |
|---|---|---|---|
| | ~~Area (km$^2$)~~ | | |
| ~~R1 (Low)~~ | ~~160.29~~ | ~~254.29~~ | ~~318.80~~ |
| ~~R2 (Medium)~~ | ~~137.26~~ | ~~191.89~~ | ~~262.03~~ |
| ~~R3 (High)~~ | ~~56.70~~ | ~~79.23~~ | ~~110.29~~ |
| ~~R4 (Very High)~~ | ~~3.92~~ | ~~5.73~~ | ~~9.23~~ |
| ~~Total~~ | ~~358.17~~ | ~~531.14~~ | ~~700.35~~ |

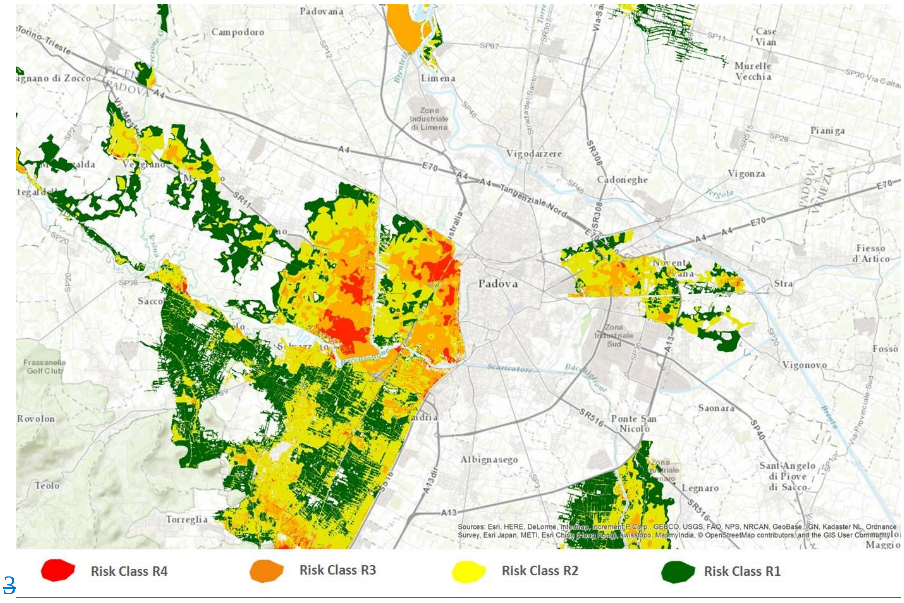


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Figure 5: Risk map for the metropolitan area of Padua for a 100-year flood event before implementation of a CO on flood risk management.

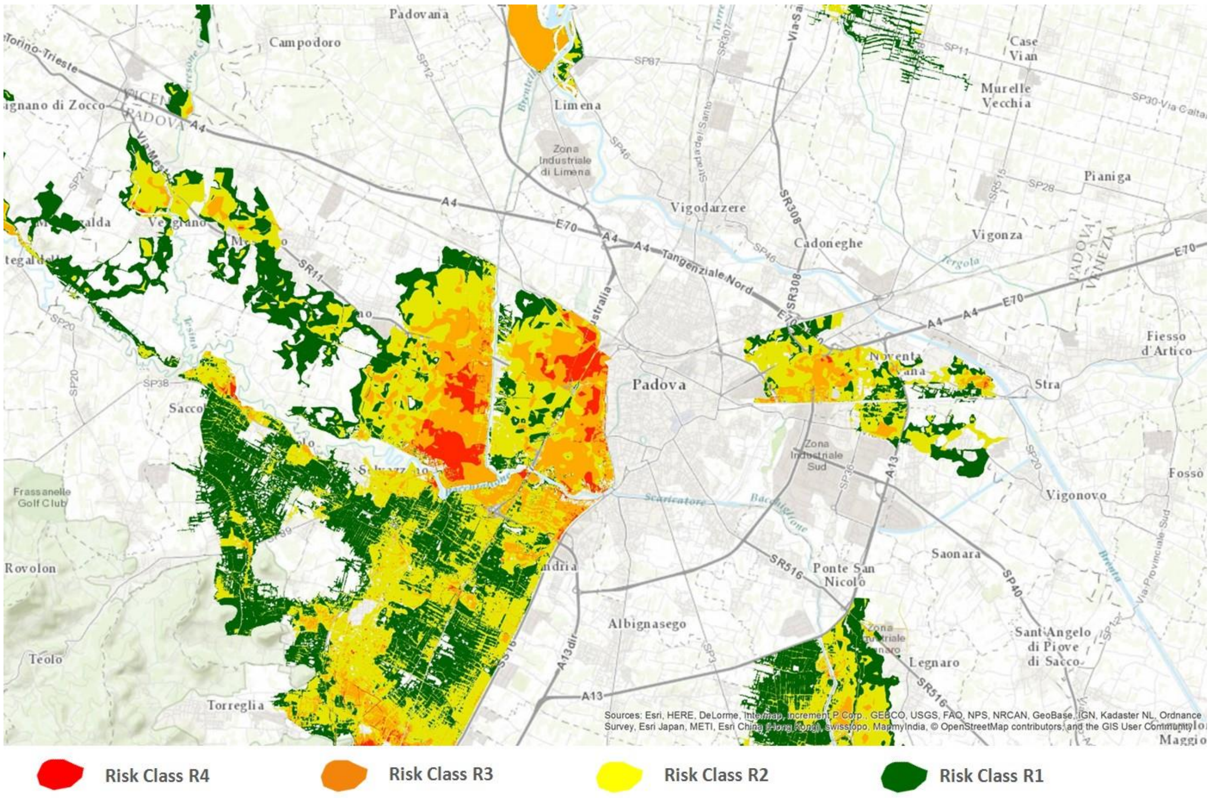
### 4.1.2 Expected damage

~~Based on the methodology in section 2.3, the~~The direct damage was calculated for the three flood scenarios: high chance of occurrence (every 30 years), medium (every 100 years) or low (every 300 years~~). The results are~~) and is summarized in Table 10.

**Table ~~10: Valuation of the direct~~10: Direct damage ~~due to~~(without the CO) for three flood ~~events with difference chances of occurrence~~scenarios.**

| **Scenarios** (chance of flood occurrence) | **Return period** | **Damage ~~(€)~~(million €)** |
|---|---|---|
| High | 30 years | 7,053~~,068,187~~ |
| Medium | 100 years | 8,670~~,252,625~~ |
| Low | 300 years | 10,853~~,328,570~~ |

~~It can be observed that in~~In the event of very frequent flood events, urban areas will be damaged. Furthermore, ~~it can be observed that passing~~moving from an event with a high probability of occurrence to one with a medium probability results in a significant increase in the area flooded (i.e., a 48% increase as shown in Table 8) but with a smaller increase in damage (i.e., around 20%). This is explained by the fact that the flooded areas in a 100-year flood event (but not present in a 30-year flood event) are under agricultural use. Similar ~~observations~~patterns can be ~~made~~observed when comparing floods with a low and high probability of occurrence. Substituting the values in Table 10 into equation (~~7~~5), we obtain an expected average annual damage (EAD) of ~~€~~ 248~~,517,347~~.5 million Euros.



~~**Figure 11: Risk map for the metropolitan area of Padua for a 100-year flood event.**~~

## ~~3~~4.2 ~~The result after the intervention of a Citizen Observatory in the Brenta-Bacchiglione catchment~~

**~~The results of the numerical simulations, carried out according to the methodology described in section 2, show that~~Flood risk estimation with the implementation of ~~the CO is able to significantly reduce the damage~~a flood risk management CO**

### 4.2.1 Hazard and ~~consequently the risk for the inhabited areas of Vicenza, Padua, Torri di Quartesolo, Longare and Montegaldella. The~~ risk

As mentioned previously, the hazard remains unchanged (i.e., the results reported in Table 8~~). The results of the simulations are provided~~), but the risk is reduced after implementation of a CO for flood risk management as shown in Table 11~~, which summarize~~ due to the reductions in vulnerability outlined in section 3.1.5. The areas affected in the ~~catchment for different degrees of risk for 30-, 100- and 300-year flood events.~~high (R3) and very high classes (R4) are significantly reduced (R4 to almost zero) compared to the results shown in Table 9 but the areas in the lower risk classes increase. The risk map for a 100-year flood event for the territory of Padua is shown in Figure 6, where the reduction in areas at high and very high risk are clearly visible compared to the situation before implementation of the CO, which is shown in Figure 5.

**Table ~~11:~~11: The risk classes for each return period of flooding in terms of area ~~affected~~flooded after implementation of the CO.**

| Risk class | 30 year return period | 100 year return period | 300 year return period |
|---|---|---|---|
| | Area (km$^2$) | | |
| R1 (Low) | 170.96 | 268.68 | 337.78 |
| R2 (Medium) | 168.99 | 235.18 | 322.41 |
| R3 (High) | 18.19 | 27.19 | 40.04 |
| R4 (Very High) | 0.03 | 0.09 | 0.12 |
| Total | 358.17 | 531.14 | 700.35 |

~~Comparing results in Tables 9 and 11, although the same areas are at risk, the areas affected in the high (R3) and very high classes (R4) are significantly reduced (R4 to almost zero) but at the detriment of an increase in areas affected in the lower risk classes. The results of the simulations showing areas at risk for a 100-year flood event for the territory of Padua~~

~~are shown in Figure 12. The reduction in areas at high and very high risk are clearly visible compared to the situation before the intervention shown in Figure 11.~~

~~The results of the numerical simulations carried out according to the methodology described in section~~

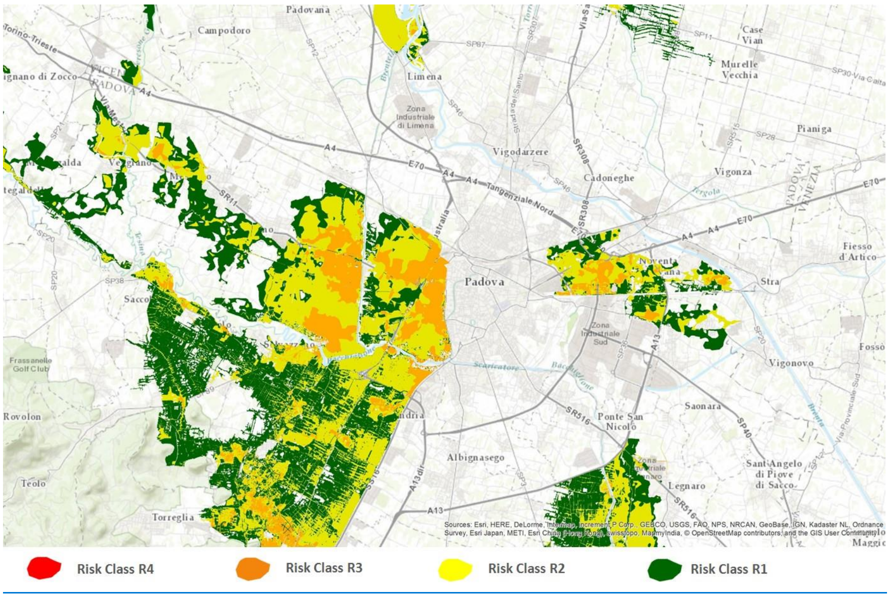


**Figure 6: Risk map for the metropolitan area of Padua for a 100-year flood event after implementation of a CO on flood risk management.**

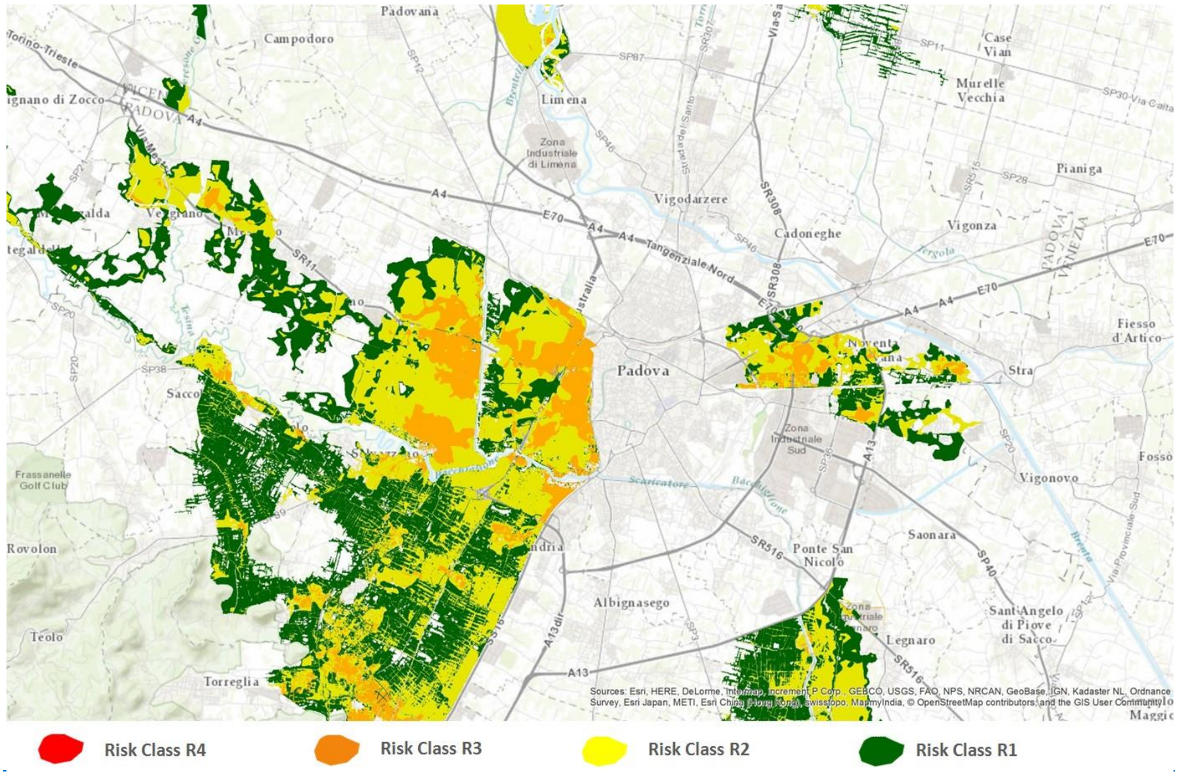
### 4.2.2 ~~have shown that the CO is able to reduce the~~Expected damage ~~from the flood in the three different scenarios due to a reduction in the vulnerability, in particular in terms of improving the coping capacity of the population (Figure 3) through increasing the number of people involved in the emergency, improving the response time and the reliability of the early warning system. The direct~~

The residual damage was calculated for the three flood scenarios ~~with~~after implementation of the CO ~~intervention. The results are~~on flood risk reduction, which is shown in ~~Table 12.~~Table 12. Substituting ~~the~~ these residual damage values ~~in Table 12~~ into equation (~~7~~5), we obtain an EAD of ~~€~~ 111~~,344,596~~.3 million Euros, which is a 45% reduction in the damage compared to results before the CO ~~intervention~~implementation.

**Table ~~12: Valuation~~12: Comparison of the direct (without CO) and residual damage ~~due to~~(with CO) for three flood ~~events with~~ scenarios and the cost difference ~~chances of occurrence~~.**

| **Scenarios** (chance of flood occurrence) | **Return period** | **~~Damage (€)~~Direct damage (million €)** | **Residual damage (million €)** | **Difference in costs (million €)** |
|---|---|---|---|---|
| High | 30 years | 7,053 | 1,~~572,774,084~~573 | -5,480 |
| Medium | 100 years | 8,670 | 5,~~439,785,419~~440 | -3,230 |
| Low | 300 years | 10,853 | 3,~~419,635,261~~420 | -7,433 |

The CO for ~~Water in the Flood Risk Management Plan of the Eastern Alps~~flood risk management has an estimated cost of around ~~€ 5,000,000. Based on the assessments made previously~~5 million Euros (as detailed in Table S2 in the Supplementary Materials). Taking the EAD with and without implementation of the CO, the annual benefit in terms of avoided damage is approximately ~~€ 137,172,000, with an~~ 137.2 million Euros. Hence the benefits considerably outweigh the costs. The ISRR value ~~of~~is 2.5~~. The CBA index, calculated using equation 6, is equal to 2. This value shows~~, which also indicates a ~~higher benefit to cost ratio compared with other hydraulic works planned in the Eastern Alps District and demonstrates the feasibility of the CO approach. For example, using the~~positive reduction in risk. The same methodology~~, a CBA~~ was ~~undertaken for~~applied to the construction of a retention basin in the municipalities of Sandrigo and Breganze to improve the hydraulic safety of the Bacchiglione River. Against an expected cost of ~~€~~ 70~~,700,000~~.7 million Euros, which is much higher than the estimated cost for implementing the CO, a significant reduction in flooded areas would be obtained although high risk would still be evident in the ~~territory of the~~ city of Padua. In terms of damage reduction with the construction of the retention basin, we would obtain an EAD of ~~€ 140,685,400, which is still higher than that incurred by the implementation of the CO~~140.7 million Euros so the cost to benefit ratio would be much lower.



~~**Figure 12: Risk map for the metropolitan area of Padua for a 100-year flood event after the intervention of a Citizen Observatory.**~~

## ~~4~~5 Discussion and Conclusions

~~The~~There is currently a lack of available, appropriate and peer-reviewed evaluation methods and evidence on the added value of ~~COs is holding back the uptake and adoption of COs~~citizen observatories, which is required before they will be more widely adopted by policy makers and practitioners. This paper has aimed to fill this gap by ~~presenting and applying a generic methodology for capturing the value of COs by means of a tailored, detailed~~demonstrating how a traditional cost-benefit analysis~~. The~~ can be used to capture the value of a CO for flood risk management. Although the CO is still being implemented, the proposed methodology was applied using primary empirical evidence from a CO pilot that was undertaken by the WeSenseIt project in the ~~Brenta-~~smaller Bacchiglione catchment~~. As such,~~ to guide changes in the values associated with social vulnerability once the ~~contribution of this paper has been two-fold.~~

~~First, it has outlined and demonstrated~~CO is implemented. This allowed the ~~application of a generic methodology for capturing~~ risk and flood damages to be calculated with and without implementation of the ~~costs and benefits of implementing a CO in the FRM domain. The generic nature of the methodology means that it can be applied to other catchments in any part of Italy or other parts of the world that are considering the implementation of a CO for FRM purposes. Secondly, the paper has produced case-specific insights. The CO cost-benefit analysis has shown that the~~CO, which showed that implementation of a CO in the Brenta-Bacchiglione is able to reduce the damage, and consequently the risk, for the inhabited areas from an expected average annual damage (EAD) of €248~~,517,347~~.5 to €111~~,344,596~~.3 million euros, i.e., a reduction of 45%. –Hence, the implementation of the CO could significantly reduce the damage and consequently the risk for the inhabited areas of Vicenza, Padua, Torri di Quartesolo, Longare and Montegaldella. The nature of the methodology also means that it can be applied to other catchments in any part of Italy or other parts of the world that are considering the implementation of a CO for flood risk management purposes.

The evidence on the costs and benefits of COs for ~~FRM~~flood risk management generated by ~~the~~this case study ~~elaborated in this paper provides~~can provide insights that policy makers, authorities and emergency managers can use to make informed choices about the adoption of COs for improving their respective ~~FRM~~flood risk management practices. In Italy, in general, citizen participation in ~~FRM~~flood risk management has been relatively limited. The previous strategy in the Brenta-Bacchiglione catchment has focused on structural flood mitigation measures, dealing with emergencies~~,~~ and optimizing resources ~~and effective and~~for rapid response~~ mechanisms~~. The inclusion of a CO on ~~water~~flood risk management has been a true innovation in the ~~FRM~~flood risk management strategies of this region. Future research can focus on the application of the methodology in other catchments as well as to other fields of disaster management beyond floods. Such applications will serve to generate a broader evidence base for ~~the validation~~using these types of ~~the proposed COCBA~~ cost-benefit ~~methodology~~methodologies.

However, there are also limitations associated with this approach. For example, the~~ cost-benefit~~ analysis presented here did not consider indirect costs, such as those incurred after the event takes place, or in places other than those where the flooding occurred ~~(Merz et al., 2010).~~(Merz et al., 2010). In accordance with other authors ~~(e.g., van der Veen et al., 2003)~~(e.g., van der Veen et al., 2003), all expenses related to disaster response (e.g., costs for sandbagging, evacuation) ~~were~~are classified as indirect damage. ~~The~~However, the presence of the CO in ~~the territory~~this catchment does~~, however,~~ reduce the costs related to emergency services, securing infrastructure, sandbagging and evacuation, all of which can be substantial during a flood event. Therefore, an analysis that takes indirect costs into account could help to further convince policy makers of the feasibility of a CO solution. Similarly, intangible costs were not considered, i.e., the values lost due to an adverse natural event where monetary valuation is difficult because the impacts do not have a corresponding market value (e.g., health effects). Furthermore, the vulnerability assessment of economic activities considers only water depth and flow velocity but not additional factors such as the dynamics of contamination~~, building materials~~ propagation in surface waters during the flood or the duration of the flood event, all of which could be taken into account in estimating the structural damage and monetary losses in the residential, commercial and agricultural sectors.

Another limitation is that this methodology is built on many assumptions, i.e., the numerous coefficients, value functions and weights used to estimate the exposure and vulnerability. Many of these values have been derived through expert consultation and experience and validated internally within AAWA or other Italian agencies. Value functions, in particular, are a way of capturing human judgement in way that can be quantified in situations of high uncertainty. We would argue that the expert consultations have not been undertaken lightly and have often resulted in conservative estimates in the values. Other values have been derived from the literature, all of which will have some uncertainties associated with their derivation. We have not undertaken an uncertainty analysis or a sensitivity analysis. Although we might be able to demonstrate a range of costs and benefits through such an approach, the current benefits heavily outweigh the costs so tweaking individual parameters will be unlikely to have large effects. That said, this cost-benefit analysis is hypothetical because the CO for flood risk management is still being implemented. Hence the real benefits will only be realized once the CO is fully operational. At that stage it will be interesting to validate the assumptions about reductions in social vulnerability and which indicators are the key to reducing flood risk.

Despite these various limitations, this analysis has highlighted the feasibility of a non-structural flood mitigation choice such as a CO for ~~water~~flood risk management compared to the implementation of much more expensive structural measures (e.g., retention areas) in terms of the construction costs and the cost of maintenance over time. By involving citizens in a two-way communication with local authorities through a CO, flood forecasting models can be improved, increased awareness of flood hazard and flood preparedness can be achieved, and community resilience to flood risk can be bolstered.

## Acknowledgements

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