

Response to RC1

We would like to thank the reviewer for their comments. These appear in bold typeface; our responses follow below each comment.

General comments

Ferri et al. assess the flood risk and related costs in the Brenta-Bacchiglione catchment in Italy to evaluate the contribution of the establishment of a citizen observatory to flood risk mitigation. The authors also use this case study to demonstrate the validity of cost-benefit analysis to assess the value of citizen observatories in flood risk mitigation. As citizen science is a fairly 'hot topic' in hydrology at the moment, I think this is a timely study, providing a relevant tool that can be applied in flood risk management. The manuscript is well-written and fits well within the scope of HESS.

Response: Thank you for these positive comments.

I do, however, have a few questions and comments that I would like the authors to address. In the introduction you mention that several studies identified that the link of COs to authorities and policy does not necessarily lead to increased participation or improved participation. Yet, in the cost-benefit analysis with CO, you assume a positive impact of the CO on numerous social vulnerability indicators based only on the outcomes of the pilot study. I understand that the focus of this manuscript is to demonstrate the use of a cost-benefit analysis in this context, but it would nevertheless be interesting to discuss how citizen science or CO projects in other regions affected these social vulnerability indicators. This would also put the results of this study in a broader context, which is currently missing.

Response: Based on the positive outcome of the pilot, you are correct in asserting that the CO is assumed to have positive impacts on the social vulnerability indicators. To provide a broader context, we have now included reference to the work of Bremer et al. (2019), who found in their case study in Bangladesh that citizen science has had a high impact on adaptive capacity in terms of individual awareness and understanding of local rainfall, learning that they applied in adaptive practices at work and at home, as well as local leadership. Other relevant indicators of social vulnerability refer to social capital (trust, sharing experience and formal/informal interactions) for which improvements were also measurable. However, impacts on policy were lower. So CO impacts do not necessarily (have to) materialise (only) via formal policy mechanisms. Both coping and adaptive capacity have individual, community as well as policy dimensions, not all of which are impacted in parallel nor to the same degree. Moreover, adaptive capacities are context specific.

This brings me to another point. From the methods, results and discussion I got the impression that most of the benefit of the citizen observatory came from the increased awareness and participation rather than just data provisioning. In the introduction, the role of citizen science and COs in data collection is actually highlighted. Also in Section 2.3, where the CO in the Brenta-Bacchiglione catchment is described, the role of 'experts' and citizens seems to focus on data acquisition, whereas the impact on estimating other flood risk drivers has not been explained as much. If you could elaborate on how the CO contributes to these aspects, this would support the (rather many) assumptions made within this study.

Response: The increased awareness/participation and data provisioning are closely related, i.e., the app provides information about flood risk to citizens while at the same time asking for inputs/participation that can be used to feed the model and/or, in real-time, to provide information to help emergency response. The concept of a CO is built on the idea of two-way communication between the

citizens/experts and the local authorities. We can make this point clearer in the discussion to emphasize this aspect of the CO.

Regarding the impact on estimating other flood risk drivers, at present, the impact of citizens is not evaluated in the hazard component as the inputs from citizens would be used in real-time rather than the baseline modelling that was done to establish the areas flooded, the height and the flow velocity under three different flood return periods. Instead, this is incorporated into the Early Warning System (EWS) component of social vulnerability through improvements in the reliability, lead time and information content of the EWS (Figure S2 in the Supplementary Information) as well as components of Adaptive Capacity (Hazard and risk information updating and Citizen involvement - Figure S3 in the Supplementary Information). Similarly, there is currently no impact of citizens/experts on exposure or physical vulnerability as this analysis is based on land use categories rather than individual buildings, where in the latter it might be possible to capture small changes done at the household, building or feature level. However, this is not part of the current methodology. We state in the paper that hazard, exposure and physical vulnerability are not impacted by the implementation of the CO. However, we have added a paragraph to the Discussion and Conclusion section that highlights these points.

In addition, it would be interesting to discuss at some point in the manuscript how the additional data (especially water levels) could contribute to improved hazard evaluation in your case study.

Response: Data collected by citizens, although characterized by being asynchronous and, at times, inaccurate, can still complement traditional networks that are made up of a few highly accurate, static sensors, and hence, can improve the accuracy of the flood forecasts. For this reason, improvements to the monitoring technology have led to the spread of low-cost sensors to measure hydrological variables, such as water level, in a more distributed way. The main advantage of using this type of sensor (i.e., “social sensors”) is that they can be used not only by technicians but also by any citizen. Moreover, due to their reduced cost and the voluntary labour by the citizens, they result in a more spatially distributed coverage.

In the Brenta-Bacchiglione catchment, crowdsourced observations of water level are assimilated into the hydrological model by means of rating curves assessed for the specific river location, and directly into the hydraulic model. Examples of studies we did include the following: (i) Mazzoleni et al. (2017) assessed the improvement of the flood forecasting accuracy obtained by integrating physical and social sensors distributed within the Brenta-Bacchiglione basin; and (ii) Mazzoleni et al. (2018) demonstrated that the assimilation of crowdsourced observations located at upstream points of the Bacchiglione catchment ensure high model performance for high lead times, whereas observations at the outlet of the catchments provide good results for short lead times.

We have added some of this explanation to section 3.2.1 on Flood Hazard Mapping.

Mazzoleni, M., Verlaan, M., Alfonso, L., Monego, M., Norbiato, D., Ferri, M. and Solomatine, D. P.: Can assimilation of crowdsourced data in hydrological modelling improve flood prediction?, *Hydrol. Earth Syst. Sci.*, 21(2), 839–861, doi:10.5194/hess-21-839-2017, 2017.

Mazzoleni, M., Cortes Arevalo, V. J., Wehn, U., Alfonso, L., Norbiato, D., Monego, M., Ferri, M. and Solomatine, D. P.: Exploring the influence of citizen involvement on the assimilation of crowdsourced observations: a modelling study based on the 2013 flood event in the Bacchiglione catchment (Italy), *Hydrol. Earth Syst. Sci.*, 22(1), 391–416, doi:10.5194/hess-22-391-2018, 2018.

More specific comments and requests for further clarification on certain points in the manuscript are provided below.

Specific comments L. 19-20: I would use citizen observatories in this sentence as well, since your manuscript evaluates how these can contribute to risk reduction.

Response: We have added citizen observatories to this sentence. It now reads as follows:

Thus, linking citizen science and citizen observatories with hydrological modelling to raise awareness of flood hazards and to facilitate two-way communication between citizens and local authorities has great potential in reducing future flood risk in the Brenta-Bacchiglione catchment.

Figure 1: Please add legend to map and clearly indicate the boundaries of the Brenta-Bacchiglione catchment.

Response: We have added the boundaries of the Brenta-Bacchiglione catchment and the river network to Figure 1 (which is now Figure 2). We have also added a legend.

L. 143-145: What is the sustainability of such an arrangement, whereby the technicians get paid for each trip, once the project ends? Where would the funds come from?

Table S6 contains the costs of the components of the Citizen Observatory (CO) for Flood Risk Management where we have foreseen a financial safety net of 5 years to develop and operate all components of the CO (for developing the technology, maintenance, education campaigns, etc.). After this period, we will evaluate the results and pursue the opportunity to fund the initiative further. We added a line to this effect where Table S6 is referred to in the results.

L. 151-159: Could you be more specific on the kind of observations that citizens can contribute? I would imagine these are less 'complicated' than the contributions of the trained volunteers and technicians. Furthermore – as mentioned in the general comments – how will citizen engage further in risk reduction such that flood risks can be reduced?

Citizens can easily send and share reports regarding measured hydrological quantities, for example: the water level of a river at a section equipped with a hydrometric measuring rod and QR code or the level of the snowpack where a snow gauge equipped with a QR code has been installed. They can also send reports about the presence of flooded areas indicating the water height. They can also send 'smart' measurements, which are simplified measurements of some hydrological variables (e.g., the amount of rain, the forest cover of the banks, weather conditions, etc.). Instead of entering a value, citizens can choose from a series of photos/videos that represent the phenomenon, and which are associated with ranges of values (e.g., for the intensity of the rain: drizzle, moderate, heavy, very heavy). The citizen chooses the photo most similar to what they see when they send the report.

In exchange, citizens can receive flood-related information (e.g., weather and river level forecasts, notifications from the authority concerning the declaration of a state of alert or its cessation, specific communications to citizens present in a specific area of interest/danger in a specific period of time (based on a geolocation function). This two-way communication can help to reduce flood risks.

We have added parts of this text above to section 2.3 to provide additional clarification.

Note that technicians, as any citizen, can send alerts or observations but they can also provide technical data (e.g., the status of the embankments, vegetation cover, water levels, clearance below the bridge) that are considered as trusted (and already validated) because of their expertise.

L. 185: Supplementary tables: Please change the numbers of the supplementary tables in such a way that they are numbered according to their appearance in the text.

Response: Thank you for spotting this error. We have now made these changes, renumbering the supplementary tables in the order that they appear in the text and reordering them in the supplementary material. We marked these changes in yellow in the supplementary material document.

L. 223-227: The section on EE and EECH is quite unclear and could do with some more detail, as I cannot really follow what has been done based on the current description.

The EU Flood Directive and Italian law requires a description of the type and spatial distribution of the economic activities in the flooded area in order to provide an assessment of the potential negative consequences for the different activities. The relative exposure of economic activities (E_E) was used in the methodology as the physical exposure, expressed by the restoration costs, the costs due to missed production and service losses. The values used to represent this economic factor are reported in Table 3.

Similarly, to define the exposure values for the environmental and cultural heritage component (E_{ECH}), we proceed by assigning relative values to different land use categories, taking into account the potential modifications that can occur during an adverse event to the various environmental and cultural features contained within these different land use categories. Those values are also presented in Table 3.

We have rewritten this section to try to make this explanation clearer. We have also provided Tables S3 and S4, which provides the reasoning for how the costs are translated into relative values. See the next response.

Table 3: Are these relative values based on the data explained in the previous paragraphs? This seems straightforward for EP, but it is not clear how EE and EECH translate from costs to a relative value. And how have these values been tested and shown to be valid?

The relative values are based on the data explained in the previous paragraph and have been derived by the Provincia Autonoma di Trento (2006) from decades of experience with understanding exposure related to flood risk. We have added Tables S3 and S4 to the Supplementary Material to provide further information on the relation between the costs and the relative values.

Figure 3: I would place this figure in Section (ii), where you explain how the weights and values have been obtained. How did you define the indicators? Is this based on existing literature? And could you provide more information on the stakeholder engagement to identify weights and values? Which stakeholders were engaged and how were the weights and values determined? Average of what different stakeholders provided? Or did certain stakeholder provide info for certain indicators only?

We agree with the reviewer and we have moved Figure 3 to Section (ii). The indicators in Figure 3 (now Figure 5) are based on existing literature (Mojtahed et al., 2013). The weights given to each indicator were derived from an expert consultation process. The principal aim of this procedure was to assign a value between 0 and 1 to people's vulnerability, considering the relative weight of each indicator. The

stakeholders engaged were the members of the Technical Committee of the water basin authority made up of technical representatives of the regional and provincial administrations belonging to the Eastern Alps District, as well as experts from the professional and academic sectors (i.e., around 20 people). The process to identify the weights started with several discussions, the results of which were interpreted and translated into values/weights by AAWA, who then re-proposed these to the experts, obtaining their consensus. We have added this to the text to provide clarification.

Mojtahed, V., Giupponi, C., Biscaro, C., Gain, A. K. and Balbi, S.: Integrated Assessment of Natural Hazards and Climate Change Adaptation: The SERRA Methodology. Università Cà Foscari of Venice, Dept of Economics Research Paper Series No. 07/WP/2013, 2013.

Table 4: Include the references to your data sources in the table (either in the caption or as footnote) if the values are directly taken from the studies you mention in L. 252-254.

Response: We have added the following source to the Table 4 caption: Source: ISPRA (2012), with reference to DEFRA and UK Environment Agency (2006)

Figure 4 and similar figures: Are only the values 0.25, 0.75 and 1.0 included in the analysis? If so, why particularly these values and not values in between?

These three values of V_p were proposed in the ISPRA (2012) guidelines. This has been added to the text. We have also added this to relevant figures in the Supplementary Material.

L. 266-268: How were the value functions for the different indicators defined? Was this also part of the stakeholder consultation?

Similarly to what was done to identify the weights in Figure 3 (now Figure 5), AAWA formulated an internal study for the definition of the value functions for the different indicators, which were then proposed and discussed with the members of a Technical Committee (see response above), obtaining their consensus. We added an additional line to the text to clarify this (following the explanation provided to the comment above about Figure 3).

L. 284-288: How were content and reliability quantified? Simply assigning it to one of the categories shown in Figure S2 could be quite subjective.

Content and reliability were assigned to one of the categories shown in Figure S2 based on the following assumptions:

- **Reliability:** The Early Warning System (EWS) reliability increases to very high due to the involvement of trained citizens who provide information and sensor readings that are used to validate and feed the hydrological/hydraulic model (i.e., the data assimilation module). The assumption was made based on the results obtained in Mazzoleni et al. (2017, 2018) and by considering a hypothetical situation in which a widely distributed crowdsourcing data acquisition process is in place due to the expected high level of citizen engagement.
- **Content:** With the CO, we will be obtaining very detailed information further enriched by citizen reports (including reports from waterways that were not previously equipped with measuring instruments) and by a monitoring network that will be equipped with a further eight thermo-pluviometric stations, 12 hydrometric stations (equipped with a double transmission system), and 58 hydrometric and six snow measuring rods. The forecasted water level is available at every

section of the Brenta-Bacchiglione River system. Overall the content is enhanced through the implementation of the CO.

These explanations were added close to Table 6, which explained the changes in social vulnerability before and after implementation of a CO on flood risk management.

L. 299-302: More information on this is required. From what is provided, it is difficult to understand how to interpret Figure S3d. What does no category mean? That no citizens are involved (which would correspond to zero citizen involvement and thus increased vulnerability)?

Response: 'No category' has been changed in Figure S3d to 'No involvement', i.e., this corresponds to zero citizen involvement and thus increased vulnerability. We have modified Figure S3d and updated it in the Supplementary Material. The caption is highlighted in yellow to flag this changed figure.

L. 318-319: In the caption of Figure S3, it says these values are for network infrastructure. Does this only apply to roads? If so, please change accordingly.

Response: Here we assume that you are referring to Figure S5. Yes, the network infrastructure applies only to roads, so we have changed the figure caption to read: Vulnerability values of the road infrastructure as a function of water height (h) and flow velocity (v).

L. 356-358: If social vulnerability decreases to 0.63, what was its original value?

The original value was 0.9. We have added this figure to the text.

Tables 8-11: If you combine the tables, the reader would have a better overview of the results of the different scenarios with and without CO without having to move from page to page to compare values. E.g. some information in Table 11 is already presented in Table 9.

Response: Tables 8 and 10 have been combined to more clearly show the areas by risk class before and after implementation of a CO into a new Table 8. Table 9 has been removed as the data already appear in Table 11, where Table 11 has subsequently been renumbered to Table 9. This has also required some reorganization of the text, but we agree that combining the results for before and after the CO implementation are clearer for the reader.

L. 451-453: Not clear: were these calculations for the retention basin done within this study or do you refer to this as an example/comparison? If this was done as part of this study, I would have liked to see more information on the calculations.

Response: We refer to this only as an example since the retention basin calculations were done as part of another study independent of this CO.

L. 489-490: Could you add a sentence on how the presence of a CO reduces costs related to emergency services?

Although the people involved in the emergency services are the same, they are employed in a much more efficient way as a result of the technology developed within the CO, which allows for better management

of the teams responding to the event and the efficient assignment of tasks based on an operator's location.

We have added the above statement to the discussion.

For further clarification, the authorities can assign critical tasks to rescue teams and produce reports on progress, they can monitor the movements of the teams, and they can assign new tasks to teams once a job is finished based on the proximity job principle. Furthermore, civil protection plans can be updated more frequently, which also draw upon more active citizen participation in reporting risk situations in their surroundings.

Response to RC2

We would like to thank the reviewer for their comments. These appear in bold typeface; our responses follow below each comment.

General comments

This publication by Ferri et al. discusses a cost-benefit analysis for citizen observatories based on a specific catchment in Italy. The content is relevant and will be a valuable addition to citizen science research. One of the current limitations of this paper is the lack of a broader context and the limited discussion. Questions that would be interesting to see addressed in the discussion section are: Why is it mostly the “social dimension of vulnerability” (L 354-355) that changes the calculations and not the additional data obtained through the CO? Is this additional data not helping to further improve the hydraulic model? What aspect of the “social dimension of vulnerability” do the authors contribute most of the reduction in costs to? This is slightly hinted at in the methods (L 357-362), but as one of the main messages in this paper this should be addressed more extensively in the discussion. A full discussion of the results and the broader context of the study would make the value of the publication clearer to the reader.

Response: We thank the reviewer for their positive comments regarding relevance and a valuable addition to citizen science research. The additional data obtained through the CO are indirectly part of the improvements to social vulnerability rather than the hazard component that involves the hydrological-hydraulic model as one might be expecting. This is because the hazard modelling is done as a baseline while the data collected by the citizens/expert volunteers will be in near-real time so this will affect the early warning system, the involvement and hence awareness of citizens, and the updating of the hazard and risk information, which are all part of social vulnerability. We have added some additional text to section 3.1.2 on flood hazard modelling. We have also added an additional paragraph to the discussion regarding the contribution to citizens to the social vulnerability component to make this clearer.

One of the aspects that contributes most to a reduction in costs is related to the **emergency services**. Although the people involved in the emergency services are the same, they are employed in a much more efficient way as a result of the technology developed within the CO, which allows for better management of the teams responding to the event and the assignment of tasks based on an operator's location. For example, the authorities, in response to real-time reports from citizens and based on reliable model forecasts, can assign critical tasks to rescue teams, monitor the movements of the teams and assign new tasks to teams once a job is finished based on the proximity job principle. Secondly, among the factors of social vulnerability, the involvement of citizens contributes to changing those behaviours that are the

main causes of death and/or serious economic damage; an example would be actions such as trying to save your car during a flood event or trying to rescue your belongings from a flooded basement, which would be stopped or reduced as a result of the CO. We have added more text in the discussion to clarify how the CO improves the emergency services.

Specific comments:

Overall there are too many abbreviations (e.g. L 214, 258, table 6, L 369, L 379). I was not able to find the definition of the abbreviation “EWS” (table 6).

Response: Regarding L214, this is a blank line in our version of the paper unless you are referring to L215, which defines one of the variables in equation 2? Regarding L258, is the reviewer referring to FHR or Vp as an acronym? If it is FHR, this was defined further up in the text and used in equation 3. If Vp, then we have now added this to the caption of Figure 4. In Table 6, we have changed the acronym EWS to read Early Warning System as this was not defined previously in the paper so thank you for pointing this out. On L369, CLC refers to Corine Land Cover but we have now replaced the acronym with the words wherever they appear in the text. L379 defines variables that are then used in equations 5 and 6 and further in the text.

L 55-59: Not all of the cited literature actually refers to a CO and the description of at least some of the stated studies is not accurate.

Response: We have checked the referenced literature and deleted those references that do not refer to COs (Etter et al., 2018; Mazzonleni et al., 2017; Butaert et al., 2014) but to other forms of citizen science. Moreover, we have attributed the statement regarding the link of COs with authorities and policy more specifically as follows:

“Specifically, Wehn et al. (2015) 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.”

L97-100: How often do these observations get made and how many were collected in total? It would be very informative to include a photograph of such a “staff gauge with a QR code”.

During the WeSenseIt project, more than two hundred people were recruited for practical activities and were trained to use the WeSenseIt technologies. The data collected took place during the evaluation exercises organized to test the technology and to collect feedback for further development and to make improvements. From an exercise that took place between 15-18 Nov 2019, number of reports collected by those trained in the technology was around 1,100. During these events, the response of the volunteers was enthusiastic as well as their participation in sending environmental reports and information. Examples of photographs with the staff gauge and QR code have been added as a new Figure 1 to the paper.

L 104: Did the volunteers operate the physical sensors? Or was this done by someone else?

Response: No, the physical sensors are operated by AAWA in collaboration with the Regional Department for Soil Protection, the Environmental Agency, the Civil Protection Agency and their related professionals. We have added this information to the text.

L 197 / table 1: It is not clear to me which of these data inputs are derived from citizen scientists and which are implemented anyway. Please make this distinction clearer so that the added value is more obvious.

Response: None of the data in Table 1 (version posted online) are derived from citizen scientists. We have now added the input from citizen scientists to the Flood Vulnerability component as follows in the final row of Table 1.

These data are used indirectly in the calculation of social vulnerability, i.e., the Early Warning System (EWS) component through improvements in the reliability, lead time and information content of the EWS (Figure S2 in the Supplementary Information) as well as two components of Adaptive Capacity (Hazard and risk information updating and Citizen involvement - Figure S3 in the Supplementary Information).

L 425: It would be helpful to add a range to this value, so as to show the associated uncertainty.

Although we understand the point of the reviewer, we do not have a range around the expected average annual damage because it is already based on three probabilistic flood scenarios, so this damage value is an average across these scenarios. We recognize that there are multiple assumptions and uncertainties in this methodology, but we have not quantified them as such. Since the exercise is currently a hypothetical one but it provided sufficient evidence for funding of the CO for five years, going back and doing a full uncertainty analysis would not bring any further value for the operational running of the CO. Instead, once the CO is operational, it will then be more interesting for us to verify the results from the cost-benefit analysis. We do mention this future verification at the end of the Discussion and Conclusions section.

L 430-432: Why do you think there is a difference, i.e. why is R3 and R4 reduced, but R1 and R2 increased? Add this to the discussion.

Response: This occurs because the total area affected by the flood hazard is the same before and after implementation of a CO. What changes is the distribution between risk classes, i.e., R3 and R4 are reduced, which means that the areas at risk in classes R1 and R2 will increase. We added this to the results because it explains this finding directly after it is presented.

Also table 9 does not show any areas, just damage, so the reference here probably refers to table 8?

Response: Thank you for pointing out this error. We have corrected this but in the process of responding to reviewer 1, we have also combined tables, i.e., Table 8 and 10 are now combined (risk before and after the implementation of a CO in terms of area) and Table 9 and 11 (damage in euro amounts before and after the implementation of a CO). The text has also been updated accordingly.

L 469: You mention that this method can be transferred to different catchments. It would be interesting to read your thoughts on what type of catchments this would be suitable for, e.g. what catchment scale.

Once activated in the Brenta-Bacchiglione, the CO will also be extended to the other basins of the hydrographic district of the Eastern Alps, which are similar in size and hydrological characteristics. These are complex hydrographic basins with very variable regimes, from rapid response/torrential rainfall events of the alpine territories to the alluvial plain, which is composed of mountain and lowland river networks, artificial networks of reclamation and natural and/or artificial reservoirs. In general, we suggest

applying this methodology to catchments larger than 100 km². For catchments of this size and greater, we would have basin compatible response times, and hence, it would make sense to use model forecasts. We have added some of this text to the end of the discussion.

Another point to note is that for the application of the CO methodology, it is necessary that the population residing in the basin can be easily reached through such an initiative, and that they are familiar with, and are able to access, the technology (i.e., via a tablet, PC, smartphone).

Technical corrections:

L 92: 7th (th in superscript)

Response: Thank you for spotting this error. We have now corrected this.

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

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Abstract. Citizen observatories are a relatively recent form of citizen science. As part of the flood risk management strategy
10 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
15 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 and citizen observatories with hydrological modelling to raise awareness of flood hazards and
20 to facilitate two-way communication between citizens and local authorities, ~~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
25 (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
30 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
35 mitigated through hard engineering strategies such as implementation of structural flood protection schemes, soft
engineering approaches comprising more natural methods of flood management (Levy and Hall, 2005), and community-
based flood risk management (Smith et al., 2017). As part of requirements in the EU Flood Risk Management Directive, any
mitigation actions must be accompanied by a cost-benefit analysis.

Flood hazard is generally determined through hydrological and hydraulic modelling. Hence accurate predictions are critical for effective flood risk management, particularly in densely populated urban areas (Mazzoleni et al., 2017). The input data required for modelling are often incomplete in terms of resolution and density (Lanfranchi et al., 2014), which translates into variable accuracy in flood predictions (Werner et al., 2005). New sources of data are becoming available to support flood risk management. For example, the rise of citizen science and crowdsourcing (Howe, 2006; Sheldon and Ashcroft, 2016), accelerated by the rapid diffusion of information and communication technologies, is providing additional, complementary sources of data for hydrological monitoring (Njue et al., 2019). Citizen science refers to the involvement of the public in any step of the scientific method (Shirk et al., 2012). However, one of the most common forms of participation is in data collection (Njue et al., 2019). Citizen observatories (CO) are a particular form of citizen science in so far as they constitute the means not just for new knowledge creation but also for its application, which is why they are typically set up with linkages to specific policy domains (Wehn et al., 2019). COs must, therefore, include a public authority (e.g., a local, regional or national body) to enable two-way communication between citizens and the authorities to create a new source of high quality, authoritative data for decision making and for the benefit of society. Moreover, COs involve citizens in environmental observations over an extended period of time of typically months and years (rather than one-off exercises such as data collection ‘Blitzes’), and hence contribute to 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). Specifically, Wehn et al. (2015) 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.

~~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 (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 WeObserve¹ Community of Practice on the value and impact of citizen science and COs, and the development and application of methods for measuring the impacts of citizen science by the H2020 project MICS². To date, the societal and science-related impacts have received the most attention, while the focus on economic impacts, costs and benefits has been both more limited and more recent (Wehn et al., 2020a). The studies that do focus on economic impacts related to citizen science (rather than citizen observatories) propose to consider the time invested by researchers in engaging and training citizens (Thornhill et al., 2016); to relate cost and participant performance for hydrometric observations in order to estimate the cost per observation (Davids et al., 2019); to estimate the costs as data-related costs, staff costs and other costs; and the benefits in terms of scientific benefits, public engagement benefits and the benefits of strengthened capacity of participants (Blaney et al., 2016); and to compare citizen science data and in-situ data (Goldstein et al., 2014; Hadj-Hammou et al., 2017). Wehn et al. (2020b) assessed the value of COs from a data perspective and a cost perspective, respectively, to 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

¹ <https://www.weobserve.eu/>

² <https://mics.tools/>

80 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
85 take a different approach to previous studies by using a more conventional cost-benefit analysis framework to assess the 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
90 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.

95 **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 AltoUpper 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
100 before and during a flood event. The CO involved many stakeholders concerned with the management and use of the water resources, and with water-related hazards in the Bacchiglione River basin. The main actors included the local municipalities, the regional and local civil protection agencies, environment agencies and the irrigation authorities. The Alto Adriatico Water Authority (AAWA) facilitated access to a highly trained group of citizen observers, namely civil protection volunteers, who undertook the observations (i.e., using staff gauges with a QR code to measure the water level and reporting
105 water way obstructions – see [Figure 1](#)) 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
110 physical sensors, which are operated by AAWA in collaboration with the Regional Department for Soil Protection, the Environmental Agency, the Civil Protection Agency: 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
115 investigated (Mazzoleni et al., 2017, 2018) and found to complement traditional sensor networks.

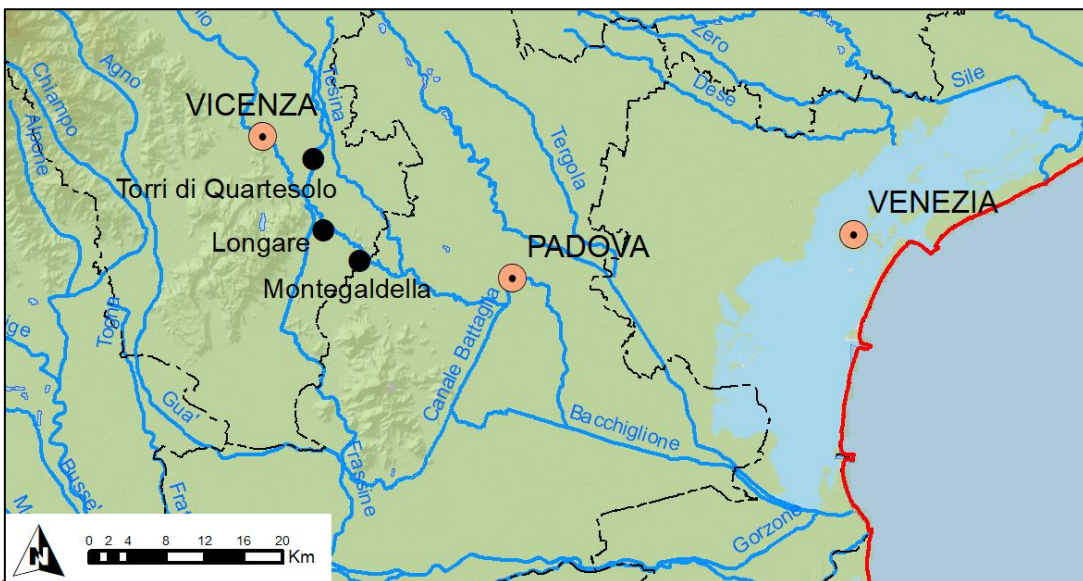


Figure 1: Photos showing staff gauges and QR codes used in the WeSenseIt project.

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

2.2 The Brenta-Bacchiglione Catchment

The Brenta-Bacchiglione River catchment ~~includes the Retrone and Astichiello Rivers, and~~ falls within the Trento-Alto-Adige and Veneto Regions in Northern Italy ~~and~~ ~~which~~ includes the cities of Padua and Vicenza (Figure 2). 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.



135



Figure 21: Location of the Brenta-Bacchiglione catchment and its urban communities.

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

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

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

190 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 and share reports regarding the water level of a river at a section equipped with a hydrometric measuring rod and QR code, the level of the snowpack from a snow gauge
195 equipped with a QR code, the presence of flooded areas including the water height, as well as simplified measurements of hydrological variables such as the amount of rain, weather conditions, etc. using photographs and other smart ways to identify the phenomenon. By providing important information about flooding, ~~which then this will~~ contributes to everyone's safety. In exchange, citizens can receive flood-related information (e.g., weather and river level forecasts, notifications from the authority concerning the declaration of a state of alert or its cessation, specific communications to citizens present in a
200 specific area of interest/danger in a specific period of time, based on a geolocation function). This two-way communication can help to reduce flood risks. 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
205 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.

210 3.1 Flood risk mapping

~~Figure 3~~ 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 as set out in the EU
215 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).

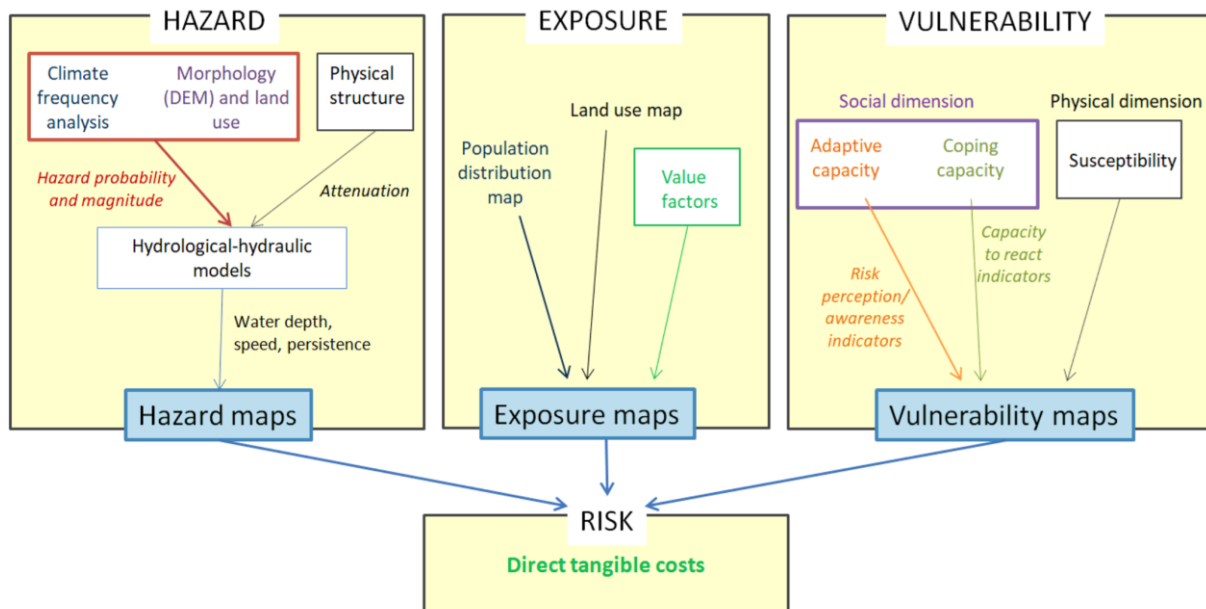


Figure 32: Flowchart outlining the determination of risk in a flood risk assessment context.

220 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

225 citizens have directly experienced a flood, their perception of flood risk is higher (e.g., Thistlethwaite et al., 2018) although the factors that determine flood risk perception are varied. Moreover, the results from different studies can be ambiguous and/or contradictory (Lechowska, 2018). Social vulnerability can be divided into: (i) adaptive capacity, which is the capacity of an individual, community, society or organization to prepare for and respond to the consequences of a flood event (IPCC, 2012; Torresan et al., 2012); and (ii) coping capacity, which is the ability of an individual, community, society or

230 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 S14 in the Supplementary Material.

235 3.1.1 Input data

There are several data sets used as inputs to the assessment of flood risk as outlined in Table 1. For the evaluation of flood hazard, the water height, flow velocity and flooded areas are provided by AAWA using the methodology described in the Supplementary Materials. Several data sets are used to evaluate flood exposure and vulnerability, but a key data set is Corine Land Cover (CLC) 2006 produced by the European Environment Agency (Steemans, 2008). Other data sets used to

240 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 Corine Land Cover. 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
	<u>Water height from simple gauges equipped with QR codes, which are read by technicians and citizens as well as photographs and other flood-relevant information collected via an app</u>	<u>Collected by AAWA</u>

245 3.1.2 Flood Hazard Mapping

According to Article 6 of the 2007/60/CE Flood Directive (EU, 2007), when local authorities implement a Flood Risk Management Plan, three hazard scenarios must be 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
- 250 3. A flood with a high probability, which is a 30-year return period in the study area.

These have been calculated using a two-dimensional hydrological and hydraulic model to generate the water levels and the 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.

255 At present, the impact of the CO is not evaluated in the hazard component as the inputs from citizens are used in real-time rather than the baseline modelling that was done to establish the areas flooded, the height and the flow velocity under three different flood return periods. In the Brenta-Bacchiglione catchment, crowdsourced observations of water level are assimilated into the hydrological model by means of rating curves assessed for the specific river location, and directly into the hydraulic model. In the past, Mazzoleni et al. (2017) assessed the improvement of the flood forecasting accuracy obtained by integrating physical and social sensors distributed within the Brenta-Bacchiglione basin and Mazzoleni et al.

260 (2018) demonstrated that the assimilation of crowdsourced observations located at upstream points of the Bacchiglione catchment ensure high model performance for high lead times, whereas observations at the outlet of the catchments provide good results for short lead times.

3.1.3 Flood Exposure Mapping

265 The 2006 Corine Land Cover map provides the underlying spatial information to calculate exposure; the land use classes used here are shown in Table S42 in 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:

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

270 where F_d is a factor characterizing the density of the population in relation to the number of people present (Table 2),
 which uses gridded population from the census (Table 1), and F_t , which is the proportion of time spent in 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). The relative values by land use
 class for E_P are provided in Table 3.

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

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

280 The physical exposure or impact on economic activities (E_E), which is the second macro-category, is calculated from the
 restoration costs, and the costs resulting from losses in production and services. These various costs were obtained from the
 Provincia Autonoma di Trento (2006) and have been calculated for each of the land use classes in Table S2. Using these
 costs, the relative values of E_E were determined, which are listed in Table 3. Table S3 in the Supplementary Material
 provides a further explanation of the relation between the costs and how the relative values were derived. 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. Similar to E_E , the costs were obtained from the Provincia Autonoma
 di Trento (2006) and calculated for each land use class in Table S2. The relative values of E_{ECH} were then determined (listed
 in Table 3), where the logic behind these values is provided in Table S4 in the Supplementary Material. Note that all the
 relative values in Table 3 ~~These various costs were obtained from the Provincia Autonoma di Trento (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 in Table 3. These values~~ have been derived by the Provincia Autonoma di
 Trento (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.

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

ID	Description	E_P	E_E	E_{ECH}
1	Residential	1	1	1
2	Hospital facilities, health care, social assistance	1	1	1
3	Buildings for public services	1	1	1
4	Commercial and artisan	0.5 - 1	1	0.8
5	Industrial	0.5 - 1	1	0.3 - 1
6	Specialized agricultural	0.1 - 0.5	0.3 - 1	0.7
7	Woods, meadows, pastures, cemeteries, urban parks	0.1 - 0.5	0.3	0.7
8	Tourist recreation	0.4 - 0.5	0.5	0.1

ID	Description	E_P	E_E	E_{ECH}
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.~~

300

(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:

305

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

310

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

~~Table 4~~ [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).

315

Table 4: The Debris Factor (DF) for different water heights (h), flow velocities (v) and land uses. [Source: ISPRA \(2012\), with reference to DEFRA and UK Environment Agency \(2006\)](#)

Values of h and v	Grazing/Agricultural land	Forest	Urban
$0 \text{ m} < h \leq 0.25 \text{ m}$	0	0	0
$0.25 \text{ m} < h \leq 0.75 \text{ m}$	0	0.5	1
$h > 0.75 \text{ OR } v > 2 \text{ m/s}$	0.5	1	1

Using the FHR, the physical vulnerability of the population can be calculated, which is summarized in [Figure 4](#)
 320 [3Figure-4](#). These three values of V_p were proposed in the [ISPRA \(2012\) guidelines](#).

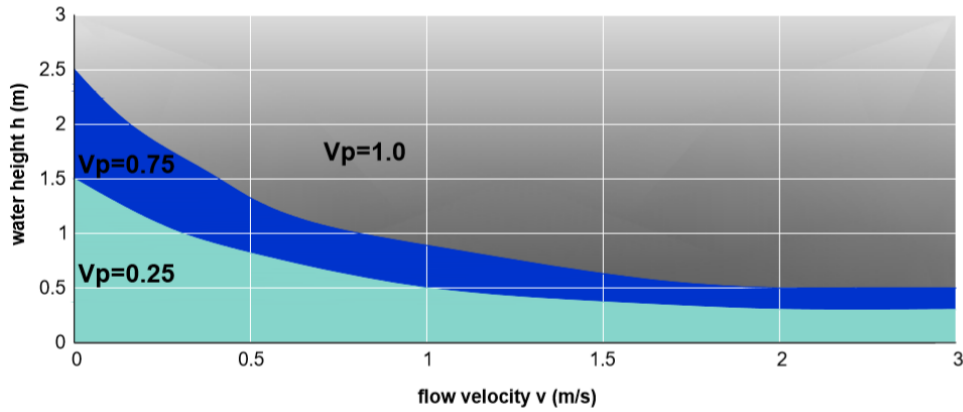
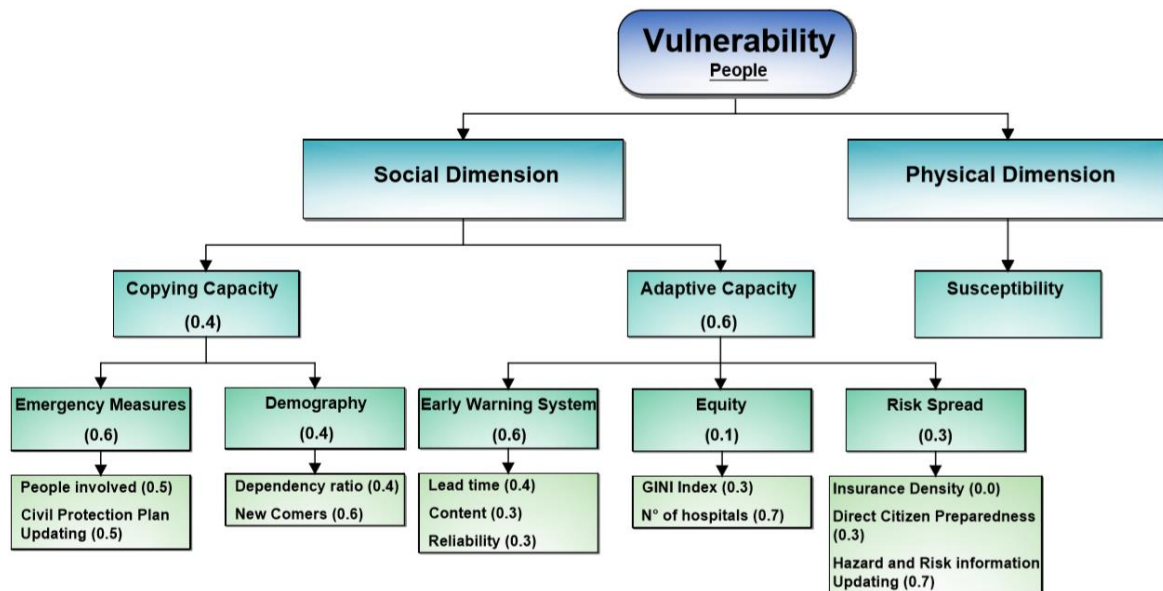


Figure 44: Physical vulnerability (V_p) values for the population as a function of water height (h) and flow velocity (v).

(ii) Social vulnerability of people affected by flooding

325 [Figure 5](#)[Figure 4](#)[Figure 3](#) shows the components of social vulnerability, i.e., the adaptive and coping capacity and their respective indicators, along with the weights associated with each of them.



330 Figure 53: Hierarchical combination of indicators and relative weights (in brackets) to calculate the vulnerability of the population.

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

335 function' was chosen because it represents a mathematical expression of a human judgement that can be compared in a
systematic and explicit way (Beinat, 1997; Mojtahed, et al., 2013). The principal aim of this consultation process was to
assign a value between 0 and 1 to people's vulnerability, considering the relative weight of each indicator. The stakeholders
engaged were the members of the Technical Committee of the water basin authority made up of technical representatives of
the regional and provincial administrations belonging to the Eastern Alps District, as well as experts from the professional
340 and academic sectors (i.e., around 20 people). The process to identify the weights started with several discussions, the results
of which were interpreted and translated into values/weights by AAWA, who then re-proposed these values to the experts,
obtaining their consensus. Similarly to what was done to identify the weights, AAWA formulated an internal study for the
definition of the value functions for the different indicators, which were then proposed and discussed with the members of
the Technical Committee, obtaining their consensus.

345 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
350 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
355 new hydraulic, urban and technological information is incorporated into civil 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
360 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.

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

- Gini Index: a measure of the inequality of income distribution within the population. A value of 0 means perfect
equality while 1 is complete inequality.
- Number of hospital beds: this is calculated per 1000 people.
- Insurance density: this is the ratio of total insurance premiums (in €) to the total population (Lenzi and Millo, 2005).
370 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
375 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 shows the maximum achievable value in the ~~different three~~ categories of citizen involvement.

380 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, 385 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 goods is around 50%, which is based on an evaluation made by Risk Frontiers, an independent research center sponsored by the insurance industry. The structural vulnerability of 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 390 applied to land use types containing buildings (Table S24). For the camping land use type 11 (Table S24), the values have been modified based on results from Majala (2001).

Vulnerability of the road network is evaluated for land use types 12 and 13 in Table S42, 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 395 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 S42), we assume a vulnerability value equal to 1 if the water height and flow velocity are greater 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 S24), we assume that the damage is related to harvest loss, and when considering higher flow velocities and water heights, to agricultural buildings and internal 400 goods. Citeau (2003) provides relationships that take water height and flow velocity into account, e.g., the maximum height is 1 m for orchards and 0.5 m for vineyards, and the maximum velocity varies from 0.25 m/s for vegetables and 0.5 m/s for orchards. Concerning cultivation in greenhouses, the maximum damage occurs at a height of 1 m. Finally, high velocities can cause direct damage to cultivated areas but can also lead to soil degradation due to erosion. The vulnerability values for four different types of land as a function of water height and flow velocity are shown in Figure S6. In the case of 405 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 stagnant flooded 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 410 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 S24). 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 S24), the presence of relevant pollution sources was identified (Tables 1 and 415 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 height was less than or equal to 1 m; otherwise it was 0.5. Regarding cultural heritage (land use type 21 in Table S24), we assigned a vulnerability of 1 to these areas.

3.1.5 Mapping flood risk before and after implementation of a CO on flood risk management

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

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

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
$0.1 < R \leq 0.2$	Low risk where 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/cultural heritage is possible, which does not affect the safety of people, the usability of buildings or economic activities	R2
$0.5 < R \leq 0.9$	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
$0.9 < R \leq 1$	Very high risk including 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 was implemented, this component had a value of 0.9 close to 1. Based on the experience gained in the WeSenseIt project and the goals of the CO, the changes in social vulnerability with the implementation of the CO are shown in Table 6, which decreases the social vulnerability to a value of 0.63. For example, in the coping capacity, the number of people employed in emergency management does not change but as a result of the CO, they will work in a much more efficient manner due to the technology that allows for better emergency management. In terms of content of the Early Warning System, -with the CO, very detailed information will be obtained further enriched by citizen reports (including reports from waterways that were not previously equipped with measuring instruments) and by a monitoring network that will be equipped with a further eight thermo-pluviometric stations, 12 hydrometric stations (equipped with a double transmission system), and 58 hydrometric and six snow measuring rods. The forecasted water level is available at every section of the Brenta-Bacchiglione River system. Hence, the content will be enhanced through the implementation of the CO. The reliability of the Early Warning System increases to very high due to the involvement of trained citizens who provide information and sensor readings that are used to validate and feed the hydrological/hydraulic model (i.e., the data assimilation module). The assumption was made based on the results obtained in Mazzoleni et al. (2017, 2018) and by considering a hypothetical situation in which a widely distributed crowdsourcing data acquisition process is in place due to the expected high level of citizen engagement. 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.

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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 Early Warning SystemEWS	< 6 hours	24-72 hours
	Content of Early Warning SystemWS	Little information	Very detailed information
	Reliability of Early Warning SystemEWS	None	High
	Citizen involvement	None	Citizens of large area
	Hazard and risk information updating	> 5 years	1-2 years

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

485 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 [Corine Land CoverC](#) developed by Huizinga (2007) for the 27 EU member states, which are based on replacement and productivity costs and their gross national products. The replacement costs for damage to buildings, soil and infrastructure assume complete rebuilding or restoration. Productivity costs are calculated based on the costs associated with an interruption in production activities inside the flooded area. The maximum flood damage values for the EU-27 and various EU countries are provided in [Table S35](#). 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 €/m²) has been applied. Moreover, in discontinuous urban areas, 50% of the value of the damage related to continuous urban areas (i.e., 309 €/m²) was applied, due to the lower density of buildings in these areas.

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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):

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

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

where w_{Dj} is the weight of the damage class, *j* is the damage category and *D* is the damage value shown in [Table S35](#). 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.

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4 Results

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

530 4.1.1 Hazard and flood risk estimates before and after implementation of a flood risk management CO

The results of the numerical simulations from the hydraulic model, which were carried 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 ha flooded, 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.

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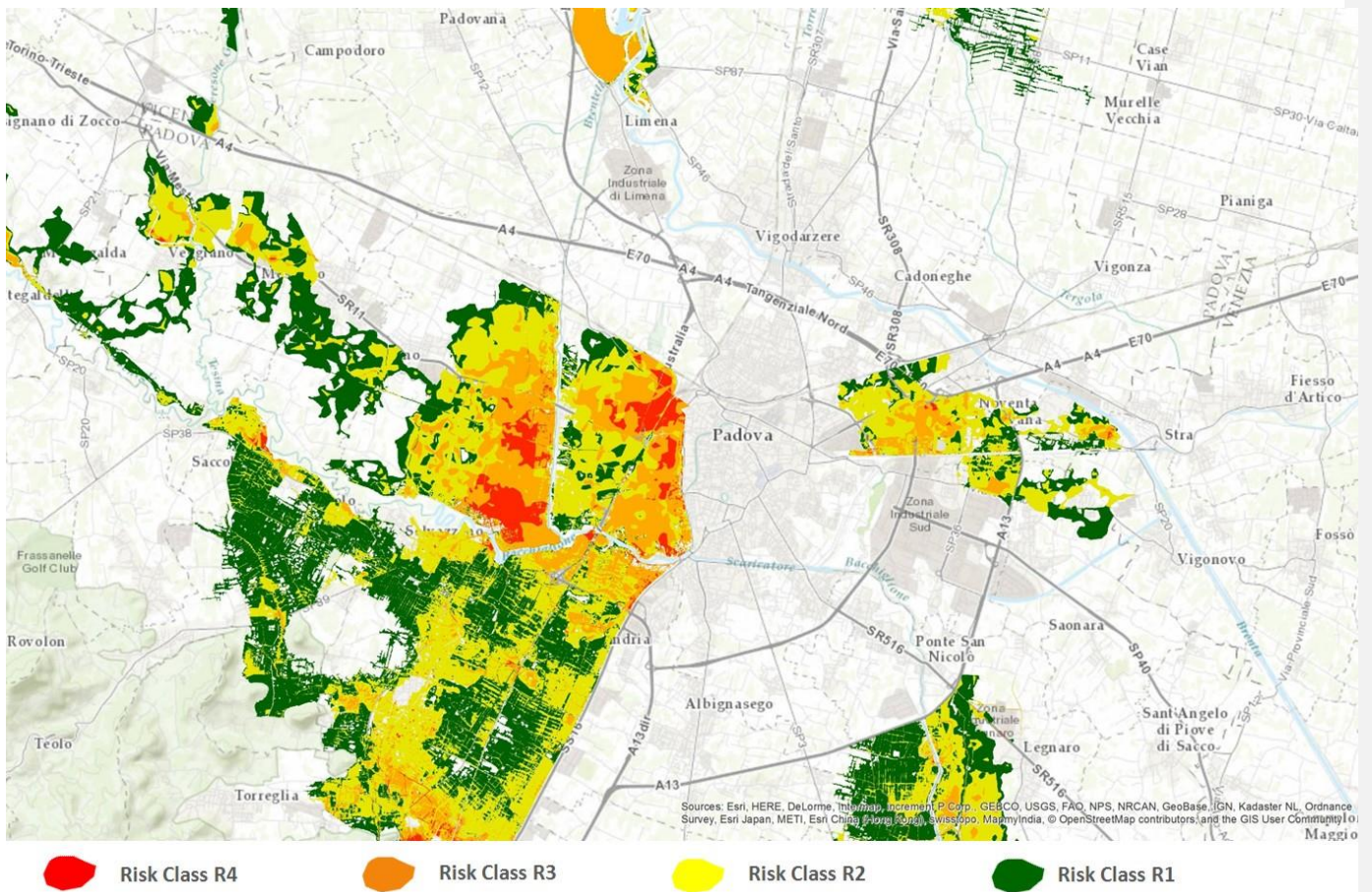
Table 7: The hazard classes for each return period in terms of area flooded.

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 flooded (km²) before and after implementation of the CO.

Risk Class	<u>Before implementation of the CO</u>			<u>After implementation of the CO</u>		
	30 year return period	100 year return period	300 year return period	<u>30 year return period</u>	<u>100 year return period</u>	<u>300 year return period</u>
Low (R1)	160.29	254.29	318.80	<u>170.96</u>	<u>268.68</u>	<u>337.78</u>
Medium (R2)	137.26	191.89	262.03	<u>168.99</u>	<u>235.18</u>	<u>322.41</u>
High (R3)	56.70	79.23	110.29	<u>18.19</u>	<u>27.19</u>	<u>40.04</u>
Very High (R4)	3.92	5.73	9.23	<u>0.03</u>	<u>0.09</u>	<u>0.12</u>
Total	358.17	531.14	700.35	<u>358.17</u>	<u>531.14</u>	<u>700.35</u>

545 ~~Figure 6~~~~Figure 5~~ Figure 5 shows the areas at risk in the territory of Padua for a 100-year flood event before implementation of a CO on flood risk management. Risk classes R1 (low risk) and R2 (medium risk) have the highest areas for all flood event frequencies. Although areas in R3 (high risk) and R4 (very high risk) may comprise a relatively smaller area when compared to the total area at risk, these also coincide with areas of high concentrations of inhabitants in Vicenza and Padua.



565 **Figure 65:** Risk map for the metropolitan area of Padua for a 100-year flood event before implementation of a CO on flood risk management. Sources: Esri, HERE, DeLorme, Intermap, Increment P. Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China HongKong, swisstopo, MapmyIndia, © OpenStreetMap contributors 2020. Distributed under a Creative Commons BY-SA License, and the GIS User Community

570 After implementation of a CO for flood risk management, the flood risk is reduced (Table 8) 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) but the areas in the lower risk classes increase. This occurs because the total area affected by the flood hazard is the same before and after implementation of a CO. What changes is the distribution between risk classes, i.e., R3 and R4 are reduced, which means that the areas at risk in classes R1 and R2 will increase. The risk map for a 100-year flood event for the territory of Padua is shown in [Figure 6](#) [Figure 7](#), where the reduction in areas at high and very high risk are clearly visible compared to the situation before implementation of the CO ([Figure 6](#) [Figure 5](#)).

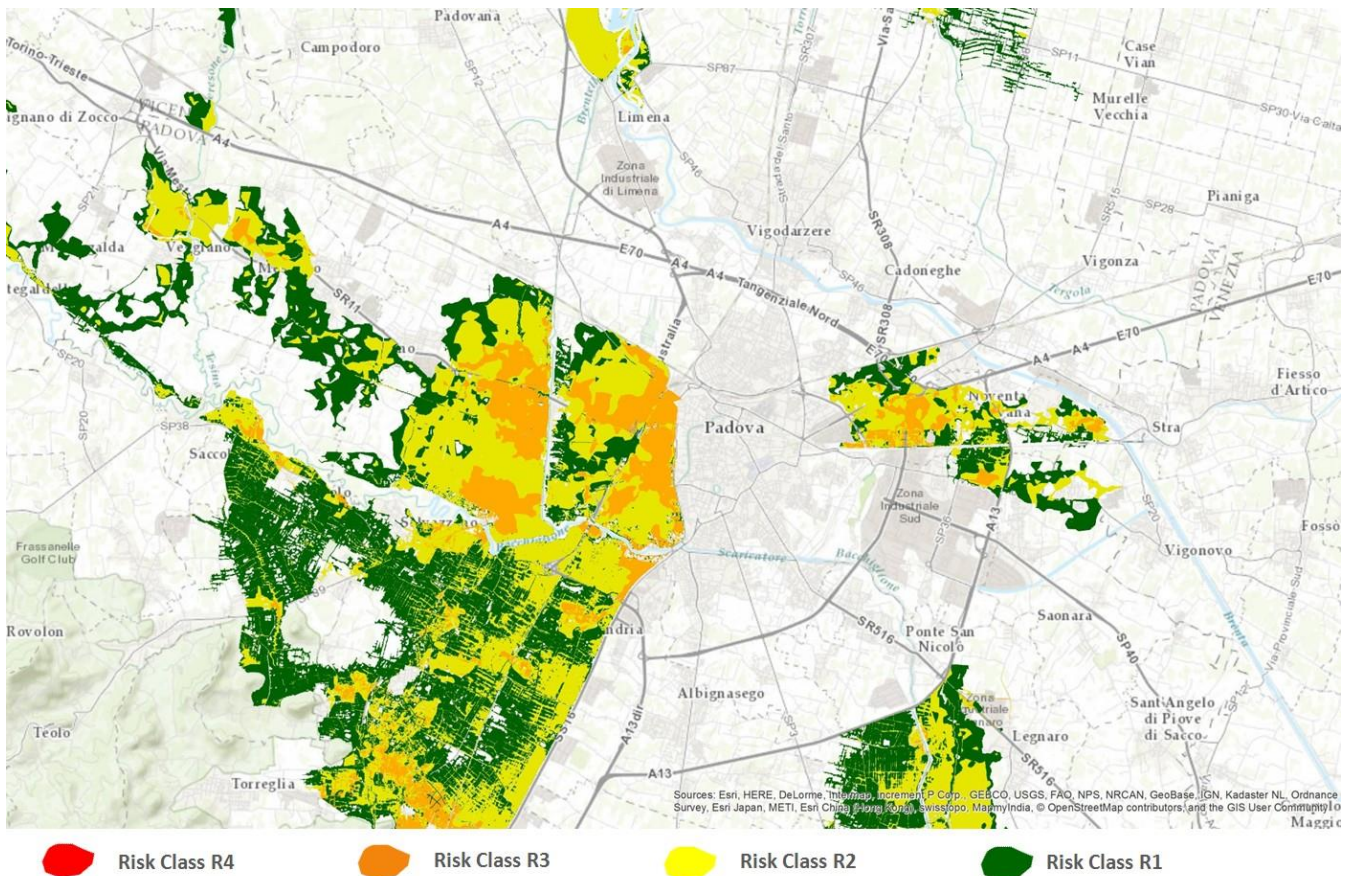


Figure 76: Risk map for the metropolitan area of Padua for a 100-year flood event after implementation of a CO on flood risk management. Sources: Esri, HERE, DeLorme, Intermap, Increment P. Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China HongKong, swisstopo, MapmyIndia, © OpenStreetMap contributors 2020. Distributed under a Creative Commons BY-SA License, and the GIS User Community

4.1.2 Expected damage with and without implementation of a flood risk management CO

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), which is summarized in Table 9. In the event of very frequent flood events, urban areas will be damaged. 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. The residual damage was then calculated for the three flood scenarios after implementation

of the CO on flood risk reduction, which is shown in ~~Table 9~~ Table 11. Substituting these residual damage values into equation (5), we obtain an EAD of 111.3 million Euros, which is a 45% reduction in the damage compared to results without implementation of the CO.

The CO for flood risk management has an estimated cost of around 5 million Euros (as detailed in Table S26 in the Supplementary Materials), after which it will be evaluated and further funding sought. 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 Breganze (in an independent exercise) to improve the hydraulic safety of the Bacchiglione River. 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 of 140.7 million Euros so the cost to benefit ratio would be much lower.

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Table 94: 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

5 Discussion and Conclusions

610 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 before they 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.

625 The main impact of the CO on flood risk management has been to lower the social vulnerability of risk, both in terms of adaptive as well as coping capacity. This finding is consistent with other studies of citizen science that aim to capture the impacts on social vulnerability. Bremer et al. (2019) in their case study in Bangladesh found that citizen science has had a high impact on adaptive capacity in terms of individual awareness and understanding of local rainfall, learning that they applied in adaptive practices at work and at home, as well as local leadership. Improvements in social capital (trust, sharing experience and formal/informal interactions) were also measurable. This provides support for the argument that CO impacts, especially capacity-related ones, do not necessarily (have to) materialise (only) via formal policy mechanisms. Both coping and adaptive capacity have individual, community as well as policy dimensions, not all of which are impacted in parallel nor to the same degree; moreover, adaptive capacities are context specific.

630 Regarding the impact on estimating other flood risk drivers, at present, the impact of citizens is not evaluated in the hazard component as the inputs from citizens would be used in real-time rather than the baseline modelling that was done to establish the areas flooded, the height and the flow velocity under three different flood return periods. Instead, the contribution of citizens is incorporated into the Early Warning System component of social vulnerability through improvements in the reliability, lead time and information content of the system (Figure S2 in the Supplementary Information) as well as components of Adaptive Capacity (Hazard and risk information updating and Citizen involvement - Figure S3 in the Supplementary Information). Similarly, there is currently no impact of citizens/experts on exposure or physical vulnerability as this analysis is based on land use categories rather than individual buildings, where in the latter it might be possible to capture small changes done at the household, building or feature level. However, this is not part of the

640 current methodology. A second aspect is increased awareness/participation in combination with data provisioning, i.e., the app provides information about flood risk to citizens while at the same time asking for inputs/participation that can be used to feed the model and/or, in real-time, to provide information to help emergency response. The concept of a CO is built on the idea of two-way communication between the citizens/experts and the local authorities.

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 S14 of the Supplementary Material. Many of these values have been derived through expert consultation and experience, and they have 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 S14. 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 solution in 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. Although the people involved in the emergency services are the same, they are employed in a much more efficient way as a result of the technology developed with the CO, which allows for better management of the teams responding to the event and the efficient assignment of tasks based on an operator's location. Therefore, an analysis that takes indirect costs into account could help to further convince policy makers of the feasibility of a CO solution. Similarly, intangible costs were not considered, i.e., the values lost due to an adverse natural event where monetary valuation is difficult because the impacts do not have a corresponding market value (e.g., health effects). Furthermore, the vulnerability assessment of economic activities considers only water depth and flow velocity but not additional factors such as the dynamics of contamination propagation in surface waters during the flood or the duration of the flood event, all of which could be taken into account in estimating the structural damage and monetary losses in the residential, commercial and agricultural sectors.

Despite these various limitations, this analysis has highlighted the feasibility of a non-structural flood mitigation choice such as a CO for 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, which can also be transferred to other catchments. There are plans to extend the CO to other basins in the Eastern Alps, which are similar in size and hydrological characteristics. These are complex hydrographic basins with very variable regimes, from rapid response/torrential rainfall events of the alpine territories to the alluvial plain, which is composed of mountain and lowland river networks, artificial networks of reclamation and natural and/or artificial reservoirs. In general, this methodology can be applied to catchments larger than 100 km² where model forecasts would be most useful.

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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