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The KULTURisk Regional Risk Assessment methodology for water-related natural hazards – Part 1: Physical-environmental assessment

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Abstract

In recent years, the frequency of catastrophes induced by natural hazard has increased and flood events in particular have been recognized as one of the most threatening water-related disasters. Severe floods have occurred in Europe over the last decade causing loss of life, displacement of people and heavy economic losses. Flood disasters are growing as a consequence of many factors, both climatic and non-climatic. Indeed, the current increase of water-related disasters can be mainly attributed to the increase of exposure (increase elements potentially at risk in floodplains area) and vulnerability (i.e. economic, social, geographic, cultural, and physical/environmental characteristics of the exposure). Besides these factors, the strong effect of climate change is projected to radically modify the usual pattern of the hydrological cycle by intensifying the frequency and severity of flood events both at local, regional and global scale. Within this context, it becomes urgent and dramatically relevant the need of promoting and developing effective and pro-active strategies, tools and actions which allow to assess and (possibly) to reduce the flood risks that threats different relevant receptors. Several methodologies to assess the risk posed by water-related natural hazards have been proposed so far, but very few of them can be adopted to implement the last European Flood Directive (FD). The present study is intended to introduce and present a state-of-the-art Regional Risk Assessment (RRA) methodology to evaluate the benefits of risk prevention in terms of reduced environmental risks due to floods. The methodology, developed within the recently phased out FP7-KULTURisk Project (Knowledge-based approach to develop a cULTURe of Risk prevention – KR) is flexible and can be adapted to different case studies (i.e. large rivers, alpine/mountain catchments, urban areas and coastal areas) and spatial scales (i.e. from the large river to the urban scale). The FD compliant KR-RRA methodology is based on the concept of risk being function of hazard, exposure and vulnerability. It integrates the outputs of various hydrodynamics models (hazard) with sito-specific bio-geophysical and socio-economic indicators (e.g.

slope, land cover, population density, economic activities) to develop tailored risk indexes and GIS-based maps for each of the selected targets (i.e. people, buildings, infrastructures, agriculture, natural and semi-natural systems, cultural heritages) in the considered region, by comparing the baseline scenario with alternative scenarios, where different structural and/or non-structural mitigation measures are planned. As demonstrated in the companion paper (Part 2, Ronco et al., 2014), risk maps, along with related statistics, allow to identify and prioritize relative hotspots and targets which are more likely to be affected by flood and support the development of relevant and strategic adaptation and prevention measures to minimizing flood impacts. Moreover, the outputs of the RRA methodology can be used for the economic evaluation of different damages (e.g. tangible costs, intangible costs) and for the social assessment considering the benefits of the human dimension of vulnerability (i.e. adaptive and coping capacity).

1 Introduction

Extreme weather and climate events, the physical contributors to disaster risk, interacting with exposed and vulnerable human and natural systems, can lead to severe catastrophes (IPCC, 2012). Floods are the most threatening water-related disaster that affects humans, their lives and properties (Hewitt, 1997; Penning-Rowsell et al., 2005; Balica et al., 2009; Bates et al., 2008; Kubal et al., 2009), growing as a consequence of many factors both climatic (increase heavy precipitation, changing in water natural cycle) and non-climatic (land use change, increases in population, economic wealth and human activities in hazard-prone areas and urban development). The combination of dramatic consequences, rarity, and human as well as physical determinants makes disasters difficult to study, however, there are scientific evidences of an increase in precipitation intensity, which implies that extreme floods events might become more frequent (Hirabayshi et al., 2013). At the same time, consequences for disaster related risks and impacts related to floods might be exacerbated due to increase exposure and vulnerability of elements at risk linked to population dynamics and the associated economic and urban development in flood-prone areas. Thus, even if not considering climate change factors connected to increase frequency of floods disaster, an increase of these catastrophic events may be expected (Mitchell, 2003).

In Europe, floods, storms and other hydro-meteorological events account for around two thirds of the damage costs of natural disasters, and these costs have increased since 1980, according to EEA (2012). Between 1998 and 2009, in particular, Europe suffered over 213 major damaging floods that have caused some 1126 deaths, the displacement of about half a million people and at least € 52 billion in insured economic losses, including the catastrophic floods along the Danube and Elbe rivers in summer 2002 (see Fig. 1) (Barredo, 2007).

Traditionally, the European floods control and management practices have been focused on reactive practices and largely relied on control of floods through structural measures, only later supported by sporadic non-structural measures. Now, it is widely recognized that a paradigm shift is required to move from defensive to proactive action towards a culture of prevention by managing the risk of and living with floods (Annamo and Kristiansen, 2012).

In this context, the European Flood Directive (FD) 2007/60/EC (2007) represents an ad hoc legislative framework which specifically support the development of proper flood management strategies, in order to reduce the adverse consequences for human health, the environment, cultural heritage and economic activities of such calamities. By distinguishing clearly between hazard and risk maps, the FD asks for a more sophisticated analysis of natural hazards and moves furher steps head towards the improvement of notions and concepts of risk management. In particular, risk maps shall allow to visualize the spatial distribution of (flood) risks in the specific (flood) scenario, by considering the risk as the combination of hazard, exposure and vulnerability and pointing out (cit.): “the potential adverse consequences associated with flood scenarios”, by quantifying in particular, the number of people and economic activities potentially affected. Eventually, while it is indisputable that the European Union emanated a set of general reports which aim to support the current EU regulations, a lack of integrated, specific criteria, methodologies and tools concretely supporting their practical implementation at the regional scale has been widely recognized. Available risk-based methods, in fact, have been developed in recent years but they are fragmented across different scientific disciplines (e.g. engineering, environmental sciences, economics and social sciences), geographic and policy contexts; they focused mostly on flood hazard mapping (Di Baldassarre et al., 2009, 2010; Rotach et al., 2012) while comprehensive approaches (i.e. integrating environmental, social and economic perspectives) are poorly represented (Cirella et al., 2014). In fact, these approaches are mainly focused on the analysis of the consequences and damages of floods on specific receptors – for instance, population, buildings or agriculture (Clausen and Clark, 1990; Citeau, 2003; DEFRA, 2006) – neglecting the coexistence of multiple receptors living in the same geographical region. By acknowledging different roots of the vulnerability paradigms, embedded in multidisciplinary theories underpinning either a technical or social origin of this concepts, Fuchs et al. (2012) stated that methodologies for structural, economic, institutional or social vulnerability assessment should be inter-woven in order to enhance its understanding. Furthermore, efforts to reduce exposure to hazards and to create disaster-resilient communities require intersection among disciplines and theories, since human actions cannot be seen independently from environmental features, and vice versa (Hufschmidt et al., 2010). Moreover, the current and future flood risk assessments are also characterized by considerable uncertainty, which needs to be addressed and clearly communicated to decision-makers (Peppenberg et al., 2012). Finally, as suggested by Montanari et al. (2013) through the new “Panta Rhei – Everything Flows” paradigm for hydrological disciplines, now the challenge is to look at these (hydrological) processes as a changing interface between environment and society, whose dynamics are essential to set priorities for a (proper, effective and sustainable) environmental management, through an interdisciplinary approach between socio-economic sciences and geosciences in general.

Accordingly, there is the need to develop a comprehensive risk assessment methodology that could integrate information coming from deterministic as well as probabilistic flood forecasting; as well as the multi-faceted physical/environmental, social and economic aspects of exposure and vulnerability, in order to evaluate flood risks for different receptors/elements at risk, as required by the Floods Directive. In this paper, the physical-environmental dimension of risk has been assessed by considering hazard, exposure and vulnerability analysis of flood risk.

After a rapid overview of the current approaches on flood risk assessment, the paper will introduce both the conceptual framework and, in particular the computational procedure used to assess the physical-environmental (relative) risk posed by floods to a selected cluster of receptors. Before coming to the conclusion, the article will also present a simple but effective algorithm, based on Multi Criteria Decision Analysis, to combine the receptor-related relative risk into a single general (total) risk index. The (ultimate) objective of the methodology, successfully applied in the Sihl river valley in Switzerland (see the companion paper, Part 2, Ronco et al., 2014), is to identify and prioritize areas and targets at risk in the considered region, in order to evaluate the benefits of different risk prevention scenarios to support relevant stakeholders and decision makers in science-based (land) planning and decision making.

2 Approaches and tools on flood risk assessment

Several methodologies have been developed in order to assess flood risk; the choice of one methodology over another largely depends on the objectives of the analysis, the availability of dataset, the peculiarities of the context of application, the level of detail to be achieved, the dimensions of risk to be addressed. Cirella et al. (2014) recently published a comprehensive review and classification of current approaches and methodologies for the assessment of risks posed by a wide range of water-related natural hazards (coastal storms, tsunamis, river floods, avalanches, landslides, etc.). Based on different indicators and criteria (e.g. hazard of concerns, conceptual framework, analytical approach, role of experts and stakeholders, elements at risk (receptors), spatial scale, input and output, tools and models used, uncertainties, etc), the review demonstrated that there are very few examples of methodologies that consider the complete suite of elements at risk (receptors) pointed out by the FD through an integrated and multidisciplinary approach, encompassing the entire varieties of risk dimensions (i.e. physical/environmental, social and economic). Most of the available methodologies, in fact, only targeted "classical" receptors, such as buildings, or infrastructures or population (e.g. Forte et al., 2005; Büchele et al., 2006; Kubal et al., 2009), that are usually analysed separately, in monetary terms and related damages only. Moreover, while most of the approaches made a considerable use of GIS-based tools both for computational and outcome purposes, they were mainly developed for very specific contexts at a very local scale, with an high level of complexity and data demanding (e.g. Forte et al., 2005; Meyer et al., 2009; Kubal et al., 2009; Forster et al., 2008), and they can hardly be employed for a wide range of case studies. A recent attempt has been made by Balica et al. (2009) in proposing an innovative parametric approach for the estimation of the vulnerability of a system by using only few (readily available) parameters related to that system. Finally, as affirmed by Papathoma-Kohle et al. (2011) and Fuchs et al. (2012) that recently revising the current approaches in vulnerability assessment, only through a multidimensional and dynamic approach, the overall aim of reducing natural hazards risk can be achieved.

3 The KULTURisk Regional Risk Assessment (KR-RRA) methodology

3.1 Conceptual framework

The KULTURisk Conceptual Framework (KR-FWK) developed by Giupponi et al. (2014) within the above mentioned project, shaped the basis for the development of the presented methodology to evaluate the benefits of risk prevention. By considering three main tiers of analysis, namely (1) the physical/environmental Regional Risk

Assessment (RRA), (2) the social and (3) the economic valuation of potential consequences, the Conceptual Framework has been built upon the consolidated formalization of risk being a function of hazard, exposure, and vulnerability, defined as: (i) hazard, as "the potential occurrence of a natural or human-induced physical event that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, and environmental resources" (IPCC, 2012); (ii) exposure, as "the presence of people; livelihoods; environmental services and resources; infrastructure; or economic, social, or cultural assets in places that could be adversely affected" (IPCC, 2012); (iii) vulnerability, consisting of susceptibility as a Physical/Environment (P/E) component, and adaptive and coping capacities as the Social component. The P/E component is captured by the likelihood that receptors located in a considered area could potentially be harmed.

The above described elements are combined to calculate the Risk delineated as the combination of the probability of a certain hazard to occur and of its consequences.

The presented study only addresses the first tier of the analysis, namely the Regional Risk Assessment (RRA) that considered the flood hazard and the physical/environmental dimension of vulnerability (i.e. susceptibility) to identify and classify physical/environmental risks associated to floods for different receptors. The others two tiers are grouped into a single cluster of assessment, namely the Socio-Economic Assessment (SERRA) developed by Giupponi et al. (2014), where the information utilised for the RRA are merged with other social and economic indicators and monetary values of the assets at risk. The RRA provides an estimation of the physical/environmental risks that can be used as input for the social and economic tiers of analysis. These tiers can be used separately (i.e. considering only the social or the economic dimension) or sequentially (i.e. estimating the effects of the social and value indicators, together with the physical/environmental ones, on the expected costs).

3.2 Regional Risk Assessment: background, features and objectives

Since its first applications in 1997, the RRA approach has been successfully used at a variety of sites across the world, including marine coastal areas, fjords and hydrographic basins habitats (Landis and Wiegers, 1997). The RRA is aimed at providing a quantitative and systematic way to estimate and compare the impacts of environmental problems that affect large geographic areas (Hunsaker et al., 1990), by considering the presence of multiple habitats, multiple sources releasing a multiplicity of stressors impacting multiple endpoints (Landis, 2005). Specifically with the aim to rank potential impacts, targets and areas at risk from water-related natural hazard at regional scale, the KR-RRA integrates four steps of analysis, as follow:

- *hazard assessment* is aimed at characterizing the flood pattern by means of relevant metrics (e.g. flow velocity, water depth, flood extension) coming from hydraulic models, (deterministic or probabilistic) according to different scenarios to be investigated (baseline or alternative);
- *exposure assessment* is aimed at identifying the elements at risk. This step requires the analysis of land use/land cover datasets for the localization of people, environmental resources, infrastructures, social, economic and cultural assets that could be adversely affected by a flood;
- *susceptibility assessment* is aimed at evaluating the degree to which the receptors could be affected by a flood hazard based on physical/environmental site-specific information;
- *risk assessment* combines the information about a certain flood hazard scenario with the exposure and susceptibility of the examined receptors, providing a first evaluation of risks related to each receptor through the computation of a relative risk score. Risk scores varies from 0 (i.e. no risk) to 1 (i.e. higher risk for the considered area). The ranges for risk classes can be defined using different

methods (e.g. Equal interval, Jenks optimization) and qualitative classes should then be assigned to them (i.e. low, medium, high risk). After the normalization of the receptor-related risk, a total (integrated) risk index is calculated by means of Multi Criteria Decision Analysis (MCDA) functions.

As suggested by the Flood Directive (2007/60/EC), the KR-RRA methodology considers the following receptors:

1. people;
2. economic activities, including: (i) buildings, (ii) infrastructures, (iii) agriculture;
3. natural and semi-natural systems;
4. cultural heritage.

As depicted in Fig. 3, the main outputs of the RRA are GIS-based maps of receptor-related risks and of the total risk.

The KR-RRA method has been developed for analysis at the meso-scale level, adopting the land use/land cover classes proposed by the CORINE Land Cover, as major spatial units of reference (EEA, 2006). However, it is flexible to be applied at different spatial levels (i.e. the macro or the micro scales) based on the purposes of the assessment, the geographical extent of the case study and the level of detail of input dataset. The methodology can be applicable in different problem contexts, case studies and spatial scales with the aim to provide a benchmark for the implementation of the Floods Directive at the European level. In addition, GIS-based maps and outcomes result useful to communicate the potential implications of floods in non-monetary terms to stakeholders and administrations and can be a basis for the management of flood risks as they can provide information about the indicative number of inhabitants, the type of economic activities, natural systems and cultural heritages potentially affected by flooding. Concluding, the KR-RRA methodology allows to identify and prioritize areas and targets at risk in the considered region and to evaluate the benefits of different prevention scenarios.

In the next paragraphs, the computational procedure to estimate the relative risks, receptor-by-receptor, will be introduced, starting from the initial setting of the hazard scenario.

3.3 Scenario development

In general, the proper selection of robust and reliable hazard scenarios, defined as the plausible image of a possible future system state under different circumstances (baseline or alternative scenario), is primary for the quality and the robustness of the risk assessment (Mazzorana et al., 2009) since it allow the comparison of different (risk) scenario and, therefore, to evaluate the benefits of risk prevention measures. In fact, several approaches can be followed in scenario development, depending on level of detail, data availability and degree of experts involvement. For example, Mazzorana et al. (2009) provided a useful insight about the various scenario planning procedure and approaches by classifying the scenario analysis in three different types, among holistic (experts elicitation), model analysis (based on system modelling) and Formative Scenario Analysis, based on qualitatively assessed impact factors and tested in different case studies. When combined with conventional modelling, the last one, initially proposed by Scholz and Tietje (2002), by meeting basic, operational and multidimensional principles and integrating bounding uncertainties represents a robust technique for the development of reliable future hazard scenarios. The KR-RRA asks for a preliminary analysis and screening of different hazard scenario (baseline and alternative) based on different hazard magnitude, probability and/or alternative settings where structural and non-structural mitigation and adaptation measures are planned but it does not provide or suggest a particular (bounded) method for scenario construction, rather it takes advantages from available techniques and models, depending on their applicability and reliability to the specific case study.

3.4 Physical/environmental risk assessment to people

River floods have the potential to cause serious risk to people and are considered as the most threatening water-related disaster that affects humans, their lives and properties (Hewitt, 1997; Penning-Rowsell et al., 2005; Balica et al., 2009; Kubal et al., 2009). Both river and coastal flooding affect millions of people in Europe each year influencing human health through drowning, heart attacks, injuries, infections as well as psychosocial consequences (Fig. 4) (www.eea.europa.eu). During the past 10 years, floods in Europe have killed more than 1000 people and affected 3.4 million others (Jakubicka et al., 2010). Nevertheless, it is difficult to classify which deaths are actually associated with a flood. Immediate flood deaths are best recorded, but deaths during clean-up and longer-term mortality associated with flooding are often not recorded as such (Menne and Murray, 2013).

In 2008 Jonkman et al. (2008) provided an in-depth review of available methods, tools and approaches for the estimation of loss of life due to different types of floods (e.g. for dam breaks, coastal floods, tsunamis), that are normally based on empirical data of historical flood events only, without any physical direct approach. Furthermore, the authors proposed a new method based on the subsequent assessments of hazard, exposure and vulnerability features, primarily developed for the risk related to the breaching of flood defences in the Netherlands and for similar low-lying areas. Despite being robust and scientifically sound, the method looks very case-specific and rather difficult to apply to a wide range of geomorphological situations and different water related hazards, as the KR-RRA is intended for.

The proposed KR-RRA approach allows the assessment of flood risks to human health (i.e. in terms of potential fatalities and injuries) associated with a flood event, by making the best use of available information at the meso-scale (i.e. CORINE Land Cover polygons). For this reason it focuses on residential areas identifying them as major hotspots where people live (Jonkman, 2008). In particular, the proposed approach is based on the methodology developed by Ramsbottom et al. for the UK

Department for Environment, Food and Rural Affairs (DEFRA, 2006) for a wide range of case studies. The method was based on a multi-criteria assessment of factors that affect Flood Hazard, the chance of people in the floodplain being exposed to the hazard (Area Vulnerability) and ability of those affected to respond effectively to flooding (People Vulnerability).

3.4.1 Hazard, exposure and susceptibility assessments

The flood hazard classification considers the degree of impact and it is related to the specific physical characteristics of an individual (i.e. height, mass, age) which is identified by different population typology (i.e. children, elders and infirm/disable; adult woman; adult man). The flood hazard assessment step identifies water depth and velocity as relevant physical metrics in direct (linear) relationship with the flood hazard (i.e. when water depth and velocity increase, the flood hazard increases). Moreover, case by case, it is possible to consider also the presence of debris factor (i.e. floating material such as trees, cars, etc.) where it poses a threat to the lives of people. The (flood) hazard to people is calculated using the following equation:

$$H_{\text{people}} = d \cdot (v + 1.5) + \text{DF} \tag{1}$$

where H_{people} = hazard score for people; d = water depth [m]; v = velocity [m s^{-1}]; DF = debris factor [0; 1].

Equation (1) allows to define an hazard map, in which the resolution depends on the outcomes and resolution of the hydraulic modeling and/or the historical dataset used to calculate and/or retrieve the physical metrics. The DF requires the assignation of a value between 0 (i.e. low probability that debris would lead to a significant hazard) and 1 (i.e. high probability that the debris would lead to a significant hazard), according to different ranges of water depth and flow velocity (DEFRA, 2006).

The exposure assessment requires the localization of the people potentially affected, that can be defined using census data of population density or the number of inhabitants per civic number within the residential areas, as Jonkman (2008) suggested. At any particular time, people may be present in various location (e.g. outdoors, indoors within a multi-storey building) that can be associated to different levels of risk. However, as stated above the assumption is that all the people are present in their homes at the low ground where people do not have safe areas as refuge. However, for a sake of simplification, coping capacity during the event (people that are able to evacuate and/or shelter, as well as the solutions implemented by local Authorities to manage the emergencies) and adaptive capacity before-after the event (solutions implemented by people and Authorities in order to deal with the hazard) are not considered by the RRA since these terms are fully enclosed in the subsequent cluster of the KULTURisk methodology, the SERRA one (see Giupponi et al., 2014).

To characterize the susceptibility of people, namely the degree to which the receptors could be affected by the hazard, the KR-RRA methodology suggests to consider: (i) the percentage of resident aged 75 years or over, and (ii) the percentage of residents suffering from long term illness. These conditions are considered as factors that could increase the susceptibility because aged people can be more prone to health and stability problems in a flood event and also because many pre-existing medical conditions can increase the probability of health problems related to flooding and of death (e.g. mortality for hypothermia). The susceptibility score (Eq. 2) is therefore calculated by summing these two indicators (DEFRA, 2006):

$$\mathrm{SF}_{\mathrm{people}} = \mathrm{sf}_1 + \mathrm{sf}_2 \qquad (2)$$

where $\mathrm{SF}_{\mathrm{people}}$ = susceptibility score for people (%); sf_1 = % of people over 75 years; sf_2 = % of people with disabilities.

The susceptibility assessment is based on census data allowing the assignation of a susceptibility score to each census unit (e.g. municipality, census district) and a creation of a related susceptibility map. Indicators and data sources for the assessment of hazard, exposure and susceptibility of people at the meso-scale are reported in Table 6.

3.4.2 Risk assessment

The risk assessment provides a relative risk index that allows to identify and rank areas and hotspots at risk in the studied area. Hazard (Eq. 1), exposure and susceptibility (Eq. 2) are used within the risk assessment to provide the number of people injured (R_1) and dead (R_2) during a flood event, as follow (DEFRA, 2006):

$$R_1 = \frac{\left(2 \cdot E \cdot H_{\text{people}} \cdot \frac{\text{AV}}{100} \cdot \text{SF}_{\text{people}}\right)}{100} \tag{3}$$

$$R_2 = 2 \cdot R_1 \cdot \frac{H_{\text{people}}}{100} \tag{4}$$

where R_1 = number of injuries; R_2 = number of fatalities; E = exposure (i.e. the number of people that can be potentially inundated); H_{people} = hazard score to people; AV = area vulnerability; $\text{SF}_{\text{people}}$ = susceptibility score for people (%).

As per the DEFRA (2006) approach, the area vulnerability (AV) is defined as the sum of flood warning, speed of onset and nature of area, ranging from 3 (i.e. low social vulnerability, high adaptive and coping capacity) to 9 (i.e. high social vulnerability, low adaptive and coping capacity). Moreover, in order to aggregate all the receptor-related risk in the total risk, this step requires a phase of normalization aimed at rescaling the receptor-related risk scores into a common closed numerical scale (0–1) (Zabeo et al., 2011). The normalization is performed at CORINE polygon-scale, where this size is selected according to the degree of (spatial) resolution of the data available. For the people, the normalization is provided considering the number of people injured/dead and the number of people in the highest populated polygon, according to Eqs. (5) and (6):

$$R_1' = \frac{R_1}{\text{number of people in the highest populated polygon}} \tag{5}$$

$$R_2' = \frac{R_2}{\text{number of people in the highest populated polygon}} \tag{6}$$

where R'_1 = normalized risk score for injuries; R'_2 = normalized risk score for fatalities; R_1 = number of injuries (Eq. 4); R_2 = number of fatalities (Eq. 5).

This normalization allows defining risk scores between 0 (i.e. no people injured/dead) and 1 (i.e. all the people living in the highest populated polygon are injured/dead).

3.5 Physical/environmental risk assessment to economic activities

To fulfil with the requirements of the FD, the flood risk assessment related to economic activities has considered three relevant sub-receptors: buildings, infrastructures and agriculture.

3.5.1 Physical/environmental risk assessment to buildings

Floods have a potential massive impact on buildings infrastructures (e.g. to the structures and to the indoor goods), particularly in populated areas, corresponding to residential and commercial-industrial sites, triggering dramatic (socio-) economic damages.

Papathoma-Kohle et al. (2011) and Fuchs et al. (2012) recently provided an insight of the current approaches and future needs on vulnerability assessment of buildings, when stricken by water-related natural hazards. The most frequent approach concerned the use of (empirical) stage-damage functions that linked inundation depth to expected losses, that is reliable method for standing waters but do not consider the impact of flowing waters to the structures as relevant indicator (Buchele et al., 2006). It is worth to notice that, without making any explicit reference the general concepts of the (complete) risk assessment procedure, the authors remarked a lack of multidimensional and dynamic approaches to this topic, and outlined some key issue to be addressed by an ultimate approach to this topic. Some of these suggestions have been included into the KR-RRA, in particular as far as the involvement of end users, transferability of methods, spatial approach (GIS based) and hazard dependency are concerned. Finally, in the proposed KR-RRA the receptor is define by considering the buildings footprint in the area as well as its economic use, according to the CORINE Land Cover classes of industrial and residential areas. At meso-scale level, this classification allows to define the percentage and the typology of buildings that could be stricken by a flood event with different degrees of structural damage.

Hazard, exposure and susceptibility assessments

We should underline that the mentioned methods of vulnerability assessment to the buildings were characterized, to some extent, by a consistent use of sophisticated physical approaches and screening methods, only applicable to the very local scale (micro-zonation). For example, by considering the damage related to different building typologies as suggested by Schwarz and Maiwald (2008), or by considering the material construction and its quality, the building level, the state of conservation, contamination and precautionary principles (Büchele et al., 2006; Mebarki et al., 2012; Totschnig and Fuchs, 2013). Without excluding the possibility of further improvement, refinement and enhancement of the proposed method by matching the level of detail and data availability required by such approaches with the necessary portability of the same, some degree of simplification was necessary in order to develop and fully apply a RRA methodology at meso scale level, in particular as far as the physical vulnerability (susceptibility) is concerned.

Within the proposed KR-RRA, reference is made to the approach proposed by Clausen and Clark (1990) where, by assuming that all the buildings are characterized by the same structure, the risks was evaluated by directly considering the relationships between flood hazard classes and potential structural damages (Fig. 5).

Risk assessment

Based on the classes proposed by Clausen and Clark (1990), the methodology allowes to define the percentage and the typology of buildings characterized by different risk classes defined in Table 1 (i.e. inundation, partial damage, and total destruction). As shown in Table 1, this method provides three risk classes differentiating the potential consequences of floods in a qualitative way, based on thresholds determined by flow velocity values and by the product between water depth and flow velocity (intensity). The risk assessment to buildings (R_3) allowes the estimation of the surface (km^2) and the percentage of flooded buildings belonging to different uses (i.e. CORINE Land Cover polygons related to residential, commercial-industrial areas) in each risk class (i.e. inundation, partial damage, total destruction) in the form of tables (summarizing the statistics) and maps (highlighting the areas at different risks). Again, this step requires a phase of normalization aimed at rescaling the receptor-related risk scores into a common numerical scale (0–1) (Zabeo et al., 2011). The scores proposed in Table 2 have been defined by the authors by using a dedicated qualitative evaluation. Of course, different scores based on site-specific knowledge, literature data and expert judgments, can be assigned during the application of the proposed methodology.

3.5.2 Physical/environmental risk assessment to infrastructures

Floods can affect infrastructures causing a loss of services (e.g. not practicable road and connections, no power supply) in addition to structural direct damages (e.g. cracks to roads, collapse of the highways). Studies of past flood events have showed that the majority of losses arise in urban areas, due to impairment of structures, costs of business shut-down and failure of infrastructure (EEA, 2010c; ADBI and The World Bank, 2010). A very recent example comes from the severe flooding experienced in Central-East Europe (June 2013) that had a significant cost for infrastructure-related businesses. Evacuations, property damage and infrastructure closures are amongst the challenges faced by those operating in a wide range of industries, including manufacturing, retail, transport, agriculture and tourism.

According to the Flood Directive (2007/60/EC), the KR-RRA methodology allows to identify roads and railways affected by flood hazard, by considering only the inundation of the infrastructures as main impact of interest. In this sense, the risk should be considered as the loss of services for the infrastructure during and after the event.

In fact, for a sake of simplification, the methodology does not consider any structural damages related to the flood event (damage and/or collapse of roads, bridges, railways, etc.).

Hazard, exposure and susceptibility assessments

Based on these premises, the flood hazard assessment only considers the flood extension (flooded area) as relevant hazard physical metric. The exposure assessment step focuses on the spatial localization and distribution of the roads, railways and pathways. These objects are geometrically characterized by their linear extension (length) rather than by their surface extension (area). Finally, the susceptibility assessment step assigns the same score to the whole set of assets (e.g. roads, highways, railroads). As for the buildings, at micro-scale level the physical susceptibility assessment can be improved by considering the construction typology, functions and dimensions of the considered infrastructure.

Risk assessment

Accordingly, the infrastructure-related risk (R_4) is calculated from the intersection between the flood extension map and the road and railway atlas in order to identify and characterize the items inundated by the flood event. In this case, the physical/environmental risk assessment step to infrastructures results in the estimation of the length (km) and the percentage of infrastructures potentially affected by flood in each CORINE Land Cover polygon in the form of tables (summarizing the statistics) and maps (highlighting the areas at risk). Again, this step requires a phase of normalization aimed at rescaling the receptor-related risk scores into a common numerical scale (0–1) (Zabeo et al., 2011). For infrastructures the normalization is performed considering the length of flooded infrastructures in each polygon and the total length of infrastructures in the same polygon, provided by Eq. (7):

$$R'_4 = \frac{R_4}{\text{total length of infrastructures in the same polygon}} \quad (7)$$

where R'_4 = normalized risk score for infrastructures; R_4 = length of flooded infrastructures in each polygon.

The normalization assumes that if in a polygon all the infrastructures are flooded, people cannot secure their health and their goods (i.e. all the safety way are not accessible). The normalization phase moves towards the development of infrastructures-related risk scores between 0 and 1 that are integrated in the calculation of the total risk index.

3.5.3 Physical/environmental risk assessment to agriculture

Floods can potentially damage crops that become oversaturated, but can also provide damages to farmland and infrastructures. These impacts can lead to economic damages both direct and indirect (e.g. loss of agricultural soil due to erosion, scarcity of cereals, etc.) with only few methodological approaches available for their (monetary) quantification (Dutta et al., 2003; Meyer et al., 2009). Recent events in Modena Province (Northern Italy) confirmed the importance of considering the massive floods impact on the agricultural sector with € 54 M of losses for the sole have been caused by (only) 2 days of heavy rainfall in late January 2014 (ANSA, 2014). The KR-RRA approach is aimed at mapping potential flood risk to agriculture making the best use of available information at the meso-scale (i.e. CORINE Land Cover polygons of the agricultural areas). Specifically, the aim of the RRA methodology for agriculture is to define the percentage of the harvest loss due to a flood event, without any consideration about the damage to agricultural buildings.

Hazard, exposure and susceptibility assessments

Based on the analysis proposed by Citeau (2003) concerning bibliographic data and in situ surveys, the proposed assessment requires the identification of water depth and velocity as relevant physical metrics to characterize the hazard. The exposure assessment step allows the localization of the different agricultural typologies (i.e. vegetables, vineyards, fruit trees and olive groves) in the case study area, according to the land use pattern provided by the mentioned dataset of reference. Moreover, a set of thresholds for the hazard metrics have been established for different agricultural typologies (e.g. vegetables, vineyards, trees) characterized by a different susceptibility factor, also according to the seasonality (e.g. the spring, summer and autumn) (Table 3). For example, since vegetables are more susceptible than fruit trees to inundation phenomena, the relative threshold for the flow velocity is lower for the first ones. Nevertheless, updated and site-specific thresholds can be established, when available.

Risk assessment

Within the risk assessment phase, giving the flood hazard thresholds provided by Table 3, it is possible to define if an agricultural area is inundated (i.e. if the flood hazard values are below the identified thresholds) or loss (i.e. if the flood hazard values exceed the thresholds) due to a flood event and therefore to calculate the total flooded agricultural area (km^2) and the percentage of agriculture typologies stricken in the form of tables, summarizing the statistics, and maps, highlighting the areas at different risk levels. Specifically, the agriculture-related risk (R_5) is calculated for spring, summer and autumn seasons by assuming that during the winter time there are no cultivations exposed to the impact of flood. Therefore, for this season, it is only possible to distinguish between inundated and not inundated agricultural areas. Finally, the normalization phase provides values between 0 and 1, according to the authors' evaluation, as summarized in Table 4. Local stakeholders and others can assign different scores based on site-specific knowledge, literature data and expert judgments.

3.6 Physical/environmental risk assessment to natural and semi-natural systems

Floods tend to degrade natural systems by removing vegetation, degrading hill-slopes, rivers, altering the pattern of erosion/sedimentation processes and the transfer of both sediment and nutrients. Other negative effects include loss of habitats, dispersal of weed species, release of pollutants, lower fish production and loss of recreational areas. Accordingly, the aim of the proposed KR-RRA methodology is to identify those environmental systems (i.e. natural and semi-natural ecosystems, protected areas, wetlands) that can be affected by a flood event due to their physical characteristics (e.g. slope, vegetation cover, soil type) causing a permanent, or temporal, loss of ecosystems services.

3.6.1 Hazard, exposure and susceptibility assessments

Flood extension area (km^2) has been selected as relevant physical metric to characterize the hazard impacting natural and semi-natural systems. Moreover, the exposure assessment allows localizing the receptor by considering the CORINE Land Cover classes related to forest, semi-natural areas and wetlands.

As far as the susceptibility assessment is concerned, following Pasini et al. (2012), a series of indicators have been selected to characterize the physical intrinsic characteristics of the analysed territory reflecting variations in the degree to which the natural and semi-natural systems may be affected by a flood event (see Table 6). Each susceptibility indicator is later classified and scored by expert judgment. For the vegetation cover factor, for example, susceptibility classes are defined by considering different land cover typologies such as grass, shrub and forest. Specifically, the susceptibility of soil to floods increases when vegetative cover decreases (Preston et al., 2008; Torresan et al., 2012), while the slope factor classes considers the range of possible slopes in the area by using the equal interval classification (Zald et al., 2006). When it comes to the impact of floods on natural systems to be intended as loss of biodiversity and ecological value, especially in the medium-long term, environments characterize by lower slopes are more susceptible to flood since they are subject to water stagnation and therefore soil degradation, while steeper slopes are less susceptible as they do facilitate the water evacuation (Preston et al., 2008). The same applies for the soil type factor, where classes and thresholds are established considering that the more waterproof soil type typologies are the most susceptible to flooding because they cannot drain the standing waters (Yahaya, 2010). Moreover, the higher susceptibility scores has been assigned to wetlands with lower surface area, which may be more sensitive to flood pressures than wider ones (Torresan et al., 2012).

Once susceptibility classes are defined, the assignation of relative scores is provided by experts and local stakeholders following the linguistic evaluations reported in Table 5. Moreover, the expert could assign a weight to susceptibility factors in order to represent their relative importance in the analysed area. The phase of scoring and weighting allows the normalization of the susceptibility indicators between 0 (i.e. no susceptibility) and 1 (i.e. the higher susceptibility in the considered region).

Finally, the suggested susceptibility indicators are then aggregated through a Multi-Criteria Decision analysis (MCDA) function named "probabilistic or" (Kalbfleisch, 1985, details in Appendix A), which provides a single normalized score of susceptibility for homogeneous areas, as follow:

$$S_{\text{nat}} = \otimes_i^n \left[\text{sf}'_i\right] \tag{8}$$

where S_{nat} = susceptibility score of the cell; $\otimes$ = "probabilistic or" function; sf'_i = ith susceptibility factor score (classified in [0,1]).

When applying the "probabilistic or" function (Eq. 8), if just one susceptibility factor (sf) assumes the maximum value (i.e. 1) then the susceptibility score will be 1. On the other side, sf with low scores contribute in increasing the final susceptibility score:

the more is the number of low susceptibility factor scores, the greater is the final susceptibility.

3.6.2 Risk assessment

Finally, in the risk assessment step the hazard and the susceptibility scores are aggregated in a relative risk score (R_6) to identify and prioritize exposed natural and semi-natural systems potentially affected by loss of ecosystem services, as follow:

$$R_6 = H_{\mathrm{nat}} \cdot S_{\mathrm{nat}} \tag{9}$$

where R_6 = natural and semi natural systems related risk; H_{nat} = hazard score (1 in flooded area); S_{nat} = susceptibility score calculated according to the "probabilistic or" function (Eq. 8).

The results of the physical/environmental risk to natural and semi-natural systems, are grid based layers where it is possible to calculate the surface (km^2) and the percentage of the flooded receptor in each risk class (e.g. low, medium, high) in the form of tables (summarizing the statistics) and maps (highlighting the areas at different risks). As for the other receptors, a phase of normalization aimed at rescaling the qualitative risk classes (i.e. low, medium, high) following the qualitative evaluations summarized in Table 6 is performed. Again, case study experts can assign different scores based on site-specific knowledge, literature data and expert judgments.

3.7 Physical/environmental risk assessment to cultural heritage

Flooding can damage architectural heritage, historic buildings and sites as well as objects of art standing alone or firmly attached as an integral group of buildings. All these objects are subjected to various forces (e.g. static or hydrostatic pressure, flow velocity and waves) and actions during flood situations (Nedvědová and Pergl, 2013; Drdácký, 2010). According to the Flood Directive (2007/60/EC) which requires the localization of the potential cultural heritages affected by floods, the KULTURisk-RRA method includes cultural heritage as a relevant receptor for the integrated flood risk assessment.

3.7.1 Hazard, exposure and susceptibility assessments

It is worth to specify that the analysis of risk at meso-scale level is not oriented to the evaluation of structural damages to cultural assets but only to the identification of stricken (flooded) items. Therefore, flood extension area (km^2) is identified as relevant physical metric to characterize the hazard assessment. The World Heritage Convention by UNESCO (1972) distinguishes three different typologies of cultural heritages: monuments (which are of outstanding value from the point of view of history, art or science), groups of buildings (separate or connected buildings) and sites (which are of outstanding universal value from the historical, aesthetic, ethnological or anthropological points of view). Spatially they can be considered as points (i.e. monuments) and areas (i.e. buildings and sites) overlapping with the polygons of the CORINE Land Cover.

Starting from the available information at the meso-scale (i.e. location and typology of cultural heritages) and assuming that the cultural assets are affected in the same way by the flood, the susceptibility assessment assumes a score equal to 1 for the entire suite of items.

3.7.2 Risk assessment

The risk assessment step for the cultural heritages aims at providing the number of flooded monuments, the surface (km^2) and percentage of inundated cultural buildings and archaeological/historical sites in the form of tables (summarizing the statistics) and maps (highlighting the cultural heritages at risk). Accordingly, the cultural heritage-related risk for single monuments (R_7) and sites (R_8) are calculated from the intersection between the flood extension map and the cultural heritage map in order to identify the number and surface of the cultural assets inundated by the flood.

For this receptor, the normalization phase is performed by considering the number of inundated monuments in each CORINE Land Cover polygon and the totality of monuments lying in the polygon most populated by cultural objects (Eq. 10), as well as the cultural sites flooded area (km^2) in each CORINE Land Cover polygon and the total area (km^2) of cultural sites in the polygon more extensively covered by cultural assets (Eq. 11).

$$R'_7 = \frac{R_7}{\begin{array}{c}\text{total number of monuments of the polygon}\\ \text{with the highest number of monuments}\end{array}} \tag{10}$$

where R'_7 = normalized risk score for cultural heritages (monuments); R_7 = number of flooded monuments in each polygon.

$$R'_8 = \frac{R_8}{\begin{array}{c}\text{cultural sites [km}^2\text{] in the polygon with}\\ \text{the highest cultural site area}\end{array}} \tag{11}$$

where R'_8 = normalized risk score for cultural heritages (sites); R_8 = cultural sites flooded area [km^2], in each polygon.

Again, when more detailed information related to the cultural heritage (e.g. site-specific surveys and archives) are available, a deeper analysis at the micro-scale (structural damages) can be performed by considering further physical susceptibility indicators, such as the material construction, the state of conservation, etc.

3.8 Total risk index

Total risk index is calculated by aggregating different receptor-related risks by means of Multi Criteria Decision Analysis (MCDA) method. The (very) final result of the KR-RRA methodology is a GIS-based Total Risk Map which allows to identify and rank areas and hotspots at risk in the analysed area and, therefore, to establish relative priorities for intervention, to identify suitable areas for human settlements, infrastructures and economic activities, and to provide a basis for land use planning.

The KR-RRA methodology uses the weighted average (Eq. 12) as effective method of aggregation, that is useful in liner additive contexts only, where receptors' risk are considered to be linearly additive and nor synergic neither redundant effects among risks and indicators are present.

$$R_{\text{tot}} = \frac{\sum_{\forall r} w_r R'_r}{\sum_{\forall r} w_r} \quad w_i \in [0,1] \forall r \tag{12}$$

where R_{tot} = total risk; w_r = weight associated with the r-receptor-related risk; R'_r = normalized risk score associated to the r-receptor-related risk. The assignment of weights to the proposed receptors is performed by experts and local stakeholder's consultation. The ranking process is supposed to give numerical priority to those whose flooding damaging consequences are considered as burdensome. In this sense, weighting is a typical political decision making process and the involvement of relevant stakeholders is seen as a fundamental prerequisite for its effectiveness (Yosie and Herbst, 1998)

The final output is a Total Risk Map (with risk scores between 0 and 1) where classes has been defined using Equal Interval GIS tool (see Table 8). Risk scores are not absolute predictions about the risks related to flood, rather they provide relative classifications about areas and targets that are likely to be affected by flood events more severely than others in the same region, and, as a consequence, to localize hot spots at risk, such as hospitals, schools, harbours, railway stations, airports, protected areas, potential installations causing pollution etc. Finally, a more detailed analysis of the most affected areas could be performed by examining the specific receptor-related risks.

4 Conclusions

The paper proposes a state-of-the-art physical/environmental Regional Risk Assessment methodology, developed within the FP7-KULTURisk Project and shaped on the framework established by the European Flood Directive, for the integrated assessment of water-related hazards at the regional scale (i.e. meso-scale) on multiple receptors/elements at risk (i.e. people, economic activities, natural and semi-natural systems and cultural heritages). The methodology is completed by a separate cluster devoted to the socio-economic assessment (see Giupponi et al., 2014). For each of the selected receptors-elements at risk, and by making a considerable use of Geographic Information Systems (GIS) tools, the methodology proposes a specific procedure for the estimation of a (normalized and spatially distributed) relative risk index, based on the subsequent levels of analysis, namely the hazards, exposure and vulnerability assessments. Together with the GIS-based maps, the outcomes of the application are indicators and statistics that quantify the risk for the considered receptors (e.g. number of people at risk, km^2 of flooded infrastructures at higher risk, percentage of residential buildings and commercial buildings at risk, km^2 of losses agricultural areas, etc.). Finally, the Total risk is calculated by aggregating the different receptor-related risks by means of Multi Criteria Decision Analysis (MCDA) through experts and local stakeholders' elicitation. The KR methodology should not attempt to provide absolute predictions about flood impact. Rather, this instrument, by means of MCDA and GIS-based tools, provides the ranking of the area, sub-areas and hotspots at risk that are more vulnerable and possibly more dramatically affected by the flood within the investigated region, to evaluate the benefits of different risk prevention scenarios (i.e. baseline and alternative scenarios) where structural and/or non-structural measures are implemented. Finally, with the ultimate aim to underpin risk prevention measures and, therefore, to communicate to decision makers and stakeholders the potential implications of floods in non-monetary terms, the proposed KR-RRA methodology demonstrate that prevention is accountable and its benefits are measureable, because different scenario can be compared. As a matter of fact, this adaptable practical methodology is both rigorous and flexible as it can be adapted to different case studies (i.e. large rivers, alpine/mountain catchments, urban areas and coastal areas) and spatial scales (i.e. from the large river to the urban scale). On this base, investments on prevention by Public Administrations can be better evaluated and shared with citizens, also in order to support the rising of a culture of prevention in the whole society. In this sense, the proposed methodology represents an important scientifically sound instrument towards the implementation of the Flood Directive in different environments and contexts. The proposed methodology can be further developed and improved by taking into consideration the outcomes of its application to different case studies, representing different hydro-climatic regimes and being exposed to different types of water-related risks, and the feedbacks from relevant end-users (see the companion paper, Part 2, Ronco et al., 2014). Moreover, an attempt towards the concept of dynamics in flood risk assessment by considering the new insights of the spatial-temporal evolution pattern of the four considered steps, as proposed by Mazzorana et al. (2012) for the vulnerability assessment, could be performed. Finally, in order to propose a harmonized overall approach to risk prevention for natural hazards other than floods, both the suitability and applicability of the KULTURisk methodological approach to other types of risks (earthquakes, forest fires, etc.) will be analyzed in detail, through the involvement of a number of experts in these fields.

Appendix A: Mathematical background

The "Probabilistic or" function (Kalbfleisch, 1985) is expressed as:

$$\otimes_{i=1}^{4}[f_i] = f_1 \otimes f_2 \otimes f_3 \otimes f_4 \quad \text{(A1)}$$

where:

f_i = ith generic factor f.

The "probabilistic or" operator can be evaluated as follow, due to the associative and commutative proprieties:

$$f_1 \otimes f_2 = f_1 + f_2 - f_1 f_2 = F_1 \quad \text{(A2)}$$

$$F_1 \otimes f_3 = F_1 + f_3 - F_1 f_3 = F_2 \quad \text{(A3)}$$

$$F_2 \otimes f_4 = F_2 + f_4 - F_2 f_4 = \otimes_{i=1}^{4}[f_i] \quad \text{(A4)}$$

The process can be repeated until evaluating all operands.

If just a factor (f) assumes the maximum value (i.e. 1) then the result of the "probabilistic or" will be 1. On the other side, f with low scores contribute in increasing the final "probabilistic or" score: the more is the number of low factor scores, the greater is the final score.

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References

ADBI, Asian Development Bank Institute and The World Bank: Pakistan Floods 2010: Preliminary Damage and Needs Assessment, Asian Development Bank, Islamabad, 2010.

Annamo, E. and Kristiansen, G.: Challenges in Flood Risk Management Planning. An example of a Flood Risk Management Plan for the Finnish-Norwegian River Tana, Norwegian Water Resources and Energy Directorate, Oslo, ISSN:1501-2832, Report no. 16, 2012.

ANSA: 54 Mln Danni da Alluvione a Agricoltura, available at: https://www.ansa.it/web/notizie/rubriche/cronaca/2014/02/03/54-mln-danni-alluvione-agricoltura_10008712.html (last access: 3 February 2014), 2014 (in Italian).

Balica, S. F., Douben, N., and Wright, N. G.: Flood vulnerability indices at varying spatial scales, Water Sci. Technol., 60, 2571–2580, 2009.

Barredo, J. I.: Major flood disasters in Europe: 1950–2005, Nat. Hazards, 42, 125–148, 2007.

Bates, B. C., Kundzewicz, Z. W., Wu, S., and Palutikof, J. P.: Climate Change and Water: IPCC Technical Paper IV, Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 2008.

Büchele, B., Kreibich, H., Kron, A., Thieken, A., Ihringer, J., Oberle, P., Merz, B., and Nestmann, F.: Flood-risk mapping: contributions towards an enhanced assessment of extreme events and associated risks, Nat. Hazards Earth Syst. Sci., 6, 485–503, doi:10.5194/nhess-6-485-2006, 2006.

EEA, European Environment Agency: CLC2006 technical guidelines, Publications Office of the European Union, Luxembourg, 2007.

Cirella, G. T., Semenzin, E., Critto, A., and Marcomini, A.: Natural hazard risk assessment and management methodologies review: Europe, in: Sustainable Cities and Military Installations: Climate Change Impacts on Energy and Environmental Security, edited by: Linkov, I., Springer, the Netherlands, 329–358, 2014.

Citeau, J. M.: A New Control Concept in the Oise Catchment Area, Definition and Assessment of Flood Compatible Agricultural Activities, FIG Working Week, Paris, France, 2003.

Clausen, L. and Clark, P. B.: The development of criteria for predicting dam break flood damages using modelling of historical dam failures, in: International Conference on River Flood Hydraulics, edited by: White, W. R., Hydraulics Research Limited, John Wiley & Sons Ltd., Wallingford, UK, 369–380, 1990.

DEFRA: Flood Risk to People Phase 2, FD2321/TR2 Guidance Document, Department for Environment, Food and Rural Affairs, London, UK, March 2006.

Di Baldassarre, G., Castellarin, A., Montanari, A., and Brath, A.: Probability weighted hazard maps for comparing different flood risk management strategies: a case study, Nat. Hazards, 50, 479–496, 2009.

Di Baldassarre, G., Schumann, G., Bates, P. D., Freer, J., and Beven, K.: Floodplain mapping: a critical discussion on deterministic and probabilistic approaches, Hydrolog. Sci. J., 55, 364–376, 2010.

Directive 2007/60/EC: On the Assessment and Management of Flood Risks, The European Parliament and of the Council of 23 October 2007, Brussels, Belgium, 2007.

Drdácký, M.: Impact of Floods on Heritage Structures, J. Perform. Constr. Fac., 24, 430–431, 2010.

Dutta, D., Herath, S., and Musiake, K.: A mathematical model for flood loss estimation, J. Hydrol., 277, 24–49, 2003.

EEA, European Environment Agency: Mapping the Impacts of Natural Hazards and Technological Accidents in Europe – an Overview of the Last Decade, Publications Office of the European Union, Luxembourg, 2010.

EEA, European Environment Agency: Water Resources in Europe in the Context of Vulnerability, Publications Office of the European Union, Luxembourg, 2012.

Förster, S., Kuhlmann, B., Lindenschmidt, K.-E., and Bronstert, A.: Assessing flood risk for a rural detention area, Nat. Hazards Earth Syst. Sci., 8, 311–322, doi:10.5194/nhess-8-311-2008, 2008.

Forte, F., Pennetta, L., and Strobl, R. O.: Historic records and GIS applications for flood risk analysis in the Salento peninsula (southern Italy), Nat. Hazards Earth Syst. Sci., 5, 833–844, doi:10.5194/nhess-5-833-2005, 2005.

Fuchs, S., Birkmann, J., and Glade, T.: Vulnerability assessment in natural hazards and risk analysis: current approaches and future challenges, Nat. Hazards, 64, 1969–1975, 2012.

Giupponi, C., Mojtahed, V., Gain, A. K., Biscaro, C., and Balbi, S.: Integrated risk assessment of water related disasters. The SERRA approach, in: Hydro-Meteorological Hazards and Disasters, edited by: Paron, P. and Di Baldassarre, G., Elsevier, in press, 2014.

Hewitt, K.: Regions of Risk. A Geographical Introduction to Disasters, Longman Ltd., Essex, UK, 1997.

Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kim, H., and Kanae, S.: Global flood risk under climate, Nature Climate Change., 3, 816–831, 2013.

Hufschmidt, G. and Glade, T.: Vulnerability analysis in geomorphic risk assessment, in: Geomorphological Hazards and Disaster Prevention, edited by: Alcantara-Ayala, I. and Goudie, A., Cambridge University Press, Cambridge, 233–243, 2010.

Hunsaker, C. T., Graham, R. L., Suter II, G. W., O'Neill, R. V., Barnthouse, L. W., and Gardner, R. H.: Assessing ecological risk on a regional scale, Environ. Manage., 14, 325–332, 2010.

IPCC, Intergovernmental Panel on Climate Change: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp., 2012.

ISPRA, Istituto Superiore per la Protezione e la Ricerca Ambientale: Proposta Metodologica per l'Aggiornamento delle Mappe di Pericolosità e di Rischio, Roma, Italy, Attuazione della

Direttiva 2007/60/EC Relativa alla Valutazione e alla Gestione dei Rischi da Alluvioni Decreto Legislativo n. 49/2010, 2012.

Jakubicka, T., Vos, F., Phalkey, R., and Marx, M.: Health Impacts of Floods in Europe: Data Gaps and Information Needs from a Spatial Perspective, a MICRODIS Report, Centre for Research on the Epidemiology of Disasters, Brussels, 2010.

Jonkman, S. N., Vrijling, J. K., and Vrouwenvelder, A. C. W. M.: Methods for the estimation of loss of life due to floods: a literature review and a proposal for a new method, Nat. Hazards, 46, 353–389, 2008.

Kalbfleisch, J. G.: Probability and Statistical Inference, vol. 1: Probability, Springer Texts in Statistics, the Netherlands, 1985.

Kubal, C., Haase, D., Meyer, V., and Scheuer, S.: Integrated urban flood risk assessment – adapting a multicriteria approach to a city, Nat. Hazards Earth Syst. Sci., 9, 1881–1895, doi:10.5194/nhess-9-1881-2009, 2009.

Landis, W. G. (Ed.): Regional Scale Ecological Risk Assessment. Using the Relative Risk Model, CRC Press, Boca Raton, FL, USA, 2005.

Landis, W. G. and Wiegers, J. A.: Design considerations and a suggested approach for regional and comparative ecological risk assessment, Hum. Ecol. Risk Assess., 3, 287–297, 1997.

Mazzorana, B., Hübl, J., and Fuchs, S.: Improving risk assessment by defining consistent and reliable system scenarios, Nat. Hazards Earth Syst. Sci., 9, 145–159, doi:10.5194/nhess-9-145-2009, 2009.

Mazzorana, B., Levaggi, L., Keiler, M., and Fuchs, S.: Towards dynamics in flood risk assessment, Nat. Hazards Earth Syst. Sci., 12, 3571–3587, doi:10.5194/nhess-12-3571-2012, 2012.

Mebarki, A., Valencia, N., Salagnac, J. L., and Barroca, B.: Flood hazards and masonry constructions: a probabilistic framework for damage, risk and resilience at urban scale, Nat. Hazards Earth Syst. Sci., 12, 1799–1809, doi:10.5194/nhess-12-1799-2012, 2012.

Menne, B. and Murray, V.: Floods in the WHO European Region: Health Effects and Their Prevention, World Health Organization, Regional Office for Europe (WHO), edited by: Menne, B. and Murray, V., Copenhagen, Denmark, 2013.

Meyer, V., Scheuer, S., and Haase, D.: A multicriteria approach for flood risk mapping exemplified at the Mulde river, Germany, Nat. Hazards, 48, 17–39, 2009

Mitchell, J. K.: European River Floods in a Changing World, Risk Anal., 23, 567–574, 2003.

Montanari, A., Young, G., Savenije, H. H. G., Hughes, D., Wagener, T., Ren, L. L., Koutsoyiannis, D., Cudennec, C., Toth, E., Grimaldi, S., Bloschl, G., Sivapalan, M., Beven, K., Gupta, H., Hipsey, M., Schaefli, B., Arheimer, B., Boegh, E., Schymanski, S. J., Di Baldassarre, G., Yu, B., Hubert, P., Huang, Y., Schumann, A., Post, D. A., Srinivasan, V., Harman, C., Thompson, S., Rogger, M., Viglione, A., McMillan, H., Characklis, G., Pang, Z., and Belyaev, V.: "Panta Rhei – Everything Flows": change in hydrology and society – the IAHS scientific decade 2013–2022, Hydrolog. Sci. J., 58, 1256–1275, 2013.

Nedvědová, K. and Pergl, R.: Cultural heritage and flood, CESB 2013 PRAGUE – Central Europe Towards Sustainable Building 2013: Sustainable Building and Refurbishment for Next Generations, Prague, Czech Republic, 2013.

Pappenberger, F., Stephens, E., Thielen, J., Salamon, P., Demeritt, D., van Andel, S. J., Wetterhall, F., and Alfieri, L.: Visualising probabilistic flood forecast information: expert preferences and perceptions of best practice in uncertainty communication, Hydrol. Process., 27, 132–146, 2013.

Pasini, S., Torresan, S., Rizzi, J., Zabeo, A., Critto, A., and Marcomini, A.: Climate change impact assessment in Veneto and Friuli Plain groundwater. Part II: A spatially resolved regional risk assessment. Sci. Total Environ., 440, 219–235, 2012.

Penning-Rowsell, E., Floyd, P., Ramsbottom, D., and Surendran, S.: Estimating injury and loss of life in floods: a deterministic framework, Nat. Hazards, 36, 43–64, 2005.

Preston, B. L., Smith, T. F., Brooke, C., Gorddard, R., Measham, T. G., Withycombe, G., Mcinnes, K., Abbs, D., Beveridge, B., and Morrison, C.: Mapping Climate Change Vulnerability in the Sydney Coastal Councils Group, prepared for the Sydney Coastal Councils Group and the Commonwealth Department of Climate Change by the CSIRO Climate Adaptation Flagship, Canberra, 2008.

Ronco, P., Bullo, M., Torresan, S., Critto, A., Olschewski, R., Zappa, M., and Marcomini, A.: The KULTURisk Regional Risk Assessment methodology for water-related natural hazards – Part 2: Application to the Zurich case study, Hydrol. Earth Syst. Sci. Discuss., 11, 7875–7933, doi:10.5194/hessd-11-7875-2014, 2014.

Rotach, M. W., Arpagaus, M., Dorninger, M., Hegg, C., Montani, A., and Ranzi, R.: Uncertainty propagation for flood forecasting in the Alps: different views and impacts from MAP D-PHASE, Nat. Hazards Earth Syst. Sci., 12, 2439–2448, doi:10.5194/nhess-12-2439-2012, 2012.

Scholz, R. and Tietje, O.: Formative scenario analysis, in: Embedded Case Study Methods, edited by: Scholz, R. and Tienje, O., Sage, Thousand Oaks, 79–116, 2002.

Schwarz, J. and Maiwald, H.: Damage and loss prediction model based on the vulnerability of building types, 4th International Symposium on Flood Defence: Managing Flood Risk, Reliability and Vulnerability, Toronto, Ontario, Canada, 6–8 May 2008, 74-1 to 74-9, 2008.

Torresan, S., Critto, A., Rizzi, J., and Marcomini, A.: Assessment of coastal vulnerability to climate change hazards at the regional scale: the case study of the North Adriatic Sea, Nat. Hazards Earth Syst. Sci., 12, 2347–2368, doi:10.5194/nhess-12-2347-2012, 2012.

Totschnig, R. and Fuchs, S.: Mountain torrents: quantifying vulnerability and assessing uncertainties, Eng. Geol., 155, 31–44, 2013.

UNESCO: Convention Concerning the Protection of the World Cultural and Natural Heritage, Adopted by the General Conference at its Seventeenth Session, Paris, 16 November, 1972.

WMO, World Meteorological Organization: Integrated Flood Management as an Adaptation Tool for Climate Change: Case Studies, APFM Technical Document No. 15, Flood Management Tools Series, Associated Programme on Flood Management, Geneva, 2011.

Yahaya, S., Ahmad, N., and Abdalla, R. F, Multicriteria analysis for flood vulnerable areas in Hadejia-Jama'are River basin, Nigeria, Eur. J. Sci. Res., 42, 71–83, 2010.

Yosie, T. F. and Herbst, T. D.: Using Stakeholder Processes in Environmental Decision making. An Evaluation of Lessons Learned, Key Issues, and Future Challenges, American Industrial Health Council, Ruder Finn, Washington, 1998.

Zabeo, A., Pizzol, L., Agostini, P., Critto, A., Giove, S., and Marcomini, A.: Regional risk assessment for contaminated sites, Part 1: Vulnerability assessment by multicriteria decision analysis, Environ. Int., 37, 1295–1306, 2011.

Zald, A. E., Summer, S., and Wade, T.: A to Z GIS: An Illustrated Dictionary of Geographic Information Systems, Information Bulletin, 38, 118 pp., 2006.

Table 1. Identification of the building-related risk classes according to different hazard thresholds for water depth (d) and water velocity (v), as proposed by Clausen and Clark (1990).

Flood hazard threshold	Building-related risk classes (R_3)	Definition
$v \leq 2$ or $v \cdot d \leq 3$	Inundation	Damage similar to that caused by a natural low-velocity river flood. No immediate structural damage.
$v > 2$ and $3 < v \cdot d \leq 7$	Partial damage	Moderate structural damage, i.e. windows and doors knocked out. Little damage to the major structural elements of the building.
otherwise	Total destruction	Total structural collapse or major damage to the structure necessitating demolition and rebuilding.

Table 2. Physical/environmental risk classes and normalized scores for buildings.

Classes	Normalized scores
Not inundated	0
Inundation	0.2
Partial damage	0.6
Total destruction	1

Table 3. Thresholds for the flood hazard metrics for different agricultural typologies in the spring, summer and autumn seasons (adapted from: Citeau, 2003).

Agricultural typologies	Maximum water depth [m]	Maximum water velocity [$\mathrm{m\,s^{-1}}$]
Vegetables	–	0.25
Vineyards	0.5	0.25
Fruit trees and olive groves	1	0.5

Table 4. Risk classes and normalized scores for the agriculture receptor.

Risk classes	Flood hazard thresholds	Normalized scores
Not inundated	No flood	0
Inundated	Flood metrics values are below the thresholds	0.6
Destructed	Flood metrics values are over the thresholds	1

Table 5. Qualitative evaluations supporting the expert in the assignation of relative scores to susceptibility and risk classes.

Linguistic evaluation	Score
Most important class	1
Weakly less important class	0.8
Rather less important class	0.6
Strongly less important class	0.4
Less important class	0.2
No susceptibility	0

Table 6. Physical/environmental risk classes and normalized scores for natural and semi-natural systems.

Classes	Normalized scores
Not inundated	0
Low	0.2
Medium	0.6
High	1

Table 7. Summary of the indicators and data sources used to characterize the three steps of analysis during the application of the physical/environmental Regional Risk Assessment methodology at the meso-scale, for the selected receptors (P: People, B: Buildings, I: Infrastructures, A: Agriculture, NS: Natural and Semi-Natural Systems, CH: Cultural Heritage).

Steps of the physical/ environmental RRA	Indicators/metrics	Data sources	Receptors
Hazard	Water depth	Flood modelling	P – B – A
	Water velocity	Flood modelling	P – B – A
	Flood extension	Flood modelling and mapping	I – A – NS – CH
	Debris Factor	land cover map	P
Exposure	Presence of people in residential areas	Census data, land cover/land use map	P
	Presence of buildings	land cover/land use map	B
	Presence of infrastructures	Road and railway atlas	I
	Presence of agricultural typologies	land cover/land use map	A
	Natural and semi-natural systems	land cover/land use map, protected area map	NS
	Presence of cultural heritages	Regional technical map, UNESCO cultural heritage map	CH
Susceptibility	People over 75 years and infirm/ disable/long term sick	Census data	P
	Vegetation cover	land cover/land use map	NS
	Slope	Digital Elevation Model (DEM)	NS
	Soil type	Geomorphologic/soil map	NS
	Wetland extension	land cover/land use map	NS

Table 8. Risk classes score definition used to classify the total risk index (GIS Equal Interval classification).

Risk Classes	Score
Not at risk	0
Very low	0–0.2
Low	0.2–0.4
Medium	0.4–0.6
High	0.6–0.8
Very high	0.8–1

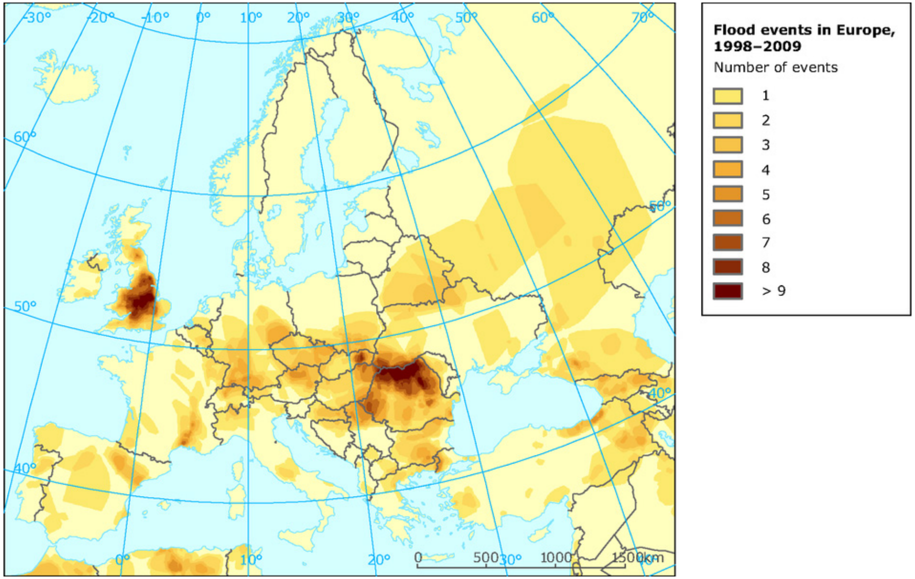

Figure 1. Occurrence of major floods in Europe (1998–2009; source: http://www.eea.europa.eu/legal/copyright). Copyright holder: European Environment Agency (EEA).

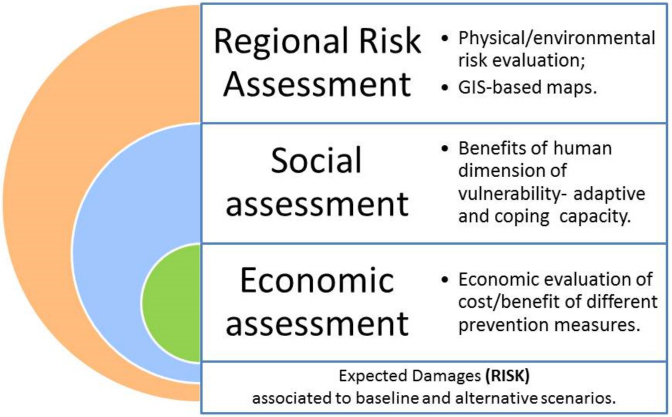

Figure 2. Tiers of analysis for the implementation of the KULTURisk methodology to estimate risk levels.

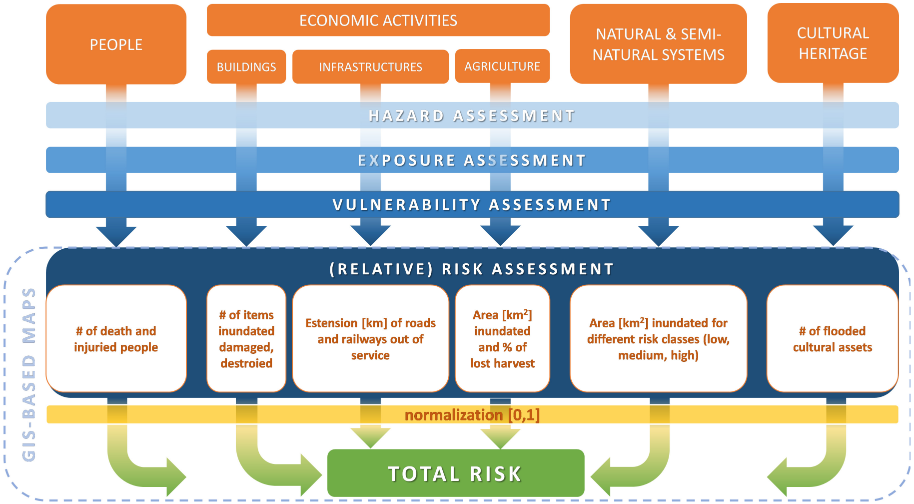

Figure 3. Physical/environmental KR-RRA, receptors, steps and outputs.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◀| |▶

◀ ▶

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

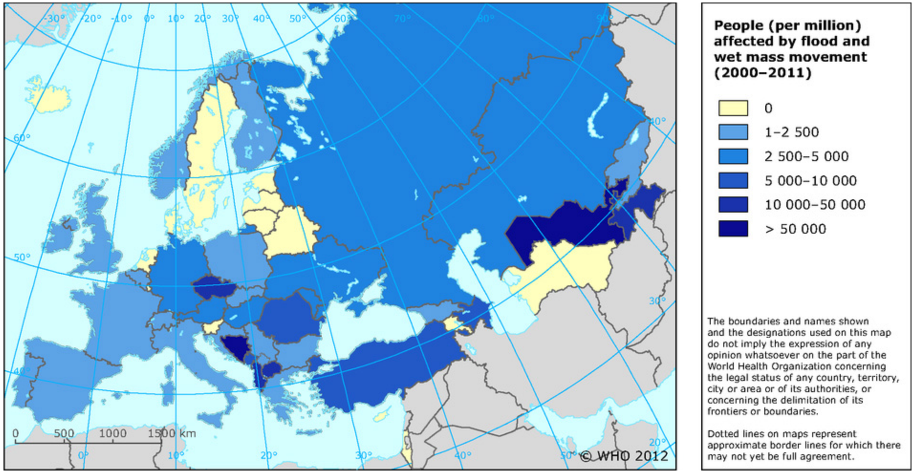

Figure 4. People affected by flooding in Europe from 2000 to 2011, per million population (WHO European Region; source: http://www.eea.europa.eu/legal/copyright). Copyright holder: World Health Organization Regional Office for Europe (WHO/Europe).

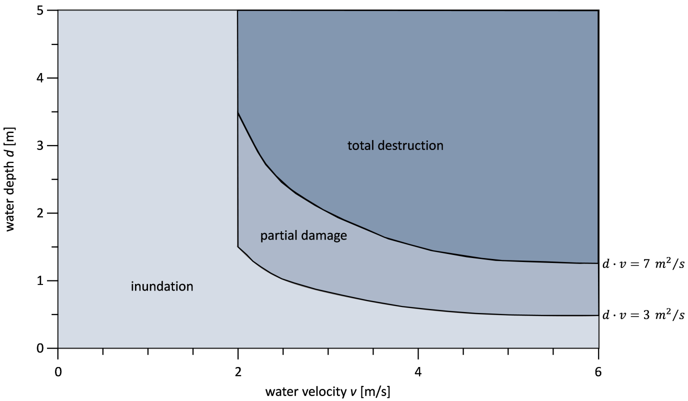

Figure 5. Identification of risk classes for different products of flow velocity and depth for buildings (from Clausen and Clark, 1990).