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Modelling the socio-economic impact of river floods in Europe

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Abstract. River floods generate a large share of the socio-economic impact of weather-driven hazards worldwide. Accurate assessment of their impact is key priority for governments, international organizations, re-insurance companies and emergency responders. Yet, available databases of flood losses over large domains are often affected by gaps and inconsistencies on reported figures. In this work, a framework to reconstruct the economic damage and population affected by river floods at continental scale is applied. Pan-European river flow simulations are coupled with a high resolution impact assessment framework based on 2D inundation modelling. Two complementary methods are compared in their ability to estimate the climatological average flood impact and the impact of each flood event in Europe between 1990 and 2013. The event based method reveals key features, such as the ability to include changes in time of all three components of risk, namely hazard, exposure and vulnerability. Furthermore, it skilfully reproduces the socio-economic impact of major flood events in the past two decades, including the severe flooding hitting the Central Europe in June 2013.

1 Introduction

The devastation caused by severe river floods in different areas of the world is brought by the media to the people's attention on a daily basis. Yet, in its physical abstraction, 'flooding' is simply a temporary covering by water of land not normally covered by water (European Commission, 2007). Consequently, the interest in floods grows only when such land is occupied by dwellings and businesses, which are disrupted by the flood inundation. Latest relevant directives on flood prevention and preparedness define the flood risk as product of flood hazard, exposure (of population and assets) and their vulnerability (European Commission, 2007; Kron, 2005; UNISDR, 2009).

Flood risk is characterized by strong spatial variability, due to its dependence on land use, local infrastructures, and the elevation and distance in relation to the surrounding river network, among others. Hence, the use of high resolution datasets and methods are of utmost importance to achieve a meaningful mapping of the flood risk. Physically consistent delineation of the flood extent and depth for a range of event magnitudes is derived through hydraulic floodplain models, commonly used in regional flood risk assessments (Broekx et al., 2011; Falter et al., 2015; Foudi et al., 2015; Koivumäki et al., 2010; te Linde et al., 2011). The computing resources needed by these models grow fast with the simulation area, so that applications to large river basins are rare (Falter et al., 2014). Because of such constraint, pan-European and global flood hazard mapping has been traditionally performed through simplified approaches based on topographic indices (e.g., Lugeri et al., 2010), on planar approximation of water levels (Barredo et al., 2007; Rojas et al., 2013) or at coarser resolution, often coupled with methods for downscaling to finer grid resolution (Hirabayashi et al., 2013; Pappenberger et al., 2012; Winsemius et al., 2013). Recent advances in large-scale flood hazard mapping led to pan-European and global inundation maps derived through high resolution 2D hydraulic modeling (Alfieri et al., 2014a; Sampson et al., 2015), opening new opportunities in global and continental flood impact assessment.

In this work, we assess the impact of river floods in Europe by coupling continental scale hydrological simulations between 1990 and 2013 with high resolution mapping of the potential impact of floods for different return levels. Resulting flood risk is expressed in terms of direct damage and population affected and aggregated over different spatial and temporal scales. We show two complementary approaches for flood risk assessment, namely an integral method and an event based method, using the same underlying data and models. A modified version of this risk assessment framework was recently used by Alfieri at

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al. (2015) to project the future flood risk in Europe under climate change. Yet, this research shows the first large scale application of the impact model based on a high-resolution observational meteorological dataset. Results are compared and discussed by stressing strengths and limitations of both methods.

2 Data and methods

The proposed approach follows a modelling framework composed of five different steps (see Figure 1), described in the following: 1) continuous hydrological simulation, 2) extreme value (EV) analysis, 3) flood inundation modelling, 4) impact modelling and 5) flood risk assessment.

2.1 Continuous hydrological simulation

Hydrological simulations were performed with the Lisflood distributed model (Burek et al., 2013; van der Knijff et al., 2010). For this work we used the operational dataset of the European Flood Awareness System (EFAS, see Alfieri et al., 2014b; Thielen et al., 2009), in the form of daily streamflow in the European river network from 1/1/1990 to 31/12/2013. Streamflow maps at 5 km grid resolution are produced by forcing Lisflood with the EFAS-Meteo dataset (Ntegeka et al., 2013), which includes daily precipitation, temperature and evapo-transpiration maps derived through spatial interpolation of point observations. The current Lisflood version is calibrated at 693 stations across Europe against up to 8 years of daily observed discharge. In addition, extensive work is continuously carried out on the model to improve the representation of hydrological processes, the parameter calibration, the simulation of key features along the river network, and the improvement of the underlying spatial datasets. Recent improvements include the parameterization of 182 lakes and 34 large reservoirs, and the simulation of water withdrawals through monthly maps of water use from the SCENES project (Kamari et al., 2008).

2.2 Extreme value analysis

Simulated streamflow maps from 1990 to 2013 were analyzed statistically to estimate analytical curves relating extreme flow peaks to their probability of occurrence and consequently to their return period. For each grid point of the European river network, the set of maximum annual discharge peaks was fitted with a Gumbel extreme value distribution, using the L-moment approach (see Hosking, 1990). L-moment estimators are nearly unbiased for a wide range of sample sizes and distributions (Vogel and Fennessey, 1993), and are particularly useful for relatively short samples as in this study. In addition, we calculated the mean of the annual maximum discharge over different durations, from 1 up to 30 days, based on the same sample of streamflow data. The resulting information are key descriptors of the peak flow and of the related hydrograph volume, and are thus used to produce coherent flood hydrographs for any point of the river network, using the procedure described by Maione et al. (2003).

2.3 Flood inundation modelling

Flood inundation maps for the entire European domain were produced at 100 m resolution using the Lisflood-FP floodplain model (Bates et al., 2010; Neal et al., 2012) forced by the flood hydrographs with specific return period described in the previous section. The full procedure to derive pan-European flood hazard maps is described in details by Alfieri et al. (2014a). The procedure was semi-automated to speed up the computing time and was then repeated for six different return periods TF={10, 20, 50, 100, 200, 500} years. Each flood hazard map defines the maximum flood depth and extent caused by the corresponding flood return period, and is produced by merging the results of over 37,000 hydraulic simulations along the European river network.

2.4 Impact modelling

The impact model used in this study is focused on estimating the population affected and the direct economic damage due to river floods. The potential population affected (PPA) by floods of a specific return period is estimated by overlaying the corresponding flood hazard map with the 100 m resolution map of European population density by Batista e Silva et al. (2013). The potential damage (PD) of floods is estimated through piece-wise linear functions relating the flood depth to the corresponding direct damage. For this task we used the country specific depth-damage functions defined by Huizinga (2007) for different land uses, while the spatial variability in exposure is determined according to the refined version of the Corine Land Use provided by Batista e Silva et al. (2012). To account for the large regional differences in exposed assets for a given land use class that exist in some countries, country specific depth-damage functions were further rescaled by the Gross Domestic Product (GDP) per capita of NUTS2 administrative level (see http://ec.europa.eu/eurostat/web/nuts/overview). For regions in countries where no damage function was available, average depth-damage functions were scaled by the regional GDP per capita. Impact data on damage and population affected by flood peaks with selected return period is first assessed at 100 m resolution and then aggregated to 5 km resolution maps through the corresponding Areas of Influence (AoI) as defined by Alfieri et al. (2015). AoI are polygons at 100 m resolution which define a univocal link between the high and low resolution maps by assigning the flooded area to the 5 km grid point of the causative inflow hydrograph.

2.5 Flood risk assessment

Flood risk is the combination of the impact of events and their frequency of occurrence. Here, it is assessed through the following two different approaches.

2.5.1 Integral method

This method estimates the average annual impact of floods by computing a piece-wise integral of the damage-probability curve for a selected range of return periods, as done by Feyen et al. (2012), Rojas et al. (2013) and by Winsemius et al. (2013) in previous European and global risk assessments. For both damage and population affected, the integral sum is truncated at the return period of the protection level of the corresponding location, assuming that no impact occurs for events of lower magnitude. In this step, we used the European flood protection map derived by Jongman et al. (2014).

2.5.2 Event based method

This method estimates the damage of each simulated flood, rather than considering the theoretical probability of occurrence. It is based on a selection of all discharge peaks (POT) exceeding the flood protection level (by Jongman et al., 2014) at any location. For each discharge peak, first the return period is calculated through the corresponding analytical extreme value distribution estimated in Sect. 2.2. Then, it is assigned a value of direct damage and population affected by interpolating linearly between the impacts of the two closest return periods among those available. As in the previous method, discharge peaks exceeding the 500-year return period are assigned impact values corresponding to the 500-year event. Annual damage and population affected is estimated by summing the impact values of all events simulated within the year.

3 Results

The two approaches described in Sect. 2.5 were run over the time span 1990-2013 on a large portion of Europe, including 26 countries of the European Union (all except Malta and Cyprus), Norway, and the Republic of Macedonia. Impact values are based on population density estimates of 2006 and GDP Purchasing Power Standards (PPS) of 2007. Average annual estimates of damage (AD) and population affected (APA) are shown in Figure 2, spatially aggregated for the 28 considered countries. Values plotted in Figure 2 are expressed as ratios of the respective country GDP and country population, while absolute values

are shown as labels aside each color bar. Blue bars are based on statistical frequencies of occurrence, hence are representative of the country average vulnerability to extreme events. Largest relative damage is found in Hungary, at 2.6‰ of the country GDP, while about 1.9‰ of the Dutch population is estimated to be affected annually by river floods. On the other hand, values in green give an indication on the impact of extreme events occurred in the simulation period 1990-2013. Largest relative damage was found in the Baltic Republics, while the ratio of population affected was the largest in Croatia. When absolute impact values are considered, the largest annual damage is found in Italy (929 and 645 M€/year for the integral and event based approach, respectively) while population affected is the highest in Germany (40,000 pp/year in both methods).
Estimates of flood impact at the European Union level are compared with figures by the European Environment Agency (EEA, 2010), who reported an average damage around 5 B€/year and population affected of 250,000 pp/year over the time window 1998-2009. Aggregated figures for the same years derived through the event based method hereby proposed lead to 5.4 B€/year and 220,000 pp/year, while long term averages of the integral method indicate 5.9 B€/year and 239,000 pp/year.

3.1 Integral method

The integral method is based on statistical frequencies of occurrence of extreme events derived by analytical distributions. Hence, estimates of the average impact made with such approach are robust also when applied to relatively small spatial aggregations. Estimates of annual damage and population affected at the NUTS 2 aggregation level are shown in Figure 3. Average estimated impact among all the considered NUTS 2 regions amounts to 21 M€/year of damage and 900 pp/year of population affected. Despite the high protection standards assumed for the whole of the Netherlands (1 in 1000 years, Jongman et al., 2014), the highest estimated impacts among NUTS 2 regions are found in South Holland (255 M€/year of damage and 19,000 pp/year), as a consequence of the considerable exposure of people and assets in case of extreme events exceeding the flood protection level. Other regions at high risk are found in the north of Italy, France, Croatia, Austria and Hungary. It is worth noting that the presented approach is focused on rivers with upstream area larger than 500 km^2. Hence, the flood risk is likely to be underestimated in regions where the hydrography is dominated by smaller streams (e.g., coastal regions of Greece, South of Italy, Croatia, Norway, UK, Denmark, as well as some mountainous regions in the Alps) where local storms and flash floods are major components of the overall impact of floods. Similarly, the impact of coastal floods is not modeled in the results shown.

3.2 Event based method

The peculiarity of the event based method is its applicability to any desired time window, from single events to annual aggregations. On the other hand, observed impact data of past floods are scarcely available, and in addition are usually affected by considerable uncertainty levels (Merz et al., 2010; Penning-Rowsell, 2015). A report by Fenn et al. (2014), prepared for the European Commission Directorate-General for the Environment (DG Env), includes an assessment of financial, economic and social impacts of river floods in the countries of the European Union between 2002 and 2013. Fenn et al. (2014) addressed the scarcity of flood impact data by extrapolating the cost of major floods in the European countries on the basis of the available data, so that the overall estimated flood impact is given by the sum of extrapolated and quantified data. Figure 4 compares annual flood damage aggregated over the European Union of the event based method from 1990 to 2013 and data by DG Env for the available years. Data from the two datasets are in good qualitative agreement. The event based approach proves its ability to spot the years when the most severe flood events occurred, including the “Millennium flood” of the Oder (and Vistula) river which hit Poland, Czech Republic and Germany in 1997 causing more than 100 fatalities and material damages estimated at 5.7 B$ (EM-DAT, 2015).

3.2.1 Case study - Central Europe floods in 2013

The catastrophic floods hitting the Central Europe in June 2013 was selected as case study to test the performance of the event based method for rapid risk mapping. Figure 5 shows maps of damage and population affected in Central Europe, based on the simulated discharge maps from 25 May to 10 June 2013. Impact data in the figure are aggregated over NUTS 2 regions, while grey circles indicate hotspots of simulated damage larger than 100 M€ and population affected in excess of 5,000. Aggregated estimates of direct damage in Germany, Austria and Czech Republic amount to 10.9 B€ and 360,000 people affected by the flood event. These estimates are in agreement with reported figures ranging between 11.4 and 16 B€ (Aon Benfield, 2014; Munich Re, 2014; Swiss Re, 2013), especially if one considers that the higher estimates from insurance companies account for total combined economic losses, rather than just direct damage. As indication, indirect costs are commonly estimated within 5% and 40% of direct damage (Jongman et al., 2012).

The spatial distribution of estimated damage and population affected shown in Figure 5 correctly locates hotspots of observed flood damage during the event. Among the most affected areas, extensive damage from flooding was reported along the Elbe river and its tributaries Mulde and Saale in Central Germany and Western Czech Republic (Schröter et al., 2015), along the Danube, particularly near the German-Austrian border, and its tributaries Inn, Isar, Aist, Kamp (Blöschl et al., 2013), and in the Neckar river basin in the region of Stuttgart in the South-Western Germany, often as a consequence of major dike breaches (Schröter et al., 2015; Zurich, 2014). In comparison to reported figures, major differences with the proposed approach are the underestimation of the flood impact for the city of Prague (no simulated impact) and neighboring areas along the Vltava and Elbe rivers, and the overestimation of the flood damage in the Austrian regions of Salzburg and Upper Austria (1 B€ reported versus 5 B€ simulated). In the first case, reasons are found in the underestimation of the simulated discharge along the Vltava and the upper Elbe rivers (see Supplement material) and of the consequent inundated area. In the case of Austria, the actual impact was lower than our estimates as a result of the significant investments to improve the flood protection following the disastrous floods of 2002 (Blöschl et al., 2013; Fenn et al., 2014), which is not reflected in the flood protection map used in our simulations.

4 Discussion and Conclusions

This work presents a comparison of two methods to reconstruct the socio-economic impact of river floods in Europe in the present climate. The two methods are based on the same data framework though they provide complementary information of key importance for effective flood risk assessment at European level. The integral method is a tool to estimate average flood losses at region (NUTS 2) and country level under a stationary climate. On the other hand, the event based method is able to reproduce the impact of simulated events in time. Hence it is more suitable for damage assessments over specific time windows and as operational tool for real time flood risk mapping. When the event based method is applied to sufficiently long time windows representing adequately the climatic variability, it can be used to estimate average flood losses, which can be compared to estimates of the integral method, as shown in Figure 2. Yet, the event based approach is not suitable to estimate average flood losses in case of a small sample of extreme events, as it would give the estimate insufficient robustness. This normally occurs when the aggregation area is not large enough or when the average protection level is particularly high, making flood inundation an extremely rare event. Is these cases, one can see substantial differences in results obtained with the two proposed methods (see Figure 2), as for Luxemburg and the Netherlands, where no event above the protection level was simulated in the years 1990-2013. It is worth noting that, being based on actual event occurrences, the event based method is more suitable to account for non-stationary climates such as under changes in the frequency and magnitude of extreme floods (see Alfieri et al., 2015). Similarly, it can account for changes in time of the flood exposure (e.g., through land use changes and population development) and vulnerability (e.g., through increase in the flood protection levels or reduction of the damage potential).

The proposed approach assigns each peak over threshold with specific return period a pre-computed hydrograph with the same flood frequency and daily discharge values consistent with the flow duration curve of the simulated time series. In comparison to fixed hydrograph shapes, this approach is more appropriate to reproduce coherent hydrograph shapes and their statistics, occurring in large model domains featured by a variety of climate regimes. It assigns a univocal link between peak flow and corresponding hydrograph, hence neglecting the impact variability of hydrographs with same peak discharge and different flood volume (see Falter et al., 2015). Yet, it has the advantage of drastically reducing the computing resources needed, making high resolution impact modelling possible on large scale applications.

4.1 The influence of flood protections

As previously noted by Ward et al. (2013), impact estimates of assessment frameworks based on flood threshold exceedance are very sensitive to the assumed flood protection standards. This issue may be exacerbated in the event based method, where the magnitude of events is estimated from the simulated peak discharge, and their frequency might deviate from the theoretical one, assumed by their statistical extreme value distribution. In the limit abstraction of peak flow magnitude close to the flood protection level, one would obtain either no impact or very high impact following minor deviations changing the relative rank of these two values. Flood risk assessments are affected by various sources of uncertainty (Apel et al., 2008; Koivumäki et al., 2010), hence a probabilistic approach is likely to bring benefits to the methodology by accounting for the uncertainty range around the central impact estimate. In this work, the characterization of uncertainty was deliberately not included, so to stress the comparison between the two approaches shown.

In observed events, often the impact of flood inundation is caused by the collapse of flood protection measures at specific sites, which concentrates the damage in a certain area and reduces the likelihood of flooding more downstream due to the floodplain storage and consequent reduction of the peak discharge (e.g., Zurich, 2014). Research work by Hall et al. (2005) tackled this process by including estimates of the probability of defense failure for each river section, under a range of load conditions. This approach might be difficult to apply at continental scale, due to the difficulty in gathering detailed information for such an extensive river network. However, simplified approaches could prove beneficial in improving the impact estimates.

A further comment must be addressed to the so called "Adaptation effect" (see Di Baldassarre et al., 2015), which is related to a reduction of vulnerability following disastrous flood events, due to the increased awareness and the implementation of structural and non-structural flood protection measures. The benefits of adaptation to floods have been demonstrated in a number of research works and can be measured in a clear reduction of the impact on economy and society in regions hit by series of floods within a time frame of few years (Blöschl et al., 2013; Bubeck et al., 2012; e.g., Jongman et al., 2015; Wind et al., 1999). If the adaptation effect is not considered, the impact assessment can lead to overestimations in areas hit by floods in the recent years, as seen in Sect. 3.2.1. Yet, this process can be accounted for in the proposed event-based method, provided that reliable vulnerability information is timely made available, to improve future flood risk assessment.

As final remark, we want to stress the large potential in coupling the event-based method with numerical weather predictions as input data, which opens the way to flood impact forecasting applications at European scale. Its implementation is currently being tested within EFAS, with the aim of providing probabilistic forecast of areas at risk of flooding in the coming 10-15 days, with direct estimation of possible consequences on people affected and economic damage. This is of crucial importance in the early assessment of the magnitude of imminent events, to support the planning of emergency actions and ultimately speed up the recovery phase.

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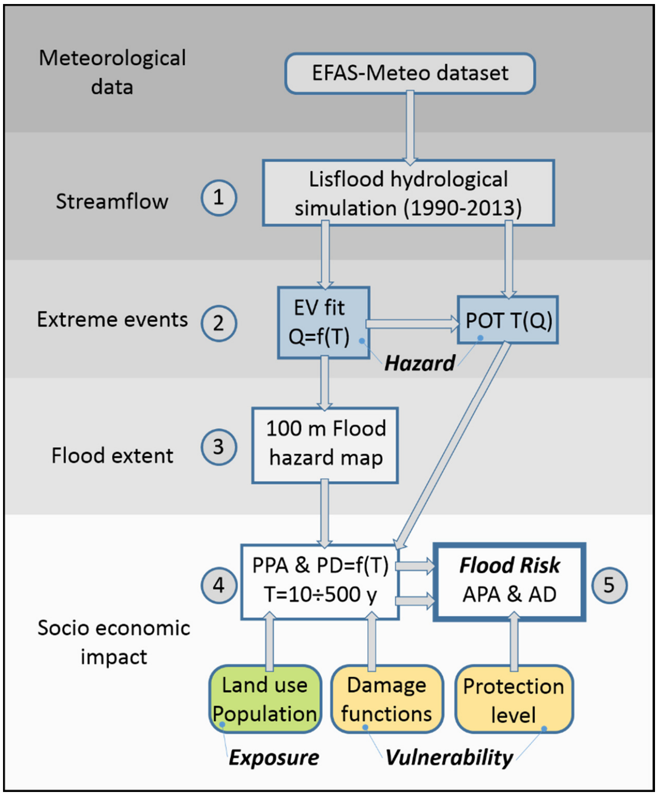

Figure 1. Schematic view of the proposed modelling framework for flood risk assessment.

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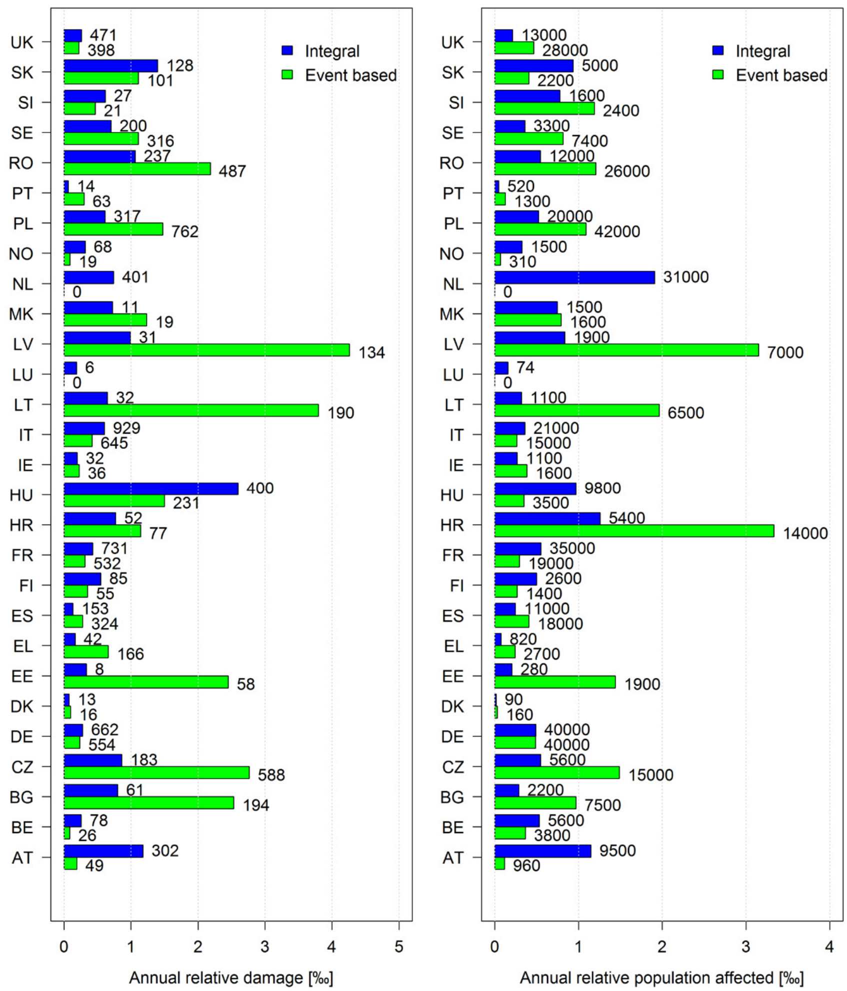

Figure 2. Annual relative damage and population affected for the considered European countries (ISO country code) between 1990 and 2013. Absolute figures are shown aside each color bar (in M€ and people affected, respectively).

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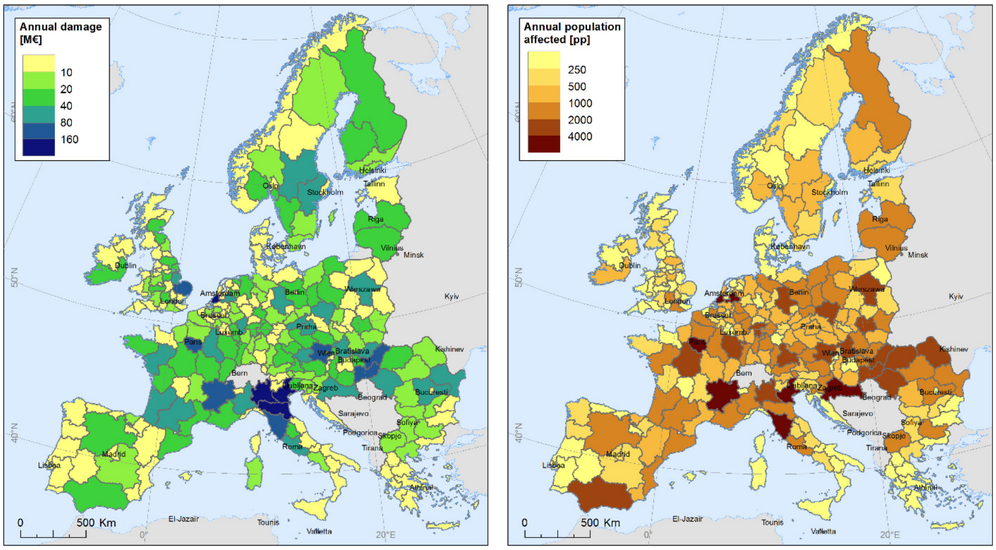

Figure 3. Mean annual damage and population affected at NUTS 2 level estimated through the integral method.

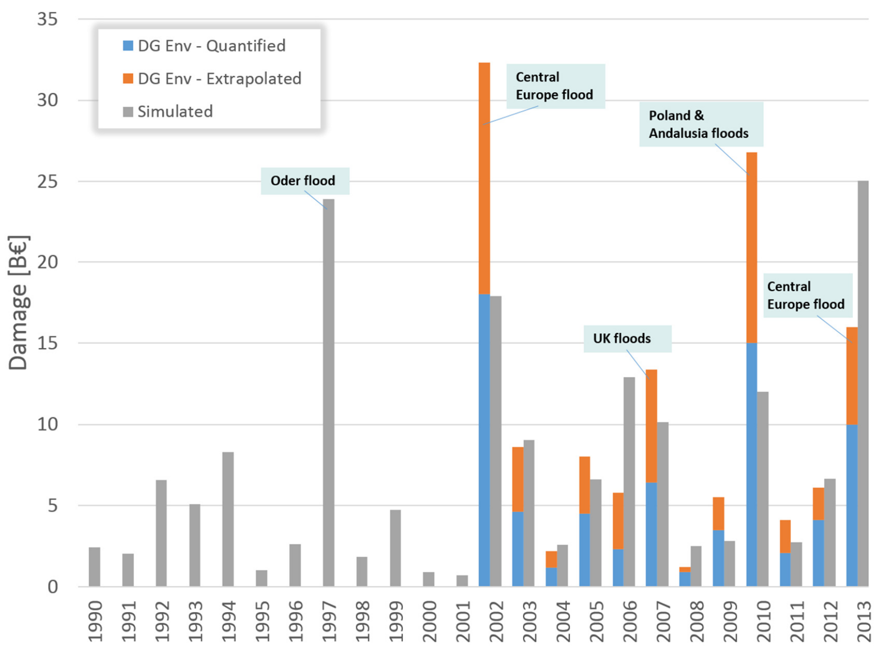

Figure 4. Annual estimates of flood damage in the EU over 1990-2013 (PPS of 2013) using the event based method (in grey) and comparison with data by DG Env (Fenn et al., 2014).

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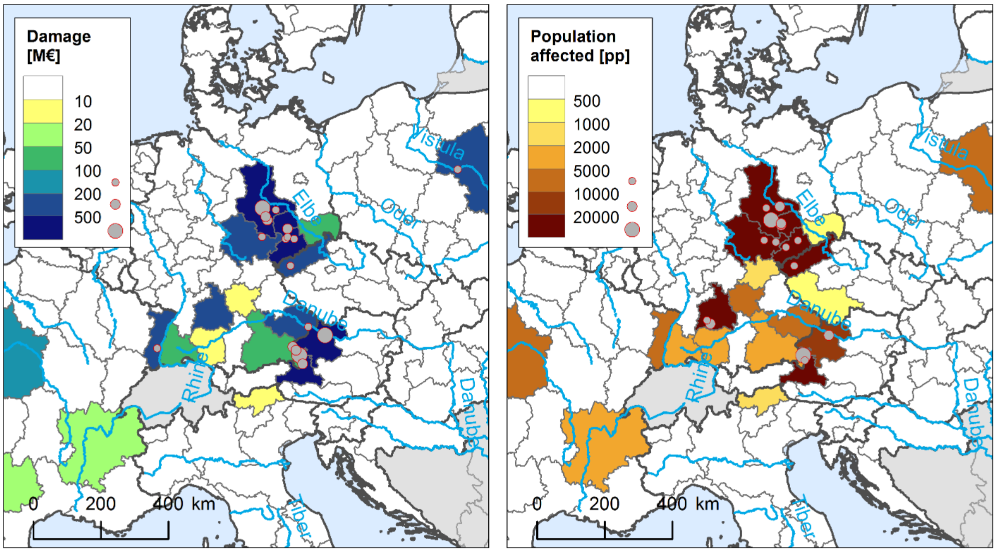

Figure 5. Estimates of damage and population affected (event based method) in Central Europe from 25 May to 10 June 2013.