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Integrated Assessment of Natural Hazards and Climate-Change Adaptation: II. The SERRA Methodology

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Abstract
We propose an integrated methodology to evaluate the four possible socio-economic costs namely direct/indirect and tangible/intangible costs due to adverse consequences of flood. Although SERRA is based on full monetization of costs and benefits of risk, it can allow for other methods of economic appraisal such as cost-effectiveness when controversial or unethical. By considering social aspect of vulnerability, meaning adaptive and coping capacities of the affected society, we arrive at a more accurate estimation of risk. This further allows us to evaluate the set of risk reduction measures with a focus on non-structural ones, which consequently helps the decision-maker to select the optimal measure given her constraints. Our methodology attempts to be comprehensive with respect to the set of receptors that is an enhancement compared to Regional Risk Assessment that is the mainstream method in the literature.

Keywords
Adaptive/coping capacities, Indirect costs, Intangible costs, Vulnerability, Total Cost Matrix
JEL Codes
Q51, Q54, D81

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1. *Introduction*

This paper is the second part of a broader study on "Integrated Assessment of Natural Hazards and Climate-Change Adaptation" developed by the authors. In the first part, we presented the KULTURISK framework and discussed the differences in the two main schools of thought on evaluation of environmental risk: Disaster Risk Reduction (DRR) and Climate Change Adaptation (CCA). In current note, we discuss the SERRA methodology that accompanies the KULTURisk framework.

The literature of flood risk assessment has been mainly cantered on direct and tangible appraisal of a certain receptor, e.g. people, economic activities, etc. Receptors are physical or non-physical assets negatively harmed by a hydrological disaster such as floods and landslides. Receptors have an intrinsic value, which is determined either at market or by the help of other methods when they are not traded in any market. This appeals for an integrated and comprehensive risk assessment that is not limited to a single receptor and comprises a broader set of costs namely indirect and intangible costs. By integrated, we mean an assessment, which not only addresses physical/environmental risk but also considers the economic value at risk and the societies' capacities in adopting and dealing with natural disasters ex-ante or ex-post respectively. To overcome the first need, i.e. assessment of multiple receptors, we adopt Regional Risk Assessment (RRA). However, in RRA, the concept of risk is only centred on the physical dimensions of vulnerability to produce physical/environmental risk maps. We extend the RRA to, additionally, consider the social dimension of vulnerability and economic value factors, with the aim of providing a broader assessment of risk. As a consequence, we support decisions regarding the implementation of non-structural measures, which by and large subside the human dimension of vulnerability apart from the common structural measure for mitigating flood risk. This is based upon consolidated methodological approaches, and in particular, Cost-Benefit Analysis (CBA), Cost-Effectiveness Analysis (CEA), and Multi-Criteria Analysis (MCA).

Our study is built upon two pillars; first, we stress on the society's capacity in dealing with risk; second, we deal with economic valuation of risk. We identify two complementary approaches (S-RRA and E-RRA), which are designed to be implemented within the KULTURisk conceptual framework described in Part I of this study (Giupponi et al., 2013), thus producing the proposed approach named as SERRA: Socio-Economic Regional Risk Assessment. Overall, the SERRA is designed to fit within the well-established formula, which calculates risk as the multiplicative combination of Hazard, Vulnerability and Exposure.

In order to be consistent with the multiplicative approach, and to provide an economical estimation of costs as an outcome associated to well specified risks (e.g. estimated costs associated with a flood event with predicted return time X on area Y), the first two dimensions

(H and V) are calculated as non-dimensional indices to be treated as multipliers of the index E, expressed in monetary units, thus obtaining a notion of economic risk as a final outcome of the implementation of SERRA.

This paper is organized as follows. In Section 1, we define the economic appraisal and discuss the pros and cons of popular methods of their implementation. In Section 2, we review the RRA methodology and discuss its deficiencies in advocating flood risks. The concept of vulnerability and its components are introduced and explained in Section 3. We provide a diverse set of methods in quantifying and monetizing flood risk as part of SERRA in Section 4. Finally, we conclude and discuss remarks in the Conclusions.

2. *Economic Appraisal*

Cost-Benefit Analysis (CBA) is the expected application context, whereby the economic risk calculated for the baseline situation (before the adoption of Risk Reduction Measures, RRMs) is compared with expected benefits in terms of risk reduction estimated for one or more possible RRMs and their costs. The costs of the measure(s) are thus compared in monetary terms with the benefits in terms of risk reduction, and in case of multiple measures considered at once to select the one to be preferred. The best is indeed the one with the highest benefit to cost ratio, with the possible consideration, when needed, of other criteria, such as the meeting of risk predefined abatement objectives.

The description above is known as "economic appraisal" and there are wide ranges of techniques among which the most common forms are: i) Cost-Minimization; ii) Cost-Effectiveness; iii) Cost-Benefit, and iv) Cost-Utility analyses. These methods should help decision-makers (DMs) to rank RRMs on the basis of the benefits per unit of cost. In addition, there is Cost-Consequence Analysis, which differs from others in that the range of costs and consequences are reported without attempting to aggregate the costs or benefits into a single measure. This resembles to cost-effectiveness, but it is applied to evaluate RMMs with multiple multidimensional outcomes. In Cost-Minimization Analysis, we choose the cheapest RRM after comparing the costs of achieving a given outcome (e.g. saving lives of all citizens of a village, keeping a road/railroad/highway functional). Similarly, CEA, often comprising Cost-Minimization Analysis, compares the cost per unit of outcomes among alternative RRMs that produce the same effect. A cost-effective RRM is the one that exceeds alternative measures in numbers of positive outcomes calculated by dividing the net cost of a RRM by its net effectiveness. This method is narrow as only one outcome is evaluated, and it cannot be used for evaluating a single measure or to compare heterogeneous alternatives, unless aggregation procedures are included. In CBA, the outcomes of RRMs are viewed as benefits, which is a monetary value assigned to the outcome. If benefits exceed costs, then the RRM should be implemented else rejected (absolute efficiency). Cost-Benefit can also be expressed as a ratio with benefits in numerator and costs in the denominator (relative efficiency). Worth to note is the fact that CBA allows us to embody discount factor to consider the time value of the money. This is an important factor given the nature of the problem at our hand characterized by future streams of costs and benefits, long-term effects of climate change, and trade-off between valuations of several generations. At the same time, it can also be a quite controversial component of the valuation, since the identification of the discount rate to be adopted is always a quite challenging exercise. However, use of CBA is controversial, when it comes to assessing human's health. This issue can be overcome, to some degree, by using the concept of Willingness To Pay (WTP).

Cost-utility analysis is a modified version of cost-effectiveness analysis, which is particularly applied to health. In this case, it measures a RRM's effect on both quantitative and qualitative aspects of health (mortality and morbidity). This method focuses on the increased quality of life. It is expressed either as cost per quality-adjusted life years (QALY), which indicates the size of health gain from a RMM or disability adjusted life years (DALY), which expresses years of life lost due to premature death and years lived with a disability. All the three above-mentioned methods can be applied to circumstances where budget is fixed and maximum outcome is sought or when the objective is fixed and the minimum cost method of achieving the objectives is sought.

As mentioned above, while the SERRA approach provides operational solutions for a full monetisation of various dimensions of the problem, it is envisaged that in some cases such full monetisation is either impossible or not within the will of decision makers. Cases of limited possibilities to reach full monetisation could be, for example, those in which the monetary valuation of expected environmental damages by means of the stated preference methods proposed by the environmental economics literature (e.g. contingent valuation) is impossible for time, skill, or resources constraints. Cases of decision makers being reluctant to adopt CBA are instead those in which monetisation may raise cultural, ethical or political issues, typically when the value of statistical life is applied to consider potential casualties related to specific hazards and the resulting costs are to be compared with others, related for example to physical assets.

In those cases, other approaches mentioned above can adequately support decisions about risk mitigation strategies and measures. In practice, the possibility of converging on a simple comparison of costs and benefits is thus impossible any more, and in particular, it is the calculation of $\boldsymbol{E}$ (exposure) as an aggregated monetary index. Therefore, exposure has to be considered as a disaggregated notion (e.g. for the different receptors) expressed in different units (e.g. Euros, but also hectares of damaged ecosystems, or lives at risk). In those cases Cost

Effectiveness Analysis should be considered, and the valuation exercise can thus be formalised in terms of the identification of the cheapest measure allowing to meet predefined risk mitigation goals (e.g. number of people at risk below a given number), or as the identification of the measure that given a predefined constraint of financial resources available for risk mitigation, can obtain the better performances for one or more receptors.

Having multiple dimensions to consider (e.g. multiple receptors) and quantified with multiple units raises the issue of making a synthesis out of likely trade-offs, which may be encountered whenever, for example a given measure provides a very good environmental performance to the expenses of some economic activities, or vice versa. In other words, the effectiveness of the considered measures could show trade-offs amongst the various receptors. Multi-Criteria Analysis, not always considered within the economic valuation methods, may support in all those cases the aggregation of multiple dimensions into a single score, by means of a plethora of aggregation rules available from the literature. This could be the case of CEA applications, in which the need emerge to aggregate multidimensional notions of effectiveness, into a single index, to be compared with costs. The methodological issues related to the calculation of a concise index out of series of indicators (normalisation of multidimensional indicators, weighting and aggregation) are common also to the calculation of the vulnerability index, and they will be briefly treated in Section 3.

3. *Review on Regional Risk Assessment*

The main purpose of ecological risk assessment is to systematically understand, quantify, and estimate the risk from environmental hazard. Regional Risk assessment (RRA) was first introduced by Hunsaker et al. (1989) to study the risk of an ecological disaster beyond a single site or small geographical area. This methodology was later developed and extended by several other studies (Barnthouse and Suter, 1986; Suter, 1990; Hunsaker et al., 1990; Graham et al., 1991; Landis & Wiegers, 1997). The RRA divided the continuum of spatial scale risk assessment into two main classes namely local and regional (Hunsaker et al., 1990). However, given the interconnectivity of economies and globalization, the causes and consequences of an environmental hazard can be connected through complex networks. This is the case when the cause can be a regional phenomenon but the consequences can become national or global. For instance, a flood can cut the transportation possibilities and hence disrupt the trade of raw materials, finished goods or even limit the mobility of labour force and this can propagate further through the network. Hence, by using the term regional, we are not limiting the risk assessment to only one region but rather a set of interconnected regions including many types of receptors.

Similarly to Barnthouse and Suter (1986), we identify the following steps for an integrated and comprehensive risk assessment:

(1) Qualitative and quantitative description of the hazard (e.g. pluvial/fluvial, flow velocity, inundation depth, debris factor etc.), which leads to producing Hazard maps.

(2) Identification and description of the environment that receives the effect (e.g. urban area, ecosystems). For this step we can use CORINE land cover maps produced by European Environment agency. However, these maps are mainly suitable for a meso or macro scale risk assessment as we explain later.

(3) Selection of receptors (residential buildings, industrial zones, warehouses, retailers, people, infrastructures, vehicles, etc.). This step is part of the identification and creation of Exposure maps at a micro or meso scale.

- As part of this step, we identify the dependent receptors, which are linked to directly exposed receptors and hence flood will influence them indirectly.

(4) Estimation of spatio-temporal patterns of exposure using appropriate models or available data (timing of cultivation or harvesting, position of infrastructure network in a certain grid using GIS data, etc.). This step is further classified to:

- Identifying *Adaptive* and *Coping* capacities' indicators for every feasible type of receptor.
- Identifying the *Susceptibility* characteristics for each type of receptor
- Assembling *Vulnerability* index at the end of step 4.

(5) Identifying the set of value factors for exposed receptors and their indirect dependents.

(6) Calculating *Risk* from previous steps.

(7) Designating the risk of receptor into Total Cost Matrix (TCM) quadrants.

We can express the steps above with the following formula for calculating total direct risk of flood in a region:

$$R = \sum_t \sum_j \sum_i \sum_s \sum_l P_{ij}^{lt}(Ch_{ij}^t).H_{ij}(fv_{ij}, id_{ij}, df_{ij}).V_{ij}^{ts}(su_{ij}^{ts}, ac_{ij}^{ts}, cc_{ij}^{ts}).evf_{ij}^{ts}, \quad (1)$$

where P^{lt}_{ij} is the probability of flood event *l* at time *t* in grid *(i,j)* with certain annual exceedance probability (AEP). The parameters or the functional forms of the probability distribution can change in the course of time and it is a function of climate change (Ch^t_{ij}) factors. H_{ij} is the hazard at grid *(i,j)* as a function of flow velocity (fv_{ij}), inundation depth (id_{ij}), and debris factor (df_{ij}); V^{ts} represents vulnerability index of receptor *s* at time *t* as a function of its physical susceptibility (su^{ts}), adaptive capacity (ac^{ts}), coping capacity (cc^{ts}); evf^{ts} is economic value factor of receptor *s* at time *t*.

While hazard is spatially dependent, vulnerability and value factors are contingent on time as characteristics of the society or land-usage change in the course of time and receptors might substitute each other in short time. One of the aims of this study is to elaborate on the modelling of vulnerability and its capacity in alleviating the risk. As shown above, vulnerability is directly affected by three factors but indirectly it is a function of other variables that compose the above including any structural or non-structural measures to reduce risk, characteristics of a society, physical attributes of each receptor, etc.

Traditionally RRA is restricted to steps 1-3 without measuring the role of societies' characteristics in building up capacities to confront deleterious repercussions of flood. Moreover, in RRA there is little distinction between expected monetary risks to e.g. Manhattan versus the downtown of a small town in Nevada, as EVFs and indirect impacts are not taken into account. After the flooding of Thailand in 2011 causing 30% reduction (The Guardian, 25, October, 2011.) in production of hard drives, Decision Makers (DMs) are seeking to develop methodologies that can also appraise indirect risks.

4. *Social-RRA: Appraisal of the human dimension of vulnerability and risk*

Vulnerability refers to the propensity of exposed receptors to be negatively affected by hazard events (IPCC-SREX) considering both human and physical dimensions. The physical dimension of vulnerability is considered as susceptibility, whereas, the human dimension of vulnerability consists of both adaptive capacity and coping capacity. These three dimensions have to be assessed and aggregated in order to provide a spatial quantification of vulnerability, and this section provides a methodological proposal for both assessment and aggregation procedures.

1.1. Methods

As the notion of vulnerability is the result of complex and combined effects of different social and biophysical variables, it is hard to imagine that a mechanistic (i.e. physically based) static or dynamic model can measure vulnerability in an objective and scientifically sound way. Instead, the literature is rich of empirical models based on concise indicators, combined with rather simplified formulas, sometimes making use of statistical/mathematical algorithms for normalization, weighting, and aggregation. Subjectivity thus emerges as a relevant dimension to be considered and treated, by defining, for example, robust and transparent methods for the weighting of the selected indicators (Giupponi et al., 2012).

Given that multiple dimensions are considered to produce a single index of vulnerability to be used for the calculation of risk, the following methodological issues emerge:

1. the selection of indicators;
2. the normalisation of indicators' values into non-dimensional scales (typically 0 to 1);

3. the weighting of (normalised) indicators, to take into consideration their relative relevance to contribute to a single notion of vulnerability of the social and ecological system under consideration:
4. the aggregation algorithm to be adopted to calculate the vulnerability index by processing the values of the various indicators.

The following sections will briefly deal with those issues.

1.1.1. Selection of indicators

Before selecting indicators and assessing vulnerability and risk, the application context needs to be defined. The indicators of vulnerability components mainly vary with the hazard types, and the spatial scale considered for the study. For example, the indicators for assessing flood risk are different from the indicators of seismic risk. Since, we are here dealing with flood hazard, the proposed indicators represent how society is capable to cope with and be adapted to floods, and how various assets, structures and infrastructures are susceptible to the flood itself. The choice of indicators also depends upon various selection criteria, and in particular the spatial scale (e.g. micro, macro, and meso-scale). For assessing flood risk, different types of scales have specific interest (Gain et al., 2012): a scale representing the physical water resources subsystem and a scale representing the administrative subsystem (see **Figure *1***). The bio-physical (water resources) scale ranges from a single watershed to the global hydrologic system whereas the administrative scale ranges from postal code area to state. Among the mentioned scales, at least, biophysical and administrative units of analysis need to be congruent with the purpose of the assessment and they should be adequately treated by means of Geographical Information System (GIS) based techniques.

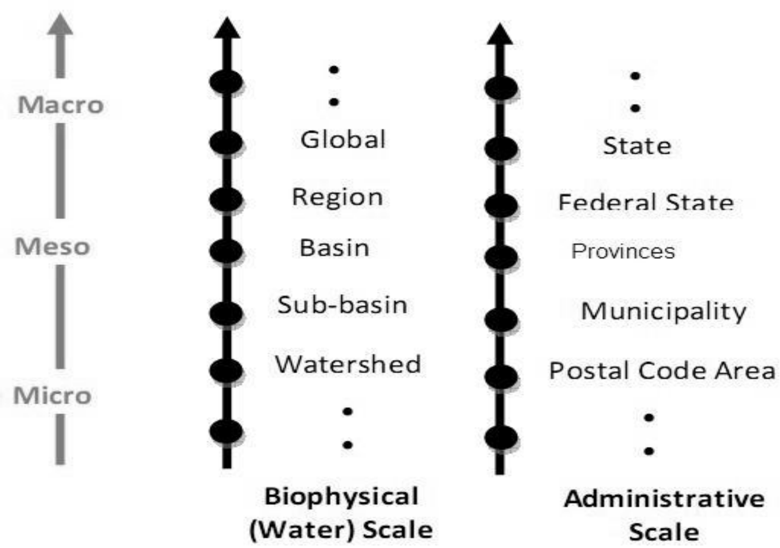


Figure 1 - Schematic illustrations of different scales.

In this section the proposed list of indicators of vulnerability is provided for the selected receptors i.e., population (P), economic activities – further classified into building (B), infrastructure (I), and agriculture (A), ecosystems and cultural heritages (ECH) and is shown in Appendix B. Moreover, buildings are distinguished in two types i.e., i) residential (R) and ii) commercial and industrial (CI), which is further classified into three categories: structure (S), content (C), business activity (B). For ecosystems, the social role of vulnerability is not relevant and we are restricted to Physical/Environmental (PE) risk assessment.

1.1.2. Normalization

A preliminary step for the aggregation of indicators is normalization, which is the procedure of transforming indicator values with different units of measure into a dimensionless number. Several normalization techniques exist in literature (Nardo et al., 2005) and are also discussed in part I of this paper (Giupponi et al., 2013).

However, the best choice of the normalization methods depends on the underlying indicators and the preferences of the decision maker.

The normalisation algorithm can adopt various formula, for example Min-Max, 0-Max, etc., or in general a value function, i.e. a mathematical representations of human judgments, which offer the possibility of treating people's beliefs, and judgments explicitly, logically, and systematically (Beinat, 1997). In order to apply a value function, we need to determine upper and lower thresholds and a series of values representing different significant levels of performance with reference to defined goal. For example, an indicator of social welfare can be transformed into a dimensionless indicator to be used for the calculation of vulnerability by means of a simple linear formula expressing the notion that the higher the welfare status, the lower is the expected vulnerability. In other cases there could be an optimal interval for a given indicator, with decreasing normalised values to be given to both too high and too low indicator values; in those cases a trapezoidal value function should be adopted.

The identification of suitable value function can be achieved through the elicitation of expert knowledge.

Normalized values can be further categorised as reported in **Table *1***, in which 0 represents not vulnerable cases and 1 represents fully vulnerable ones.

Table 1 - Definition of normalized scores.

Normalized value	Vulnerability level
0	Not vulnerable
0.25	Slightly vulnerable
0.50	Highly vulnerable
0.75	Extremely vulnerable
1	Fully vulnerable

1.1.3. Weighting and Aggregation

The vulnerability index is the result of the combination of several indicators. Therefore, a hierarchical aggregation tree is suggested, to combine sub-sets of indicators in each node where they converge. To aggregate them, we choose suitable aggregation algorithms, not only in accordance with the logic of the conceptual model, but also according to the elicited preference of the decision makers (DMs). Preferences should also be considered for the definition of weights, whenever the relative importance of the various indicators varies. Only to some extent a methodological framework such as SERRA can define generally valid proper solutions. In this regards, the case of weighting is emblematic: no universally valid weight vector exists for the set of proposed indicators. Therefore, weights have to be defined in each implementation and proper methods have to be implemented for their elicitation and for their consideration in the aggregation algorithm used to calculate the vulnerability index.

Aggregation of indicators is obviously not a trivial task since the chosen (among many) methodology has meaningful impacts on the computation of the final index; furthermore, the choice of the aggregation method typically involves trade-offs between loss of information, computational complexity, adherence to DMs' preference structure and transparency of procedure.

Among the different aggregation methods, weighted averages (WA), geometric averages (GA) and non-additive measures (NAM) can be mentioned here (Grabish, 2009), but the final choice stands on the expert being involved in the real world implementation cases. WAs are typically compensatory (i.e. a bad score in one criterion can be offset by a good score in another one) and more importantly they are not able to consider any interaction among the criteria, while GAs can cover only a smaller set of preference structures: those at the limit of logical conjunction and disjunction. Therefore, more complex methods such as the NAMs have been proposed to overcome the main drawbacks of the methods mentioned above and thus represent a more generalised approach

In the WA method, stakeholders need to be involved to collect relative weights of the indicators in each node where converge. As an example, variable *vi* can be a function of the normalized indicators x_1, x_2, x_3, which can be aggregated by Equation (2). The weights w_1, w_2, and w_3 represent the relative weights of x_1, x_2, and x_3 respectively. Having previously defined a hierarchical combination of the indicators like in the example provided in Figure 2, we can eventually calculate aggregate vulnerability index with a value between 0 and 1.

$$vi(x_1, x_2, x_3) = w_1 \cdot x_1 + w_2 \cdot x_2 + w_3 \cdot x_3 \qquad (2)$$

The same hierarchical combination can be implemented by substituting WA with a weighted multiplicative approach, thus moving from full compensation to the opposite in which a single indicator with value equals to zero determines the whole aggregated value resulting as zero. This is shown in Equation (3).

$$vi(x_1, x_2, x_3) = w_1 \cdot x_1 \cdot w_2 \cdot x_2 \cdot w_3 \cdot x_3 \quad (3)$$

More complex methods for weighting and aggregation such as the NAMs raise relevant methodological issues in implementation, for example in the design of ad hoc questionnaires for the elicitation of weights (see Giupponi et al., 2012).

By applying weights to normalised indicators and aggregating them by means of the preferred aggregation rule, one vulnerability index is obtained per each receptor with a score ranging between 0 and 1, where 0 represents no vulnerability whereas 1 represents full vulnerability.

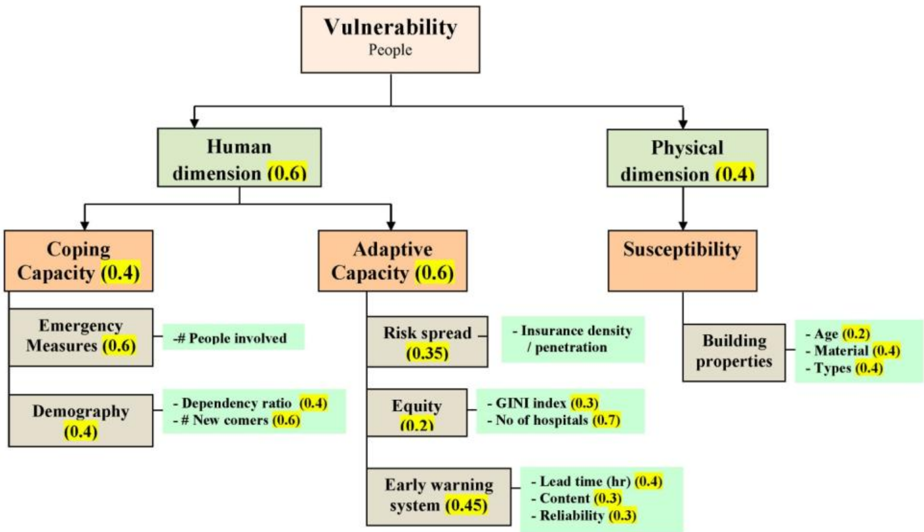


Figure 2 - Hierarchical combination of indicators with relative weights.

1.2. Application for Each Receptor

1.2.1. People vulnerability

Vulnerability to people is determined by the characteristics of susceptible buildings where they live and the available social capacities to cope and adapt with the flood hazard. Improved early warning systems (EWS), risk-spreading mechanisms i.e., insurance coverage, and ensuring equity can be used to prepare for and undertake actions to reduce adverse impacts, moderate harm, or exploit beneficial opportunities of the people. Similarly, emergency measures and demographic properties e.g., number of migrants, dependency ratio have an important role to overcome ex-post hazard. Therefore, the indicators of these variables are considered as adaptive capacity and coping capacity. The list of indicators along with definition and data source is provided in Appendix B. For the people, the hierarchical combination of the indicators is shown in Figure 2, where values of weights are provided, just as an exemplification of the procedure, but they should instead be defined according to the preferences of the relevant actors involved in each case.

Following our described methods, each of the selected indicators needs to be normalized. For the illustration, the indicators of lead-time and reliability for early warning system are normalized in the following example (Figure 3). The measurement unit of EWS lead-time can be found in hours. In this example, it is considered that if EWS is provided in less than 3 hours, the community is not able to save any resources. Therefore, it is considered as fully vulnerable with the normalized score 1, whereas if EWS is provided seven days in advance, most or all of the resources can be saved and hence normalized value can be represented by 0. Similarly, value judgment is used for the qualitative indicator, i.e. reliability. If the EWS is completely reliable, the normalized value can be considered as 0 and 1 for the opposite case. Using this procedure, all the indicators used in computing the 'vulnerability' index are normalised, and can be subsequently treated as fuzzy variables.

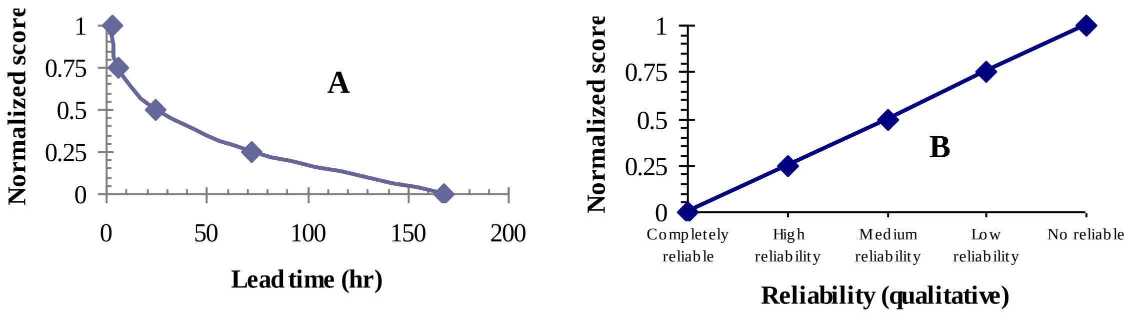


Figure 3 - Normalization of Lead-time (hr) and reliability of early warning system.

As the next step, we need to aggregate indicators in order to calculate vulnerability index. For the aggregation of the indicators in each convergence node of hierarchical structure (

Figure 2), we define aggregation rules according to the specific meaning of the node and the expected results. We provide two examples with reference to Figure 3. In the case of coping capacity and more specifically its demographic indicator, we may for example consider both the dependency ratio and the number of newcomers contributing to the definition of vulnerability indicator. There is no reason to believe that in case of no newcomers (indicator value = 0) the aggregated indicator would be zero independently from the dependency ratio. In this case the weighted average method is an effective solution to be applied with the relative weights of indicators elicited from local actors (i.e. 0.4 and 0.6 in the example reported in Figure ***2***). The index of EWS provides a different example. It is proposed that it is calculated through the aggregation of Lead-time, Content and Reliability, but in this case it is intuitive that in case of a system with no reliability, the resulting contribution to the vulnerability index should be 0 and thus Equation (3) should be preferred.

Similarly, indicators can be aggregated in each convergence node, and eventually we can calculate aggregate vulnerability index for people with a value between 0 and 1 following the hierarchical combination of Figure 2.

1.2.2. Vulnerability of economic Activities

The receptor of economic activities is further categorised as i) Buildings; ii) Infrastructures; iii) Agriculture. Vulnerability assessment for these sub-categories is discussed below.

Buildings

Vulnerability assessment for building is complex, as there are different dimensions of heterogeneity. First, building types are different, which include residential, industrial, and commercial centres. Second, each of these building types includes content and structure. In addition, business activity is also included in the industrial and commercial buildings. For the structure and content, the age, material and type of building properties are considered as proxy of susceptibility. Conversely, for the business activities, beside the own sector and size, susceptibility is approximated by taking into account the interconnectivity and specialization of the economy. People involved in emergency measures is considered as coping capacity both for content and business activity of the buildings, but for vulnerability to building structure this is not considered as in the emergency situation people are not engaged to save structure of the buildings. For the structure, EWS and insurance are considered as adaptive capacity. In addition to these, income and revenue are added to content and business respectively.

For each sub-receptor, the list of indicators along with definition and data source is provided in Appendix C.

Infrastructures

Infrastructure is another important receptor to be considered for vulnerability assessment. Considering definitions adopted and stated in Part I of this paper (Giupponi et al., 2013), the indicators of adaptive and coping capacities and susceptibility for infrastructure are selected as provided in Appendix C. During floods, network properties and interconnectivity of the economy are susceptible components of infrastructure. Hence, these are considered as susceptibility although they are not physical properties of the system. Early warning system and people involved in emergency management are considered as adaptive capacity and coping capacity respectively.

Agriculture

For the vulnerability assessment of agriculture, flood timing and the economic context are considered as susceptibility. Flood timing takes into account the season and duration of inundation whereas the economic context includes interconnectivity and specialization of the affected agricultural production systems. Improved EWS and insurance coverage can be used to reduce adverse impacts on agriculture. Similarly, people involved in emergency measures have an important role to overcome post-event crises. Therefore, the indicators of these variables are considered as factors of adaptive capacity and coping capacity, respectively.

Cultural Heritage

For the assessment of the vulnerability of cultural heritage, buildings/assets properties are considered as susceptibility. EWS as well as people involved in emergency management are considered as adaptive capacity and coping capacity, respectively.

4. *Socio-Economic RRA*

This section, building upon S-RRA, attempts to provide a method for systematically calculating benefits and costs of risk reduction measures, regulations, or decisions. We acknowledge that this might not always be possible or desired, especially when it comes to quantifying the benefits of minimizing the harm to human life and well-being.

In this section, we characterize the set of value factors and the methods for assessing each type of damages per receptor. Value factors are a set of diverse factors such as value of statistical life, willingness to pay or accept, value transfer tables, value of businesses, number of direct or indirect users, clean up & repair unit cost, etc., that support DMs to monetize damages and assign them to TCM. We confront the intangible costs by discussing the popular methods of evaluating non-marketable goods and services such as cultural heritages and ecosystems.

4.1 Damages to Receptors

Hereunder, we discuss the damages to the four categories of the receptors. Distribution of some receptors such as people and cultural heritages can be derived from census data, as CORINE land covers are not sufficient.

4.1.1 Damages to People

With no doubt one of the highest and irreversible costs of any natural hazard is the possible loss of people, which is considered as an intangible damage. It is also important for many insurance companies as well of authorities to have an estimate of psychological trauma and the injuries of the people in the flood zone. Our approach in assessing the damages to people is based on CBA. However, the morality of such method could be questionable and many stakeholders might prefer using alternative methods such as CEA.

We define Flood Severeness (*fs*) as a function of variables that contribute to the magnitude of flood risk including flood frequency (*p*), flow velocity (*fv*), inundation depth (*id*), and presence of debris factor (*df*) as following.

$$fs = f(P(\cdot), fv, id, df)$$

Flood severeness interacts with area vulnerability (*av*) and people's vulnerability (*pv*). Examples of area vulnerability are types of housing classes (presence of basement, multi-storey, etc.), EWS, and speed of onset. People's vulnerability is constructed by taking into account the age classes and the percentage of disables or sick people (DEFRA & Environment Agency, 2009). The vulnerability index (*vi*) can include the above-mentioned variables used to construct *av* and *pv*, or be more comprehensive depending on available data and characteristics of the impacted society. Once the *vi* is constructed, we can define the number of people at risk (npr_{ij}) as the product of the number of people n_{ij} living in a GIS cell (i,j) with the rate of people at risk (rpr_{ij}).

$$npr_{ij} = n_{ij} \cdot rpr_{ij}, \tag{4}$$

$$rpr_{ij} = fs_{ij} \cdot vi_{ij}, \tag{5}$$

where the rate of people at risk depends on severeness of the flood computed in the area and on the vulnerability of the area. Both *fs* and *vi* are indexes bounded by 0 and 1.

The rate of injuries rin_{ij} in a grid (i,j) is proportional to the amount of people older than 75 years old and sick divided by the total amount of people living in that area (DEFRA & Environment Agency, 2006).

$$rin_{ij} \sim \frac{\alpha(old_{ij} + sick_{ij})}{n_{ij}}. \tag{6}$$

The rate of injuries multiplied by number of people at risk, gives the number of expected injuries nin_{ij} in the area (i,j).

$$nin_{ij} = npr_{ij} \cdot rin_{ij} \tag{7}$$

The rate of Fatalities *rf* is defined as the rate of injuries times the flood severeness in an area (i,j):

$$rf_{ij} \sim rin_{ij} \cdot fs_{ij} \tag{8}$$

Thus, the number of fatalities, $ndth_{ij}$ is multiplied by the number of people at risk of injury or death in a given area as given by RRA:

$$ndth_{ij} = npr_{ij} \cdot rf_{ij} \tag{9}$$

Based on the value of statistical life (VSL) (e.g. OECD 2012), the average monthly house rent as our value factors and the above rates, we can identify the following costs:

Cost of people injuries, *cpi*

$$cpi_{ij} = nin_{ij} \cdot b_1 \cdot vsl, \tag{10}$$

where b_1 is the value of an average injury compared to the loss of life, default setting could be 0.02.

The cost of people fatalities, :

$$cpdth_{ij} = ndth_{ij} \cdot vsl \tag{11}$$

The cost of psychological trauma, *cpt*:

$$cpt_{ij} = ndth_{ij} \cdot b_2 \cdot vsl/2 \tag{12}$$

Finally the computation of the cost due to the disruption of households should be based on the regional average monthly rent (AR) and on the regional average household size (AH), according to the proposed formulation:

The cost of disruption to households, *cdh*:

$$cdh_{ij} = npr_{ij} \cdot \frac{rf_{ij}}{2} \cdot \frac{ar}{ah} \tag{13}$$

Table 2 – Categories of damages to people.

Costs	**Description**
Class 1 – Direct intangible costs	
1. Causalities	Estimated cost of the loss of lives in terms of willingness to pay to avoid additional cases of death.
2. Injuries	Average injuries that can be provoked by a flood
Class 2 – Direct tangible costs	
1. Emergency	Cost of people and means employed during the emergency
2. Evacuation	Cost of moving the people at high risk
Class 3 –Indirect intangible	
1. Psychological Trauma	Stress and anxiety, post traumatic stress disorder, insomnia
Class 4 – Indirect tangible	
1. Forgone Income	Revenue lost to impossibility of working (derived from VSL)
2. Disruption of households	Temporary housing needs of evacuees or disrupted households
2. Medical cost	Cost of hospitalization and cure for the duration of the injury (derived from VSL)

4.1.2 Damages to Economic Activities

Damage to economic activities is the most widely used gauge of potential flood damages. This section attempts to monetize the direct and indirect damages to economic activities.

Buildings

The RRA methodology, in this category, provides us with three classes i.e. inundated structure, partially damaged, or totally destructed (Claussen & Clark, 1990). As a next step, we need to approximate the vulnerability of the receptor (S-RRA). It is a common practice in the literature (e.g., Smith, 1994; Kiefer & Willett 1996) to determine percentage of damage, susceptibility, to a certain type of receptor depending on the hazard metrics such as depth and debris factor. However, buildings' structures differ in their level of susceptibility that is based on used materials and age. This complicates the computation of the economic assessment, as to evaluate it, we need to gather accurate data that must be multiplied by the hazard metrics that are provided by engineers. In practice, since the detail of each building is often not available or it is costly to acquire, different buildings are not considered individually, but they are clustered into blocks (Scawthorn et al., 2006).

Also the damages to buildings' content, susceptibility indexes, are formed based on buildings' features such as the value of buildings, the type of businesses, city zones, and others.

The E-RRA procedure starts from the identification of the cost per square meter of a new construction (given the foundation, material, etc.) that enables us to calculate the value of structure by multiplying it by the total square metres of building. To avoid over-estimation, we have to consider depreciated replacement value by deducting the depreciation percentage from the value of the new structure (Central Valley Flood Protection Plan, 2012).

To estimate clean-up costs, it is important to collect two more pieces of information on a) the percentage of buildings with basement and b) the presence of debris factor.

Damages to buildings and their content depend on the characteristics of the type of building k, aggregated in the susceptibility index, to resist the impact of a flood and by its characteristics, specifically its depth (e.g., Smith, 1994; Kiefer & Willett 1996).

$$\text{damage ratio}_k \propto \text{Flood Severeness} \cdot \text{Susceptibility}_k \qquad (14)$$

The damage function of the receptor is given by depth-damage functions (or stage-damage functions) based on hydrological simulations that normally combine the inundation depth with the resilience of buildings based on observable metrics like materials of constructions, age, etc.

Our approaches builds on prior studies (e.g., Dutta et al., 2003), and includes the yearly probability P of return of a flood, computed according to the historical frequency and then uniformly distributed over the years: for a flood of 100-yr return period, the probability of occurring in each year is 0.01.

For a micro-level analysis computed on each cell *(i,j)* in the GIS grid, we represent the expected structural damage to residential buildings, *Dr*, in the following (adapted from Dutta et al., 2003)

$$Dr_{ij} = P \cdot \sum_{k=1}^{2} \left[NR_{ij,k} \cdot ASM_{ij,k} \cdot UCR_{ij,k} \cdot VR_{ij,k} \right], \qquad (15)$$

where (*i,j*) is the cell in row i and column j in the GIS grid; and k represents the type of the buildings: single storied building have (k=1) and multi-storied (k=2). $NR_{ij,k}$ is the number of residential buildings of class k in the grid cell *(i,j)*, with average square meter equal to $ASM_{ij,k}$; $UCR_{i,j,k}$, the price per square meter in the area *(i,j)* for building class k, and $VR_{i,j,k}$ the vulnerability of the building of type k. It follows that the total structural damage for the whole inundated area is provided as:

$$Dr = \sum_{ij} Dr_{ij} = P \cdot \sum_{i} \sum_{j} \sum_{k=1}^{2} \left[NR_{ij,k} \cdot ASM_{ij,k} \cdot UCR_{ij,k} \cdot VR_{ij,k} \right]. \quad (16)$$

Similarly, the content damage, D_{cr}, of the groundfloor and basements of households in each cell (i,j) is

$$Dcr_{ij} = P \cdot \sum_{l=1}^{3} \left[NH_{ij,l} \cdot ASM_{ij,k} \cdot \gamma UCR_{ij,k} \cdot VCR_{ij,l} \right], \quad (17)$$

where, l is the type of the household that vary in the income level: low-income (l = 1), medium (l = 2) and high-income (l = 3); $NH_{i,j,l}$ is the number of households on the ground floor and basements of each class l in a grid cell *(i,j)*; γ is the proportion of the of the value per square meter *UCR*; $VCR_{ij,l}$ is the vulnerability for the content. The total cost is given by Equation (18).

$$Dcr = \sum_{ij} Dcr_{ij} \quad (18)$$

For commercial and industrial buildings, we identify three types of damages: i) Structural ii) Content iii) Business. The first two types of damages are very similar to the residential buildings. However, for calculating the damage to the business, we need further data.
The damage to the structure of non-residential buildings *Dsnr* is given by (Dutta et al., 2003):

$$Dsnr_{ij,h} = P \cdot \sum_{h=1}^{2} \left(NNR_{ij,h} \cdot ASM_{ij,h} \cdot UCsnr_{ij,h} \cdot Vsnr_{ij,h} \right), \quad (19)$$

where *NNR(i,j,h)* is the number of non-residential buildings per grid cell for respective sectors and size of companies, and h is the building class (h=0, in single-storey building, h=1 in multi-storey buildings); *UCsnr(i,j,h)* is the price per square meter for each building class, and *Vsnr(i,j,h)* is the vulnerability of each building class.
Again, the total *Dcr* is the sum of Dcr_{ij} over all i and j, computed analogously to Equations (16) and (18).

Similarly, the content damage, $Dcnr_{ij,h}$, is formalized by:

$$Dcnr_{ij,h} = P \cdot \sum_{h=1}^{2} \sum_{m=1}^{N} \left(PA_{ij,h,m} - DEPR_{ij,h,m} \right) \cdot Vcnr_{ij,h,m}, \quad (20)$$

Where *PA(ij,h,m)* is the value of the physical assets available from the financial position (or balance sheet) for the firm *m* that is held in the non-residential building of type *h* in the cell *(i,j)*. The values of m go from 1 to *N*. And DEPR(i,j,h,m) is the value of depreciation of the physical assets, available in the financial position as well. The value of the content, in brackets, must be multiplied by the vulnerability of the content $Vcnr_{ij,h,m}$. In the cases in which the building collapses, $Vsnr_{ij,h} = 1$, we set $Vcnr_{ij,h,m} = 1$ to compute the content damage.

In the European Union, micro-enterprises are removed from the requirements to produce annual accounts (EC press release: IP/08/1771). Micro-enterprises are those, which have less than 10 employees and either the turnover or the total balance sheet of less than 2 m €. When there is the impossibility to obtain the balance sheet, the value of the content (the one within parentheses in Equation 20) must be computed on its liquidation value.

Furthermore, we need to compute the economic assessment of floods on business activities, and we call it business loss *BL*. We provide a rough estimate by multiplying the vulnerability of the content with the number of days in which the content is not efficient and the average daily turnover, as in Equation (21).

$$BL_{ij,h} = P \cdot \sum_{h=1}^{2} \sum_{m=1}^{N} \left(\#\text{days}_{ij,h,m} \cdot \text{dailyTurnover}_{ij,h,m}\right) \cdot Vcnr_{ij,h,m}, \qquad (21)$$

The estimate in Equation (21) is computed just on the business activity of the affected firm, whereas the impact may cause a cascade effect on the entire supply chain of the business. The harmful effects can propagate through an interconnected network of firms linked to the one directly affected by the hazard. The network can be forwardly or backwardly shaped. Forwardly linked are those businesses that rely on regional customers to purchase their output. Backwardly linked are those that rely on regional suppliers to provide their inputs. Thus the business of firms in the supply chain is susceptible to be negatively affected or even interrupted even if they are remote from the flooded area. To assess such indirect damages, we need to take into account the input-output interdependencies between the products of firms affected by the flood and those of their partners in the supply chain.

For estimating damages to "hot spot" buildings such as hospitals, fire stations, and other which produce an infrastructural or emergency service for the community, a customized vulnerability index is applied to take into account the lower susceptibility of these buildings against natural hazards.

Some of these buildings play a *nodal* role for the functionality of the service provided by certain types of infrastructures. A power station for instance provides the electricity to a set of consumers; therefore the damage to the power station building may have an impact on the level of service it regularly fulfils. If they are damaged in a way not to be able to provide the usual service, they must be treated analogously to the case of node removal in a network, also called site percolation, but to do so, the network of infrastructure must be mapped.

The extent of indirect losses depends on factors such as availability of alternative sources of supply and markets for products, the length of production disturbance, and deferability of production.

Similarly, we can evaluate the economic loss of tourism activity both in the demand and in the supply sides. Loss of visitors to the flood-stricken region can be treated as a demand shock that piles up with potential damages to hotels and facilities addressed to accommodating tourists that might reduce the supply capacity. The value factors needed for this assessment are the number of visitor-days lost and the period after which businesses return to normal activity.

A tax revenue loss is another important component of the indirect loss, which affects regional authorities or the governmental sector. SERRA methodology appraises the aggregated tax revenue impact by multiplying the change in sector's outputs by indirect business tax (IBT) coefficient. We can develop IBT coefficients covering property taxes, sales taxes, licenses and fees.

The loss of tax revenue due to flood in this year can affect the local or governmental income in the next fiscal year. It is also possible to enhance decision makers' view on winners and losers of the disaster by incorporating the Input-Output (I-O) matrices. This matrix contains the percentage of income that flows to each of other income brackets from each of the categories of I-O tables.

Infrastructures

The value of infrastructure is shown when the service they provide is not fully functional. Floods may also hit various elements of the infrastructure – also called "lifeline system" (O'Rourke, 2007): roads and railways (transportation), electricity pylons, lines and substations (electric power), telephone exchanges and lines (telecommunications and internet), sewerage system (waste disposal), gas and other fuels conducts (fuel lines) and water conducts (water supply). In an interconnected system, such as that of infrastructures, connections between nodes may on the one hand provoke cascade effects of propagation of a failure in one point throughout adjacent nodes of the system, while on the other hand a slightly higher capacity of the edges may increase the resilience of the network to failures, thus avoiding total breakdowns. For instance in a power grid, the failure of a transmission substation may create a cascading effect in the electrical network, rapidly degrading the efficiency of the transmission along alternative paths, if the nodes do not have enough margin to handle an increased load (Kinney et al., 2005).

The essential feature of the a system of infrastructure is that it connects nodes (i.e., pylons, substations in an electrical network, crossroads or train-stations in a transportation network, see Table 3) or set of points through edges (railways, roads, telephone or internet cables and others) that would otherwise be separated. For instance a road could be of critical importance to connect a local economy to the larger outside economy. Thereby, mitigating damages to the system that infrastructures empower is increasingly pivotal with the integration of systems.

In the CBA of damages and mitigating measures, the cost of components, the impacts to the systems' functionality, and the overall amount of time to re-establish it must be taken into account. Impact to systems' functionality can be analysed by considering the connectivity of the network, i.e., the presence of substitute paths and their efficiency in carrying the load of a non-functional path. For instance, roads can be alternative paths to a highway to reach a destination starting from the same origin, thus they can reduce the negative impact to the system produced by damages to the highways.

Tables of replacement and clean up unit cost (€ per square meter, meter, or kilometre) for any type k of infrastructure are necessary to estimate the damages.

Table 3 - Types of infrastructure and associated cost..

Types of infrastructures	Nodes (vertices)	Edges	Value Factors
Transportation	crossroads, train stations, airports, ports	Roads, railways, subway, air routes	Edges: length (km) inundated line/total length of edge, cost of cleaning (km), cost of repair (km), cost of traffic and service disruption per day based on opportunity cost.
Power grid	Power stations, substations, electricity pylons, customers	High and low voltage transmission lines	Nodes: some of the nodes, like plants or power stations, are hot spots buildings and they need to be treated as such
Water supply and treatment	Water tanks, water sources, water treatment plants, pumping stations, junction of pipes, customers	Fresh water pipes, sewerage pipes	
Gas and fuel networks	Compressor stations, junction of pipes, supply and delivery nodes	Pipes	
Telephone (T) and Internet (I)	Long-distance and local exchange (T), Network Backbone Providers (I), Internet Service Providers (I), local and regional customers	High- and low-bandwidth data routes	

To compute the costs of repairing the infrastructure, we assume that the objective is to re-establish the functionality of the system as it was prior to the occurrence of the disaster. Thus, the total damages of the system must be fully covered. Therefore, to assess them, we must start by computing the damages to infrastructure type k caused by a flood.

The total damages sustained by the type k of infrastructure are caused by the combination of severeness of the hazard and the susceptibility of the type k of infrastructure as shown in Equation (14).

Similar to the assessment of damages to buildings, we use stage-damage functions for each type of infrastructures to estimate the damages to infrastructure (susceptibility) type *k* based on its characteristics and flood severeness of event *l*.

The average damage to the system[1] sd_k is the sum of the expected damages to the infrastructure *k* for each specific flood severeness *l* given its probability. We aggregate this to all cells in the GIS grid and divide it by the total number of cells, where *I* and *J* are the total number of rows and columns of the GIS grid respectively. Thus, taking into account that the flood hits differently based on the location and topology of the cell, but still the measure provides a unique value for the damages to infrastructure *k*.

$$sd_k = \frac{\sum_{i,j} \sum_l P(\text{strengh of flood }_l) \cdot \text{Susceptibility}_{k|l}}{I \cdot J} \qquad (22)$$

By knowing the average damage on the system of infrastructure of type *k* and its unit cost of construction, it is possible to compute the approximate recovery time, and cost to bring the system to its initial level.

Yet, the costs of the distress caused by the lack of efficiency of the system must be computed and added to provide a more accurate estimate. We estimate the damage due to loss of efficiency as the sum of marginal costs (extra costs for accomplishing the same goal with an alternative path, e.g., reaching the same destination through a longer or bumpier road), or, when efficiency of the path is zero – the infrastructure is broken and does not allow the performance of the activity – as the opportunity costs.

Marginal costs can be computed as the difference of the cost of running between two different paths.

The efficiency of a path between any two points of the infrastructure, is the harmonic sum of the efficiency of each piece *e* of infrastructure that is $\text{efficiency}_{k,e} = \{1/[(1 - \text{vulnerability}_{k,e|l}) \cdot \text{capacity}_{k,e}]\}^{-1}$. In infrastructure networks, the efficiency of a path is then the harmonic mean computed on the length of a path and we call it ***transmission efficiency***.

$$\text{transmission efficiency}_k^{(*)} = \left(\sum_e \frac{1}{(1 - \text{vulnerability}_{k,e|l}) \cdot \text{capacity}_{k,e}} \right)^{-1} \qquad (23)$$

[1] We take the average damage to the system, because with the average it becomes easier to compute the total cost and time to bring the system to the original condition. However, to compute the damage of the infrastructure *k* at a cell (*i,j*), the equation is $d_{ki,j} = \sum_l P(\text{strengh of flood }_l) \cdot \text{susceptibility}_{k|l}$.

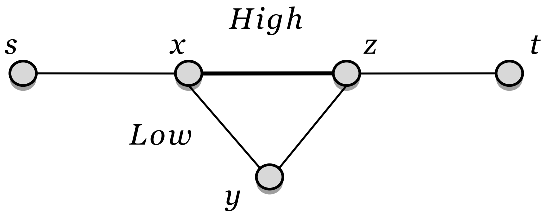
With the transmission efficiency, it is possible to rank various alternatives. We indicate transmission efficiency* as the most efficient path from a source to a target. For instance, suppose there are three roads to get from a source to a target with path (a) being 3 km long, dividable into three edges each of 1 km. Furthermore, suppose each of the legs has a damage ratio of 0.5. We also have an alternative path (b) of two km length (2 edges), and 1 km is in perfect condition, while the second km is entirely broken; a third alternative (c) is of two km length (2 edges), and each km of road has a vulnerability of 0.5. Intuitively the best path is (c) and the harmonic mean of (c), its transmission efficiency, is 1/4 larger than that of (a) that is 1/6 and of that of (b) which is 0[2].

For the capacity of roads, we can consider capacities of highways or motorways to be 1, boulevards or multi-lane extra urban streets to be 2/3, urban streets to be 1/3, and single-track roads to be 1/6. For othertypes of infrastructure, the capacity can be simply considered the capacity of the wire or pipe.

The extra effort needed to go from s to t prior to and after the flood is given by the ratio of the transmission efficiency between the best path before and after the hazard. We call the transmission efficiency of the best path before the hazard TE_k^{opt} and the ratio: extra resources$_{k,st}$.

$$\text{extra resources}_{k,st} = \frac{\mathrm{TE}_k^{opt}}{\mathrm{TE}_k^{*}} \tag{24}$$

[2] We assume that when the vulnerability is 1, thus interrupting a path, the denominator would be zero, but we take the limit to zero from the right to compute the ratio.



Capacity of xz edge = 1
Capacity of other edges = $2/3$
Damage ratio xy after flood = $4/5$

Efficiency of $High$ path:

$$\left[\frac{1}{2/3}+1+\frac{1}{2/3}\right]^{-1}=\left[\frac{8}{2}\right]^{-1}=\frac{1}{4}$$

Efficiency of Low path:

$$\left[4\cdot\frac{1}{2/3}\right]^{-1}=\left[\frac{12}{2}\right]^{-1}=\frac{1}{6}$$

Efficiency of $High\ flooded$ path:

$$\left[\frac{1}{2/3}+\frac{1}{\frac{1}{5}}+\frac{1}{2/3}\right]^{-1}=\left[\frac{16}{2}\right]^{-1}=\frac{1}{8}$$

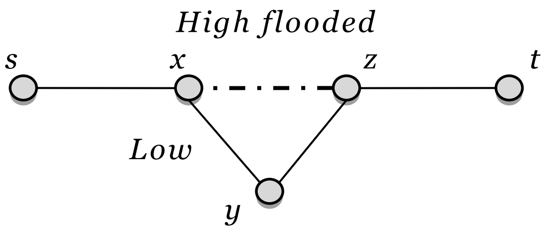


Figure 4 - Effect of flood in the network of infrastructure. Before the flood (upper side), the High path is more efficient than the Low path, while after the flood (bottom), the Low path becomes more efficient3

The value of the ratio can range from 1 to infinite, if there any path to t is interrupted. In the example in Figure 4, extra $\text{resources}_{k,st}$ to reach t from s is equal to 1.5, that can be seen as 150% of the effort to reach the destination with respect of the optimal 100%. It translates into an increase of cost and time. The additional cost is computed by calculating the cost of getting from s to t under the optimal path prior to the hazard multiplied by the extra resources and similarly for the time.

The total discomfort in money value is computed by multiplying the additional time to get from s to t, for the number of days in which such discomfort exists and the average salary per unit of time.

$$\text{discomfort cost}_{k,st}=\text{additional time}_{k,st}\cdot\text{number of days of inefficiency}\cdot\frac{\text{average salary}}{\text{unit of time}}\qquad(25)$$

In case of network disconnection, the economic impact is two folded: (i) on firms it the product of the days of network disconnection and the sum of average daily revenues of the disconnected firms; (ii) on people, it is the product of the number of days of network disconnection and the daily salary for each day in which individuals cannot reach their workplace.

Agriculture

Damages to crops depend on duration, depth of flooding, and on timing, i.e., the season of the year in which the flood occurs, thereby it is important to consider the calendar dates and seasons into flood damage estimation. Moreover, the value of crops strongly depends on the cultivation stage and it is inaccurate if one takes the average of all the agricultural phases as the damage to crops. The different phases range from land preparation, as the first phase, to harvesting and packing, as the last phases. In view of this factor, we present a comprehensive list of agricultural phases. Once the type of crop is known, and depending on the month when flood happens one can look for the respective phase of cultivation and estimate the cost associated to that phase.

The value of damages varies from cultivation cost, harvest/post-harvest costs, and establishment costs. Cultivation costs include costs of irrigation, weed control, fertilization, pest control, and subsoil treatment and are crop-specific. Costs of harvesting include costs of cutting, hauling, and packing. Establishment costs are the costs necessary to completely re-establish a crop that has been severely damaged due to a flood inundation longer than a certain days. Expenses such as preparation, planting, production, and cash overhead are part of establishment costs (Central Valley Flood protection plan, 2012):

However land clean up and rehabilitation costs are added as a fixed cost to each estimate and regardless of the type of crops.

Finally, loss of gross income should be added to the cost of agricultural damages. Gross income can be estimated based on the market prices (€) of each crop and the average yield of that crop per hectare.

The below formula adopted from Dutta et al. (2003), Ganji et al. (2012), and Citeau (2003) allow us to calculate the damages:

$$AD_{ij,k} = P_k \cdot \sum_{k=1}^{n} Y_k \cdot V_{ij,k} \cdot A_{ij,k} \, , \qquad (26)$$

$$AD_k = \sum_i \sum_j AD_{ij,k} \, , \qquad (27)$$

where *AD* is the total agricultural loss, with AD_{ij} being the loss in the area (i,j) for type of agricultural product *k*; *n* is the number of all kinds of crops; $V_{(i,j,k)}$ is the vulnerability for the type *k* of crop; $A_{(i,j,k)}$ is the total cultivated area of crop k; P_k is the estimated price per unit weight of crop $_k$; Y_k is the annual yield per unit area for crop k.

Table 4 - Damages to agricultural activities. (http://coststudies.ucdavis.edu/current.php).

Costs	Description
Group 1 – Cultivation costs	

1. Irrigation	The cost varies according to method of irrigation, crop type, and the month of the year.
2. Fertilization	The cost varies according to the type of crop.
3. Weed/Insects Control	The cost varies according to the month of the year.
4. Pest Control	
Group 2 – Harvest or Post harvest cost	
1. Cutting	
2. Hauling	
3. Packing	
Group 3 – Establishment cost	
1. Preparation	Costs of chiselling the ground to a certain depth.
2. Planting	Based on the season changes.
3. Production	
4. Cash overhead	Property tax, insurance, crop insurance, office expenses, management and supervisor costs, annual maintenance.
Group 4 – Land Clean up and Rehabilitation costs	
1. Clean Up	Cost to clean the farming land from the debris and damaged crops
2. Damage to machineries	Repairing or buying new machineries used for each process of agriculture
Group 5 – Loss of gross income	
1. Farmers	Cost associated to loss of income of farmers based on market prices and average yield of the farm.
2.Dependent Industries	Loss to income of industries or businesses that depends on the agricultural outputs as their inputs.

4.1.3 Damages to Ecosystems and Cultural Heritage

In this section we jointly discuss the damages to ecosystems and cultural heritage (ECH) as they share similar concept based on intangible valuation of non-tradable goods and services.

Fundamental for ECH is that they are irreplaceable. They do not have a market price, thus they must be treated differently in estimating the damages to them, and we need to know the public value of these sites. For this reason, we need to study and measure the preferences of the people over the sites to make the right decision in evaluating the benefits of such public goods.

By definition public goods are any goods that have two characteristics: i) non excludable: meaning that it is infeasible to prevent others from getting benefit from it. Even if it will be possible to charge those who benefit from the public good, that might not represent all the benefits generated by the good; ii) non-rivalry in consumption: many people can use the good without preventing each other from using it e.g. a park or a statue in a square. However, many of such goods exhibit some degrees of rivalry (congestible public good).

Ruijgrok (2006) defines the economic value of cultural heritage as the amount of welfare that it generates for the society, while Plaza (2012) defines the economic value of the cultural heritage as the benefits generated by it whether commercial, non-commercial, or both.

Ruijgrok (2006) describes why it is necessary to evaluate cultural heritages although it is clear that its actual value cannot be expressed in monetary terms. As he explained, valuation of cultural heritage allows us to evaluate investments in this sector through cost benefit analysis and estimate the losses to society after a possible damage to cultural sites. To this end, economic valuation helps the decision process of authorities.

Generally, we define the value that a consumer gets from using a market good as the highest amount of the money that the consumer is willing to pay for using that commodity (Navrud & Ready, 2002). Hence, for market-traded goods, the price of a good can be different from the value of the good.

For an ECH, the use value that a visitor receives is the highest amount of money that the visitor is willing to pay, above any actual entry fee, to gain access to the site. The user population may include local households (within a given spatial area around the site), visitors (dog walker, nature watching, tourism). The total use value generated by the site is the sum of the all individual visitors' willingness to pay (WTP).

Use Value vs. Non Use value:

An ECH might generate some value for those who do not use the site directly. This benefit may be motivated by a desire that the site be available for others to visit (altruistic value); that the site be preserved for future generations (bequest value); that the current non visitor might decide to become a visitor in the future (option value); or simply the site be preserved even if no one ever actually visits it (existence value) (Iacob et al., 2012).

For Cultural sites, some scholars (Thorsby, 2006; Iacob et al., 2012) distinguish further between cultural and economic value and lists symbolic, spiritual, aesthetic, prideful, historical, social, and authenticity value among the possible set of values that should be considered as part of cultural value.

It is for the existence motive that we may want to spend resources to protect ECH goods against natural disasters, which their presence give assurance to many direct or indirect consumers of ECH goods. Thus, the total value of an ECH good is written as sum of use value, non-use value, option value, etc.

We determine the non-user value in the same way as the WTP of market-traded commodities meaning the largest amount that a non-user would willingly pay to preserve a site. However, there is large incentive to free ride on donation of others and the economic theory suggests that what we will see is that the donation will be inferior to the full value that a person receives from the good. The challenge is to measure the full WTP for the good, when the user or the non-user in not obliged to pay anything. Generally, it has been observed that those who live further from a site hold a lower value for that resource.

Extent of the market:

Since the total value of a commodity depends on users and non-users values, we need to identify the number of each type. The proportion of such values, however, differs depending on the sites. While a local ECH site (e.g. local church or park) might have more direct users and fewer indirect users, for a global site (e.g. Vatican, Great Wall of China, Grand Canyon, Yellowstone Park) it can be the opposite.

Consequently, the extent of a market depends on the jurisdiction or political institution (local authority or national government), which spend the money in preserving the site. This way of estimating how much to invest can be myopic especially if there is a less-developed country containing an important global site, which has to decide how much to spend on preserving the site based on only the benefits to its own citizens and it may conclude that preservation is costly. In such scenario, international organizations should decide the amount of resources to expend on the global goods.

Cost-benefit analysis that takes into account non-market values can feed useful information to the DMs to commit to funding a project. We might preserve an ECH even if the taste of the current generation does not favour that particular type of good. We might preserve a cultural site out of moral obligations and sense of duty.

Notice that general population might value an ECH good based on their knowledge and information, and an expert's opinion might be more useful in determining the relative importance of the public goods. The experts' role in framing the preferences of public is very important and should not be neglected when it comes to determining.

Many of the studies in the literature apply the stated preferences technique to measure the user and non-user values of cultural goods. There exist few studies, which uses revealed preferences method to evaluate the economic benefits of ECH goods.

The general finding in these studies point out to the fact that people are willing to pay for conservation or restoration of sites. At the same time, in most of the studies, many people also state a zero WTP. Some of these zeros may arise from budget constraints, or as a protest against further taxes (Navrud & Ready, 2002). It is important to control for these effects in any study to arrive at the true preferences of the consumers.

It is important for the scholars who carry out the evaluation to present the ECH good accurately and with sufficient details to the respondents. The presentation must be also understandable.

For the sites that generate incomes, valuation can be easier using the available methods for benefit estimation.

Non-market methods in estimating economic value:

There are many methods proposed for economic evaluation of the ECH sites. As Bedate et al. (2004) point out, even though all these methods are far from perfection, they are the only valid methods for the related DMs regarding evaluating sites.

Hedonic Pricing Method assumes that the price of a commodity is determined by its intrinsic characteristics and specific environment (Rosen, 1974). Hence, hedonic price function is a regression where the coefficients are the marginal value of the set of observable characteristics.

Contingent Valuation pricing is the direct stated preference method for goods, which are not traded in the market. Consumers express their *willingness to pay* (WTP) or to *accept* (WTA) for an increase in their welfare or compensation for their loss of welfare. In this method, the questions can be closed referendum (yes/no answer) or open question and a statistical analysis is followed to study the variations and their cause. Despite the drawback of this method, it is considered the only solution to estimating non-use values.

Travel Cost Method is based on suggestion of Hotelling (1947) that the visitor's travel cost stand as a proxy for valuation of a particular site or point of interest. However, one can only estimate the use value of an attraction using travel method (Bedate et al., 2004). The same method can be used to derive the demand curves of a site based on utility maximization of its users. This method can be further developed along two lines: i) The zonal travel cost method, due to Clawson and Knetsch (1966), splits the visitors into groups based on distance of visitors given their point of origin from the recreational site. In the next step, the demand curve derives from the average travel cost and the number of visits from each zone. The area under the demand curve represents the consumer surplus, which approximates the monetary value of visiting the site. ii) The individual travel cost method, which attempts to estimate the demand of the recreational good for each individual at a given site. This method is more appropriate, when the travel costs of visitors from the same zone might vary from person to person. We derive an aggregate demand function by the aggregation of the individual ones. This method has several practical problems as pointed out byBedate and colleagues (2004).

The environmental effects of a flood arise due to the change it creates in an ecosystem such as habitats degraded or created. The change in the ecosystem in turn, leads to change in the services they provide and hence their impact on human welfare. In flood damage analysis, we have to identify the environmental effect i.e. the area and the type of habitat that are affected.

The above steps are for studying the environmental effects.
If performing contingent valuation is costly, we can instead attach an economic value to the sites by selecting relevant studies and transfer their estimated values.
Based on the above, we define total ECH damages, ED:

$$ED = \sum_{i,j} \sum_{k} P \cdot V_{ijk} \cdot \left(EV_{ijk}^{u} \cdot U_{ijk} + EV_{ijk}^{iu} \cdot IU_{ijk}\right) \tag{28}$$

where P is the probability of flood, V_{ijk} is the vulnerability of site k; EV_{ijk}^{u} is the economic value of an individual direct user of type k of ECH site based on her WTP; EV_{ijk}^{iu} is the economic value of individual indirect user; U_{ijk} specifies the estimated number of direct users based on proximity to the site, and IU_{ijk} is the estimated number of indirect users. No effects for adaptive or coping capacity have been found in respect to environmental goods.
Overall, the cultural heritage is a difficult category to appraise as it includes not only the heritage assets that can be seen (such as World Heritage Sites, monuments, listed buildings), but also their context and relationships (for example, conservation areas). The historic environment also includes unknown archaeology, which are traces of human history that have not been discovered.
Historic environment may include: i) Palaeo-environmental and geo-archaeological remains; ii) Archaeological remains (including wrecks); iii) Historic buildings, parks, and gardens; iv) Historic Landscapes.
We need to include:

- Impact on the physical assets themselves.
- Impact on their setting and cognitive landscapes.
- Impact on their inter-relationships with other historical assets.
- Impact on areas where there may not be any known physical assets but where there is potential for archaeological finds.

4.1.5 Emergency Costs

We examine emergency costs separately from damages to receptors since it includes those costs that are not directly classified into one of the receptors' categories.
As suggested by the CVFPP (2012), the emergency costs can be placed into five groups whether they are direct or indirect tangible damages. We report these costs in **Table 5**.

Table 5 - Cost of emergency measures.

Activities	Description
Group 1 – Evacuation Activities	
1. Evacuation	Cost of labour, capital, and transportation for evacuation.
2. Subsistence	Cost of housing peoples in emergency shelters and providing food and water, including housing during evacuation.
3. Reoccupation	Costs associated with travel time and transportation modes to preoccupied destinations.
Group 2 – Debris Removal and Clean up	
4. Debris Activities	Costs associated with sorting, transporting processing, and disposal of different types of debris.
Group 3 – Public Services Patronized	
5. Education	Cost to continue schooling in new locations to enable the routine mission of education.
6. Public Agencies	Cost to continue routine services to maintain social functions.
7. Indoor Recreation Facilities	Cost of loss to serving the public's general information and recreational needs.
8. Medical	Cost to continue providing routine services to people who would have been injured regardless of flood, at non-flooded facilities. Cost of hospital evacuation, disaster medical assistance team and elder care.
Group 4 – Public Services Produced	
9. Police	Cost to continue routine police services for flooded areas, cost to provide emergency flood responses, and relocation of facilities if necessary.
10. Incarceration	Costs associated with increased security and different transportation modes for evacuation and reoccupation of inmates.
11. Fire	Cost to continue routine fire services for flooded areas, cost to provide emergency flood responses, and relocation of facilities if necessary.
12. Legislative	Costs associated with temporary facilities, increased security needs, and relocation of facilities
13. Judicial	Costs associated with temporary facilities, increased security needs, and relocation of facilities
Group 5 – Public Utilities:	
14. Telecommunication	Cost associated with increased use of telecom equipment to carry out routine and flood activities

4.2 Risk Reduction Measures

In this section, we discuss the issues related to evaluating the benefits from investments in structural or non-structural flood risk reduction projects. The feasible scenarios of risk reduction measures (called alternatives) need to be evaluated and its costs-benefits or if relevant its cost-effectiveness, be compared with a scenario (baseline) where risk reduction measures are not implemented.

For evaluating the alternative scenarios, we need to first identify a set of future scenarios (sometimes climate-change dependent) and then evaluate the performance and vulnerabilities of each scenario under these future states of the world. The criteria for comparing the projects can be some performance metrics (either the monetary or non-monetary value of the damages to the receptors), acceptable levels of risk, past experience (adaptation), etc. (Pearce et al., 2006). As the level of future uncertainty increases, mainly due to climate change but also other factors such as socio-economic factors, it becomes more difficult to decide about a risk reduction project as they become very sensitive to the worst-case scenarios (Hallegate et al., 2012).

We have already mentioned that cost-effective analysis compares the relative costs and outcomes (effects) of two or more strategies and it is different from the cost-benefit analysis, which assigns monetary value to the measure of effects.

Improving the adaptive capacity such as early warning system, building levee, substitutes in transportation systems, improved storm water drainage, etc. of a society increases adaptation and leads to the mitigation of the communities' vulnerability.

Feasible alternatives and strategies of improving adaptive capacity vary based on characteristics (population, topology, frequency of hazard, etc.), structure, and needs of the society under study. Stakeholders or DMs might adopt strategies and scenarios suitable to their needs and subject to their constraints. In this section, we provide a brief overview of cost-benefit analysis method that can be used for assessing and comparing alternatives of risk mitigation through investment in adaptive capacity.

Throughout our analysis baseline scenario is the *status quo* without investment in adaptive capacity, which represents alternative scenarios. A community may have several options in which they can invest and their goal is to find the most beneficial or effective option. Let us denote the set of all alternatives by M. For each alternative m, we evaluate the stream of discounted expected benefits (reduction in monetary or non-monetary risks) by considering the reduction in vulnerability. The cost of each alternative is the total costs of study, construction, implementation, and maintenance. For certain alternatives such as EWS, we might have particular costs such as cost of evacuation in case of a false alarm or cost of breakdown of a levee. Some of the costs are not certain and may happen with certain probabilities. We need to know the probabilities of failures of the alternatives or have the best possible estimate for them.

The benefit (reduction in risk) from performing scenario m is given by

$$B_m = \sum_{t=0}^{T} \beta^t E(B_{it}) = \sum_{i}^{T} \sum_{t=0}^{T} \beta^t P_i B_{it} \tag{29}$$

where $B_m$is the benefits from alternative m, β^t is the discount factor at time t, E is the mathematical expectation, is the benefit from source i at time, P_i is the probability of benefit realized. Similarly the cost of scenario m is:

$$C_m = \sum_{t=0}^{T} \beta^t E(C_{it}) = \sum_{i}^{T} \sum_{t=0}^{T} \beta^t P_i C_{it} \quad (30)$$

where $C_m$is the costs from alternative m, $\beta^t$is the discount factor at time t, E is the mathematical expectation, is the cost from source i at time, P_i is the probability of costs realized. We can summarize Equations (29) and (30) as follows:

$$Em = \sum_{t=0}^{T} \beta^t E(B_t - C_t) = \sum_{t=0}^{T} \sum_{i} \sum_{j} \beta^t \left(P_i B_{it} - P_j C_{jt}\right) \quad (31)$$

where $Em$is the net benefits of scenario. Once Em is calculated for all feasible scenarios, we can rank the alternatives and pick the one that provides us the highest net benefit. In the following paragraph, we specifically discuss the evaluation of installing early warning system particularly as an example of how uncertainty regarding the performance of such option leads to certain costs.

Early warning systems (EWS) are one of the non-structural measures to risk reduction by lowering the vulnerability of people, agricultural products and content of buildings. EWS system has certain characteristics including scope, content, lead-time and reliability that define the strength of it. Scope stands for the percentage of people who receive the warning and can be approximated by the means of the media (TV, radio, SMS, siren, etc.) used for sending the warning. Content stands for the type of the message, which should be appropriate given the severeness of the flood hazard. For instance, evacuation message, warning, or various degrees of alert should be sending with respect to expected degree of hazard to be effective and prevent economical costs or under-estimated adverse consequences.

Nevertheless, EWS measure is subject to uncertainty based on its reliability in forecasting weather and flood. As summarized in the **Table *6***, it might be the case that what our EWS forecasts be different from what is observed with the probabilities shown in the parentheses. In case of a 'Hit', the society bears the costs of evacuation with probability P1. In the case of 'Miss', due to higher vulnerability, the society bears higher costs and damages since they are not ready. Therefore, the policy maker who decides whether or not to install EWS, or any other structural or non-structural risk reduction measures (e.g. dikes, embankment, levee, etc.) should: 1) perform an uncertainty analysis of the measures; 2) take results of step 1, and assess different values for the vulnerabilities with or without that measure together with their probabilities; 3) estimate the risk of flood for different values of vulnerability; 4) compare the costs associated with installing that measures with the benefits that provide by reducing the expected flood risk.

Table 6 – Reliability of Early Warning System.

		Forecasted	
		Flood	**No Flood**
Observed	**Flood**	Hit (P_1)	Miss (P_2)
	No Flood	False Alarm (P_3)	Correct Negative (P_4)

Based on the probabilities mentioned in **Table 6**, which can be based upon empirical observation or expert judgment, we can form an index of reliability (RI) of EWS, previously introduced in paragraph 2.3.1 as:
$RI = 1 - (P_2 + P_3)$.

5. *Conclusions*

In the flood-risk literature, where we posit our work, only the physical dimension of vulnerability was considered. Our contribution extends the concept of vulnerability with social elements such as coping and adaptive capacities that were so far neglected.
Our methodology, SERRA, can be considered as two separated workflows: S- and E- RRA, where the former combines the Regional Risk Assessment (RRA) with a set of social (S-) indicators representing the ability of the society to cope and adapt to natural disasters and mitigate them.
In the latter, E- stands for economic, and we provide a toolbox to assign money value to a vast array of receptors.
With this work, we want to provide decision makers with practical, systematic and precise tools to assess alternative measures of risk reduction compared to a baseline scenario whereby no measure is implemented. Our method can help insurance companies to assess and share the risk with potentially affected receptors and provide them with policies. This will lead to increase receptors' adaptive capacity.
Following the methods described in Section 3.1 (Methods) and the explanations provided in Section 3.2 (Application for Each Receptor), the aggregate notion of vulnerability for all types of receptors can thus be assessed and contributed to the calculation of an improved notion of risk. Risk can be also expressed in monetary terms (see Section 4) to calculate different categories of flood damages, i.e., direct, indirect, tangible and intangible costs.
Accurate flood damage estimation requires a higher effort to collect micro-scale data regarding types of businesses, set of adaptive-, coping-capacity indicators, and willingness to pay of direct

and indirect users. Overall, SERRA is a flexible methodology as it can be adjusted to the local conditions and data availability. Nevertheless, compared to RRA, SERRA requires more data on value factors and social indicators.

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Appendices

Appendix A. Abbreviations

AC	Adaptive Capacity
AEP	Annual Exceedance Probability
CBA	Cost-Benefit Analysis
CC	Coping Capacity
CEA	Cost-Effective Analysis
CH	Climate Change
CV	Contingent Valuation
DALY	Disability-Adjusted Life Years
DM	Decision Maker
EVF	Economic Value Factor
EWS	Early Warning System
GA	Geometric Average
MCA	Multi-Criteria Analysis
NAM	Non-Additive Measure
P/E	Physical / Environmental
QALY	Quality-Adjusted Life Years
RRA	Regional Risk Assessment
RRM	Risk Reduction Measure
USACE	US Army Corps of Engineers
VSL	Value of Statistical Life
WA	Weighted Average
WTA	Willingness to Accept

Appendix B: Data required for S-RRA

Components	**Variables**	**Indicators**	**Definition & Notion**	**Further details**	**Sources**	**Receptors** #
Adaptive Capacity (AC)	Economic wealth***	Income/Revenue	People with higher number of per capita income lead to increase AC and consequently decrease vulnerability (VUL)	Per capita income/GDP/value added	Census data	P, R, CI
	Risk spread***	Insurance density/ penetration	Values with higher insurance density lead to increase AC and decrease VUL	Ratio of total insurance ($) to total population	National association of insurers	P, A, R(S,C), CI(S,C,B)
	Equity	GINI index*	A measure of statistical dispersion about the income of the population;	A value with 0 expresses perfect equality (lowest VUL), whereas 1 represents maximum inequality (high VUL)	Census data	P
		No. of hospitals***	Values with higher number lead to decrease VUL		Census data	P
	Early warning system (EWS)*** †	Lead-time (hr)	EWS with high lead-time, enough information content and reliable warning leads to decrease VUL	Requires information about the EWS in place. The indicator can be approximated assigning a score to each of the four dimensions.	Local/reg. emergency authority	P, I, R(S, C), CI(S,C,B), CH, A
		Content (0,1)				
		Reliability (0,1)				
		Scope (0,1)				
Coping capacity (CC)	Demography	Dependency ratio (%)*	Population with higher DR leads to increase VUL	It is an age-population ratio of those typically not in the labor force (the dependent part) and those typically in the labor force (the productive part).	Census data	P
		Newcomers (#)*	People with high no. of migrants leads to increase VUL	Can be approximated by: percent renter-occupied housing units; percent of recent residents /immigrants; percent of people living in informal houses	Census data	P

Components	Variables	Indicators	Definition & Notion	Further details	Sources	Receptors #
	Emergency management (EM)***	People involved (#)	Higher no. of people involved in EM decreases VUL	Can be approximated by: per capita number of trained volunteers; hours spent on training and manoeuvring the local civil protection, number of people from police, fire-fighters and red cross involved in emergency plans.	Local/reg. emergency authority	P, CH, I, CI(C, B), A
Susceptibility (SUS)	Building properties	Age**	Old buildings are more Vulnerable	Requires the breakdown of buildings into categories and relative % of concentration.	Local/reg. emergency authority	P, R(S, C), CI(S,C,B), CH
		Materials*	Concrete is more flood resistant than brick or wood			
		Types**	Single storied building are more vulnerable than multi-storied			
	Business properties†	Types**	Public sector is less susceptible to damage whereas industry and trade are more susceptible	Requires the breakdown of economic activities into categories (public sect., industry and trade; w-w/o warehouse) and relative % of concentration.	Chamber of Commerce	CI(C, B)
		Size*	Small companies are more vulnerable and large companies are less	Requires the breakdown of economic activities into classes of number of employees and relative % of concentration.	Chamber of Commerce	
	Economy†	Inter-connectivity***	Economy with high values of interconnectivity leads to increase indirect effects.	Requires the data about # of passengers/traffic for each means of transportation (local hubs).	Ministry/ Department of transportation	A, I, CI(B)
		Specialization*	Economy with specialization are likely to produce more indirect damage	E.g. in the food sector can be approximated by the number local products certified with quality assurance. Can be based on expert knowledge. For big areas the value added in each economic sector is required.	Chamber of Commerce	A, CI(B)

Components	Variables	Indicators	Definition & Notion	Further details	Sources	Receptors #
	Network†	Importance / volume***	Value with high volume leads to increase more indirect damage	It requires information about traffic in the edges of the network that is to be assessed.	Ministry/ Department of transportation/ energy	I
		Connectivity*	Infrastructure with high values of connectivity decreases vulnerability because it's more difficult to isolate a node	It is computed by the minimum number of nodes or edges, which need to be flooded to disconnect the remaining nodes. It requires knowledge about the structure of the network.	Ministry/ Department of transportation/ energy	I

 # For receptors, P denotes People, A – Agriculture, R – Residential building, CI – Commercial & Industrial buildings, I – Infrastructure, C – Cultural heritage. Inside the parentheses, S refers to Structure, C – Content, and B – Business.
**** the number of stars explains the necessity of the variable/ indicator for the implementation of the implementation of the methodology according to different levels of complexity/detail of S-RRA : 3 stars means necessary for the basic application, 2 stars means necessary for small scale applications, 1star means optional.*
† *Also used in E-RRA*

Appendix C: Data required for E-RRA

Receptos	Variables / Indicators	Description / *Notes*	Sources
P	Value of statistical life	Estimated cost of the loss of lives in terms of willingness to pay to avoid additional cases of death. An issue for the use of the VSL is discounting due to use of different currencies and due to inflation. *We propose a default value of 3.1 M € for Europe*	A. Locally used parameter B. Adjusted from literature: e.g. 1, 2
	Average monthly household rent	Could also be broken down per classes and relative % of concentration	Census data
	Average dimension of households	Could also be broken down per classes and relative % of concentration	Census data
R(S)	Building types †	Single-storey, multi-storey, with basement. Requires the breakdown of buildings into categories and relative % of concentration.	Local/reg. Emergency authority
	Average structure value per unit floor area per each building type	Takes into account Clean-up, Replacement and Depreciation	A. Locally used parameter B. Adjusted from literature: e.g. 3, 5, 6
R(C)	Type of Households †	Requires the breakdown of households into classes and relative % of concentration. Classes based on income data.	Census data
	Average content value per each household class	Takes into account Clean-up, Replacement and Depreciation	A. Locally used parameter B. Adjusted from literature: e.g.3, 4
R(S, C)	Depth-damage function per each building type	A mathematical relationship between the hazard and the damage to each building type. Hazard can come from RRA.	A. Locally used parameter B. Adjusted from literature: e.g. 3, 4, 7
CI (S, C, B)	Business type †	Requires the breakdown of economic activities into categories (public sect., industry and trade) and relative % of concentration.	Chamber of Commerce
	Business size †	Requires the breakdown of economic activities into classes of number of employees and relative % of concentration.	Chamber of Commerce
CI(S, C)	Depth-damage function per each business type	A mathematical relationship between the hazard and the damage to each business type. Hazard can come from RRA.	A. Locally used parameter B. Adjusted from literature: e.g. 3,4
CI(S)	Average structure value per unit floor area per each building type	Takes into account Clean-up, Replacement and Depreciation	A. Locally used parameter B. Adjusted from literature: e.g. 3,4
CI(C)	Average content value per each business type	Takes into account Clean-up, Replacement and Depreciation	A. Locally used parameter B. Adjusted from literature: e.g. 3,4
CI(B)	Average tax revenue per business type	Estimates the income loss of local/federal government (Indirect damage)	Chamber of Commerce
I	Average structure value per unit of network (km, %)	Takes into account Clean-up, Replacement and Depreciation	A. Locally used parameter B. Adjusted from literature: e.g. 3,4

Receptos	Variables / Indicators	Description / *Notes*	Sources
	Depth-damage function per each type of network	A mathematical relationship between the hazard and the damage to each type of network. *Hazard can come from RRA.*	A. Locally used parameter B. Adjusted from literature: e.g. 3,4
	Importance/volume †	It requires information about traffic in the edges of the network that are to be assessed .	Ministry/ Department of transportation/ energy
	Connectivity †	It is computed by the minimum number of nodes or edges which need to be flooded to disconnect the remaining nodes. It requires knowledge about the structure of the network.	Ministry/ Department of transportation/ energy
A	Average annual yield per unit area per each type of crop	Hazard and susceptibility of crops given by RRA	A. Locally used parameter B. Adjusted from literature: e.g. 5
	Estimated price per unit weight per each crop	Discounted market price	A. Locally used parameter B. Adjusted from literature: e.g. 5
	Average cultivation cost unit per unit area per crop	Takes into account clean-up, replacement of machinery with depreciation, soil erosion	A. Locally used parameter B. Adjusted from literature: e.g. 5
C	Willingness to pay (WTP) for each cultural asset	It is the individual value attached to the restoration of the cultural asset, if it was damaged due to a flood.	A. Locally used parameter: Survey, Contingent valuation B. Adjusted from literature: value transfer: e.g. 8
	Depth-damage function per each cultural asset	A mathematical relationship between the hazard and the damage to each cultural asset. *Can be derived from CI(S)*	A. Locally used parameter B. Adjusted from literature: e.g. 3,4
	Number of direct users per each cultural asset	Direct users are those who physically enjoy the cultural asset with direct use (e.g. sightseeing).	Based on available local data or on proximity of potential direct users (experts knowledge)
	Number of indirect users per each cultural asset	Indirect users are those who can virtually enjoy the cultural asset even without use. The WTP is discounted according to level of interest (global, regional, local etc.)	Based on level of interest (experts knowledge)
E	Willingness to pay (WTP) for each environmental asset	It is the individual value attached to the restoration of the environmental asset, if it was damaged due to a flood. *Susceptibility given by RRA*.	A. Locally used parameter: Survey, Contingent valuation B. Adjusted from literature: value transfer e.g. 9
	Number of direct users per each cultural asset	Direct users are those who physically enjoy the cultural asset with direct use (e.g. sightseeing).	Based on available local data or on proximity of potential direct users (experts knowledge)
	Number of indirect users per each cultural asset	Indirect users are those who can virtually enjoy the cultural asset even without use. The WTP is discounted according to level of interest (global, regional, local etc.)	Based on level of interest (experts knowledge)
R(C) , CI(C, B), A, C, E	Early warning system (EWS) †	*Can consider the 4 dimensions described in Table 1 (S-RRA)*	Local/reg. emergency authority
CI(B), A	Inter-connectivity †	Estimates indirect effect to other businesses. Requires the data about # of passengers/traffic for each means of transportation (local hubs) *as described in Table 1 (S-RRA)*	Ministry/ Department of transportation
	Specialization†	*Can be based on expert knowledge as described in Table 1 (S-RRA)*	Chamber of Commerce

All the variables/indicators are mandatory for E-RRA
† *Also used in S-RRA*
# *For receptors, P denotes People, A – Agriculture, R – Residential building, CI – Commercial & Industrial buildings, I – Infrastructure, C – Cultural heritage. Inside the parentheses, S refers to Structure, C – Content, and B – Business*

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