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River basin planning: from qualitative to quantitative flood risk assessment. The case of Abruzzo Region (central Italy)

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Abstract

Flood risk assessments are becoming an essential tool for a rational decision-making in river basin planning throughout Europe. In order to comply with the prescriptions of the Floods Directive, quantitative approaches, based on the estimation of the expected annual damage as a risk indicator, should increasingly be used for flood risk mapping in addition to the traditional qualitative methods. In this paper a comparative application of the two methodologies to the river basins of the Abruzzo Region (central Italy) was performed for evaluating their strengths and weaknesses. The analysis was limited to direct damage estimation. The results showed that qualitative mapping could not be considered a fully effective tool for the identification of appropriate flood risk management strategies due to its limits in representing the real flood risk scenarios, mainly related to the use of a coarse hazard classification. Therefore, if it could be used at the basin scale for a preliminary identification of high risk areas, it should be integrated with a more analytical assessment of the expected losses with quantitative models. However, a sensitivity analysis on the quantitative methodology showed that the large uncertainties inherent in damage modelling (with difference factors ranging from 2 to 10) may hinder the reliability of the estimates, with possible repercussions on the results of economic appraisals. Two case studies on the implementation of flood risk reduction measures confirmed that damage model uncertainty had huge influence on the results of cost-benefit analyses, with net present values switching from negative to positive according to the selection of the damage functions and the economic values of the exposed assets.

Keywords
Flood risk; mapping; hazard; flood damage; uncertainty; cost-benefit analysis

1. Introduction

Flooding is one of the most damaging from natural hazards, occurring increasingly during the last decades, due to population growth and accumulation of assets in floodplain areas (Barredo 2009; Bouwer et al. 2010; Lugeri et al. 2010; Barredo et al. 2012). Given this scenario, it is necessary to continuously improve the knowledge of the phenomena and methods for risk assessment, in order to cope with the problem in the most effective manner.

In particular, methods based on risk analysis are receiving increasing attention in river basin planning, overcoming the traditional approach based on hazard control (Sayers et al. 2002; Plate 2007; Merz et al. 2010): level of protection is no longer determined only by established safety thresholds, but also includes broader considerations involving the potential negative consequences of floods.

This new approach has been translated into the European Floods Risk Directive 2007/60/EC (European Commission 2007), which aims to reduce "the adverse consequences of flooding for human health, environment, cultural heritage and economic activity". One of the major tasks European member states must carry out to comply with the Directive is to prepare flood risk management plans (FRMP) focused on prevention, protection and preparedness. In this context, flood hazard and risk maps play a fundamental role for developing rational risk management strategies. Even though they are based on a common conceptual framework, a wide variety of methods exists to create these maps, especially regarding flood risk, due to its broad definition and different types of indicators (De Moel et al. 2009).

In fact, risk is generally defined as a combination of hazard and its potential consequences (Helm 1996; Crichton 1999; Gouldby and Samuels 2005; Kron 2005; Lugeri et al. 2010). In addition, a more analytical measure for flood risk can be expressed by the expected annual damage (EAD) (Merz et al. 2009), defined as the probability of a certain flood damage within a given time period, as follows:

$$R = EAD = \int_{h_0}^{\infty} f(h) \cdot D(h)dh \quad (1)$$

where $D(h)$ is the damage caused by inundation depth h (related to a certain return period flood); $f(h)$ is the probability density function of inundation depth h; and h_0 is the threshold water level above which flood damage occurs.

According to these definitions, the procedure for risk assessment consists essentially of the following phases:

• Hazard assessment, aimed at analysing the hydrological and hydraulic characteristics of the river basin; and

• Assessment of potential damage as a function of exposure and vulnerability in flood prone areas.

Each step can be conducted following different approaches and at different levels of detail. Consequently, the resulting information can range from a qualitative one, in which flood risk is expressed by a combination of hazard and potential damage classes, to a quantitative, more analytical, micro or meso scale approach, in which risk is expressed in monetary terms based on (1). However, considering that, according to Art. 7 of the Directive 2007/60/EC, FRMP have to include measures for flood risk reduction, taking also into account "relevant aspects such as costs and benefits", it is evident that only qualitative risk assessments, commonly used in Italy and Europe for river basin planning (Ministero dell'Ambiente 2013; De Moel et al. 2009), are not alone sufficient to comply with these prescriptions and that more sophisticated quantitative methods should be adopted.

Given this framework, the aim of the present paper is twofold. Firstly, it compares and analyses the different outcomes deriving from using quantitative methodologies and the usual qualitative ones for flood risk assessment by applying them for the river basins of the Abruzzo Region, in central Italy (Figure 1). Secondly, it investigates the implications of modelling uncertainties in quantitative flood damage models for risk management decisions as cost-benefit analyses of flood mitigation measures.

2. Methods and materials

2.1 Hazard assessment

Flood hazard can be determined using methods of different complexity (Büchele et al. 2006), depending on the availability of data, resources and time. Despite the variety, the conceptual basis is quite general and consists of a hydrological and a hydraulic phase. The first is related to the determination of flow rates for different return periods through statistical analysis, regionalisation procedures and rainfall-runoff models, while the second is aimed at determining the hydraulic characteristics of flood events, i.e. inundation extent, water depth and velocity spatial distributions.

Several approaches based on different simplifications have been developed during the last decades for simulating floods (Horrit and Bates 2001, 2002; Büchele et al. 2006; Woodhead et al. 2007; Cook and Merwade, 2009; Di Baldassarre et al. 2009). The simplest models are based on one-dimensional (1D) approaches, that describe the river channel and floodplains as a series of discrete cross-sections perpendicular to the flow direction. Given the advances in data availability, numerical methods and computational power, two-dimensional (2D) models have increasingly been applied to overcome the limitations of 1D schemes in calculating water propagation in the floodplains. However, the main drawback is related to their high requirements for data and computational time. For this reason, coupled 1D/2D models represent nowadays a good compromise for simulating floods for river basin planning purposes due to their flexible schematisation options, time for model development and use, accuracy and numerical robustness (Stelling and Verwey 2006; Apel et al. 2009).

In this study, hazard assessment for the 17 river basins of the Abruzzo Region (Figure 1) was performed using a 1D/2D model with a spatial resolution variable between 10 and 40 m (Regione Abruzzo 2014). The input hydrographs were determined by using the regionalisation procedure VAPI proposed by the CNR-GNDI (2001) for assessing river flows in Italy. The final output was a spatial representation of the results concerning different inundation scenarios. An example is given in Figure 2, in which hazard can be directly expressed by highlighting local water depths occurring on the ground level, in the form of square mesh grids as resulting from the 1D/2D model (Figure 2a), or processed in terms of "flood hazard maps" (Figure 2b), through zoning water levels and velocities occurring for different return period floods. In particular, the Flood Risk Management Plan in force for the Abruzzo Region (Regione Abruzzo 2014) was based on the definition of four hazard zones, distinguished as follows:

- “Very high hazard zone”: characterised by water depths greater than 1 m and flow velocities greater than 1 m/s for the 50 years return period flood;
- “High hazard zone”: characterised by water depths between 0.50 and 1 m for the 50 years return period flood and water depths greater than 1 m and flow velocities greater than 1 m/s for the 100 years return period flood;
- “Moderate hazard zone”: characterised by water depths greater than 0 m for the 100 years return period flood; and
- “Low hazard zone”: characterised by water depths greater than 0 m for the 200 years return period flood.

2.2 Flood damage and risk assessment

It is clear that the type of representation of the hazard component has a direct influence on the subsequent determination of risk. In fact, hazard zoning can be associated with a qualitative procedure for damage and risk assessment, while the use of local and accurate information for the different inundation scenarios, as in Figure 2a, is suitable for a more analytical calculation of risk on a quantitative basis, for example in economic terms by means of equation (1).

2.2.1 Qualitative damage and risk assessment

The qualitative assessment of potential damage was essentially based on the identification and localisation of the various land-use classes in flood prone areas. Therefore, the basic information was derived from land-use maps (Corine Land Cover map, regional land-use map), regional technical map (scale of 1: 5000), orthophotos and regional/local planning regulations.

In a second step, direct surveys increased the spatial definition of the exposed assets up to the size of individual significant settlements, which may not be deducible from the cartographic documentation, such as public and/or strategic facilities and minor infrastructures.

The graphic result of these operations was represented by the "Map of the exposed assets" (Figure 3 a), in which the elements at risk could be then classified into: urban areas (high/medium/low density urban areas, areas for public and private services, recreational areas and sports facilities, green urban areas, industrial and commercial areas, highways, railways, airports, roadways); pipeline networks and technological systems (network infrastructures, mining areas, dumpsites); agricultural areas (arable and permanent crops); vegetated areas (natural vegetation and wooded areas); protected areas (parks and reserves); environmental, historical and archaeological sites.

These elements were then classified into zones of different potential damage, based on their intrinsic exposure (Figure 3c):

- "Very high potential damage": including high density urban areas, industrial and commercial sites and primary infrastructure systems, where floods can cause loss of human lives and significant economic damages;
- "High potential damage": including lower density urban areas and secondary infrastructure systems;
- "Moderate potential damage": including public green areas and small production activities, mainly related to the agricultural sector (permanent crops);
- "Low potential damage": including areas that enable the free flow of the floods, without causing major damages, as arable or fallow lands and vegetated areas.

Flood hazard and potential damage maps were finally combined by means of a risk matrix to obtain the flood risk map (Figure 3d). Flood prone areas were classified into four risk areas, as follows:

- "Very high risk zone (R_4)": with possible human losses and/or injuries, serious damage to buildings, infrastructures and socio-economic assets;
- "High risk zone (R_3)": with possible problems for people's safety, functional damage to buildings, infrastructures and socio-economic assets, resulting in unusability and business interruption;

- "Moderate risk zone (R_2)": with possible minor damages to buildings, infrastructures and socio-economic assets that do not affect people's safety and building usability; and
- "Low risk zone (R_1)": with possible marginal damages.

2.2.2 Quantitative damage and risk assessment

The methodology for quantitative flood risk assessment was based on equation (1), i.e. on using the expected annual damage (EAD) as a risk indicator. The negative consequences of the floods are usually classified in different categories, such as: direct damage to residential buildings and inventory, industry, agriculture and infrastructures, indirect losses as a result of business interruption of economic activities, loss of human lives, environmental damages, etc. (Jonkman et al. 2008). Even though intangible and indirect damages can account for a large share in the total flood impact (Penning-Rowsell et al. 2010), this study included only the assessment of direct tangible losses.

Various tools exist for direct damage modelling for different scales and sectors (Messner et al. 2007; Merz et al. 2010; Meyer et al. 2013) and the use of damage functions is currently recognised as the standard method for assessing the vulnerability of exposed elements. These curves are developed based on ex-post damage data (empirical functions) or on expert judgment in which damages are estimated via what-if analyses (synthetic functions) (Merz et al. 2010). They relate hazard parameters (usually water depth) to the expected damage directly in monetary terms (absolute damage curves) or as a percentage of the maximum asset value (relative damage curves) (Smith 1994; Dutta et al. 2003; Messner et al. 2007; Kreibich and Thieken, 2008; Penning-Rowsell et al. 2010; Dottori et al. 2016).

In this paper, a raster based meso-scale approach was applied to estimate direct losses. The conceptual process is summarised in the scheme shown in Figure 4. Square mesh grids providing local flood depths characterizing the inundation scenarios for different return periods, as shown in the hazard assessment section, were supplied as input data (Figure 4a). With the use of relative damage functions, these rasters were then converted in new ones bringing information on the damage ratio caused by the flood. Due to the lack of local curves for Italy, different sets of damage functions developed by the JRC (HKV Consultants 2007) for other European countries (Belgium, Czech Republic, Germany, The Netherlands, Norway, Switzerland and UK) were transferred to this study (Figure 4b). Flood losses (Figure 4c) were then quantified by multiplying the damage ratio by site-specific asset values per grid cell (Figure 4e), attributed based on land-use characteristics (Figure 4d). For example, for urban areas, these economic values were assigned based on the identified classes of the "Map of the exposed assets" and local mean market values (source: Agenzia delle Entrate, Italian Revenue Agency), adjusted for considering the actual building density in each land-use unit (Scorzini and Frank 2015). Inventory values were estimated to be equal to 50% of building value, according to previous studies (USACE 1992; Vanneuville et al. 2006; De Moel et al. 2014). Agricultural land values were calculated based on the type of cultivated crops, combined with regional data relating to the production per hectare (source: Agricultural census 2010, ISTAT, Italian National Statistics Institute) and to the prices at the source for the various products (source: ISMEA database, Italian Institute for the Agricultural and Food Market). Among the most significant land-use classes, this process resulted in average values for urban fabric areas ranging from about 300 (for industrial areas) to 360 €/m^2 (for residential areas), while values for permanent and arable land were equal to 1.5 and 0.35 €/m^2 respectively.

Once flood losses had been calculated for *N* flood events of different exceedance probabilities, the EAD was determined for each cell by discretising equation (1) as follows:

$$EAD = \sum_{j=1}^{N} \Delta P_j \cdot D_j \tag{2}$$

where ΔP_j and D_j are respectively the exceedance probability increment and average damage of two events with exceedance probabilities (P_j) and (P_{j+1}).

Therefore, by combining expected losses and exceedance probabilities of the flooding scenarios, it was possible to obtain information not only on the localisation of risk areas, but also on risk quantification in monetary terms (Figure 4f).

In this way, quantitative methodologies can be useful tools for decision-making in the context of cost-benefit analyses (CBA) of flood mitigation measures (Molinari et al. 2013), i.e. in evaluating whether related costs are adequate to flood damage reduction, while the "benefit" is determined by the difference between current expected annual losses and residual ones that may continue to occur even after the implementation of the interventions. However, uncertainties both in the hydraulic and damage components (Apel et al. 2004; Merz et al. 2004; Thieken et al. 2005; Apel et al. 2009; Freni et al. 2010; Bubeck et al. 2011; De Moel and Aerts 2011; Jongman et al. 2012; Vorogushyn et al. 2012; Scorzini and Frank 2015) can affect the results of damage calculations.

Two flood mitigation projects (Regione Abruzzo, Commissario Delegato Aterno-Pescara 2009; 2011) in the Abruzzo Region were then considered as case studies for quantifying the weight of uncertainties in damage assessments and the possible consequent effects on the results of CBA. In particular, both projects consisted of systems of detention basins, as follows:

- Case 1: the system was composed of three basins, covering a total area of about 76 hectares, resulting in an available storage volume of about $1.95 \cdot 10^6$ m^3. The total estimated cost for the intervention was equal to 50 million Euro (Regione Abruzzo, Commissario Delegato Aterno-Pescara, 2009); and

- Case 2: the system was composed of five basins, covering a total area of about 120 ha, resulting in an available storage volume of about $6.25 \cdot 10^6$ m^3. The total estimated cost for the intervention was equal to 54 million Euro (Regione Abruzzo, Commissario Delegato Aterno-Pescara, 2011).

3. Results and discussion

3.1 Qualitative and quantitative methodologies

Flood risk assessment practises implemented in the River Basin Authorities of Italy are rather diverse, both in hazard and damage potential definition (Ministero dell'Ambiente 2013). The guidelines released by the Italian Ministry for the Environment (Ministero dell'Ambiente 2013) for introducing a common framework for flood risk assessment throughout the Country have not solved the present critical point regarding the only qualitative nature of flood risk maps.

The two approaches described above have, therefore, been applied to the 17 river basins of the Abruzzo Region to highlight the possible implications on flood risk management decisions of using simple qualitative methodologies. Figure 5a summarises the results of the first approach, showing the contribution of each basin in terms of "very high" (R_3) and "high risk areas" (R_4) to the total exposed R_3 and R_4 area in the Region, whereas the pie chart indicates the percentage of flood risk area (from R_1 to R_4) for each basin to the total flood risk area in the Region. Figure 5b provides the contributions of individual basins in terms of EAD, averaged over the results of the application of the different JRC curves available for other European countries. Based on the comparison of Figures 5a and 5b, it is evident that the use of a unique methodology could lead to incorrect decisions on flood risk management, due to a misleading representation of the real risk scenarios. For example, according to the qualitative approach, the Vomano River Basin seemed to be, by far, the most exposed one, with a regional R_3-R_4 share greater than 40%. However, in economic terms, its EAD share (≈ 22%) was lower than that resulting for the Pescara River Basin (≈ 27%), which had a similar extension of the total (from R_1 to R_4) risk area (≈ 10% of the total flood risk area in the Region), but a significant lower share of qualitative R_3-R_4 areas (≈ 22%). Given the very low variability of the economic values attributed to the different land-use classes in the basins, the main reason for these differences can be found in the hazard representation of the two methodologies: according to the quantitative one, with reference to the scheme of Figure 4, local water depths were converted by means of the damage functions into relative damage, which constituted the multiplying factor of the asset values for calculating expected losses. Figure 5c shows the average flood depths resulting from the 1D/2D hydraulic modelling used in the quantitative approach, for the different basins under the three considered inundation scenarios. The average water levels registered for the Pescara River Basin were around 2.5 m, which doubled the ones of the Vomano River (≈ 1.2 m). If considering the shape of the damage curves (Figure 4b), these different hazard characteristics mean different relative damages: for instance, the two average values of 2.5 and 1.2 m are translated into a relative damage (averaged over the available residential and industrial/commercial JRC curves for European countries) of 0.55 and 0.38 respectively, with a direct influence on the expected absolute damage for a single scenario and consequently on the EAD.

On the opposite side, it is evident that in the qualitative methodology part of this detailed hydraulic information is lost, hidden in the coarse definition of the hazard classes. For example, according to the actual, qualitative, flood risk plan for the Abruzzo Region (Regione Abruzzo 2014), an area is classified as "very high hazard" for water levels greater than 1 m (and flow velocities greater than 1 m/s) for the 50 years return period flood, without any further other differentiation, when instead it is clear that, e.g., an inundation depth of 1.1 m has a very different damaging effect compared to that produced by a 3 m depth, as correctly reflected in the shape of the damage functions.

Analogous considerations can also be carried out for the other basins. The Aterno, which was characterised by the largest extension of total risk areas (≈ 21%) and about an 18% share of R_3-R_4 areas, had a significantly low EAD share (≈ 15%) compared to Pescara's. This was due, again, to its very shallow inundation depths, with an average value around 0.6 m. Similarly, the Foro River, from the outcomes of the qualitative approach, did not seem to be among the most exposed basins, but this result was confuted by its EAD, which was the fifth highest, together with Vibrata, Tordino and Fino-Tavo-Saline.

Damage potential classification played a negligible role in this comparative analysis, since exposure representation in the quantitative approach was strictly related to damage potential characteristics of the areas, i.e. the highest (lowest) economic values were attributed to "very high/high potential damage" ("moderate/low potential damage") areas. In addition, Figure 6, which displays the contribution of each basin to the total EAD calculated by applying the different curves, shows that also vulnerability modelling in the quantitative method, i.e. the choice of the JRC damage functions, had small influence on the results of the comparison between qualitative and quantitative approaches for ranking the most exposed basins within the region: indeed, although with some variability, particularly evident for Pescara and Vomano, the selection of a single damage function did not change the overall results discussed earlier in this section.

Based on these outcomes, it is possible to conclude that commonly used qualitative flood risk mapping could not be considered a fully effective tool for the identification of appropriate flood risk management strategies. In fact, if it can be useful in large-scale basin planning for the mere localisation of potentially high risk zones, on the other hand, the lack of information on any monetary estimation of the expected losses prevents the possibility of rational decision-making on investment prioritisation and optimisation of flood risk reduction measures.

3.2 Uncertainties in quantitative damage modelling and effects on flood risk management decisions

Based on the results of the previous section, methods providing an economic assessment of the consequences of floods should be preferred to purely qualitative ones for flood risk management. However, as underlined above, loss estimates are hindered by modelling uncertainties, that may undermine the reliability of the results.

For this reason, the procedure represented in Figure 4 was applied for damage calculation in the two case studies identified in Section 2.2.2 for analysing the uncertainties characterising quantitative approaches and their consequent effects on CBA results. Coupled 1D/2D hydraulic modelling was performed for 50-, 100- and 200-year flood events, with and without the implementation of the mitigation measures (i.e. "With project" and "Baseline" scenarios). Table 1 reports a summary of mean water depths and inundated areas per affected land-use in both the cases. Inundation scenarios were supplied as input data to the JRC damage functions for different European countries, with the aim of analysing the influence of damage model selection on the variability of loss estimates in cases in which transferring existing curves from one country to another is necessary because of the unavailability of local models and/or of the impossibility to validate them (Scorzini and Frank 2015). In fact, damage curves should be considered site-specific, strictly valid for the context for which they have been developed. However a transfer operation is especially required in countries where no specific damage models are available, adding extra uncertainty in the modelling process.

Table 2 and 3 show resulting absolute losses, expressed in millions of Euros, using the three baseline and "with project" scenarios for the two case studies. The difference factors between the models reported in the second part of the tables were calculated for each sector by dividing each loss value by the lowest estimate.

In both cases, the agricultural sector made a negligible contribution to the total expected losses, even though it constituted over 80% of the probable flooded areas, as opposed to the residential and industrial/commercial sectors, which were responsible for the bulk of the total damages.

The variation in loss estimates by using the different damage models was quite high. For the residential sector, similar results were found by using Belgium, Czech Republic, Germany and the Netherlands functions, with difference factors ranging from 1.10 to 1.90 for case 1 and from 1.1 to 1.60 for case 2; larger differences were observed for Norway, Switzerland and UK models, with minimum factors from about 2.5 to a maximum of 5.7. The industrial/commercial sector was

characterised by larger variability, with minimum factors of about 3-4 for the Netherlands and Germany curves and maximum exceeding 10 in case 1 and in the range of 7-9 in case 2 for the remaining curves. For agriculture, difference factors among the four available curves ranged from a minimum of 1.5 and 2.2, for the first and the second case respectively, to a maximum of 3.2.
These results were in accordance with other similar studies performed in Europe. For instance, De Moel et al. (2011) and Bubeck et al. (2011) showed that damage estimates calculated by means of Rhine Atlas (ICPR 2001), Damage Scanner (Klijn et al. 2007) and Flemish (Vanneuville et al. 2006) models can differ by a factor of up to 4. Scorzini and Frank (2015), in a validation analysis of some residential damage functions, including the JRC curves applied in this study, found maximum difference factors of about 15.
By analysing the difference factors in Tables 2 and 3, it is possible to note that in the "with project" scenarios, characterised by shallower inundation levels as an effect of the implementation of the detention basins, they were slightly lower than those of the baseline conditions, as a consequence of the shape of the damage functions and the relative differences among the models, which is more pronounced for shallow water depths (in the range 0÷1.5 m). This means that damage modelling uncertainty and consequent loss estimates calculated by means of different damage curves tends to be higher for inundated areas characterised by low water depths.
Furthermore, for comparing damage uncertainty to the one originating from the hydraulic component, the baseline 200-year return period floodings were gradually modified by adjusting water depths with five incremental steps of 15 cm, up to +75 cm. Absolute losses were then computed again for these modified inundation scenarios. For each damage model, the difference factors related to the hydraulic component were calculated by dividing the loss at the modified scenario h_{+i} (where i=15,30,45,60,75) by the value in the baseline 200-year return period condition. Table 4 shows that an adjustment in inundation depth of about 15 cm produced a variation in the estimates of a factor in the range 1.10-1.33 for case 1 and 1.01-1.13 for case 2, while a variation of 0.75 m was necessary to cause a factor up to 2. These results confirmed that damage modelling is the most important contributor to uncertainty in flood damage calculations (Apel et al. 2009; Freni et al. 2010; De Moel et al. 2011).
Based on the results of Tables 2 and 3, expected annual damages (with and without the implementation of the mitigation measures) were computed using the different models based on equation (2) to analyse the propagation of damage model uncertainty in the results of CBA. In addition to function uncertainty, also value uncertainty was considered in the analysis. This was achieved by increasing by 20% and 40% the default values associated with the exposed assets.

The net present value (NPV) was selected as an economic indicator for evaluating the cost-effectiveness of the measures. The NPV is defined as the sum of discounted benefits minus the sum of discounted costs over the lifetime of a project:

$$NPV = \sum_{t=0}^{T} B_t \cdot (1+i)^{-t} - \sum_{t=0}^{T} C_t \cdot (1+i)^{-t} \quad (3)$$

where i is the discount rate, B_t and C_t are benefits and costs at time t. A project is considered profitable if it has a positive NPV, otherwise it should be rejected.

In this case, B_t represented the expected annual damage reductions after the implementation of the detention basins ($EAD_{baseline}$-$EAD_{with\ project}$), while C_t included the total initial investment costs C_0 and the future maintenance costs over the lifetime of the measures, as estimated in the projects (Regione Abruzzo, Commissario Delegato Aterno-Pescara, 2009; 2011). Given the time value of money (i.e. money in the present is worth more than the same amount in the future), future cash flows have to be discounted by the discount rate i, determined as the expected return of other investment choices, like government bonds. Assuming a lifetime of the measures equal to 50 years and a discount rate of 3.5%, the NPV of the two projects was calculated using the different damage models and values of the exposed assets. The results are reported in Figure 7. The influence of damage functions on NPV is clear, with values ranging from negative to positive ones. In case 1, except for the UK curve, which tends to overestimate damages (Scorzini and Frank 2015), all the models gave negative NPVs, with Norway and Switzerland ones switching from negative to positive by increasing asset values. Based on the results of Figure 7, case 2 seemed to be a more cost-effective project, with clearly positive NPVs for the UK, Norway, Switzerland and Belgium curves. According to the Czech Republic model, the two mitigation measures had an almost equivalent economic convenience, independently of the asset values, as a consequence of the flat shape of the damage function (in particular for the industrial/commercial sector), which produced similar loss estimates despite different inundated areas and depths (Table 1).

This very large variability in the outcomes of the CBA suggests using multiple sets of curves, especially in cases in which there are no local and validated damage models, in order to gain a comprehensive knowledge about the possible uncertainty bounds of damage calculations and, consequently, of CBA results.

3.3 Final considerations on the use of qualitative and quantitative approaches for flood risk management

The comparative application of qualitative and quantitative methodologies to the river basins of the Abruzzo Region has pointed out the main criticalities associated with risk modelling and their possible consequences on flood risk management decisions. A summary of the lessons learnt from this case study is shown in Table 5, where the strengths and weaknesses of the two approaches are compared with respect to data requirements, model development and usability. The simplicity of the qualitative approach makes it appropriate for a preliminary large-scale recognition of high risk areas, but particular attention should be paid to hazard classification: indeed, this study has shown that a coarse hazard ranking could alter the representation of flood scenarios and, consequently, of flood risk (Section 3.1). From this point of view, the quantitative methodology seems to supply more reliable information also when transferring damage curves from other contexts (Figure 6). In addition, the main advantage of this approach is the possibility of measuring flood risk in economic terms, that enables its application for investment prioritisation and cost-benefit analyses. Nevertheless, model uncertainties, mainly arising from damage function selection and exposure assessment, may have huge influence on the outcomes of such analyses. Model validation studies, based on ex-post data, may help in improving the reliability of damage models. However, in the meantime, given the well-known paucity of such data (Merz et al. 2010), sensitivity analyses can be considered as a fundamental tool for an effective uncertainty communication (e.g. by means of tornado charts, as shown in Figure 7), since they allow to examine the implications of model assumptions and key input parameters on the overall results. From this perspective, at present, one of the main purposes of the application of quantitative methods for investment appraisal should be not to reveal “absolute results” in economic terms but to define priorities of intervention within a regional context (Figure 5b) or to determine better and worse options when comparing a range of possible solutions (Figure 7). However, the amount and detail of data required for model development and implementation could limit the practical use of quantitative approaches: for example, the spatial distribution of flow depth is not often available, especially for small river catchments.

Finally, the analysis performed in this work was limited to direct damage assessment, however both the methodologies can be embedded into a multi-criteria analysis (MCA) for evaluating also indirect/intangible consequences related to social and environmental aspects, as shown for example by Brouwer et al. (2004) and Kubal et al.(2009).

4. Conclusions

The paper has shown two methods for flood risk assessment: a qualitative one essentially based on the classification of hazard and potential damage, and a more analytical, quantitative approach, characterised by the estimation of the economic annual damage produced by different flood scenarios. Indirect and intangible damages were not included in the analysis. Due to the different complexity, amount and type of information required for their implementation, it is clear that the two methodologies should find a different but complementary use. The comparative application of the two approaches to the river basins of the Abruzzo Region has shown the limits of the qualitative flood risk mapping in representing the real risk scenarios, mainly due to a coarse hazard classification, which may lead to incorrect decisions in river basin planning. For this reason, the first one, applicable at the regional scale, can be seen as a tool for an expeditious identification of high risk areas, that should be integrated with quantitative modelling in order to perform a more in-depth assessment of the expected losses and to obtain useful information for investment prioritisation and optimisation of the flood risk reduction measures.

Nevertheless, the economic estimation of direct damages is characterised by large uncertainties, related to simplifying assumptions and lack of data for the development of reliable models. In addition, in countries where no damage models are available, a transfer operation of existing curves in literature, developed in other regions, is required for damage quantification. The choice of these curves can be questionable, since they feature significant differences in their shapes, resulting in large scatter of the computed losses. The results reported in the paper suggest that quantitative methodologies can supply useful information for a first identification of flood risk management strategies also when transferring damage models developed in other countries. However, while potential damage assessment was found to play a minor role on the results of the comparative analysis between qualitative and quantitative approaches for the ranking of the most exposed river basins within a region, the uncertainties inherent in quantitative damage modelling had huge influence when performing more detailed economic appraisals. Indeed, two case studies on the implementation of flood mitigation measures were considered to analyse the repercussions of modelling uncertainties on decision-making processes based on CBA. For this purpose, different sets of damage curves developed for some European countries were used, in combination with gradually adjusted inundation depths, in order to compare the uncertainties arising from damage and hazard modelling. The results of the sensitivity analysis indicated large uncertainties in loss estimates, with the main contribution related to the uncertainty in the damage component, with average difference factors ranging from 2 to 10, while the hydraulic component seemed to have a small contribution, as an increase in water depth of 0.75 m caused only a factor 1.5 variation (average value) in the estimated losses. This large variability due to damage model uncertainty had direct repercussions on the results of the CBA. In particular, the NPV, a commonly used economic indicator for project assessments, was found to be highly dependent on the selection of the damage functions and the economic values of the exposed assets. For instance, in the examined case studies, the application of different curves and values produced negative to positive NPVs, with evident repercussions on investment decisions.

The quality of damage models is thus of crucial importance in flood risk assessments. For this reason, further research efforts should be required, with validation analyses for existing methods and development of new ones, especially for those countries that do not have any established damage models. In absence of these, a comparison of alternative models is suggested, allowing the determination of a possible range in the estimates to inform stakeholders for rational decision-making.

References

Apel, H., Thieken, A., Merz, B. and Bloschl, G. (2004) Flood risk assessment and associated uncertainty. Nat. Hazards Earth Syst.Sci., **4**(2), 295-308.

Apel, H., Aronica, G.T., Kreibich, H. and Thieken, A. (2009) Flood risk analyses - how detailed do we need to be? Nat Hazards, **49**(1), 79–98.

Barredo, J.I. (2009) Normalised flood losses in Europe: 1970-2006. Nat. Hazards Earth Syst.Sci., **9**, 97-104.

Barredo, J.I., Saurì, D. and Llasat, M.C. (2012) Assessing trends in insured losses from floods in Spain 1971-2008. Nat. Hazards Earth Syst.Sci., **12**, 1723-1729.

Bouwer, L.M., Bubeck, P., and Aerts, J.C.J.H. (2010) Changes in future flood risk due to climate and development in a Dutch polder area. Global Environ. Chang., **20**, 463–471.

Brouwer, R. and Van Ek, R. (2004) Integrated ecological, economic and social impact assessment of alternative flood control policies in the Netherlands. Ecological Economics, **50**(1), 1-21.

Bubeck, P., de Moel, H, Bouwer, L.M. and Aerts, J.C.J.H. (2011) How reliable are projections of future flood damage? Nat. Hazards Earth Syst. Sci., **11**, 3293-3306.

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

CNR-GNDCI (2001) Progetto Speciale per la Valutazione delle Piene in Italia. National Report.

Cook, A. and Merwade, V. (2009) Effect of topographic data, geometric configuration and modeling approach on flood inundation mapping. J.Hydrol., **377**, 131-142.

Crichton, D. (1999) The risk triangle. In Natural Disaster Management, Ingleton, J., (Ed.), Tudor Rose, London, England.

De Moel, H., Van Halphen, J. and Aerts, J.C.J.H. (2009) Flood maps in Europe – methods, availability and use. Nat. Hazards Earth Syst. Sci., **9**, 289-301.

De Moel, H. and Aerts, J.C.J.H. (2011) Effect of uncertainty in land use, damage models and inundation depth on flood damage estimates. Nat. Hazards, **58**, 407–425.

De Moel, H., van Vliet, M. and Aerts, J.C.J.H. (2014) Evaluating the effect of flood damage-reducing measures: a case study of the unembanked area of Rotterdam, the Netherlands. Reg Environ Change, **14**, 895-908.

Di Baldassarre, G., Castellarin, A., Montanari, A. and Brath, A. (2009) Probability-weighted hazard maps for comparing different flood risk management strategies: a case study. Nat. Hazards, **50**(3), 479-496.

Dottori, F., Figueiredo, R., Martina, M.L.V., Molinari, D. and Scorzini, A.R. (2016) INSYDE: a synthetic, probabilistic flood damage model based on explicit cost analysis. Nat. Hazards Earth Syst. Sci., **16**, 2577-2591.

Dutta, D., Herath, S. and Musiakec, K. (2003) A mathematical model for flood loss estimation. J. Hydrol., **277**, 24–49.

European Commission (2007) EU Directive on the estimation and management of flood risks (EU/60/2007).

Freni, G., La Loggia, G. and Notaro, V. (2010) Uncertainty in urban flood damage assessment due to urban drainage modelling and depth-damage curve estimation. Water Sci. Technol., **61**, 2979–2993.

Gouldby, B. and Samuels, P. (2005) Language of Risk - Project Definitions. FloodSite Report T32-04-01.

Helm, P. (1996) Integrated risk management for natural and technological disasters. Tephra, **15**(1), 4-13.

Horrit, M.S. and Bates, P.D. (2001) Predicting floodplain inundation: raster-based modelling versus the finite-element approach. Hydrol. Process., **15**(5), 825-842.

Horrit, M.S. and Bates, P.D. (2002) Evaluation of 1D and 2D numerical models for predicting river flood inundation. J. Hydrol., 268, 87-99.

HKV Consultants (2007) Flood damage functions for EU member states. Final report for JRC – Institute for environment and sustainability.

ICPR (2001) Atlas of flood danger and potential damage due to extreme floods of the Rhine, International Commission for the Protection of the Rhine. Koblenz, Germany.

Jongman, B., Kreibich, H., Apel, H., Barredo, J.I., Bates, P.D., Feyen, L., Gericke, A., Neal, J., Aerts, J.C.J.H. and Ward, P.J. (2012) Comparative flood damage model assessment: towards a European approach. Nat. Hazards Earth Syst. Sci., **12**, 3733-3752.

Jonkman, S.N., Bockarjova, M., Kok, M. And Bernardini, P. (2008) Integrated hydrodynamic and economic modelling of flood damage in the Netherlands. Ecological Economics, **66**, 77-90.

Klijn, F., Baan, P., De Bruijn, K.M. and Kwadijk, J. (2007) Overstromingsrisico's in Nederland in een veranderend klimaat: verwachtingen, schattingen en berekeningen voor het project Nederland Later, WL Delft Hydraulics report Q4290.00.

Kron, W. (2005). Flood risk= hazard x values x vulnerability. Water International, **30**(1), 58-68.

Kubal, C., Haase, D., Meyer, V., and Scheuer, S. (2009). Integrated urban flood risk assessment– adapting a multicriteria approach to a city. Nat Hazards Earth Syst Sci., **9**(6), 1881-1895.

Lugeri, N., Kundezewicz, Z.W., Genovese, E., Hochrainer, S. and Radziejewski, M. (2010) River flood risk and adaption in Europe – assessment of the present status. Mitig. Adapt. Strateg. Glob. Change, **15**, 621-639.

Messner, F., Penning-Rowsell, E.C., Green, C., Meyer, V., Tunstall, S.M. and Van der Veen, A. (2007). Evaluating flood damages: guidance and recommendations on principles and practices. FLOODSite Report T09-06-01.

Merz, B., Kreibich, H., Thieken, A. and Schmidtke, R. (2004) Estimation uncertainty of direct monetary flood damage to buildings. Nat Hazards Earth Syst Sci., **4**(1), 153–163.

Merz, B., Elmer, F. and Thieken, A. (2009) Significance of "high probability/low damage" versus "low probability/high damage" flood events. Nat. Hazards Earth Syst. Sci., **9**, 1033-1046.

Merz, B., Kreibich, H., Schwarze, R., and Thieken, A. (2010) Assessment of economic flood damage. Nat. Hazards Earth Syst. Sci., **10**, 1697–1724.

Meyer, V., Becker, N., Markantonis, V., Schwarze, R., van den Bergh, J.C.J.M., Bouwer, L.M., Bubeck, P., Ciavola, P., Genovese, E., Green, C., Hallegatte, S., Kreibich, H., Lequeux, Q., Logar, I., Papyrakis, E., Pfurtscheller, C., Poussin, J., Przyluski, V., Thieken, A.H. and Viavattene, C. (2013) Assessing the costs of natural hazards – state of the art and knowledge gaps. Nat. Hazards Earth Syst. Sci., **13**, 1351–1373.

Ministero dell'Ambiente (2013) Indirizzi operativi per l'attuazione della Direttiva 2007/60/CE relativa alla valutazione e alla gestione dei rischi da alluvioni con riferimento alla predisposizione delle mappe della pericolosità e del rischio di alluvioni. Documento conclusivo del tavolo tecnico Stato-Regioni. 33 p.

Molinari, D., Ballio, F. and Menoni, S. (2013) Modelling the benefits of flood emergency management measures in reducing damages: a case study on Sondrio, Italy. Nat. Hazards Earth Syst. Sci., **13**, 1913–1927.

Penning-Rowsell, E., Viavattene, C., Pardoe, J., Chatterton, J., Parker, D. and Morris, J. (2010) The benefits of flood and coastal risk management: a handbook of assessment techniques. Flood Hazard Research Centre, Middlesex University, London, UK.

Plate, E.J. (2007) Flood risk management for setting priorities in decision making in: Extreme

Hydrological Events: New Concepts for Security, Vasiliev et al. (eds.), 21-44.

Regione Abruzzo, Commissario Delegato Aterno-Pescara (2009) Opere di laminazione delle piene del fiume Pescara. Progetto Definitivo.

Regione Abruzzo, Commissario Delegato Aterno-Pescara (2011) Progetto delle opere per la messa in sicurezza idraulica della città di L'Aquila. Progetto Definitivo.

Regione Abruzzo (2014) Piano Stralcio di Difesa dalle Alluvioni. Relazione generale e mappe di pericolosità e rischio da alluvione. Final report.

Sayers, P.B., Hall, J.W., Meadowcroft, I.C. (2007) Towards risk-based flood hazard management in the UK. Proceedings of ICE, Civil Engineering, **150**, 36-42.

Scorzini, A.R. and Frank, E. (2015) Flood damage curves: new insights from the 2010 flood in Veneto, Italy. Journal of Flood Risk Management (Early view) doi: 10.1111/jfr3.12163.

Smith, D.I. (1994) Flood damage estimation – A review of urban stage-damage curves and loss functions. Water SA, **20**(3), 231-238.

Stelling, G. S. and Verwey, A. (2006) Numerical flood simulation. Encyclopedia of Hydrological Sciences. 2:16.

Thieken, A.H., Muller, M., Kreibich, H. and Merz, B. (2005) Flood damage and influencing factors: new insights from the August 2002 flood in Germany. Water Resour.Res., **41**(12), W12430.

USACE (1992) Catalog of residential depth-damage functions used by the Army Corps of Engineers in flood damage estimations. IWR Report 92-R-3.

Vanneuville, W., Maddens, R., Collard, C., Bogaert, P., de Meyer, P. and Antrop, M. (2006) Impact op mens en economie t.g.v. overstromingen bekeken in het licht van wijzigende hydraulische condities, omgevingsfactoren en klimatologische omstandigheden. MIRA/2006/02, Universiteit Gent, Belgium.

Vorogushyn, S., Lindenschmidt, K.E., Kreibich, H., Apel, H and Merz, B. (2012) Analysis of a detention basin impact on dike failure probabilities and flood risk for a channel-dike-floodplain system along the river Elbe, Germany. J. Hydrol., **436-437**, 120-131.

Woodhead, S., Asselman, N., Zech, Y., Soares-Frazão, S., Bates, P. and Kortenhaus, A. (2007) Evaluation of inundation models - limits and capabilities of models. FLOODSite Report T08-07-01.

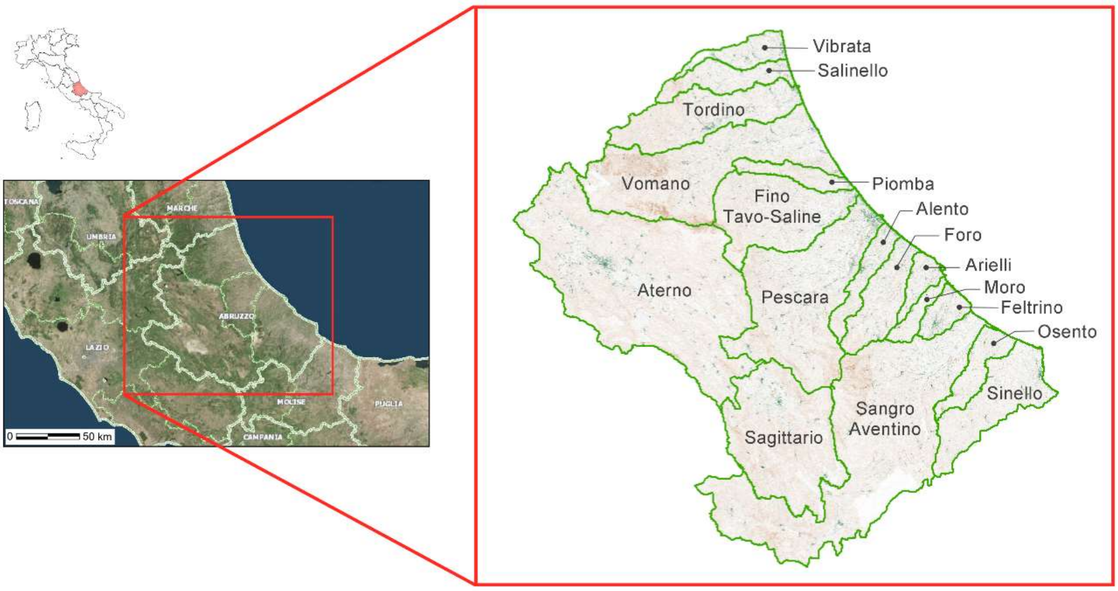

Fig. 1 Investigation area overview with the river basins of the Abruzzo Region

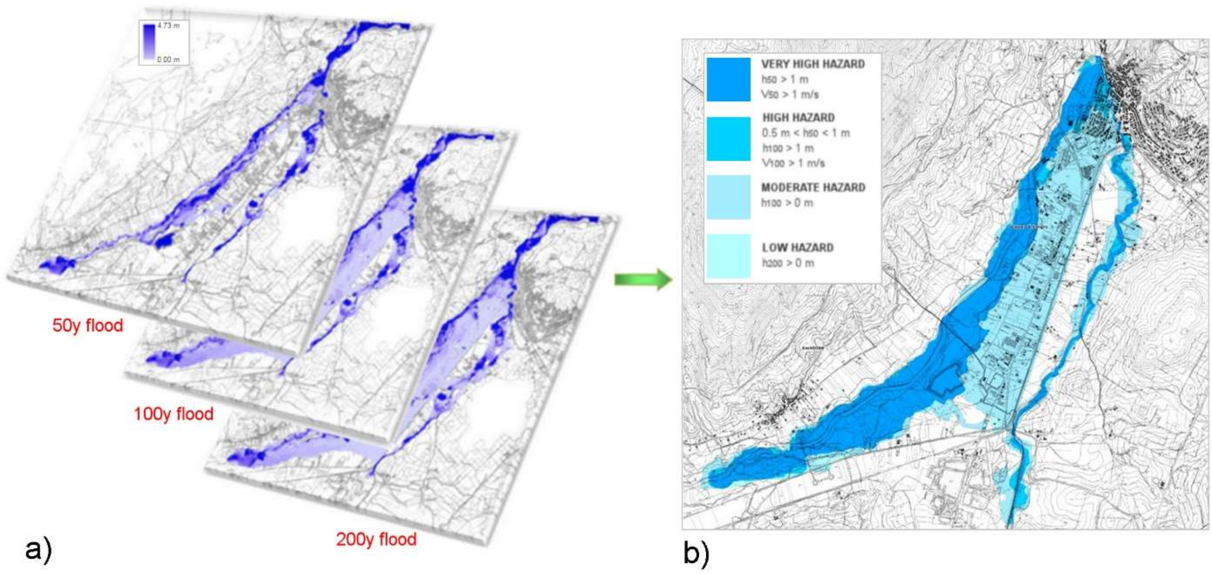

Fig. 2 Hazard assessment: a) Direct representation of local water depths in terms of square mesh grids for different flood scenarios; b) Example of a flood hazard map (adapted from Regione Abruzzo, 2014)

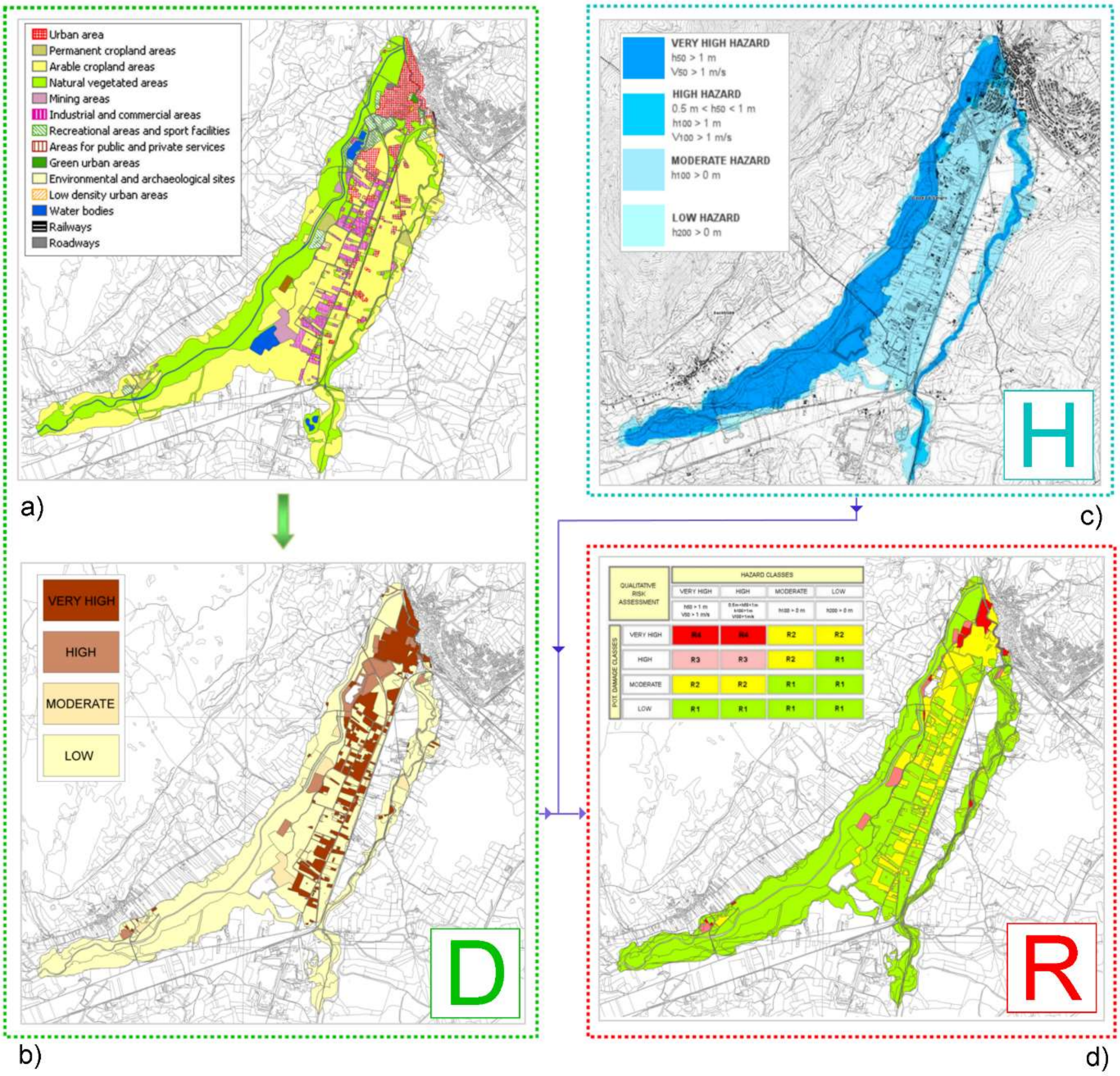

Fig. 3 Conceptual scheme for qualitative flood risk assessment: a) "Map of the exposed assets"; b) Potential damage map; c) Hazard map; d) Flood risk matrix and map (adapted from Regione Abruzzo, 2014)

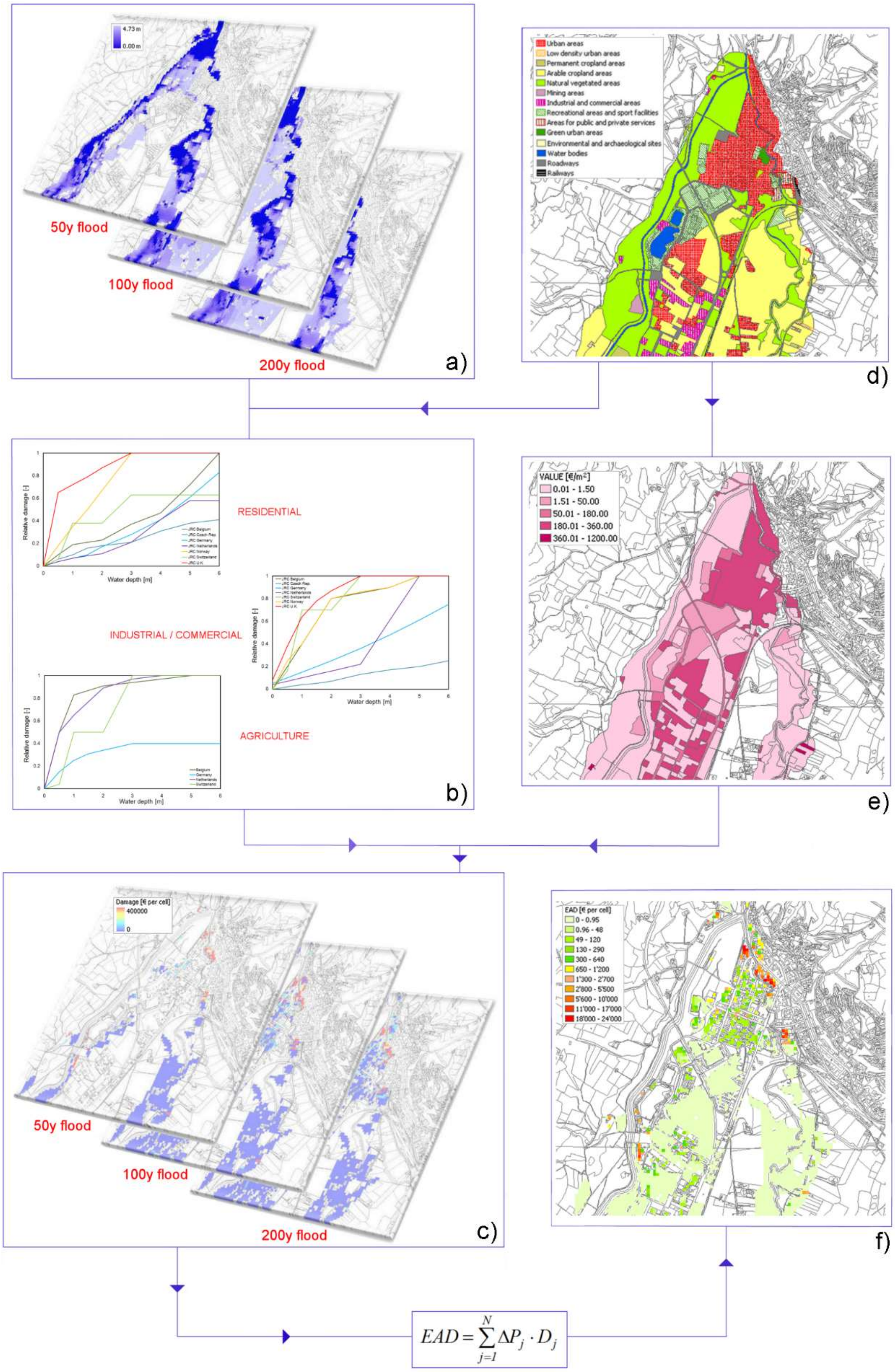

Fig. 4 Conceptual scheme for quantitative flood risk assessment: a) Rasters of inundation depths for different flood scenarios; b) JRC damage curves; c) Damage calculation for different flood scenarios; d) "Map of the exposed assets"; e) Association of economic values [€/m^2] to the exposed assets; f) Raster of calculated EAD

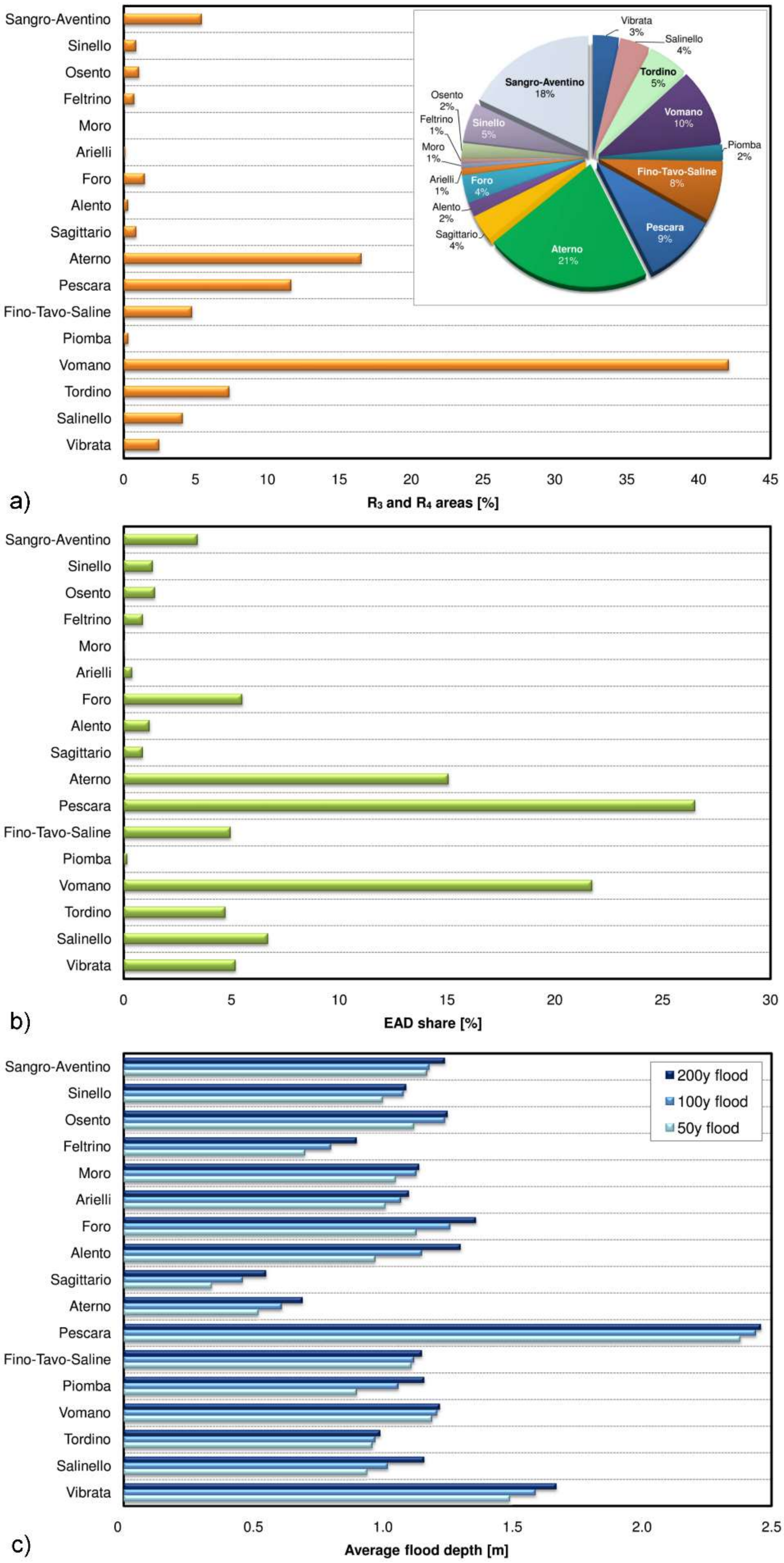

Fig. 5 Flood risk assessment results for the river basins of the Abruzzo Region: a) Qualitative approach: contribution of each basin in terms of "very high" (R_3) and "high risk areas" (R_4) to the total exposed R_3 and R_4 area in the Region (the pie chart shows the percentage of flood risk area ($R_1 \div R_4$) for each basin to the total flood risk area in the Region); b) Quantitative approach: contributions of each basin in terms of EAD to the total regional EAD; c) Average flood depths

resulting from hydraulic modelling of the different flood scenarios

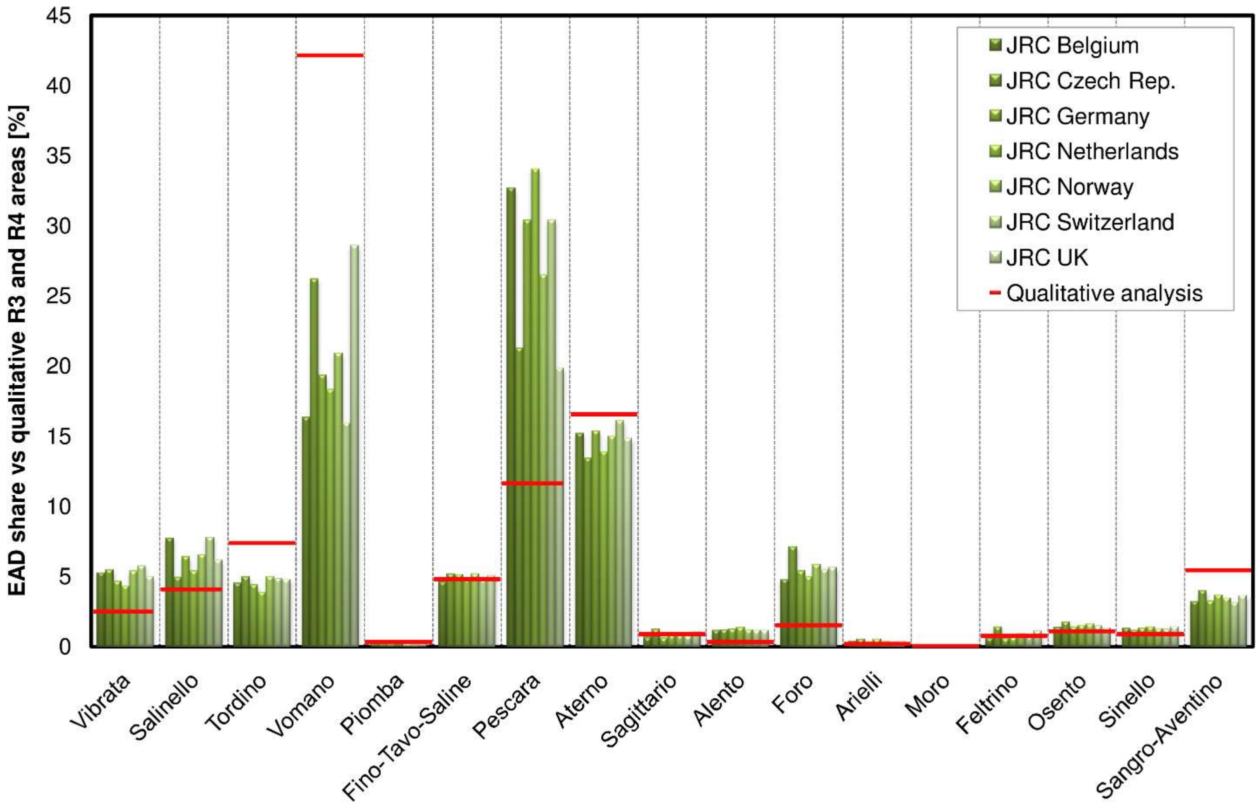

Fig. 6 Influence of damage model selection on the results of the comparative analysis between qualitative and quantitative approaches

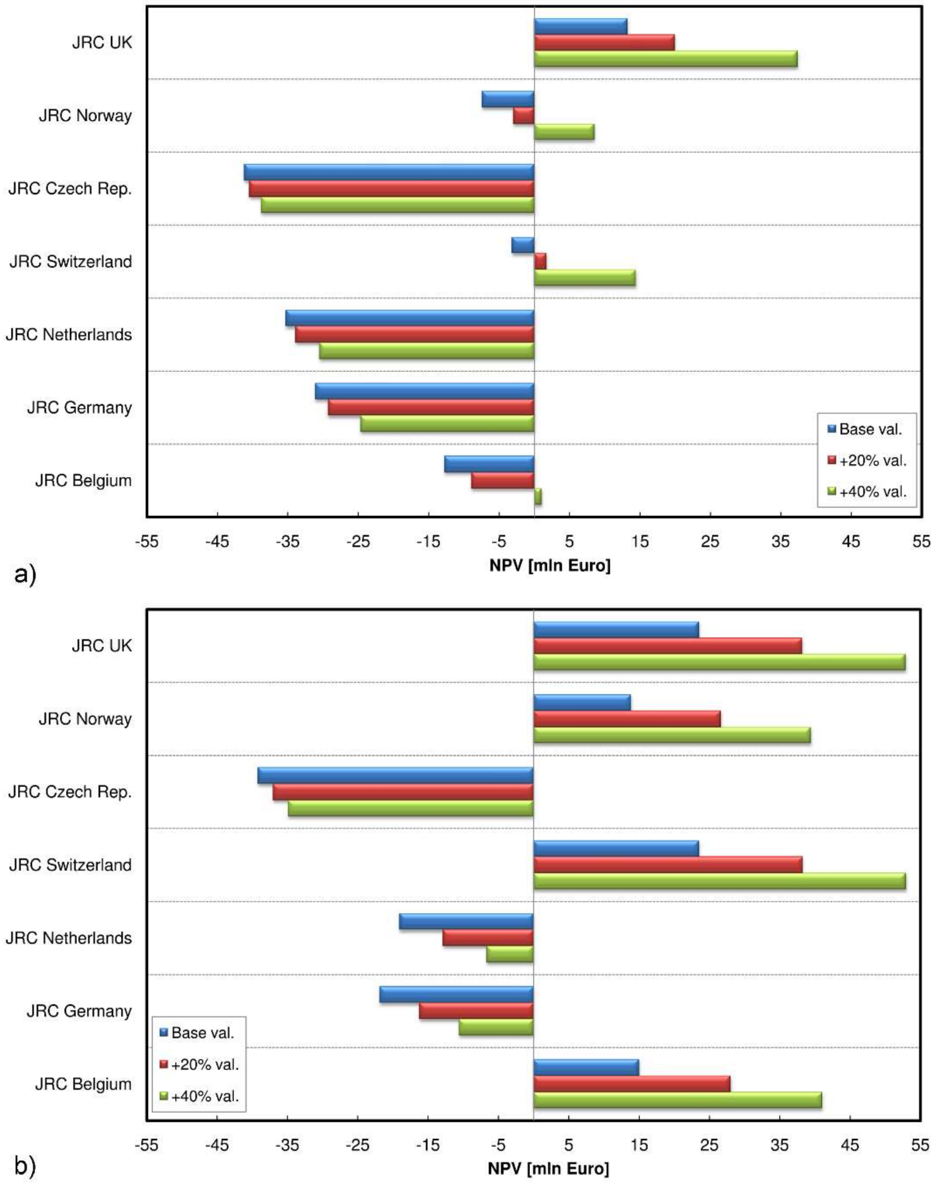

Fig. 7 Influence of damage curve selection and economic asset values on the results of cost-benefit analysis, in terms of NPV: a) case 1; b) case 2

Table 1 Inundation characteristics for analysed scenarios: mean water depths and inundated areas for different land-uses

Scenario		*Residential*				*Industrial/Commercial*				*Agriculture*			
		Baseline		*With project*		*Baseline*		*With project*		*Baseline*		*With project*	
		h_m *[m]*	*A [ha]*	h_m *[m]*	*A [ha]*	h_m *[m]*	*A [ha]*	h_m *[m]*	*A [ha]*	h_m *[m]*	*A [ha]*	h_m *[m]*	*A [ha]*
Case 1	50y	*1.31*	9.6	*1.15*	6.9	*0.98*	75.2	*0.55*	13.1	*1.59*	440.5	*1.13*	296.1
	100y	*1.54*	11.0	*1.22*	7.1	*1.35*	96.9	*0.66*	14.4	*2.04*	541.4	*1.46*	301.2
	200y	*1.70*	11.8	*1.38*	7.7	*1.44*	102.5	*0.67*	19.7	*2.34*	575.0	*1.74*	319.4
Case 2	50y	*2.25*	7.5	*1.84*	3.5	*2.55*	159.1	*1.40*	68.2	*2.55*	710.3	*1.84*	591.0
	100y	*2.60*	8.8	*1.93*	4.8	*2.94*	164.3	*1.51*	71.4	*2.90*	754.2	*1.97*	632.2
	200y	*3.22*	10.4	*2.01*	5.1	*3.14*	171.8	*1.65*	82.5	*3.15*	756.1	*2.09*	645.7

Table 2 Absolute losses and difference factors for the JRC damage models: baseline and "with project" scenarios for case 1

Damage model	50y flood			100y flood			200y flood		
	Resid.	*Ind./Com.*	*Agric.*	*Resid.*	*Ind./Com.*	*Agric.*	*Resid.*	*Ind./Com.*	*Agric.*
BASELINE SCENARIO									
Absolute loss [mln €]									
JRC Belgium	10.37	50.43	0.58	15.29	72.71	0.82	17.95	87.52	0.95
JRC Czech Rep.	7.25	5.26	-	9.08	7.50	-	10.28	8.92	-
JRC Germany	7.00	22.59	0.18	9.37	30.66	0.26	11.47	35.14	0.31
JRC Netherlands	5.74	16.02	0.49	8.50	21.758	0.74	9.50	24.92	0.84
JRC Norway	22.43	54.12	-	29.51	77.51	-	32.50	89.99	-
JRC Switzerland	14.83	65.37	0.26	21.84	90.74	0.36	23.76	108.21	0.45
JRC UK	32.63	84.73	-	47.22	117.90	-	50.15	135.86	-
Damage model difference factor									
JRC Belgium	1.81	9.59	3.30	1.80	9.69	3.16	1.89	9.81	3.10
JRC Czech Rep.	1.26	min	-	1.07	min	-	1.08	min	-
JRC Germany	1.22	4.30	min	1.10	4.09	min	1.21	3.94	min
JRC Netherlands	min	3.05	2.80	min	2.90	2.86	min	2.79	2.76
JRC Norway	3.90	10.29	-	3.47	10.30	-	3.42	10.09	-
JRC Switzerland	2.58	12.43	1.47	2.57	12.09	1.39	2.50	12.13	1.46
JRC UK	5.68	16.11	-	5.56	15.73	-	5.28	15.23	-
WITH PROJECT SCENARIO									
Absolute loss [mln €]									
JRC Belgium	4.51	7.13	0.54	5.76	9.72	0.59	6.99	12.80	0.67
JRC Czech Rep.	2.89	0.79	-	3.63	1.04	-	4.28	1.42	-
JRC Germany	2.59	3.14	0.18	3.41	3.92	0.18	4.17	5.55	0.20
JRC Netherlands	2.17	2.22	0.50	2.91	2.75	0.52	3.59	3.92	0.57
JRC Norway	10.64	7.73	-	13.45	9.92	-	16.05	13.23	-
JRC Switzerland	7.04	8.45	0.29	9.01	12.17	0.38	11.12	15.72	0.45
JRC UK	17.96	11.40	-	21.96	14.81	-	25.27	19.66	-
Damage model difference factor									
JRC Belgium	2.08	8.97	3.06	1.98	9.32	3.28	1.95	9.01	3.25
JRC Czech Rep.	1.33	min	-	1.25	min	-	1.19	min	-
JRC Germany	1.20	3.96	min	1.17	3.76	min	1.16	3.90	min
JRC Netherlands	min	2.79	2.84	min	2.63	2.88	min	2.76	2.79
JRC Norway	4.90	9.73	-	4.63	9.51	-	4.45	9.31	-
JRC Switzerland	3.24	10.64	1.63	3.10	11.67	2.09	3.10	11.06	2.18
JRC UK	8.27	14.48	-	7.56	14.19	-	7.04	13.83	-

The symbol "-" denotes the unavailability of the damage model for a certain sector, while "min" indicates the damage model reporting the lowest loss estimate for each sector.

Table 3 Absolute losses and difference factors for the JRC damage models: baseline and "with project" scenarios for case 2

	BASELINE SCENARIO								
Damage model	**50y flood**			**100y flood**			**200y flood**		
	Absolute loss [mln €]								
	Resid.	*Ind./Com.*	*Agric.*	*Resid.*	*Ind./Com.*	*Agric.*	*Resid.*	*Ind./Com.*	*Agric.*
JRC Belgium	7.92	168.29	1.83	10.19	173.99	2.05	13.75	201.30	2.21
JRC Czech Rep.	5.02	22.56	-	6.76	23.87	-	8.61	28.88	-
JRC Germany	5.67	71.10	0.60	7.07	72.93	0.64	9.86	86.81	0.69
JRC Netherlands	5.33	68.58	1.33	6.55	74.10	1.61	8.49	89.83	1.85
JRC Norway	17.68	167.29	-	22.46	168.83	-	29.69	195.37	-
JRC Switzerland	11.93	184.71	1.49	15.32	191.70	1.68	19.68	223.13	1.83
JRC UK	22.83	212.78	-	29.74	215.02	-	37.30	240.50	-
	Damage model difference factor								
JRC Belgium	1.58	7.46	3.08	1.54	7.29	3.18	1.60	6.97	3.20
JRC Czech Rep.	min	min	-	min	min	-	min	min	-
JRC Germany	1.13	3.15	min	1.07	3.06	min	1.15	3.01	min
JRC Netherlands	1.06	3.04	2.24	1.02	3.10	2.50	1.01	3.11	2.68
JRC Norway	3.52	7.41	-	3.39	7.07	-	3.45	6.77	-
JRC Switzerland	2.38	8.19	2.49	2.31	8.03	2.61	2.28	7.73	2.66
JRC UK	4.55	9.43	-	4.49	9.01	-	4.33	8.33	-
	WITH PROJECT SCENARIO								
	Absolute loss [mln €]								
JRC Belgium	2.71	34.30	1.39	7.34	84.53	1.68	9.22	115.62	1.81
JRC Czech Rep.	1.63	3.90	-	4.51	9.77	-	5.56	12.96	-
JRC Germany	1.85	13.02	0.45	4.29	40.52	0.50	5.22	47.30	0.52
JRC Netherlands	1.48	10.11	0.96	3.99	30.23	1.26	4.87	35.75	1.50
JRC Norway	7.03	33.08	-	15.57	98.77	-	19.02	124.54	-
JRC Switzerland	4.42	39.45	1.07	8.72	84.28	1.32	11.06	129.57	1.47
JRC UK	9.13	45.47	-	32.25	139.19	-	40.33	179.13	-
	Damage model difference factor								
JRC Belgium	1.83	8.79	2.87	1.84	8.65	3.35	1.89	8.92	3.50
JRC Czech Rep.	1.11	min	-	1.13	min	-	1.14	min	-
JRC Germany	1.26	3.33	min	1.07	4.15	min	1.07	3.65	min
JRC Netherlands	min	2.59	1.99	min	3.09	2.51	min	2.76	2.86
JRC Norway	4.76	8.47	-	3.90	10.11	-	3.91	9.61	-
JRC Switzerland	3.00	10.10	2.20	2.19	8.62	2.62	2.27	10.00	2.81
JRC UK	6.18	11.65	-	8.08	14.24	-	8.28	13.83	-

The symbol "-" denotes the unavailability of the damage model for a certain sector, while "min" indicates the damage model reporting the lowest loss estimate for each sector.

Table 4 Influence of the hydraulic component on absolute loss estimates: difference factors for the JRC damage models calculated by dividing the loss at the modified scenario h_{+i} (i=15,30,45,60,75) by the value in the baseline 200 year return period condition

Damage model	Residential					Industrial/Commercial					Agriculture				
	h_{+15}	h_{+30}	h_{+45}	h_{+60}	h_{+75}	h_{+15}	h_{+30}	h_{+45}	h_{+60}	h_{+75}	h_{+15}	h_{+30}	h_{+45}	h_{+60}	h_{+75}
	Case 1														
JRC Belgium	1.06	1.11	1.15	1.19	1.26	1.17	1.41	1.53	1.77	1,88	1.12	1.23	1.32	1.40	1.44
JRC Czech Rep.	1.07	1.08	1.14	1.20	1.28	1.16	1.39	1.52	1.77	1.88	-	-	-	-	-
JRC Germany	1.09	1.17	1.25	1.31	1.40	1.11	1.25	1.34	1.51	1.58	1.13	1.25	1.35	1.44	1.47
JRC Netherlands	1.05	1.07	1.16	1.23	1.30	1.09	1.23	1.30	1.46	1.51	1.11	1.22	1.29	1.37	1.42
JRC Norway	1.05	1.17	1.21	1.18	1.37	1.14	1.34	1.42	1.61	1.67	-	-	-	-	-
JRC Switzerland	1.03	1.05	1.10	1.05	1.20	1.15	1.39	1.53	1.74	1.83	1.19	1.38	1.62	1.81	1.95
JRC UK	1.01	1.07	1.07	1.08	1.12	1.12	1.30	1.37	1.53	1.56	-	-	-	-	-
	Case 2														
JRC Belgium	1.05	1.11	1.17	1.24	1.30	1.05	1.09	1.13	1.17	1.21	1.03	1.05	1.07	1.09	1.09
JRC Czech Rep.	1.05	1.05	1.11	1.18	1.19	1.07	1.13	1.21	1.27	1.34	-	-	-	-	-
JRC Germany	1.08	1.17	1.24	1.34	1.44	1.05	1.11	1.17	1.22	1.28	1.02	1.03	1.05	1.06	1.07
JRC Netherlands	1.06	1.12	1.14	1.28	1.34	1.06	1.12	1.19	1.25	1.33	1.06	1.06	1.08	1.10	1.16
JRC Norway	1.05	1.10	1.08	1.18	1.23	1.04	1.09	1.13	1.17	1.20	-	-	-	-	-
JRC Switzerland	1.03	1.06	1.06	1.12	1.15	1.04	1.08	1.12	1.15	1.18	1.04	1.09	1.13	1.17	1.19
JRC UK	1.01	1.05	1.06	1.07	1.08	1.04	1.07	1.10	1.12	1.15	-	-	-	-	-

The symbol “-” denotes the unavailability of the damage model for a certain sector.

Table 5 Strengths and weaknesses of qualitative and quantitative methodologies

Approach	**Data requirements and model development**	**Strengths**	**Weaknesses**
Qualitative	- Relatively few and simple data required (exposure data based on land-use, not necessarily high detailed hazard data) - Simple model development	- Simple and fast model implementation - Useful for a large-scale river basin planning (first identification of most exposed areas) - Possibility of integration with MCA for assessing indirect and intangible damages	- No explicit modelling of vulnerability - No quantification of risk in monetary terms, preventing the use in CBA - Results dependent on the definition of hazard classes
Quantitative	- High detailed data for hazard, exposure and vulnerability assessment - Post-event data required for model validation	- Risk expressed in quantitative (monetary) terms - Vulnerability explicitly taken into account - Useful for FRMP and CBA - Uncertainty can be quantified and communicated - Possibility of integration with MCA for assessing indirect and intangible damages	- High detailed data required, that often may be unavailable (e.g. detailed water depths) - High uncertainty in damage assessment, influencing CBA results (uncertainties dependent on damage modelling, i.e. damage functions and exposure values) - Post-event data and validation analyses required - Only direct damage assessment