Development of an IT platform for the elaboration of Flood Risk Maps

Document details

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VISFRIM

Progetto strategico co-finanziato dal Fondo europeo di sviluppo regionale
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Premise

The VISFRIM project (Interreg V-A Italy-Slovenia Cooperation Program 2014-2020 (targeted call for strategic projects n. 05/2008) aims to achieve efficient management of hydraulic risk in cross-border basins, through the development of methods and technological tools for the implementation of existing Flood Risk Management Plans (FRMPs) and their forthcoming update (2021). The project will involve governmental bodies and local authorities in developing joint measures and actions in the international Isonzo and Vipacco river basins and in the interregional Lemene river basin. They will share data and knowledge, jointly develop flood simulation models and identify mitigation measures to be implemented in the territory, previously evaluated in terms of costs and benefits trough specific IT procedures designed during the project.

In particular, in such a context, internal staff from Eastern Alps River Basin District (AAWA) wrote a report about methodologies applied for flood risk mapping purposes in its competence territory, that was shared with all the Consortium. Based on its content, one IT platform is under development in order to automatically elaborate Flood Risk Maps.

In detail, in the first part, this deliverable describes the criteria assumed for an integrated flood risk assessment, subject of the above cited report; whereas functional and technical specifications of the related IT platform are illustrated in the second part.

Methodological introduction

Criteria for an integrated risk assessment

The concept of risk is linked not only to the capability to calculate the probability that a hazardous event may occur, but also to the capability of defining the damage caused. The risk is indeed related to the possibility that a natural or man-made phenomenon may cause damage to the population, inhabited and production areas and infrastructures in a given area in a certain period of time (http://www.protezionecivile.gov.it).

Therefore risk and hazard are not the same thing: hazard is the cause, whereas risk refers to its possible consequences, in other words the damage that may be expected (http://www.protezionecivile.gov.it).

Risk can be expressed by the formula proposed by Cutter (1996), in compliance with D.P.C.M. 29 september 1998:

$$\overline{R} = \overline{H} \cdot \overline{V} \cdot \overline{E} = \overline{H} \cdot \overline{D} \quad (1)$$

where *Hazard (H)* is the probability that a phenomenon of a certain intensity will occur in a certain period of time in a given area; *Vulnerability (V)* 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; *Exposure* or *Exposed Value (E)* 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 calculated as the combination of the value of the exposed element with the value of this element with respect to an event of given intensity.

An outline is shown in Figure 1, that depicts the different steps in calculating risk for the purpose of undertaking an integrated flood risk assessment.

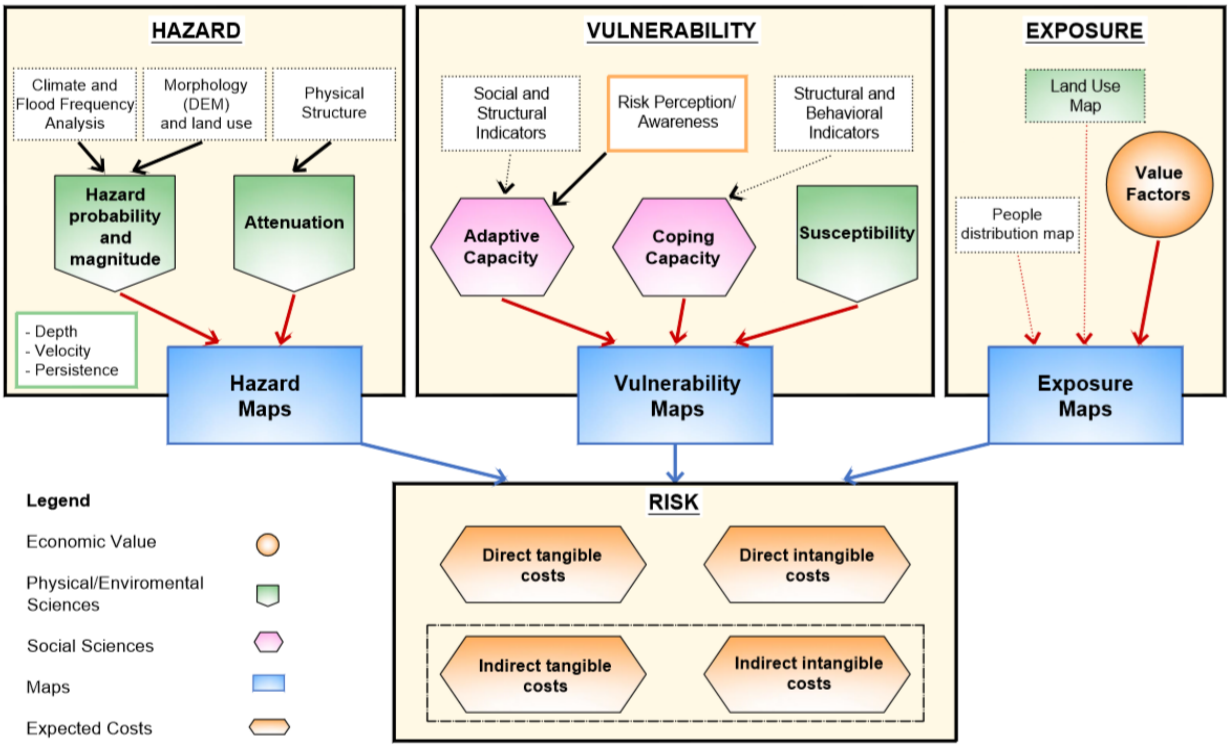

Figure 1: Flowchart outlining the determination of risk

The several individual components of risk needed will be described in more detail in next paragraphs, together with the estimation methodologies applied in the context of the Eastern Alps River Basin District.

If the impact of floods is assessed at a mesoscale, considering municipality as reference unit for example, risk can be quantified in relative terms, i.e. a value between 0 and 1, where 0 represents the absence of risk while 1 is the maximum risk of the exposed element.

In detail, the exposed elements must be expressed in terms of the following macro-categories, which are given in the EU 2007/60/CE Flood Directive, including 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 find their descriptors in the land use classes shown in Table 1, which are taken from the Corine Land Cover map 2006.

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	Unskilled agricultural, woods, meadows, pastures, cemeteries, urban parks
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, Area for collective supra-municipal equipment, Collective equipment in the subsoil
16	Technological and service networks
17	Facilities supporting communication and 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

Table 1: List of the land use classes used as descriptors for the three macro-categories from the EU 2007/60/CE Flood Directive

Hazard

According to Article 6 of the 2007/60/CE Flood Directive, three hazard scenarios must be addressed, which can be calculated using a hydrological and hydraulic model:

1. A flood with a low probability, which is 300-year return period in the context of the Eastern Alps River Basin District;
2. A flood with a medium probability, which is a 100-year return period in the context of the Eastern Alps River Basin District; and
3. A flood with a high probability, which is a 30-year return period in the context of the Eastern Alps River Basin District.

In detail flood hazard maps are evaluated by considering several scenarios for each return period, including both levee overtopping and breaching situations (more details were already provided in the report about *flood modeling approaches applied in the Eastern Alps District*).

Upon completing all simulations, the maximum envelope of flood depth is taken to generate the final map: consequently, values of maximum water depth (*h*) and velocity (*v*) are well-known in each point of the calculation domain.

Hazard can then be correlated to depth and velocity variables trough an *Intensity* function (*I*), formulated by taking into account the safety of people as vulnerable element. Specifically three *Intensity* classes, low (I_l) , medium (I_m), high (I_h), corresponding to low (H_l), medium (H_m), and high *Hazard* (H_h) classes, are defined as follows (Fig. 2):

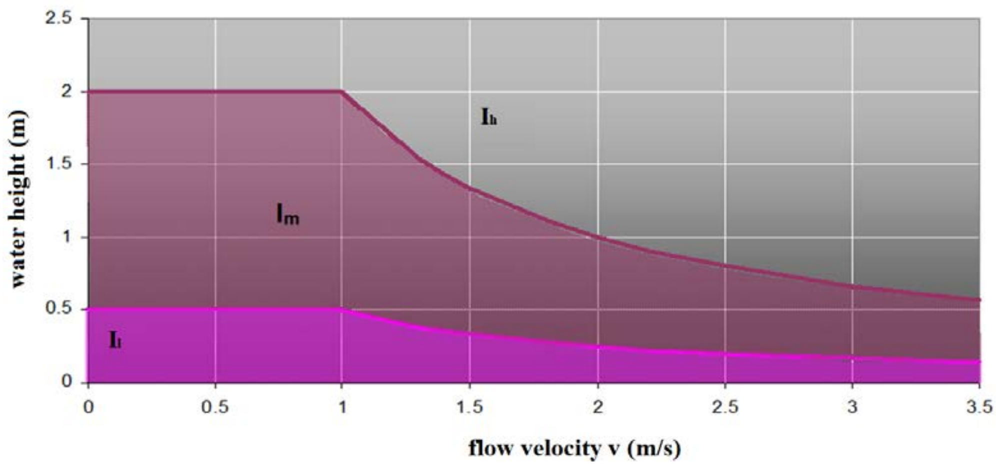

Figure 2: Definition of intensity classes (*I*)

$$I_l = \begin{cases} h \le 0.5 m \; if \; v \le 1 m/s \\ h \cdot v \le 0.5 \; if \; v > 1 m/s \end{cases} \tag{2}$$

$$I_m = \begin{cases} 0.5 < h \le 2 \; if \; v \le 1 m/s \\ 0.5 < h \cdot v \le 2 \; if \; v > 1 m/s \end{cases} \tag{3}$$

$$I_h = \begin{cases} h > 2 m \; if \; v \le 1 m/s \\ h \cdot v > 2 \; if \; v > 1 m/s \end{cases} \tag{4}$$

Since the goal is to calculate *Hazard* in relative terms, as a value comprised between 0 and 1, numerical values are associated to every *Intensity* class on the basis of literature data (Provincia Autonoma di Trento, 2006):

DESCRIPTION	**H CLASSES**	**H VALUES**
Low intensity (I_l): flooded areas by low depth water	H_l	0.4
Medium intensity (I_m): flooded areas by significant water depth and/or relevant flow velocity.	H_m	0.8
High intensity (I_h): flooded areas by deep water and/or high flow velocity	H_h	1.0

Table 2 – Hazard values related to Intensity classes.

In such a way, each point of the study area can be characterized by an *Hazard* class $H=\{H_l, H_m, H_h\}$ for every modelled scenario. In other words, for each point, there will be one hazard value for: 30 years return period (H_{Tr30}), 100 years return period (H_{Tr100}) and 300 years return period (H_{Tr300}).

If the final intention is to determine only one unique hazard value ($H_{synthesis}$), a weighted average from (H_{Tr30}), (H_{Tr100}) and (H_{Tr300}) can be estimated, by having previously defined different weights to the three return periods.

Vulnerability

Vulnerability results from the interaction between physical-environmental and social components. The first component represents the context in which the vulnerability is assessed. To define vulnerability from a physical point of view, we use the concept of the susceptibility of a potential target, i.e. 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.

The second component of vulnerability represents the perception or awareness of society regarding the possibility that an adverse event may occur. A greater awareness tends to correspond to greater preparation if the event occurs. Social vulnerability can be divided into:

- Adaptive Capacity, which is the combination of the strengths, attributes, and resources available to an individual, a 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).
- Coping Capacity or ex post adaptation capacity, which represents the ability of people, organizations and systems to cope with adverse conditions using available skills, resources and opportunities (IPCC, 2012; Torresan et al., 2012).

Vulnerability is quantified for each of the three macro-categories (i.e., people, economic activities and environmental/cultural-archaeological assets affected) as outlined below.

(i) People

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

$$FHR = h * (v + 0.5) + DF \quad (5)$$

The values of DF related to different ranges of h, v and land use are reported in Table 3.

Values of *h* and *v*	Grazing/Agricultural land	Forest	Urban
0 m < *h* ≤ 0.25 m	0	0	0
0.25 m < *h* ≤ 0.75 m	0	0.5	1
h > 0.75 and/or *v* > 2 m/s	0.5	1	1

Table 3: *DF* for different *h* and v values and different land uses

Based on the FHR values, vulnerability values related to people, V_P, can be calculated. One assumption is that people are vulnerable at water heights greater than 0.25 m. People located in “hospital and social assistance structures”, whose vulnerability is considered as 1 for FHR>0.75 represents an exception because the physical condition of people living in such structures makes them more vulnerable. The concepts described above are summarized in Figure 3.

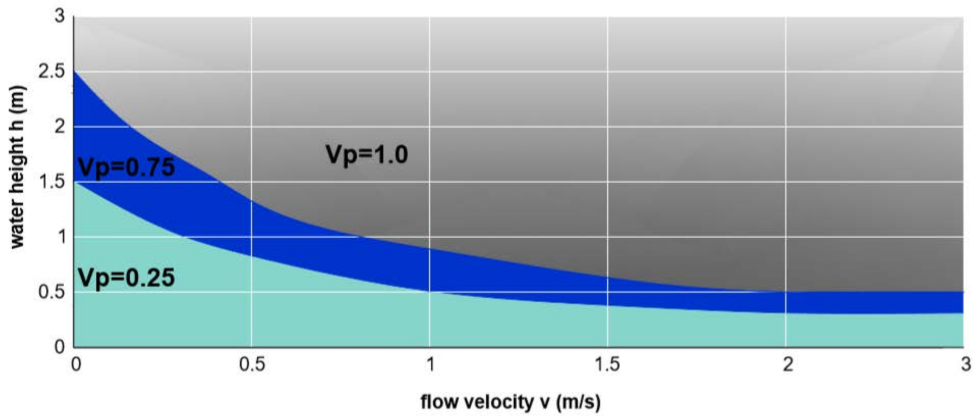

Figure 3: Vulnerability values for people as a function of *h* and *v*

Regarding the evaluation of the adaptive and coping capacities, the method adopted is based on the hierarchical combination of indicators as shown in Figure 4, where the weights used in the calculation procedure are reported in brackets. The data related to social indicators have different units of measurement. Therefore, to be able to compare them, it is necessary to adopt a normalization procedure using value functions (Mojtahed, et al., 2013).

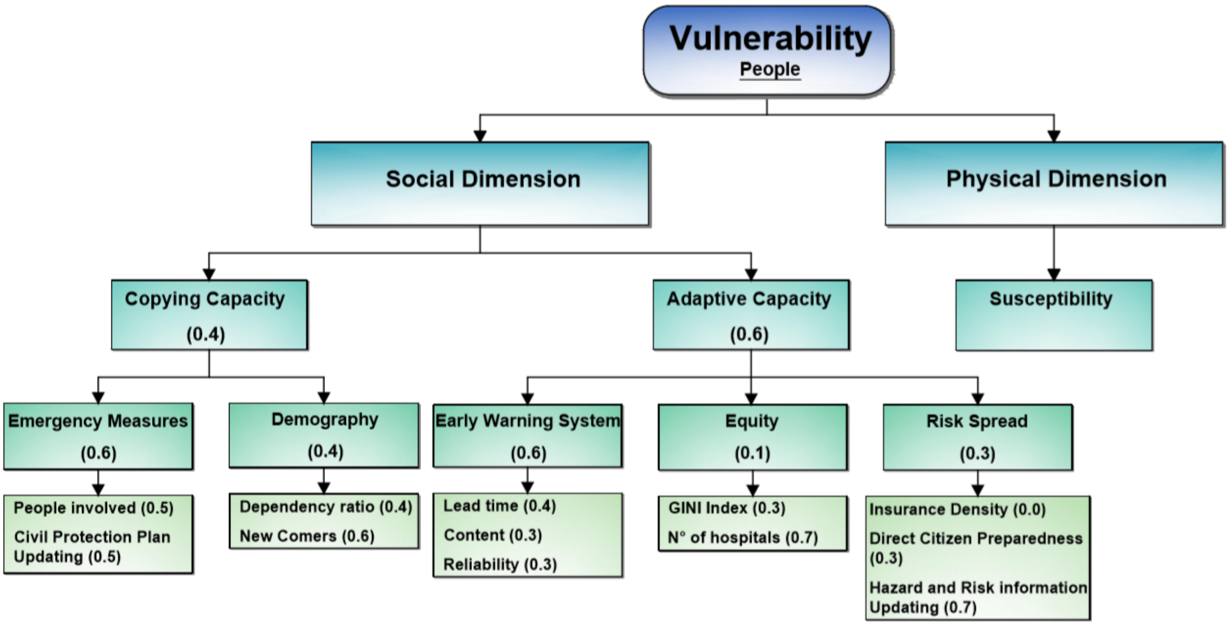

Figure 4: Hierarchical combination of indicators and relative weights

Below are the variables and related normalized functions (Figure 5) that have been identified for evaluation of the Coping Capacity:

- the Dependency ratio, which is calculated as the ratio between the number of citizens under the age of 14 and over 65 compared to the total population; a population with a high value of this index implies a reduced ability to adapt to calamitous events;
- the number of immigrants present in the area; it is likely that a society with a high number of immigrants will react with more difficulty after a flood event and during an emergency situation, for example, due to language barriers and cultural habits;
- the number of people involved in the emergency is represented by the number of operators who have been trained to manage an emergency; and
- the frequency with which contingency plans are updated, taking new hydraulic, urban and technological information available into account.

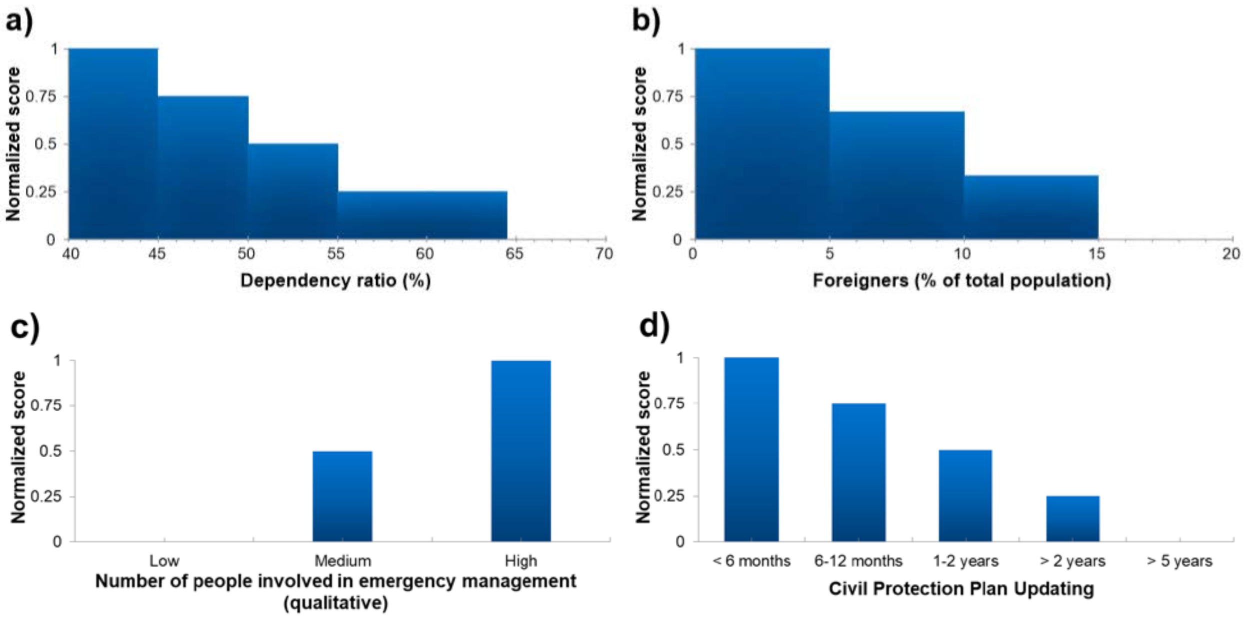

Figure 5: Normalized index functions for Coping Capacity evaluation

Similarly, for the Adaptive Capacity, the variables and related normalized functions (Figure 6) are given below as:

- the Gini Index, which is calculated as a measure of the inequality of income distribution within the population; an index equal to 0 means perfect equality in terms of economic health;
- the number of hospital beds calculated per 1000 people;
- the frequency of updating information and the ability to communicate the conditions of danger and risk by institutions;
- the direct preparation of the citizens, calculated based on the number of students, associations such as farmers and professionals, citizens reachable across large areas through social networks (WP7 WSI Team, 2013) involved in the dissemination of information. The value in Figure 6d indicates the maximum achievable in the situation where all citizens are involved that belong to this category.

The normalized functions used in the calculation of these indices are shown in Figure 6.

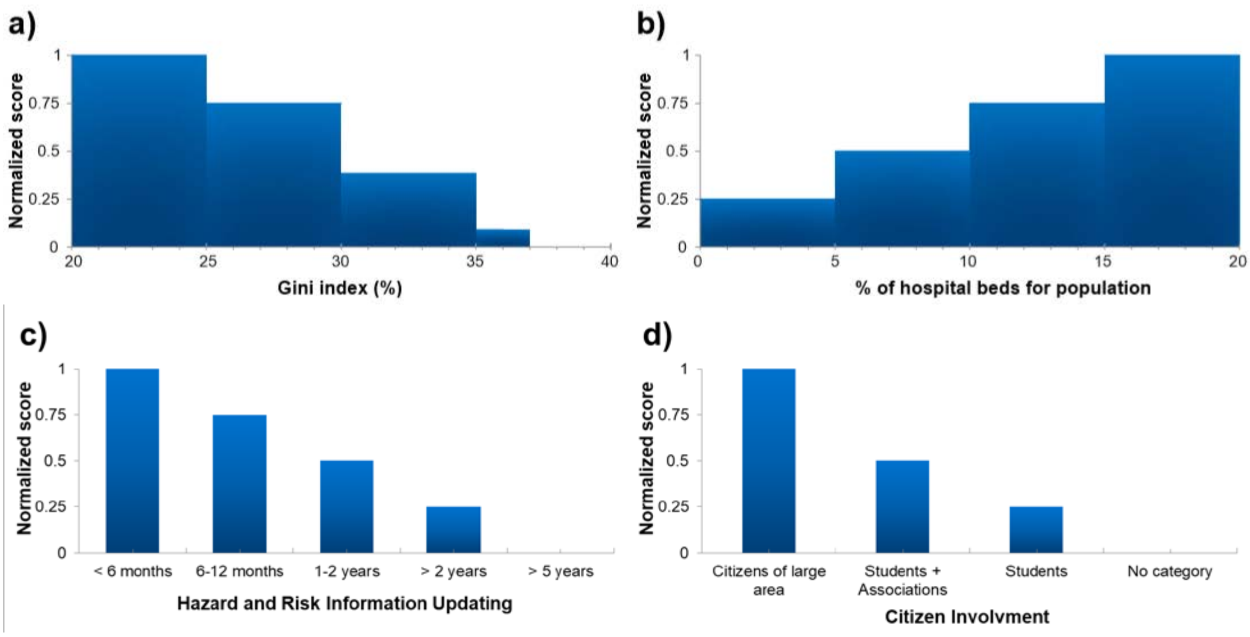

Figure 6: Normalized index functions for Adaptive Capacity evaluation

Forecasting systems are evaluated according to the value functions shown in Figure 7, which include:

- Lead time (or warning time), which is the amount time for providing information as the event approaches;
- Information Content, which is 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; and
- Reliability, which is linked to the uncertainty of the results from the meteorological hydrological models (Schroter et al., 2008). A false alarm can cause inconvenience to people and economic activities and should, therefore, be minimized.

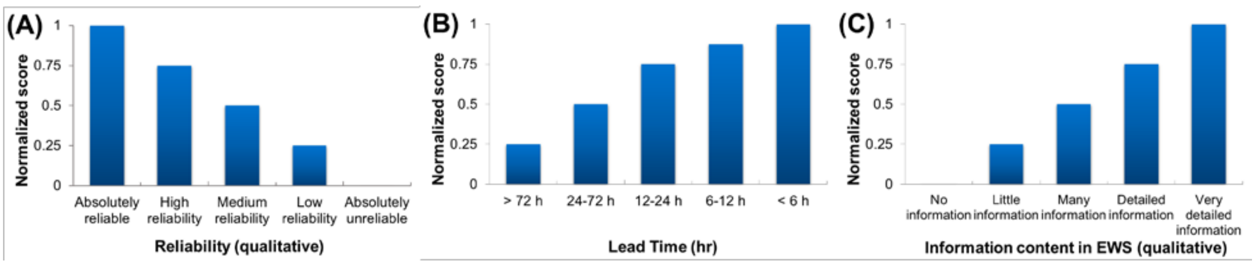

Figure 7: Normalized function of the indices linked to the forecasting systems: A) reliability, B) warning time, C) information

(ii) Economic activities

The vulnerability of economic activities is denoted as V_E. The economic activities are referred to land use categories in Table 1. Concerning buildings (categories 1, 2, 3, 4, 5, 14, 15, 17, 18, 19, 23 of Table 1), they can collapse due to water pressure, undermining of foundations or a mixture of these causes. It should also be noted that the solid material, such as debris material and wood, can be carried by a flood and can cause damage to structures.

The formulation proposed by Clausen and Clark (1990) for brick and masonry buildings was modified to take into account the evaluation made by Risk Frontiers, an independent research centre sponsored by the insurance industry, about the potential losses to indoor goods from flood damage. Laboratory results have shown that at a water height of 0.5 m, the loss to indoor goods is already around 50%. The structural vulnerability of buildings and the associated indoor goods (V_E of buildings) is shown in Figure 8. Considering camping (category 11 in Table 1), the values have been modified based on results found in Majala (2001).

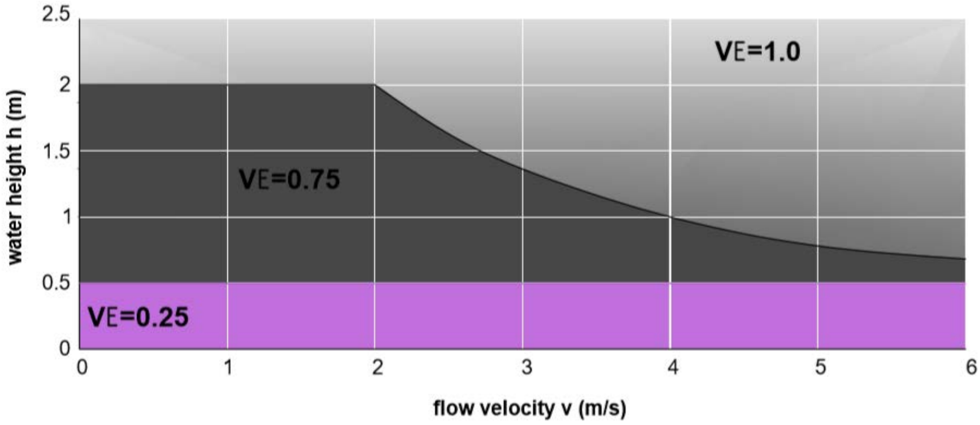

Figure 8: Vulnerability values of buildings as a function of *h* and *v*

For the land use classes corresponding to network infrastructure (categories 12 and 13 in Table 1), vulnerability depends on the impossibility of using the infrastructure and therefore on the interruption of the service. This could occur with or without structural damage to the infrastructure (i.e., simple inundation or destruction of the good).

Based on the estimation of the water height and the critical velocity for the stability of vehicles during a flood, which are derived from direct observation in the laboratory experiments of Reiter (2000), the vulnerability function for road infrastructures (V_E road) is presented in Figure 9.

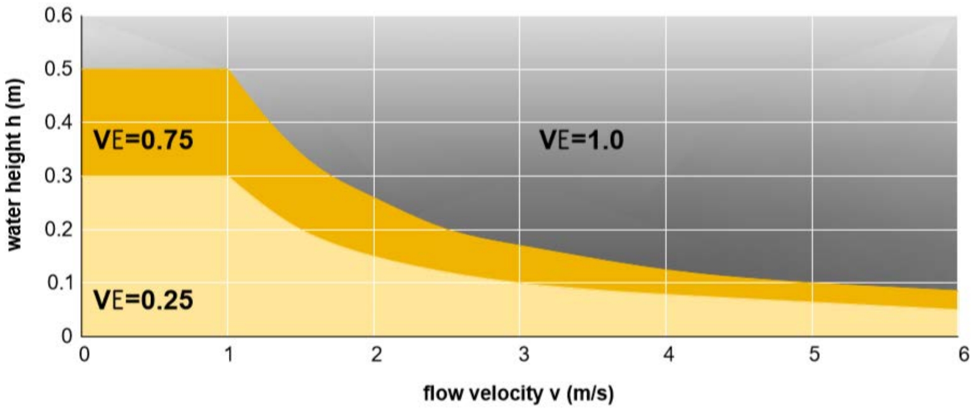

Figure 9: Vulnerability values of network infrastructure as a function of *h* and *v*

Regarding technological and service networks (category 16, Table 1), vulnerability is only assumed to exist for water height and flow velocity greater than 2 m and 2 m/s, respectively, and the V_E is equal to 1.

To assess the vulnerability in agricultural areas (categories 6 and 7 of Table 1), it is assumed that the damage is related to the loss of harvest, and when considering higher velocity and height values, to buildings and internal goods. It then becomes clear that the highest tolerable height of water that can submerge agricultural land depends on the cultivation type and vegetation height. To this end, Citeau (2003) gives some examples taking into account height and velocity of the flow: maximum height is 1 m for orchards and 0.5 m for vineyards; 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 degradation of the soil due to erosion. These evaluations are shown in Figure 10.

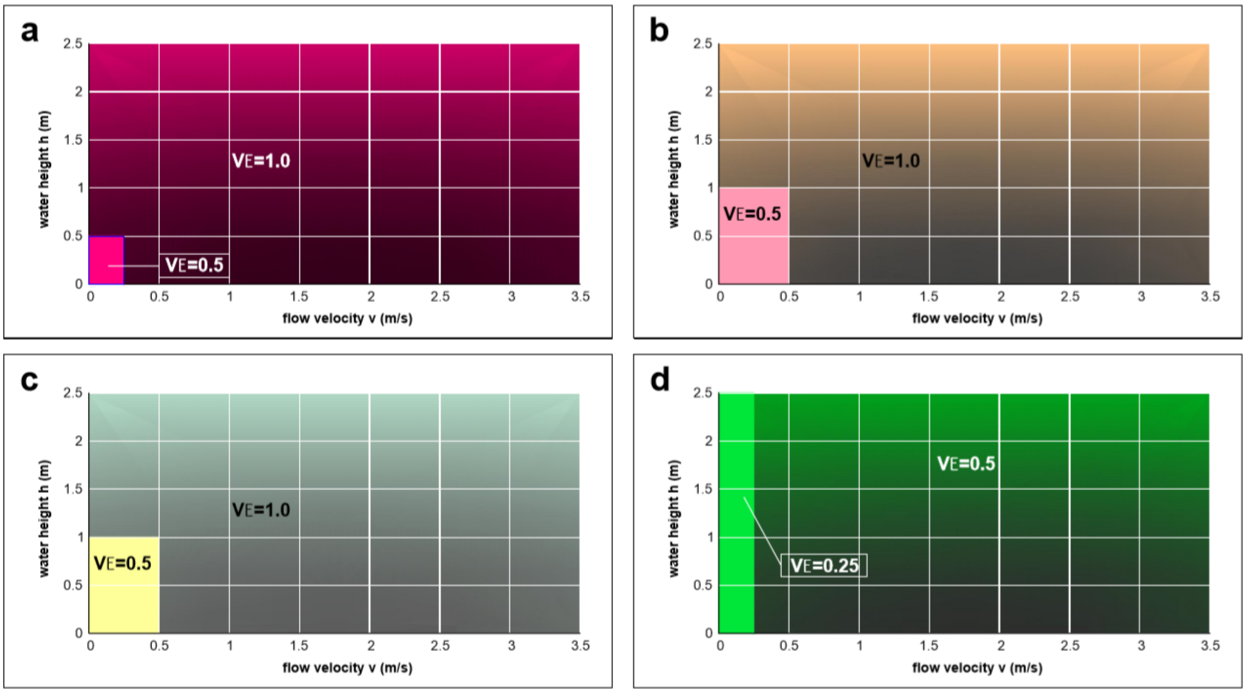

Figure 10: Vulnerability values relative to h and v of: (a) vineyards (b) orchard and olive tree (c) vegetables (d) natural and semi-natural environment

In the case of unproductive land (category 9 of Table 1), V_E is assumed to be 0.25, regardless of the *h* and *v* values.

(iii) <u>Environment and cultural heritage</u>

The vulnerability of economic activities is denoted as V_A. Evers (2006) describes the environmental flood susceptibility through three indicators: contamination/pollution, erosion and open space. Contamination is essentially caused by 3 sources: industries, animal/human wastes and stagnation of flooded water. Erosion can produce disturbance to the land surface and to vegetation and can also damage infrastructure. Open spaces are natural areas used for recreational activities, such as tourist attractions and natural protected areas.

The approach proposed is to identify the protected areas that could potentially be damaged by a flood. In the case of the presence of susceptible areas in relation to nutrients, including those identified as vulnerable in Directive 91/676/CEE (Nitrate) and areas defined as susceptible in

Directive 91/271/CEE (Urban waste), we assume a value of 1 for vulnerability (category 20 of Table 1).

Similarly, in the areas identified for habitat and species protection, including the sites belonging to the network Natura 2000 established in accordance with the Habitat Directive 92/43/CEE and with the Birds Directive 79/409/CEE (categories 8 and 22 of Table 1), the presence of Integrated Pollution Prevention and Control (IPPC) installations and/or other relevant pollution sources are evaluated. In these situations, vulnerability is 1. In all other situations, the area is managed following the relationships provided in Figure 10d.

The elements classified as “cultural heritage” are considered by the EC as one of the potential adverse consequence categories in association with a future flood event, taking into the account the limits defined in art. 1 of the Flood Directive. Currently, it is not possible to establish the specific vulnerability of single goods depending on the flood characteristics, neither has it been possible to define a scale of values regarding the relative importance of such goods in category 21 of Table 1. Therefore, subject to an in-depth analysis that allows for a different type of differentiation, we associate a vulnerability of 1 to such elements using a conservative approach.

Exposure

With reference to the three macro-categories from the EU Flood Directive (i.e., people, economic activities and environmental/cultural-archaeological assets affected), the method for quantifying the exposure is described below.

(i) People

Here the exposure of the population is characterized by two factors. The first is related to the number of people living in an area and is expressed by a density factor (*Fd*), expressed by four classes (Table 4).

Number of people	F_d
1 ÷ 50	0.90
51 ÷ 100	0.95
101 ÷ 500	0.98
> 500	1

Table 4: Factor characterizing density of human presence (F_d)

The second is the duration factor (F_t), which is calculated as the ratio between the duration spent in certain locations (e.g., houses, schools, etc. - see the categories listed in Table 1) to 24 hours in a day (Provincia Autonoma di Trento, 2006). The exposure related to people (E_P) is therefore calculated as:

$$E_p = F_d * F_t \quad (6)$$

(ii) Economic activities

With regard to legal obligations from the EU Flood Directive, the spatial distribution and the type of economic activities located in the areas of flood risk must be determined. Then an assessment of the potential negative consequences for the different activities must be provided. The relative exposure of economic activities (*EE*) is expressed by the restoration costs, the costs resulting from missed production and service losses. These are calculated for each of the land use categories provided in Table 1.

(iii) Environment and cultural heritage

Similar to the previous categories, to define the exposed value for the environmental component (E_A), we calculated relative values for the different land use categories, taking into account the possible modification caused by the adverse event relative to the environmental structure of the elements involved (Provincia Autonoma di Trento, 2006).

Table 5 lists the values that were calculated for E_P, E_E and E_A for each land use type.

ID	Description	E_P	E_E	E_A
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	Unskilled agricultural, 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	Communication and transportation networks: roads of primary importance	0.5	1	0.2
13	Communication and transportation networks: 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, Area for collective supra-municipal equipment, Collective equipment in the 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	Landfills, 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

ID	Description	E_P	E_E	E_A
21	Areas of historical, cultural and archaeological importance; cultural heritage	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

Table 5: The relative values of exposure for people, economic activities and environmental/cultural-archaeological assets by land use type

Calculation of total risk

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

$$R = \frac{w_p \cdot R_P + w_E \cdot R_E + w_A \cdot R_A}{w_p + w_E + w_A} \qquad (7)$$

where R_P, R_E and R_A represent the risk for the three macro-categories and w_P, w_E and w_A 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. To establish the level of risk (i.e., moderate, medium, high, very high), risk classes are introduced, as provided in Table 6.

Range of R	Description	Risk Category
$0.1 < R \leq 0.2$	Moderate risk for which social, economic and environmental damage are negligible or zero	R1
$0.2 < R \leq 0.5$	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 the functionality of economic activities	R2
$0.5 < R \leq 0.9$	High risk for which problems are possible for the safety of people, functional damage to buildings and infrastructures with consequent unavailability of the same, the interruption of functionality of socio-economic activities and damage related to the environmental heritage	R3
$0.9 < R \leq 1$	Very high risk for which loss of human life and serious injuries to people, serious damage to buildings, infrastructure and environmental heritage, destruction of socio-economic activities are possible	R4

Table 6: Definition of risk classes

The method described above produces the total risk for every point in the catchment that is analyzed, taking into account the three scenarios defined in art. 6 of the Flood Directive (as defined in the *Hazard* paragraph).

Development the IT platform for flood risk mapping purposes

Staff from Eastern Alps River Basin District (AAWA) has been working to the translation of the above described logics into one IT platform, designed to automatically elaborate Flood Risk Maps. Its main features are reported in the following.

Technical specifications	The platform is developed as a desktop Windows application (therefore not an online one), by employing Microsoft .NET programming tools.
Functional specifications	The system is expected to: • populate a database according to the schemes and approaches described in the WISE system (http://cdr.eionet.europa.eu/help/Floods/Floods_2018/index.html); • manage documentation (both in PDF format and URL link) associated to every element included in the above cited database; • perform controls on the correctness and completeness of entered information. In addition, data are generated in compliance with requirements from 2007/2/CE Directive (INSPIRE).
Subject: flood hazard mapping	*Thematism* The following thematism are provided for every return period: flooded areas; flood depth map; flood velocity map; flood hazard map. Such information can derive from the modeling results or can be estimated on the basis of the logics described in the *Methodological introduction* paragraph.
	The following functionalities are planned: • to assign a district code to every river trunk belonging to a specific network; • to provide different thematism, on the basis of the territory's partition in Units of Management (UoM, i.e. specific river basin districts defined by the user), including fields about the description of the UoM and its code; • to import needed thematism for flood hazard analysis; • to enable user to set the working projection system and import data characterized

<table>
<tr><td></td><td>by different projection systems;
to create, for one or more return periods, several scenarios by automatically uploading all the related information in raster format;
to launch a tool able to generate all the outputs demanded by the user, in .shp format, according to the approaches defined in the Methodological introduction paragraph;
to create reports abut the correct execution of tasks, including possible warning or errors;
to link flooded areas to relative river network: if there is no overlapping among river network and flooded areas, the system will generate a buffer, around the river centreline, in order to perform the connection. The buffer width can be defined by the user (defalut value is 200 m);
to identify flooded areas for which it was not possible to perform automatically any link with river network, so to enable the user to manually carry out the task;
to unify all the shapefiles, for every thematism, referred to a specif UoM;
to check the status of progression of activitites trough traffic light icons.</td></tr>
<tr><td rowspan="2">Subject: flood risk mapping</td><td>Thematism
The following thematism are provided for every return period: exposure of people, economic activities and environmental/cultural-archaeological assets; vulnerability of people, economic activities and environmental/cultural-archaeological assets; damage for people, economic activities and environmental/cultural-archaeological assets; risk for people, economic activities and environmental/cultural-archaeological assets.
Such information can be estimated on the basis of the logics described in the Methodological introduction paragraph.</td></tr>
<tr><td>The following functionalities are planned:
to upload all the information about the number of inhabitants for every flooded area;
to upload land use information for every flooded area;
to upload thematism about protected areas included in the Water Management Plan;
to unify all the shapefiles, for every thematism, referred to a specif UoM;
to check the status of progression of activitites trough traffic light icons.</td></tr>
</table>

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

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Abstract. 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 future flood risk in the Brenta-Bacchiglione catchment. 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 ofcitizen 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 improving the 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 can 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 developmentand 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 the most attention, while the focus on economic impacts, costs and benefits has been bothmore 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 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

[1]https://www.weobserve.eu/
[2]https://mics.tools/

implementation of a CO 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 CO in the same way as any other flood mitigation action for which a cost-benefit analysis would be undertaken in this catchment. Although the CO 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 BacchiglioneRiver basin. The main actors included thelocal 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 leveland 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 theBrenta-Bacchiglionecatchment followed by ongoing developments in the CO for flood risk management.

2.2The Brenta-BacchiglioneCatchment

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. 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.

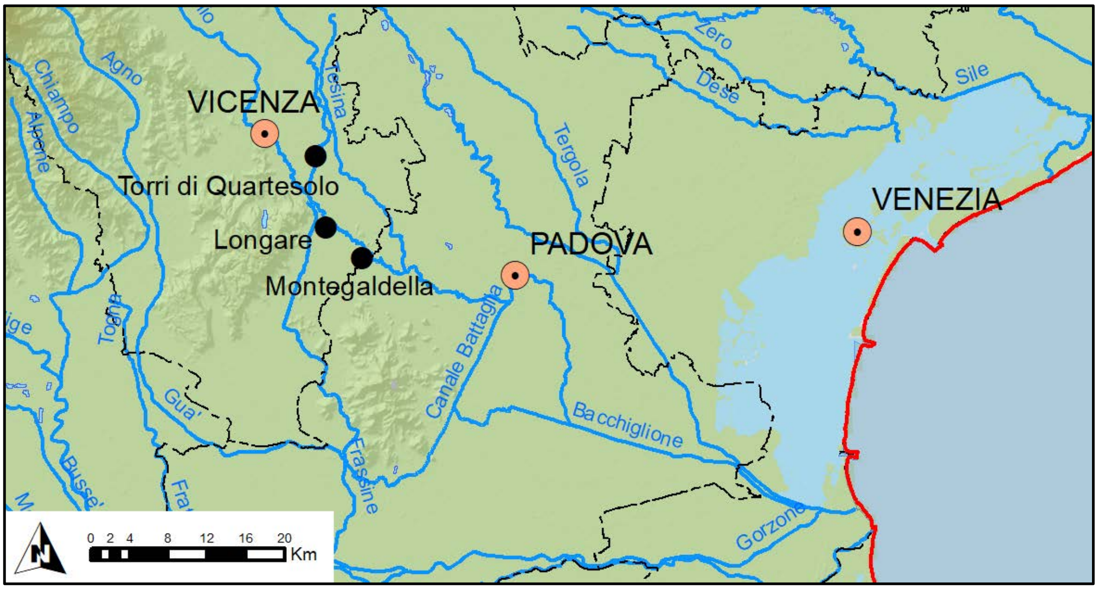

Figure 1:Location of the Brenta-Bacchiglione catchment and its urban communities.

2.3 The Citizen Observatory for Flood Risk Management for the Brenta-BacchiglioneCatchment

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 increasethe 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 expertswith official sensor data. Amobile app for data collection based on the WeSenseIt project is under development.The platform and mobile technologywill 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 through an agreement between the respective associationsand 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, whichincludes 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 participantscan provide, AAWA called upon technicians during two heavy rainfall events (November 2019; 5 days). These technicianscollected 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 two steps: (i) mapping of the flood risk (section 3.1); and (ii) quantification of the flood damage costs (section 3.2), which consider the flood risk with and without the implementation of the CO on flood risk management.

3.1Flood 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 is calculated 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 for three macro-categories asset out in the EU 2007/60/CE Flood Directive (EU, 2007): 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).

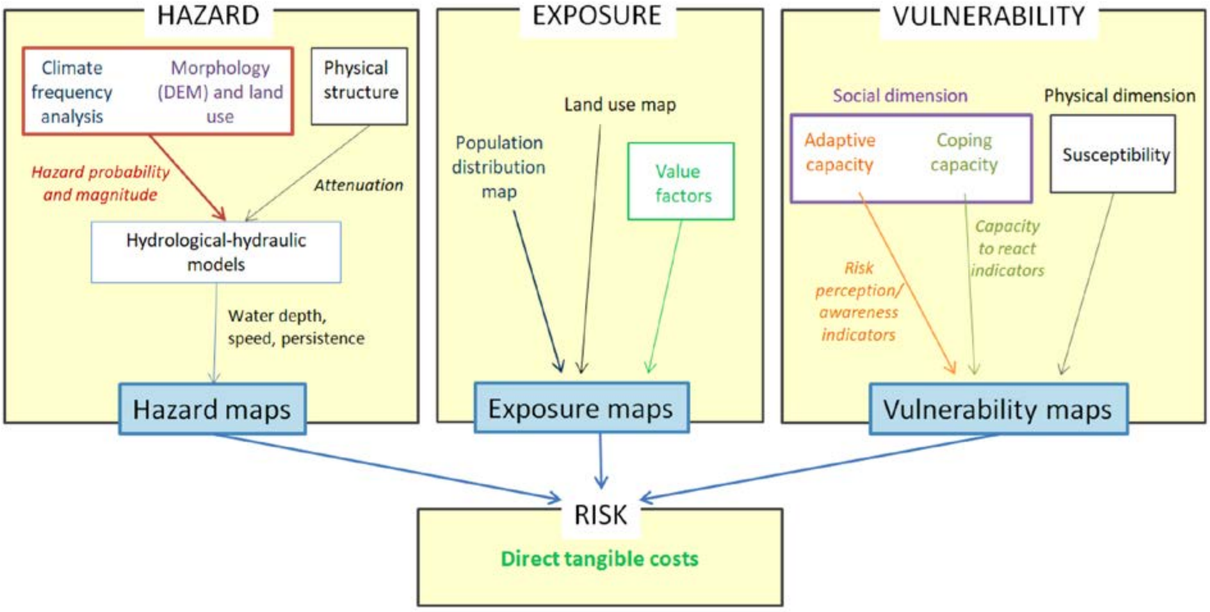

Figure 2: Flowchart outlining the determination of risk in a flood risk assessment context.

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) adaptivecapacity, which isthe 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). The model assumptions and the sources of uncertainty are summarized in Table S4 in the Supplementary Material.

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 velocityand 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 1: Input data used to calculate risk.

Component of risk	Data	Source
Flood Hazard (low, medium, high hazard scenarios)	Water height (m)	AAWA; see Supplementary Materials for model details
	Water velocity (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

3.1.2Flood Hazard Mapping

According to Article 6 of the 2007/60/CE Flood Directive (EU, 2007), when local authorities implement aFlood Risk Management Plan, three hazard scenarios must be considered:

1. A flood with a low probability, which is 300-year return period in 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 beencalculated using a two-dimensional hydrological and hydraulic model to generate the water levels and the flow velocities 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.

3.1.3Flood Exposure Mapping

The 2006 CLC map provides the underlying spatial information to calculate exposure; the land use classes used here are shown in Table S1in the Supplementary Materials. As mentioned above, the first macro-category is the people affected by the flooding, or the exposure of the population (E_P), which is calculated as follows:

$$E_p = F_d * F_t \quad (2)$$

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 theproportion of time spent in different locations (e.g., houses, schools, etc.,using the land use types listed in Table S1) over a 24 hour period(Provincia Autonoma di Trento, 2006). 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).

Table 2: A factor characterizing the densityof 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

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. The final macro-category, i.e., the exposure of assets in the environmental and cultural heritage category (E_{ECH}), is calculated from estimates of potential damage caused by an adverse flood event. These various costs were obtained from the ProvinciaAutonoma di Treno(2006) and have been calculated for each of the land use classes in Table S1.

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 inTable 3.These values have been derived by the ProvinciaAutonoma 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/culturalassets 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

ID	Description	E_P	E_E	E_{ECH}
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

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.

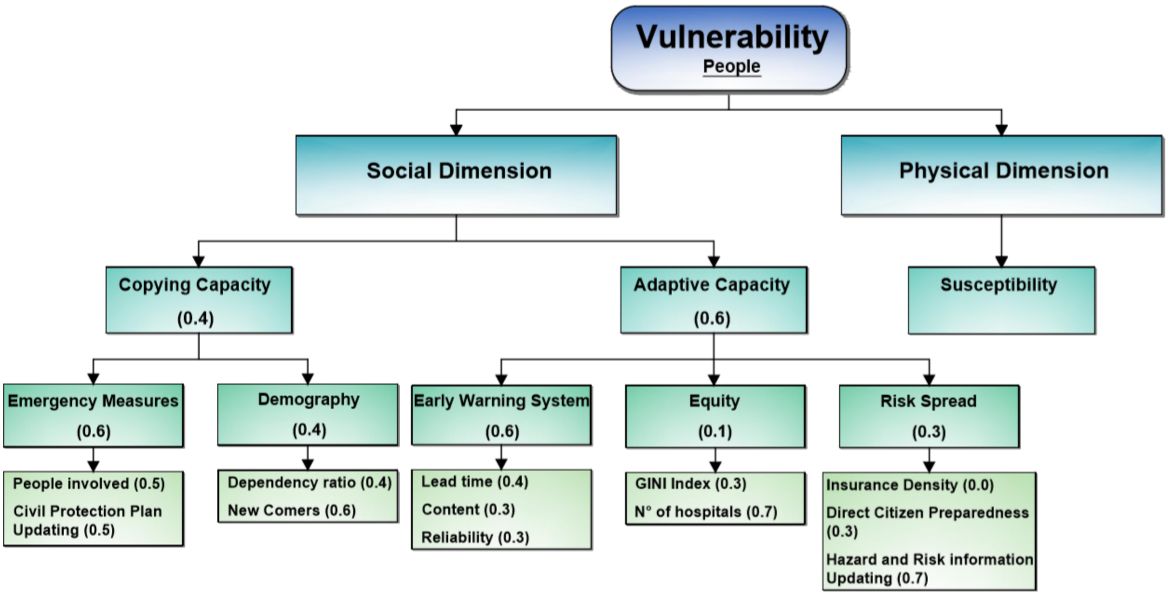

Figure 3: Hierarchical combination of indicators and relative weights (in brackets) to calculate the vulnerability of the population.

(i) Physical vulnerability of people affected by flooding

The physical vulnerability associated with people considers the values of flow velocity (*v*) and water height(*h*) 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), and critical values have been derived from the product of *h* and *v*. For example, Ramsbottom et al. (2004) and Penning-Rowsell et al. (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:

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

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: The Debris Factor (*DF*) for different water heights (*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 ORv> 2 m/s	0.5	1	1

Using the FHR, the physical vulnerability of the population can be calculated, which is summarized in Figure 4.

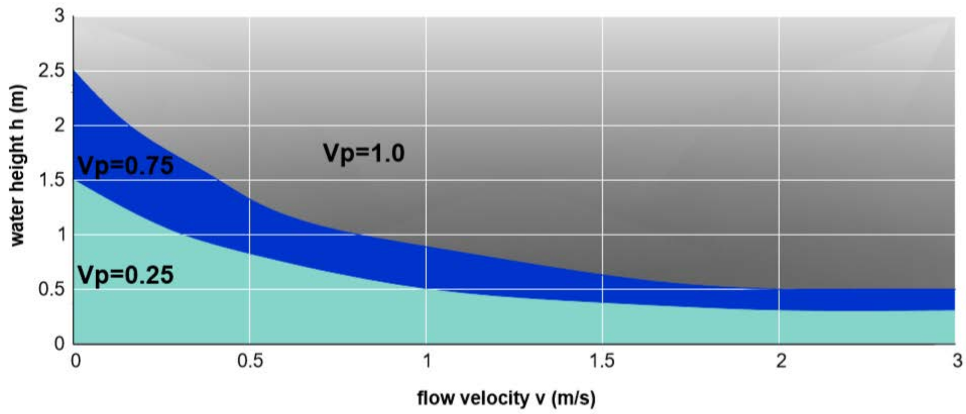

Figure 4:Physical vulnerability values for the population as a function of water height (*h*) and flow velocity (*v*).

(ii) Social vulnerability of people affected by flooding

Figure 3 shows the components of social vulnerability, i.e., the adaptive and coping capacityand 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 representsa 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 as a percentage of the total population. 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. Due to language barriers and other cultural reasons, areas with a high number of immigrants may not cope as well after a flood event and during emergency situations.
- 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.
- 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 incorporated intocivil protection plans.

The adaptive capacity is comprised of three components: the early warning system, equity and 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). 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 isthe 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 S3d show the maximum achievable value in the three categories of citizen involvement.

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 considers buildings, network infrastructure and agricultural areas. For buildings, 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). Laboratory results have shown that at a water height of 0.5m, the loss to indoor goodsis 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 buildings and losses of associated indoor goods is shown in Figure S4 as a function of the height of the water and flow velocity, which are applied to land use types containing buildings (Table S1). For the camping land use type 11 (Table S1), the values have been modified based on results fromMajala(2001).

Vulnerability of the road network is evaluated for land use types 12 and 13 in Table S1, which occurs when it is not possible to use the road due to flooding. 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 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 S5.Regarding technological and service networks (land use type 16, Table S1), we assume a vulnerability value equal to 1 if the water height and flow velocity aregreater than 2 m and 2 m/s, respectively, otherwise 0.

To assess the vulnerability in agricultural areas (land use types 6 and 7 in Table S1), we assume that the damage is related to harvest loss, and when considering higher flow velocities and water heights, to agricultural buildings and internal goods. Citeau(2003)provides relationships that take water heightand 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 heightand flow velocity are shown in Figure 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.

(iv) Physical vulnerability of environmental and cultural heritage assets affected by flooding

Environmental flood susceptibility is described using contamination/pollution and erosion as indicators. Contamination is caused by industry, animal/human waste and stagnantflooded waters. Erosion can produce disturbance to the land surface and to vegetation but can also damage infrastructure. The approach taken here was to identify protected areas that could potentially be damaged by a flood. For areas 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 S1).Similarly, in 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 S1), the presence of relevant pollution sources wasidentified (Tables 1 and S1)and assigned a vulnerability of 1. In the absence of pollution sources, the vulnerability was calculated as 0.25 if the flood velocity was less than or equal to 0.5 m/s and the water heightwas less than or equal to 1 m; otherwise it was 0.5.Regarding cultural heritage (land use type 21 in Table S1), we assigned a vulnerability of 1 to these areas.

3.1.5Mapping 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:

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

where *H*, *E* and *V* are the hazard, exposure and vulnerability associated with the three macro-categories *P*, *E* and *ECH* 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 undertaken by AAWA. To establish the level of risk, four risk classes were defined (

Table 5).

Table 5: Definition of risk classes.

Range of R	Description	Risk Category
0.1 < R ≤ 0.2	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/cultural heritage is possible, which does not affect the safety of people, the usability of buildings or 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 environmental/cultural heritage	R3
0.9 < R ≤ 1	Very high riskincluding loss of human life and serious injuries to people, serious damage to buildings, infrastructure and environmental/cultural heritage, and total disruption of socio-economic activities	R4

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 to1. 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

3.2Financial quantification of the direct damagedue to flooding with and without implementation of a flood risk management CO

To estimate the direct tangible costs due to damage resulting from a flood event, we use the maximum damage functions related to the 44 land use classes in the CLCdeveloped by Huizinga (2007) for the 27 EU member states, which arebased 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 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 associated with each 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 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):

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

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

where w_{Dj} is the weight of the damage class, *j* is the damage categoryand *D* is the damage value shown in Table S3. The EAD is calculated before and after implementing the CO for flood risk management.The monetary benefits are the "avoided" damage costs (to people, buildings, economic activities, protected areas, etc.) if the CO for flood risk management is implemented.

4 Results

4.1 Flood risk estimation without implementation of a flood risk management CO

4.1.1Hazard and risk

The results of the numerical simulations from the hydraulic model, which werecarried out based on the methodology described in 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 haflooded, additionally affecting agricultural areas. The results of the simulations are summarized in Tables 7 and 8 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 7: 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)		
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 8: The risk classes for each return period in terms of area floodedbefore 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 ofPadua for a 100-year flood event. Risk classes R1 (lowrisk) 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.

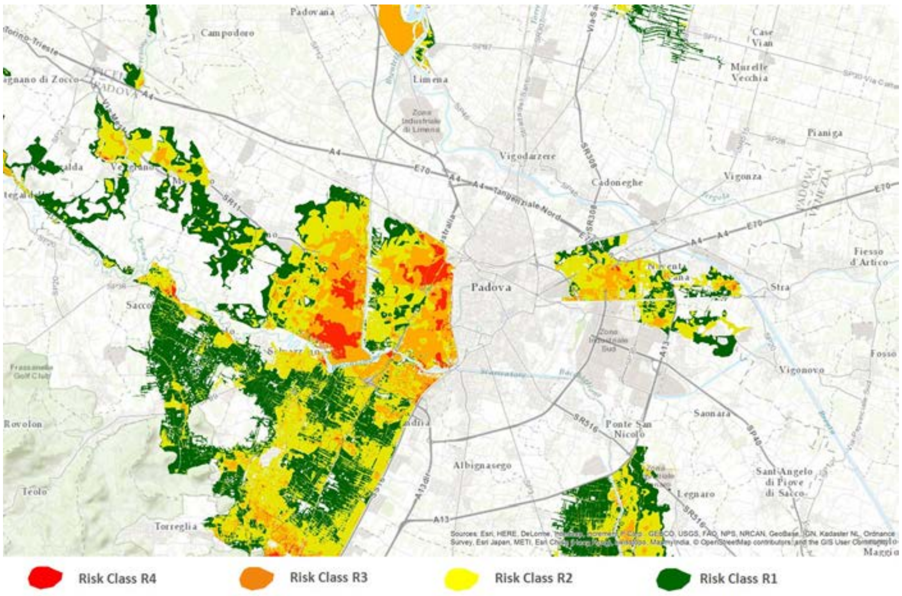

Figure 5:Risk map for the metropolitan area of Padua for a 100-year flood event before implementation of a CO on flood risk management.

4.1.2Expected damage

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),whichis summarized in Table 9.

Table 9: Direct damage (without the CO) for three flood scenarios.

Scenarios (chance of flood occurrence)	**Return period**	**Damage (million €)**
High	30 years	7,053
Medium	100 years	8,670
Low	300 years	10,853

In the event of very frequent flood events, urban areas will bedamaged. Furthermore, 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 patterns can be observed when comparing floods with a low and high probability of occurrence. Substituting the values in Table 9 into equation (5), we obtain an expected average annual damage (EAD) of 248.5 million Euros.

4.2 Flood risk estimation with the implementation of a flood risk management CO

4.2.1Hazard and risk

As mentioned previously, the hazard remains unchanged (i.e., the results reported in Table 7), but the risk is reduced after implementation of a CO for flood risk management as shown in Table 10 due to the reductions in vulnerability outlined in section 3.1.5.The areas affected in the 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 isshown in Figure 5.

Table 10: The risk classes for each return period of flooding in terms of area 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

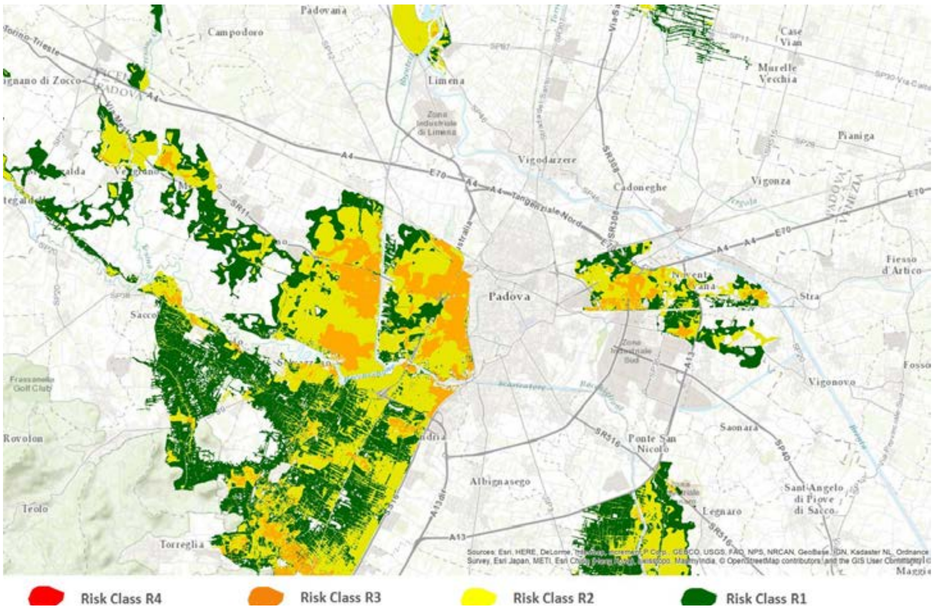

Figure 6:Risk map for the metropolitan area of Padua for a 100-year flood event after implementation of a CO on flood risk management.

4.2.2Expected damage

The residual damage was calculated for the three flood scenariosafter implementation of the CO on flood risk reduction, which is shown in Table 11.Substituting theseresidual damage values into equation (5), we obtain an EAD of 111.3million Euros, which is a 45% reduction in the damage compared to results without implementation of the CO.

Table 11: Comparison of the direct (without CO) and residual damage (with CO) for three flood scenarios and the cost difference.

Scenarios (chance of flood occurrence)	**Return period**	**Direct damage (million €)**	**Residual damage (million €)**	**Difference in costs (million €)**
High	30 years	7,053	1,573	-5,480
Medium	100 years	8,670	5,440	-3,230
Low	300 years	10,853	3,420	-7,433

The CO for flood risk management hasan estimated cost of around 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 137.2 million Euros. Hence the benefits considerably outweigh the costs. The same methodology was applied to the construction of a retention basin in the municipalities of Sandrigo and Breganzeto improve the hydraulic safety of the BacchiglioneRiver. Against an expected cost of 70.7 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 city of Padua. In terms of damage reduction with the construction of the retention basin, we would obtain an EAD of140.7 million Euros so the cost to benefit ratio would be much lower.

5 Discussion and Conclusions

There is currently a lack of available, appropriate and peer-reviewed evaluation methods and evidence on the added value of citizen observatories, which is required beforethey will be more widely adopted by policy makers and practitioners. This paper has aimed to fill this gap by demonstrating how a traditional cost-benefit analysis 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 smaller Bacchiglione catchment to guide changes in the values associated with social vulnerability once the CO is implemented. This allowed the risk and flood damages to be calculated with and without implementation of the CO, which showed that implementation of a CO in the Brenta-Bacchiglione catchment is able to reduce the damage, and consequently the risk, for the inhabited areas from an expected average annual damage (EAD) of €248.5 to €111.3 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.

We do acknowledge that this methodology is built on many assumptions, i.e., the numerous coefficients, value functions and weights used to estimate the exposure and vulnerability. We have summarized these assumptions in Table S4 of the Supplementary Material. Many of these values have been derived through expert consultation and experience, and they been validated internally within AAWA or by 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. We have tried to reflect this in Table S4. Other values have been derived from the literature, all of which will have some uncertainties associated with their derivation. The primary objective of the paper was never to do a fully-fledged uncertainty analysis but to present a methodology that could be shared with experts, and local and national authorities, to evaluate the potential of a CO solutionin monetary terms with regards to reducing the vulnerability of flood risk. The weights adopted and the assumptions made, which depend on the policies and the local context of the study area, do not affect the value of the method presented, which can be applied to other river basins with the adoption of different weights.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. Our goal will then be to verify the assumptions and the empirical weight factors adopted,via a more detailed quantitative analysis.

Another limitation of the analysis presented here is that we 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). In accordance with other authors (e.g., van der Veen et al., 2003), all expenses related to disaster response (e.g., costs for sandbagging, evacuation) are classified as indirect damage.However, the presence of the CO in this catchment does 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 wheremonetary 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 propagation in surface waters during the flood or the duration of the flood event,all of which could be taken into account in estimatingthe structural damage and monetary losses in the residential, commercial and agricultural sectors.

Despite these various limitations, this analysis has highlighted the feasibility of a non-structural flood mitigation choice such as a COfor 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.The evidence on the costs and benefits of COs for flood risk management generated by this case study 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 flood risk management practices.In Italy, in general, citizen participation in flood risk management has been relatively limited. 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. The previous strategy in the Brenta-Bacchiglione catchment has focused on structural flood mitigation measures, dealing with emergencies and optimizing resources for rapid response.The inclusion of a CO on flood risk management has been a true innovation in the flood risk management strategies of this region.Future research will focus on validating the results once the CO is operational as well as application of the methodology in other catchments and to other fields of disaster management beyond floods. Such applications will serve to generate a broader evidence base for using these types of cost-benefit methodologies to justify the implementation of COs in the future.

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Supplementary Material: 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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Hydrological and Hydraulic Modelling

The flood forecasting system developed for the Brenta-Bacchiglione River basin ingests meteorological forecasts and couples this with a hydrological-hydraulic model to predict flood events (i.e., water levels in the river, depth of flooding in flooded areas). The hydrological model can run in a continuous mode, fed by meteorological data based on different weather forecasting models (i.e., COSMO, ECMWF, MOLOCH, HIRLAM) or using real-time data. It is also coupled with a snow melt module (UEB - Utah Energy Balance Model (Tarboton and Luce, 1996)) and a data assimilation module to assimilate measured data, including observations sent by the citizen observers (i.e., water levels of the river) (Mazzoleni et al., 2017, 2018).

The hydraulic model uses the HEC-RAS software (a numerical model developed by the US Army Corps of Engineers Hydrologic Engineering Center) and can perform one and two-dimensional hydraulic calculations for a full network of natural and constructed channels. The hydrological model provides the initial boundary conditions to the hydraulic model. The hydraulic model uses geometry acquired from LIDAR data.

The outputs of the model consist of a time series of water levels evaluated at all river cross-sections across all river branches. For each of these river cross-sections, a set of three thresholds has been defined by the Civil Protection authorities. The third threshold refers to the situation when the river will overtop the bank and thus lead to flooding. The system has been used to run rainfall-runoff and hydrodynamic simulations and to provide short-term predictions (2-3 days in advance) to the authorities.

The hydrological model used in this study is part of the earlywarning system implemented and used by Alto-Adriatico Water Authority (AAWA). A description of the model is provided here but the reader is referred to Ferri et al. (2012) and Mazzoleni et al. (2017) for more detailed descriptions.The hydrological response of the catchment is estimated using a hydrological model that contains routines for runoff generation and a routing procedure. The processes related to runoff generation (i.e., surface, sub-surface, and deep flow) are modelled mathematically by applying the water balance to a control volume representative of the active soil at the sub-catchment scale. The water content, *S*, in the soil is updated at each calculation step, *dt*, using the following balance equation:

$$S(t+dt)= S(t)+P(t)– R(t) -R_{sub}(t)– L(t) - E_T(t) \quad (1)$$

where P and E_T are the components of precipitation and evapotranspiration, respectively, while R, R_{sub}, and L are the surface runoff, subsurface runoff, and deep percolation model states, respectively. The surface runoff, R, is based on specifying the critical threshold beyond which the mechanism of Dunnian flow (i.e., the saturation excess mechanism) prevails:

$$R(t) = \begin{cases} C\left(\dfrac{S(t)}{S_{\max}}\right)P(t) \Rightarrow P(t) \le f = \dfrac{S_{\max}(S_{\max} - S(t))}{(S_{\max} - CS(t))} \\ P(t) - (S_{\max} - S(t)) \Rightarrow P(t) > f \end{cases} \quad (2)$$

where C is a coefficient of soil saturation obtained by calibration, and S_{max} is the content of water at saturation point, which depends on the nature and use of the soil.

The subsurface flow is considered proportional to the difference between the water content, S, at time, t, and that at soil capacity, Sc:

$$R_{sub}(t) = c(S(t) - S_c) \quad (3)$$

while the estimated deep flow is evaluated according to the expression proposed by Laio et al. (2001):

$$L(t) = \frac{K_s}{e^{\beta\left(1-\frac{S_c}{S_{\max}}\right)}-1}\left(e^{\beta\left(\frac{S(t)-S_c}{S_{\max}}\right)}-1\right) \quad (4)$$

where K_S is the hydraulic conductivity of the soil in saturated conditions and the dimensionless exponent is characteristic of the size and distribution of the pores in the soil. The evapotranspiration is assumed to be a function of the water content in the soil and potential evapotranspiration, calculated using the formulation of Hargreaves and Samani(1982).

Knowing the values of R, R_{sub}, and L, it is possible to model the surface, Q_{sur}, sub-surface, Q_{sub}, and deep flow, Q_g, routed contributions based on the conceptual framework of the linear reservoir at the closing section of a single sub-catchment. In the case of Q_{sur}, the value of the parameter k, which is a function of the residence time on the catchment slope, is estimated by relating the velocity to the average slope length. However, one of the challenges is to properly estimate the velocity, which should be calculated for each flood event (Rinaldo and Rodríguez-Iturbe, 1996). This velocity is a function of the effective rainfall intensity and the event duration(Rodríguez-Iturbe et al., 1982). In each sub-catchment, the runoff propagation is carried out based on the geomorphological theory of hydrologic response. The overall catchment travel time distributions are considered as nested convolutions of statistically independent travel time distributions along sequentially connected, objectively identified, smaller sub-catchments. Regarding Q_{sub} and Q_g, the value of $k$was calibrated, comparing the observed and simulated streamflow at Vicenza. Calibration of the hydrological model parameters was performed by AAWA, and is described in Ferri et al. (2012), which uses the time series of precipitation from 2000 to 2010 to minimize the root mean square error between observed and simulated values of water levels at the ARPAV (Veneto Region Environmental Protection Agency) gauged stations located along the river network (i.e., Bolzano Vicentino, Longare, Lugo di Vicenza, Montegalda, Ponte Marchese, S. Agostino and Vicenza).

Based on requirements in Article 6 of the 2007/60/CE Flood Directive (EU, 2007), the hydrological and hydraulic models described above wereused to run three hazard scenarios as part of the Flood Risk Management Plan of the Eastern Alps Hydrographic District:

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

As a compromise between computational burden and result validity, the following modeling hypotheses were assumed for evaluating the hydrographs of the three return periods:

1. The return period refers to the rainfall volume at a certain time step. This simplification was applied to avoid having to consider the cumulative probability of multiple variables, such as temperature, snow water equivalent, soil moisture conditions and status of the levees during the weather event;
2. The hydrological model did not run in continuous mode but on an event basis;
3. Snow accumulation/melting and evapotranspiration processes were not simulated;
4. The initial conditions of the variables, which affected the estimation of effective rainfall, were determined by calibration, considering the heaviest rainfall event ever recorded in the catchment under investigation as the reference scenario. This approach allows for the potential underestimation due to the simplifications assumed in point 3 to be taken into account.

To estimate the Intensity-Duration-Frequency (IDF) curves associated with different return periods, a Gumbel distribution was applied to the rain gauge data covering a sufficiently long time period (i.e., at least 20 years) to guarantee the statistical significance of the outputs. The hyetograph shapes were determined by considering the trends of past extreme weather events that occurred in the territory. They were generated by assuming the following shapes: uniform; monotone increasing; triangular isosceles; and double peak; and were the result of a random binomial multiplicative process(Gupta and Waymire, 1993).Based on the results of simulations with different flood events, the reference hydrograph for an assigned return time was chosen based on maximum values at the peak while maintaining an adequate volume.

Table S1: The land use classes used inthe calculations of flood exposure and vulnerability

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 Citizen Observatory (CO) for Flood Risk Management has an estimated cost of around 5 million Euros. Table S2 provides a breakdown of these costs.

Table S2: The costs of the components of the Citizen Observatory (CO)for Flood Risk Management

Component of the CO	Cost (€)
Purchase and installation of sensors for environmental monitoring (including 5 year maintenance)	1 000 000
Implementation of a forecasting system coupled with a data assimilation module (including 5 year maintenance, hardware, software licences)	750 000
Implementation of a decision support IT platform for sensor data storage, alarm setting, communication services (including 5 year maintenance)	600 000
Implementation of information and communication campaigns aimed at the participants of the CO (citizens, students) for maintaining their involvement and improving their flood risk awareness and preparedness (5 year program)	860 000
Expert involvement of technicians in the environmental monitoring of floods (5 year duration)	400 000
Total cost including administrative costs, incentives and VAT (22%)	**4 900 000**

Table S3: Maximum flood damage values (€ / m^2) 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

Table S4: Model assumptions and sources of uncertainties

<table>
<tr><th colspan="2">Component</th><th>Assumptions/Sources of uncertainty</th><th>Source of data or assumptions</th><th>Explanations and implications</th></tr>
<tr><td>Flood hazard</td><td>Area and depth flooded, flow velocity</td><td>The model is applied to all areas that could be affected by river flooding and/or a failure of the levees during a flooding event of a certain probability. Concerning the possible failure of the levees, water infiltration (i.e., siphoning) is not considered; a failure was simulated in the situation where the difference between the water level in the river and the embankment level was less than 20 cm (as a precaution in relation to the unknown geotechnical characteristics and the possible uncertainty related to the elevation profile).

The values *h* of the maximum water depth and *v* of the maximum flow velocity that occur during an overflow event are well-known at each point; the hazard is correlated to the intensity of the phenomenon, which is a function of the depth and velocity. For the risk assessment, hazardis represented in relative terms in the interval between 0 and 1 sothree classes are defined (the function described below is generally formulated by taking the safety of people, as a vulnerable element, into account): Low Hazard (H_l), medium Hazard (H_m), and high Hazard (H_h).

<table>
<tr><th>Description</th><th>Hazard classes</th><th>Hazard values</th></tr>
<tr><td>Flooded areas with low water depth:
$h \leq 1$ m if $v \leq 0.5$ m/s
$hv \leq 0.5$ m^2/s if $v > 0.5$ m/s</td><td>H_l</td><td>0.4</td></tr>
<tr><td>Flooded areas with significant water depth and/or relevant flow velocity:
$1 < h \leq 2$m if $v \leq 0.5$ m/s
$0.5 < hv \leq 1$ m^2/s if $v > 0.5$ m/s</td><td>H_m</td><td>0.8</td></tr>
<tr><td>Flooded areas with deep water and/or high flow velocity:
$h > 2$m if $v \leq 0.5$ m/s
$hv > 1$ m^2/s if $v > 0.5$ m/s</td><td>H_h</td><td>1.0</td></tr>
</table></td><td>Hydrological-hydraulic modelling (HEC-RAS)

Hazard classes are defined on the basis of a strictly qualitative evaluation,from an assessment made by the ProvinciaAutonoma di Trento (2006)</td><td>The levee breakpoints were identified by the hydraulic model based on the reference hydrograph (for the 3 different return times) and assessed, taking the height of the levees as well as the possible presence of banks or floodplainsinto account. The number of levee failure scenariosthat were simulated along a critical section was based on the length of the river section and on historical evidence. The purpose of the investigation was not so much to analyze levee breaches from a geotechnical point of view, but to determine the effects in terms of the "propensity to flood" the area. In the situation of overlapping breaches, the maximum valuesfor the variables *h* and *v* were assumed.

Hazard values do not change with the implementation of the citizen observatory and hence remain constant in the analysis.</td></tr>
</table>

Component		Assumptions/Sources of uncertainty	Source of data or assumptions	Explanations and implications
Flood exposure	People affected	Relative values of exposure range from 0.9 to 1, increasing as the population density increases	ISPRA (2012)	Rather than assuming exposure is 1 if any people are present, this assumption decreases the exposure as the population density decreases, thereby decreasing the overall risk.Moreover, these exposure values do not change with the implementation of a citizen observatory and hence remain constant in the analysis.
	Economic activities affected	Relative values of exposure by land use type were based on restoration costs resulting from losses in production and services	Costs provided by the ProvinciaAutonoma di Trento (2006) and values derived through expert consultation	These relative values are based on decades of experience with understanding exposure related to flood risk and hence are conservative estimates.These exposure values remain constant in the analysis.
	Environmental and cultural assets affected	Relative values of exposure by land use type were based on restoration costs resulting from potential damage		
Flood vulnerability	People affected – physical vulnerability	Relative vulnerability is based on instability of people in flowing water, derived from a flood hazard rating and debris factor from laboratory experiments.	DEFRA and UK Environment Agency (2006) ISPRA (2012)	Relative vulnerability is generally low (0.25) except under conditions when the combination of water height and flow velocity are appreciable. These values remain constant in the analysis.
	People affected – social vulnerability	The carrying capacity (weighted 0.4) and the adaptive capacity (weighted 0.6) are comprised of 10 individual weighted components. These components are expressed by value functions.	Value functions, values and weights derived through expert consultation	Values are conservative estimates based on expert consultation and local context. They will affect the final result, but they can only be validated/modified once the citizen observatory becomes operational.
	Economic activities affected	Functions for relative vulnerability of buildings, roads, vineyards, orchards and olive trees, vegetables, natural and semi-natural environments were derived based on laboratory experiments.	Clausen and Clark (1990) Lab experiments by Risk Frontiers Citeau (2003)	Relative vulnerability is generally low (0.25) except under conditions when the combination of water height and flow velocity are appreciable except for agricultural areas where relative vulnerability starts at the higher level of 0.5. These values remain constant in the analysis.
	Environmental and cultural assets affected	Vulnerability is 1 if protected areas are susceptible to nitrate pollution (land use 20) or there is presence of a pollution source (land use type 8 and 22). When no pollution source present, vulnerability is 0.25 if the flow velocity is ≤ 0.5 m/s and water height is ≤ to 1m; otherwise 0.5.	AAWA with expert consultation	In the absence of specific studies, it was assumed that the indirect environmental vulnerability, i.e. that resulting from the consequent loss of functionality due to flooding, is equal to 0.25. Hence, relative vulnerability is generally low (0.25) except under conditions when the combination of water height and flow velocity are appreciable. It affects only a few land-use types, andthese values remain constant in the analysis.
		Vulnerability is 1 if an area contains assets related to cultural heritage (land use 21).	ISPRA (2012)	It affects only land use type 21 and remains constant in the analysis.
Risk		The macro-category ‘people affected’ is weighted 10 times greater than the other two (i.e., economic activities affected and environment and cultural assets affected).	Stakeholder interviews undertaken by AAWA	This weighting reflects the importance of the safety of people in the risk calculation.

Component	Assumptions/Sources of uncertainty	Source of data or assumptions	Explanations and implications
Costs of flood damage	Damage estimates by damage category were estimated for each country in the EU including Italy (Table S3).	Huizinga (2007)	These figures come from a study by Huizinga (2007)from the Joint Research Center (JRC) in Italy. In 2017, Huizinga et al. (2017)published a report on global flood depth damage functions, comparing the results in 2017 with those in 2007. The overall patterns matched the 2017 values but showed overestimates in Europe, which were corrected by assuming a 40% inalterable portion for European buildings. The numbers then matched well. Hence some uncertainty analysis has been performed by the original authors of the figures. We would also assume they are conservative, having been published in 2007.

Figure S1: Value functions for the vulnerability indicators to evaluate the Coping Capacity (De Luca, 2013)

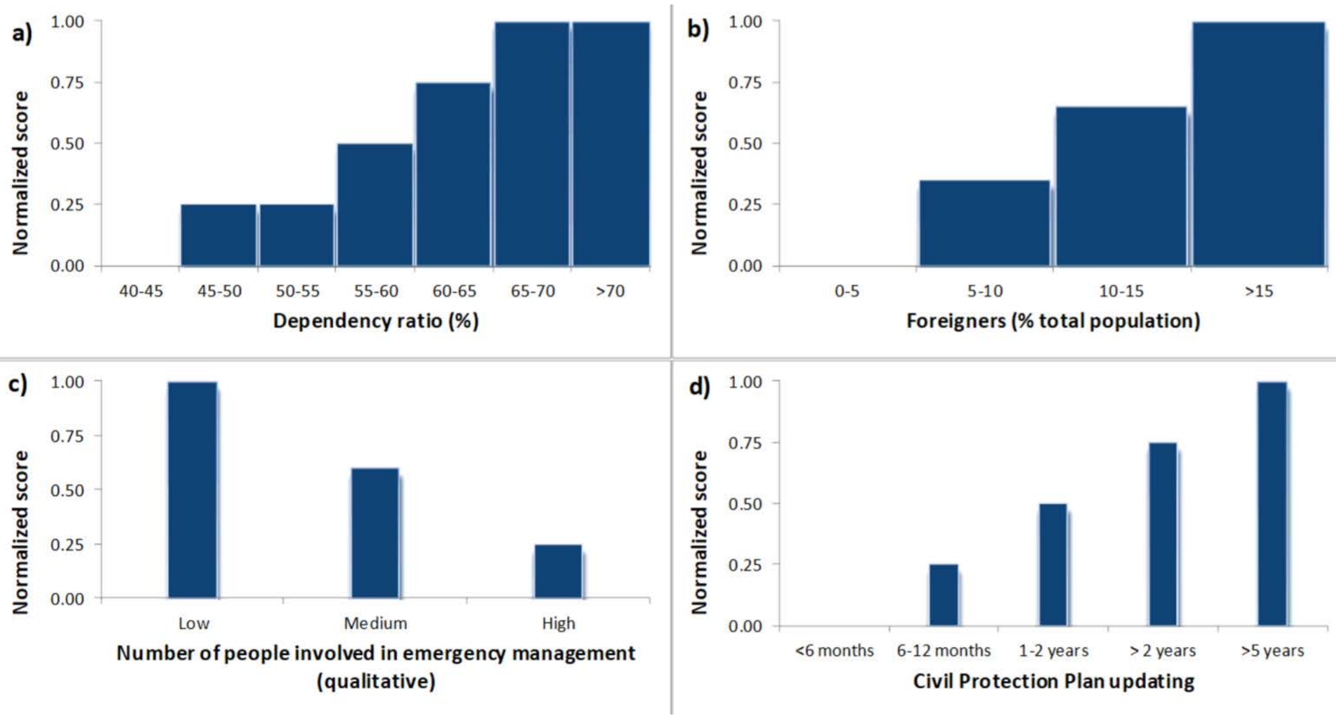


Figure S2: Value functions for the vulnerability indicators related to the Early Warning System (EWS) and Adaptive Capacity: a) reliability, b) lead time, and c) information content (De Luca, 2013)

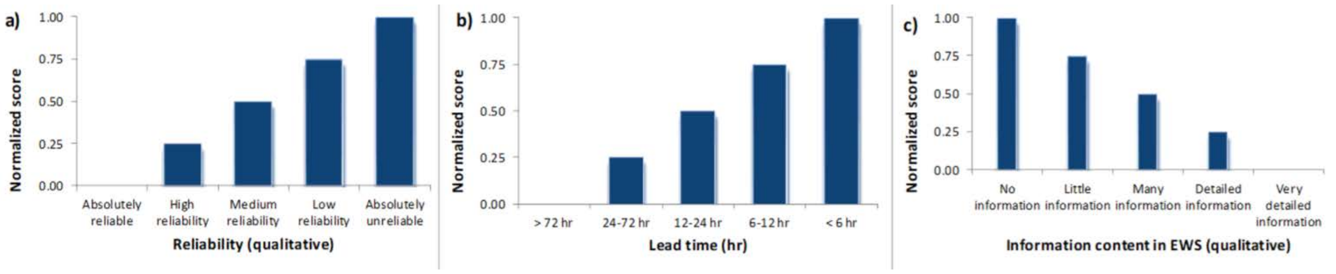


Figure S3: Value functions for the vulnerability indicators that are part of evaluating the Adaptive Capacity(De Luca, 2013)

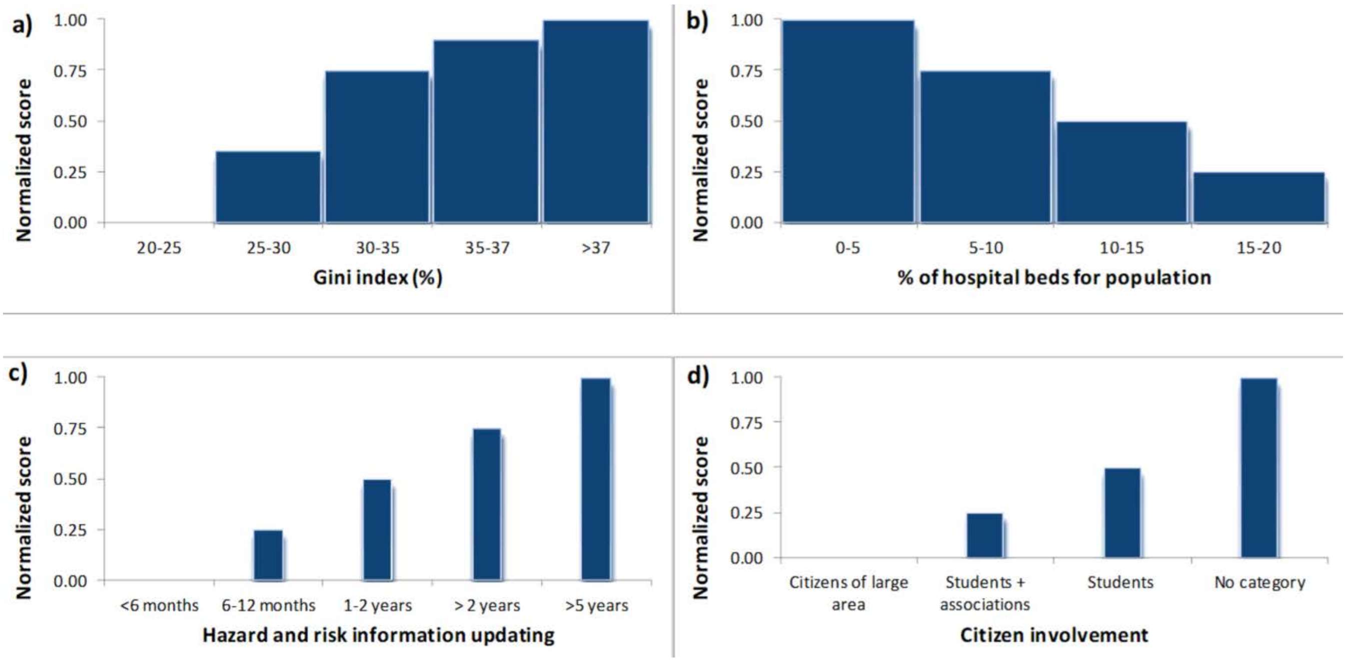


Figure S4: Vulnerability values of buildings as a function of water height (*h*) and flow velocity (*v*)

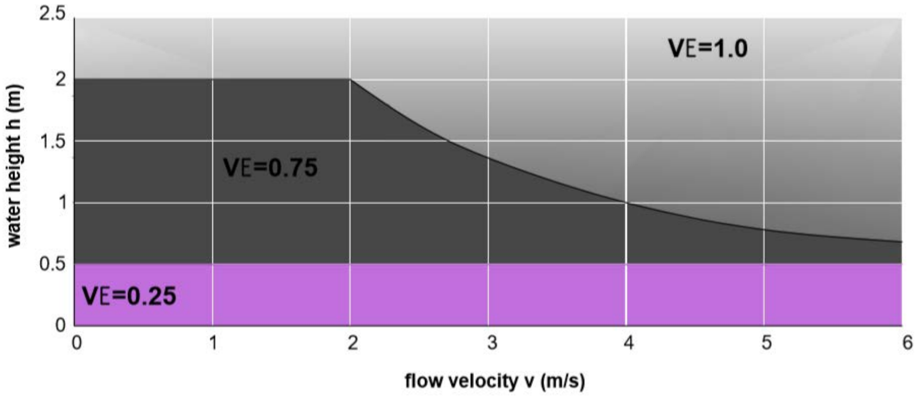


Figure S5: Vulnerability values of the network infrastructure as a function of water height (*h*) and flow velocity (*v*)

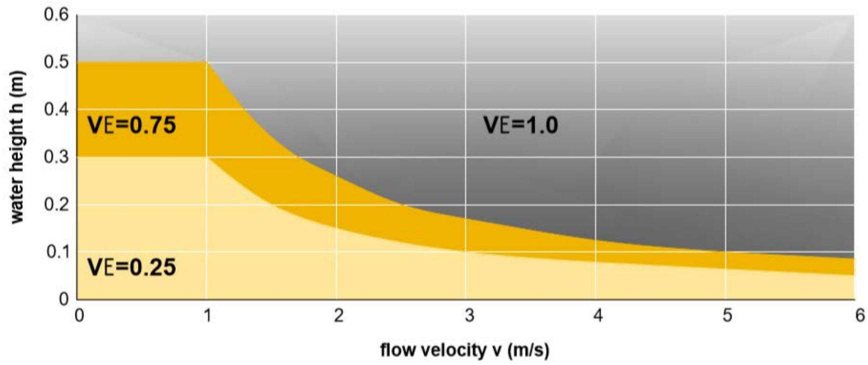
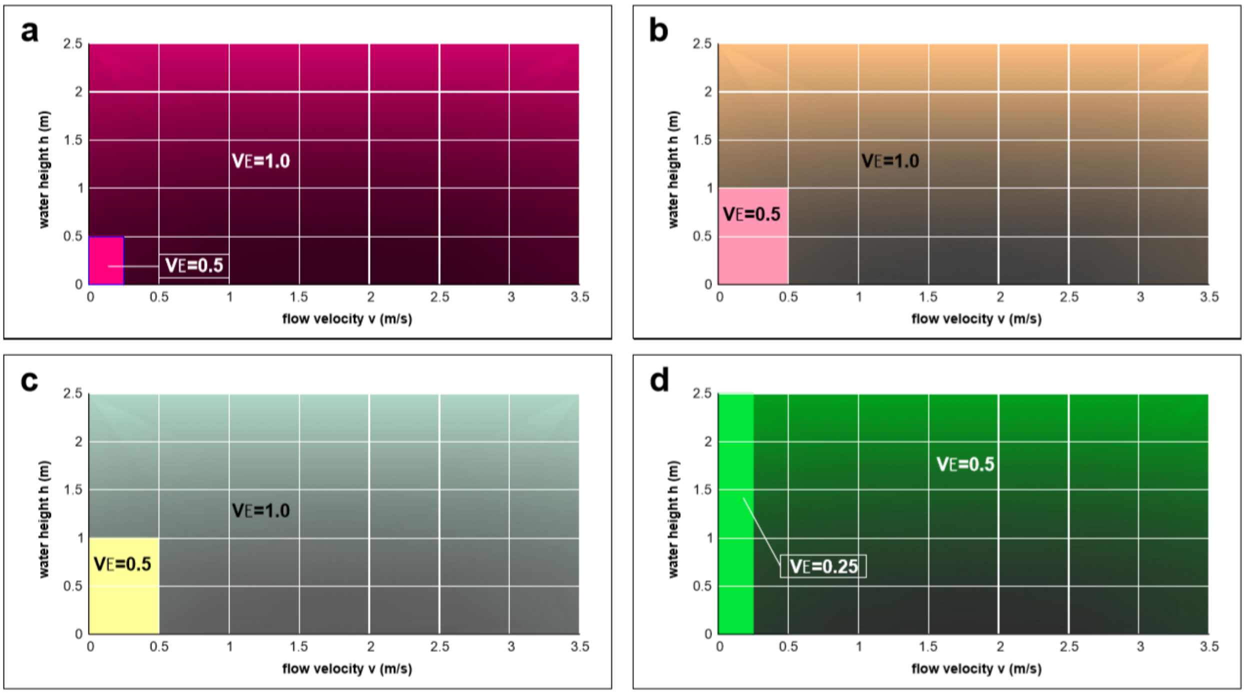


Figure S6: Vulnerability values as a function of the water height (*h*) and the flow velocity (*v*) for: (a) vineyards, (b) orchard and olive trees, (c) vegetables, and (d) natural and semi-natural environments, derived from laboratory experiments(Citeau, 2003)



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Sviluppo di una piattaforma informatica per l'elaborazione di mappe del Rischio Alluvioni e di analisi costo-beneficio di misure di mitigazione delle piene

Staff dell'Autorità di Bacino (AAWA) ha elaborato un report sulle metodologie per la mappatura del rischio di inondazione e l'analisi costi-benefici di misure di mitigazione, sulla base del quale è stata successivamente sviluppata una piattaforma informatica.
In dettaglio, nella prima parte del presente deliverable, vengono descritti i criteri considerati per una valutazione integrata del rischio di alluvione; mentre nella seconda parte sono illustrate le specifiche funzionali e tecniche della relativa piattaforma informatica.

Razvoj informacijske platforme za izdelavo kart poplavne ogroženosti in analizo stroškov in koristi ukrepov za ublažitev poplav.

Interno osebje Vodnega območja Vzhodnih Alp (AAWA) je izdelalo poročilo o metodologijah za kartiranje poplavne ogroženosti in analizo stroškov in koristi omilitvenih ukrepov. Na podlagi poročila je bila kasneje razvita ena italijanska platforma.
V prvem delu tega dokumenta so podrobneje opisani kriteriji, predpostavljeni za celovito oceno poplavne ogroženosti; medtem ko so funkcionalne in tehnične specifikacije povezane italijanske platforme prikazane v drugem delu.