Nat. Hazards Earth Syst. Sci., 16, 1401–1411, 2016
www.nat-hazards-earth-syst-sci.net/16/1401/2016/
doi:10.5194/nhess-16-1401-2016

Natural Hazards and Earth System Sciences
Open Access
EGU

Modelling the socio-economic impact of river floods in Europe

Lorenzo Alfieri[1], **Luc Feyen**[1], **Peter Salamon**[1], **Jutta Thielen**[1], **Alessandra Bianchi**[1], **Francesco Dottori**[1], **and Peter Burek**[1,2]

[1]Institute for Environment and Sustainability, European Commission – Joint Research Centre, 21027 Ispra, Italy
[2]International Institute for Applied Systems Analysis (IIASA), 2361 Laxenburg, Austria

Correspondence to: Lorenzo Alfieri (lorenzo.alfieri@jrc.ec.europa.eu)

Received: 23 December 2015 – Published in Nat. Hazards Earth Syst. Sci. Discuss.: 19 January 2016
Revised: 13 May 2016 – Accepted: 31 May 2016 – Published: 16 June 2016

Abstract. River floods generate a large share of the socio-economic impact of weather-driven hazards worldwide. Accurate assessment of their impact is a key priority for governments, international organization, reinsurance companies and emergency responders. Yet, available databases of flood losses over large domains are often affected by gaps and inconsistencies in 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 2-D 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 central Europe in June 2013. On the other hand, the integral method is capable of reproducing the average flood losses which occurred in Europe between 1998 and 2009. Strengths and limitations of the proposed model are discussed to stress the large potential for filling in the gaps of current datasets of flood impact.

1 Introduction

The devastation caused by severe river floods in different areas of the world is brought to the people's attention by the media on a daily basis. In its physical abstraction, "flooding" is simply a temporary covering by water of land not normally covered by water (European Commission, 2007). Hence, the interest in floods grows only when such land is occupied by dwellings and businesses, which are disrupted by the flood inundation. Yet, the history of river flooding and its socio-economic impact has shaped the development of civilizations for millennia (Chen et al., 2012; Di Baldassarre et al., 2013). The latest relevant directives on flood prevention and preparedness define the flood risk as a product of flood hazard, exposure (of population and assets) and their vulnerability (European Commission, 2007; Kron, 2005; UNISDR, 2009). Each of those three components can change in space and in time, following population growth along rivers, migration fluxes, river flood protection and changes in climatic extremes, among others. In addition, effective adaptation measures to reduce the flood impact can be achieved by reducing one or more of those three risk components (Alfieri et al., 2016; IPCC, 2012).

Flood risk is characterized by strong spatial variability, due to its dependence on land use, local infrastructure and the elevation and distance in relation to the surrounding river network. 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., 2016; Schumann et al., 2013). Because of such a constraint, pan-European and global flood hazard mapping have 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). Furthermore, large-scale flood risk assessments produced so far were focused on evaluating the average flood impact over long periods, assuming a stationary climate, while no research has yet considered the actual statistical frequency of occurrence of past extreme events at the pan-European scale. Recent advances in large-scale flood hazard mapping led to European and global inundation maps derived through high-resolution 2-D hydraulic modelling (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. In addition, the event-based method is used to assess the impact of the severe flood hitting a vast portion of central Europe in June 2013, and results are evaluated against reported figures from reinsurance companies and post-event reports. This research shows the first large-scale application of the impact model based on a high-resolution observational meteorological dataset. A modified version of this risk assessment framework was recently used by Alfieri at al. (2015) to project the future flood risk in Europe under climate change. Flood impact results are compared with available validation data and are then discussed by stressing the strengths and limitations of both methods.

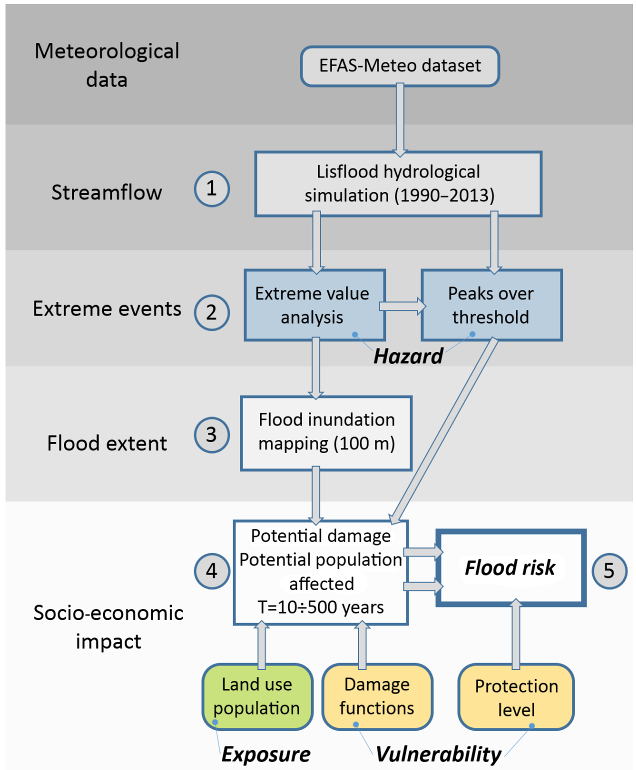

Figure 1. Schematic view of the proposed modelling framework for flood risk assessment. The three components of the risk formula, namely hazard, exposure and vulnerability, are highlighted with colours.

2 Data and methods

The proposed approach follows a modelling framework composed of five steps (see Fig. 1), described as the following: (1) continuous hydrological simulation, (2) extreme value 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). Processes simulated by Lisflood include snowmelt, soil freezing, surface run-off, infiltration, preferential flow, redistribution of soil moisture within the soil profile, drainage of water to the groundwater system, groundwater storage and base flow. Run-off produced for every grid cell is routed through the river network using a kinematic wave approach. 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 January 1990 to 31 December 2013. Streamflow maps at 5 km grid resolution covering an area of 6.5 million km^2 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 for up to 8 years of daily observed discharge. The calibration work was performed using the R package “hydroPSO”, which implements a state-of-the-art version of the Standard Particle Swarm Optimization 2011 (Zambrano-Bigiarini and Rojas, 2013). Some performance of the calibrated stations are shown in the Supplement (Fig. S1 and Table S1). 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 (Water Scenarios for Europe and Neighbouring States) project (Kamari et al., 2008).

2.2 Extreme value analysis

Simulated streamflow maps from 1990 to 2013 were analysed 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 provides key descriptors of the peak flow and the related hydrograph volume, and is 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 for deriving pan-European flood hazard maps is described in detail by Alfieri et al. (2014a), together with some performance scores of the 1-in-a-100-year simulated map vs. official regional maps available for Germany and the UK. The procedure was semi-automated to speed up the computing time and was then repeated for six different return periods commonly considered in similar flood hazard mapping (e.g. Sampson et al., 2015; Winsemius et al., 2016): $T = \{10, 20, 50, 100, 200, 500\}$ 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. Visual examples of the maps produced can be seen in Fig. S2.

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 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. (2013). Depth-damage functions per country and land use class comprise two damage indicators (Huizinga, 2007): an absolute damage value in EUR m^{-2}, which is attributed to all flood depths equal or larger than 6 m; and a damage factor relative to the maximum damage (i.e. between 0 and 1), which is defined by piece-wise linear functions. Those two indicators are derived through analysis of written documentation and data on the internet from 31 countries in Europe. 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 NUTS 2 (Nomenclature of territorial units for statistics) administrative level (see http://ec.europa.eu/eurostat/web/nuts/overview). Impact data on damage and population affected by flood peaks with selected return period are 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 two different approaches: (1) an integral method and (2) an event-based method.

The integral 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 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).

The event-based 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 over threshold (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 are 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 Fig. 2, spatially aggregated for the 28 considered countries. Values plotted in Fig. 2 are expressed as ratios of the respective country GDP and country population, while absolute values are shown as labels alongside each colour bar. Blue bars are based on statistical frequencies of occurrence, hence are representative of the country's average vulnerability to extreme events. The 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 of the impact of extreme events occurring in the simulation period 1990–2013. The largest relative damage was found in the Baltic states, 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 (EUR 929 and 645 million per year for the integral- and event-based approaches, respectively) while population affected is the highest in Germany (40 000 pp yr^{-1} in both methods).

Additional information on the attribution of the flood risk in different areas of Europe can be obtained by looking at the different components contributing to the risk formula, namely hazard, exposure and vulnerability. Those are shown in Fig. 3, in the form of the maximum simulated flood return period (T) within 1990–2013 (Fig. 3a); potential population affected by a flood with a 100-year return period (Fig. 3b); potential damage of a flood with a 100-year return period (Fig. 3c) and return period of flood protection levels (Fig. 3d). Figure 3 denotes a rather complex distribution of the three risk components, though with a general trend of high exposure and low vulnerability in central Europe and England, which is opposed to a higher vulnerability and lower exposure in the outer regions. The hazard component in Fig. 3a gives information on the most extreme events simulated in the reference period 1990–2013. It is the main reason for the differences between event-based and integral method in Fig. 2, as the latter considers theoretical probabilities of occurrence of extreme events in place of their actual statistical distribution. Indeed, one can note how the most severe events are found in the Baltic states, eastern Europe and the Iberian Peninsula, thus justifying the corresponding larger impact estimates of the event-based method in Fig. 2.

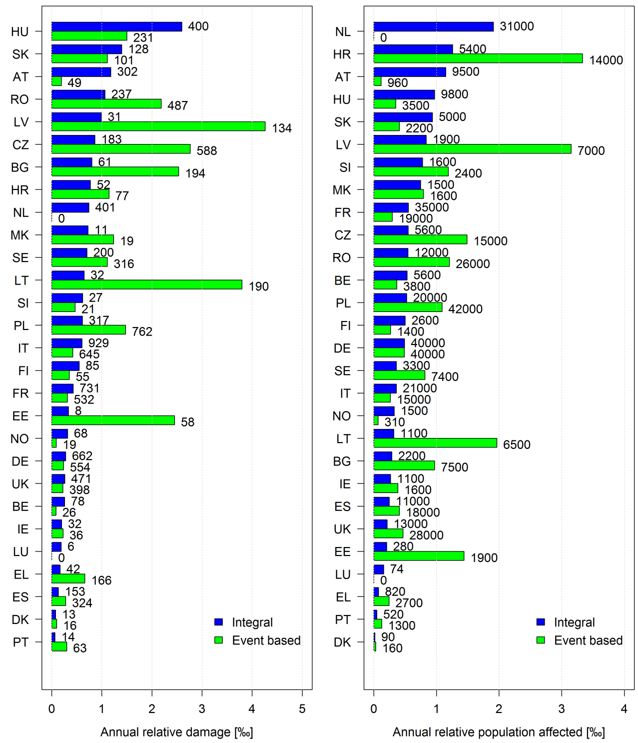

Figure 2. Annual relative damage and population affected for the considered European countries (ISO country code, see Table S2) between 1990 and 2013. Absolute figures are shown alongside each colour bar (in million Euros and people affected).

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 EUR 5 billion per year and population affected of 250 000 pp yr^{-1} over the time window 1998–2009. Aggregated figures for the same years derived through the event-based method herein proposed lead to EUR 5.4 billion per year and 220 000 pp yr^{-1}, while long-term averages of the integral method indicate EUR 5.9 billion per year and 239 000 pp yr^{-1}.

3.1 Integral method

The integral method is based on statistical frequencies of the occurrence of extreme events derived by analytical distributions. Hence, estimates of the average impact made with such an approach are also robust when applied to relatively small spatial aggregations. Estimates of annual damage and population affected at the NUTS 2 aggregation level are shown in Fig. 4. Average estimated impact among all the consid-

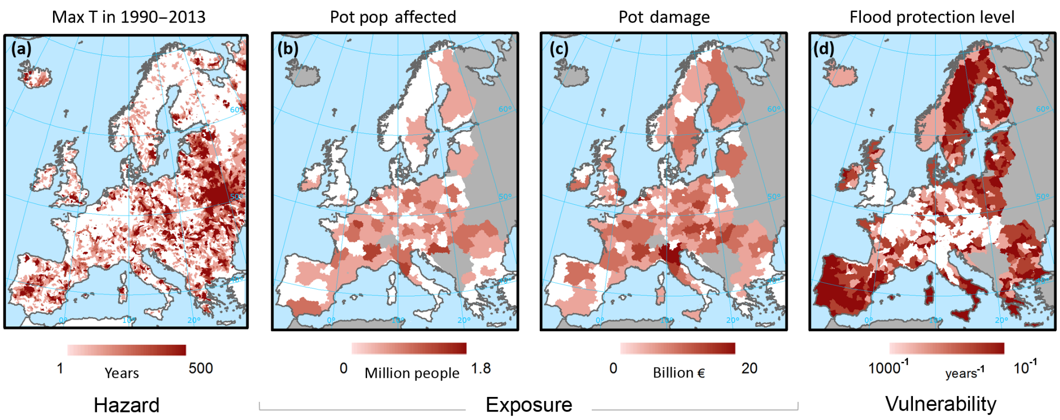

Figure 3. Modelled factors contributing to the overall flood risk: maximum simulated flood return period (T) within 1990–2013 **(a)**; potential population affected by a flood with a 100-year return period **(b)**; potential damage of a flood with a 100-year return period **(c)**; return period of flood protection levels **(d)**.

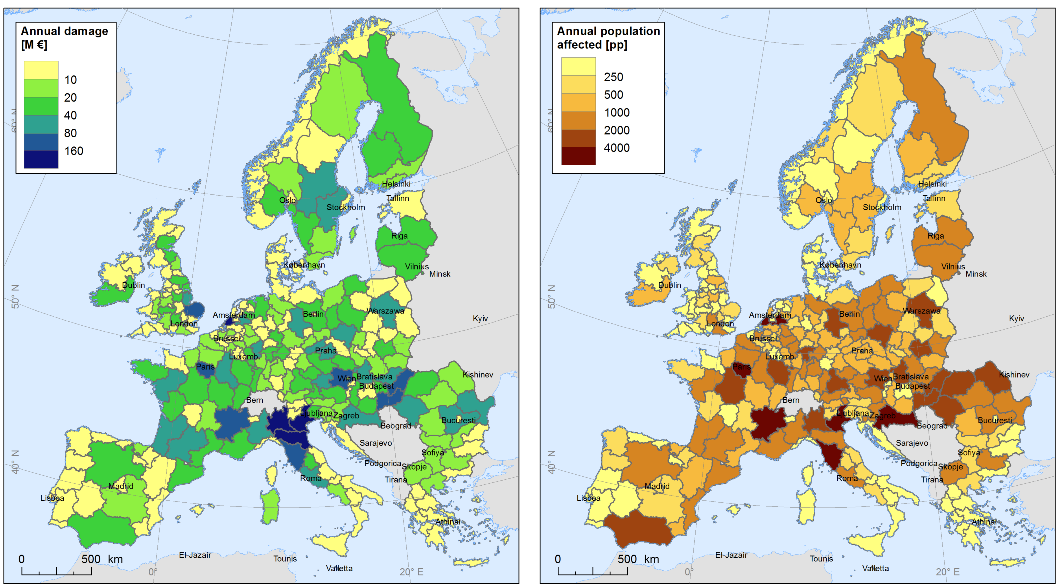

Figure 4. Mean annual damage and population affected at NUTS 2 level estimated through the integral method. Areas outside the simulation domain are masked in grey.

ered NUTS 2 regions amounts to EUR 21 million per year of damage and 900 pp yr^{-1} 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 (EUR 255 million per year of damage and 19 000 pp yr^{-1}) 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 areas 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, southern Italy, Croatia, Norway, the 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 modelled 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, based on post-event reports and estimates from insurance companies. 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 5 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, with a Pearson correlation coefficient of $R = 0.69$. The largest discrepancies are found in those years when the damage was higher (i.e. in 2002, 2010, 2013), though one should consider the substantial proportion of extrapolated damage in the validation dataset by DG Env (orange bars in Fig. 5) which poses the issue of its accuracy. 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 USD 5.7 billion (EM-DAT, 2015).

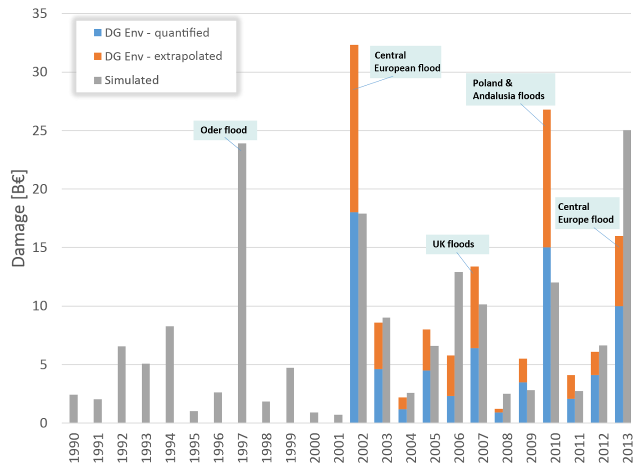

Figure 5. Annual estimates of flood damage in the EU over 1990–2013 (PPS of 2013) using the event-based method (in grey) and comparison with data by DG Env (Fenn et al., 2014).

Case study – central European floods in 2013

The catastrophic floods hitting central Europe in June 2013 were selected as a case study to test the performance of the event-based method for rapid risk mapping. This was a severe, large-scale event which affected several countries and led to the loss of lives as well as considerable damage in the Danube and Elbe river basins. The event was associated with a quasi-stationary upper-level low located north-east of the Alps and characterized by a significant contribution of orographic lifting (Pappenberger et al., 2013). Also, in the weeks leading up to the event, rainfall accumulations were significantly above normal in large parts of central Europe, exacerbating the run-off process. The return period of the discharge peaks was estimated to equal or exceed 100 years in various rivers including the Isar, Inn, Salzach, Danube, Elbe, Mulde, Saale, Rhine and Neckar (Zurich, 2014). Figure 6 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 EUR 100 million and population affected in excess of 5000. Aggregated estimates of direct damage in Germany, Austria and Czech Republic amount to EUR 10.9 billion and 360 000 people affected by the flood event. These estimates are in agreement with reported figures ranging between 11.4 and EUR 16 billion (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 an 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 Fig. 6 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 south-western Germany, often as a consequence of major dyke 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 neighbouring areas along the Vltava and Elbe rivers, and the overestimation of the flood damage in the Austrian regions of Salzburg and Upper Austria (EUR 1 billion reported vs. EUR 5 billion simulated). In the first case, reasons are found for 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 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.

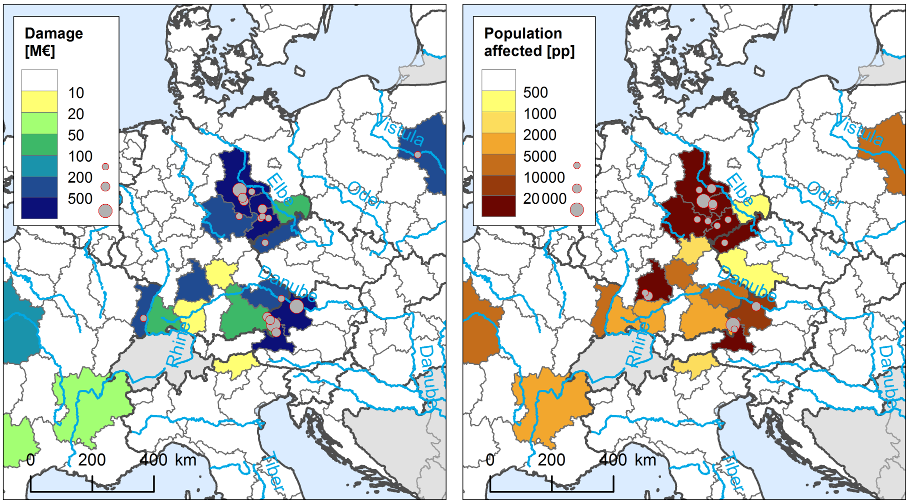

Figure 6. Estimates of damage and population affected (event-based method) in central Europe from 25 May to 10 June 2013. Grey circles indicate hotspots of simulated damage larger than EUR 100 million and population affected in excess of 5000. Areas outside the simulation domain are masked in grey.

4 Discussion

This work compares two methods of flood risk assessment based on a modelling framework and aims to stress their complementarity of use. While the integral approach has been extensively used and discussed in past research works, the event-based method has only found a few applications so far, due to the larger data requirements on the past climatic forcing in the form of seamless space–time hydrometeorological datasets. Hence, a dedicated discussion section is presented in the following.

4.1 Event-based method

When the event-based method is applied to sufficiently long time windows adequately representing 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 Fig. 2. Yet, the event-based approach is not suitable for estimating 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 Fig. 2), as for Luxembourg 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 temporal changes of the flood exposure (e.g. through land use changes and population growth) 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 precomputed 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.

4.2 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, a quantitative characterization of uncertainty was deliberately not included, so to stress the comparison between the two approaches shown.

In observed events, the impact of flood inundation is often caused by the collapse of flood protection measures at specific sites, which concentrates the damage in a certain area and reduces the likelihood of more flooding 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 in the impact assessment, flood risk is likely to be overestimated in those areas hit by a series of floods within a relatively short time range, as seen in Sect. "Case study – central European floods in 2013". Yet, this process can be accounted for in the proposed event-based method, provided that reliable vulnerability information is soon made available to improve future flood risk assessment.

4.3 Sources of uncertainty

In addition to the uncertainty related to the flood protections, the impact model discussed here is affected by a number of uncertainty sources which affect each stage of the modelling chain. Although no quantitative uncertainty analysis was performed in this work, a non-exhaustive list of potential uncertainty sources is presented in the following.

- Meteorological data: it is mostly associated to the transformation of point measurements to a seamless space–time dataset. Largest uncertainty is located in those areas with lower station density (e.g. in the Balkan countries, Ireland, Iberian peninsula), particularly in the early years of the dataset when the number of operating stations was smaller (Ntegeka et al., 2013).
- Streamflow data: it is related to the ability of the Lisflood model to accurately estimate the discharge time series in each point of the river network. Larger uncertainty is found in river basins where no calibration of the model parameters was possible (e.g. Portugal, southern Italy, Greece, Baltic states) and in several Spanish rivers, where the influence of regulation from reservoirs heavily affects the streamflow regime and the calibration performance (see Supplement).
- Extreme value analysis: it is linked to the choice of the extreme value distribution, which for simplicity is assumed to be of the same type (i.e. 2-parameter Gumbel distribution) for the entire European river network. In addition, larger uncertainty affects estimates of large return periods (i.e. up to 500 years) from samples of only 24 annual maxima.
- Flood depth and extent: most uncertainty in this stage is attributable to the quality of the digital elevation model, which in this case is derived from SRTM (Jarvis et al., 2008), with spatial resolution of 90 m and vertical noise of ~ 8.7 m over Europe (Rodriguez et al., 2006).
- Impact assessment: it is mainly related to the extrapolation of depth-damage functions for specific areas and countries to regional functions which depend on the land use class. Another source of uncertainty is related to the assumption of a constant population density layer over the simulation period, though it is expected to have a minor effect on the results due to the relatively low population growth (~ 5 %, see http://ec.europa.eu/eurostat/statistics-explained/index.php/Population_and_population_change_statistics) in the considered simulation period.

5 Conclusions

This work presents a comparison of two methods for reconstructing 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 used 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.

Results of this research show that the proposed model is a useful and relatively accurate tool for estimating the socio-economic impact of river floods in Europe, both with regard to long-term averages, over annual aggregations and for specific events. Despite the numerous sources of uncertainty potentially affecting the modelling chain, model results compare quantitatively well with flood impact data reported by EEA and DG Env at European scale. Also, one should note that the hydrological model Lisflood is the only component calibrated against the observed data. We propose this model as a valid alternative to filling in gaps of the database of socio-economic impact of floods, particularly in consideration of the following key points:

1. The model simulates the impact of all floods, independently from their magnitude.

2. The methodology is capable of retrieving comprehensive and capillary coverage of all the flood losses, which is often infeasible with alternative damage assessment methods.

3. Impact estimates of the proposed model can be produced as soon as the meteorological input data is available, hence potentially during the flood event itself, with a considerable time gain in comparison to post-event assessment.

As a 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 door 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.

The Supplement related to this article is available online at doi:10.5194/nhess-16-1401-2016-supplement.

Acknowledgements. The data used in this work were provided by the European Flood Awareness System (EFAS) and by publications listed in the references. Lorenzo Alfieri and Luc Feyen received financial support from the European Union Seventh Framework Programme FP7/2007-2013 under grant agreement no. 603864 (HELIX: "High-End cLimate Impacts and eXtremes"; http://www.helixclimate.eu).

Edited by: P. Tarolli
Reviewed by: Y. Chen and one anonymous referee

References

Alfieri, L., Salamon, P., Bianchi, A., Neal, J., Bates, P., and Feyen, L.: Advances in pan-European flood hazard mapping, Hydrol. Process., 28, 4067–4077, doi:10.1002/hyp.9947, 2014a.

Alfieri, L., Pappenberger, F., Wetterhall, F., Haiden, T., Richardson, D., and Salamon, P.: Evaluation of ensemble streamflow predictions in Europe, J. Hydrol., 517, 913–922, doi:10.1016/j.jhydrol.2014.06.035, 2014b.

Alfieri, L., Feyen, L., Dottori, F., and Bianchi, A.: Ensemble flood risk assessment in Europe under high end climate scenarios, Global Environ. Change, 35, 199–212, doi:10.1016/j.gloenvcha.2015.09.004, 2015.

Alfieri, L., Feyen, L., and Baldassarre, G. D.: Increasing flood risk under climate change: a pan-European assessment of the benefits of four adaptation strategies, Climatic Change, 136, 507–521, doi:10.1007/s10584-016-1641-1, 2016.

Aon Benfield: Annual Global Climate and Catastrophe Report, Impact Forecasting – 2013, Chicago, available at: http://thoughtleadership.aonbenfield.com/Documents/20140113_ab_if_annual_climate_catastrophe_report.pdf (last access: 14 June 2016), 2014.

Apel, H., Merz, B., and Thieken, A. H.: Quantification of uncertainties in flood risk assessments, Int. J. River Basin Manage., 6, 149–162, 2008.

Barredo, J. I., de Roo, A., and Lavalle, C.: Flood risk mapping at European scale, Water Sci. Technol., 56, 11–17, doi:10.2166/wst.2007.531, 2007.

Bates, P. D., Horritt, M. S., and Fewtrell, T. J.: A simple inertial formulation of the shallow water equations for efficient two-dimensional flood inundation modelling, J. Hydrol., 387, 33–45, 2010.

Batista e Silva, F., Lavalle, C., and Koomen, E.: A procedure to obtain a refined European land use/cover map, J. Land Use Sci., 8, 255–283, doi:10.1080/1747423X.2012.667450, 2012.

Batista e Silva, F., Gallego, J., and Lavalle, C.: A high-resolution population grid map for Europe, J. Maps, 9, 16–28, doi:10.1080/17445647.2013.764830, 2013.

Blöschl, G., Nester, T., Komma, J., Parajka, J., and Perdigão, R. A. P.: The June 2013 flood in the Upper Danube Basin, and comparisons with the 2002, 1954 and 1899 floods, Hydrol. Earth Syst. Sci., 17, 5197–5212, doi:10.5194/hess-17-5197-2013, 2013.

Broekx, S., Smets, S., Liekens, I., Bulckaen, D., and de Nocker, L.: Designing a long-term flood risk management plan for the Scheldt estuary using a risk-based approach, Nat. Hazards, 57, 245–266, doi:10.1007/s11069-010-9610-x, 2011.

Bubeck, P., Botzen, W. J. W., Kreibich, H., and Aerts, J. C. J. H.: Long-term development and effectiveness of private flood mitigation measures: an analysis for the German part of the river Rhine, Nat. Hazards Earth Syst. Sci., 12, 3507–3518, doi:10.5194/nhess-12-3507-2012, 2012.

Burek, P., Knijff van der, J., and Roo de, A.: LISFLOOD, distributed water balance and flood simulation model revised user manual 2013, Publications Office, Luxembourg, available at: http://dx.publications.europa.eu/10.2788/24719 (last access: 12 December 2014), 2013.

Chen, Y., Syvitski, J. P. M., Gao, S., Overeem, I., and Kettner, A. J.: Socio-economic impacts on flooding: A 4000-year history of the yellow river, China, Ambio, 41, 682–698, doi:10.1007/s13280-012-0290-5, 2012.

Di Baldassarre, G., Viglione, A., Carr, G., Kuil, L., Salinas, J. L., and Blöschl, G.: Socio-hydrology: Conceptualising human-flood interactions, Hydrol. Earth Syst. Sci., 17, 3295–3303, doi:10.5194/hess-17-3295-2013, 2013.

Di Baldassarre, G., Viglione, A., Carr, G., Kuil, L., Yan, K., Brandimarte, L., and Blöschl, G.: Debates – Perspectives on sociohydrology: Capturing feedbacks between physical and social processes, Water Resour. Res., 51, 4770–4781, doi:10.1002/2014WR016416, 2015.

EEA: Mapping the impacts of natural hazards and technological accidents in Europe – An overview of the last decade, European Environment Agency Technical report 13/2010, Copenhagen, Denmark, 144 pp., 2010.

EM-DAT: The OFDA/CRED International Disaster Database, Université Catholique de Louvain, Brussels, Belgium, http://www.emdat.be (last access: 14 June 2016), 2015.

European Commission: Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks, available at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32007L0060:EN:NOT (last access: 14 June 2016), 2007.

Falter, D., Dung, N. V., Vorogushyn, S., Schröter, K., Hundecha, Y., Kreibich, H., Apel, H., Theisselmann, F., and Merz, B.: Continuous, large-scale simulation model for flood risk assessments: proof-of-concept, J. Flood Risk Manage., 9, 3–21, doi:10.1111/jfr3.12105, 2016.

Falter, D., Schröter, K., Dung, N. V., Vorogushyn, S., Kreibich, H., Hundecha, Y., Apel, H. and Merz, B.: Spatially coherent flood risk assessment based on long-term continuous simulation with a coupled model chain, J. Hydrol., 524, 182–193, doi:10.1016/j.jhydrol.2015.02.021, 2015.

Fenn, T., Fleet, D., Hartman, M., Garrett, L., Daly, E., Elding, C., and Udo, J.: Study on economic and social benefits of environmental protection and resource efficiency related to the European semester final report, available at: http://ec.europa.eu/environment/integration/green_semester/pdf/RPA_Final_Report-main_report.pdf (last access: 30 April 2015), 2014.

Feyen, L., Dankers, R., Bódis, K., Salamon, P., and Barredo, J. I.: Fluvial flood risk in Europe in present and future climates, Climatic Change, 112, 47–62, 2012.

Foudi, S., Osés-Eraso, N., and Tamayo, I.: Integrated spatial flood risk assessment: The case of Zaragoza, Land Use Policy, 42, 278–292, doi:10.1016/j.landusepol.2014.08.002, 2015.

Hall, J. W., Sayers, P. B. and Dawson, R. J.: National-scale assessment of current and future flood risk in England and Wales, Nat. Hazards, 36, 147–164, 2005.

Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kim, H., and Kanae, S.: Global flood risk under climate change, Nat. Clim. Change, 3, 816–821, doi:10.1038/nclimate1911, 2013.

Hosking, J. R. M.: L-Moments: Analysis and Estimation of Distributions Using Linear Combinations of Order Statistics, J. Roy. Stat. Soc. B, 52, 105–124, 1990.

Huizinga, H. J.: Flood damage functions for EU member states, HKV Lijn in water, Lelystad, the Netherlands, 67 pp., 2007.

IPCC: 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, edited by: Field, C. B., Barros, V., Stocker, T. F., Qin, D., Dokken, D. J., Ebi, K. L., Mastrandrea, M. D., Mach, K. J., Plattner, G.-K., Allen, S. K., Tignor, M., and Midgley, P. M., Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp., 2012.

Jarvis, A., Reuter, H. I., Nelson, A., and Guevara, E.: Hole-filled SRTM for the globe Version 4, available at CGIAR-CSI SRTM 90 m Database: http://srtm.csi.cgiar.org (last access: 14 June 2016), 2008.

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.: Comparative flood damage model assessment: towards a European approach, Nat. Hazards Earth Syst. Sci., 12, 3733–3752, doi:10.5194/nhess-12-3733-2012, 2012.

Jongman, B., Hochrainer-Stigler, S., Feyen, L., Aerts, J. C. J. H., Mechler, R., Botzen, W. J. W., Bouwer, L. M., Pflug, G., Rojas, R., and Ward, P. J.: Increasing stress on disaster-risk finance due to large floods, Nat. Clim. Change, 4, 264–268, doi:10.1038/nclimate2124, 2014.

Jongman, B., Winsemius, H. C., Aerts, J. C. J. H., Coughlan De Perez, E., Van Aalst, M. K., Kron, W. and Ward, P. J.: Declining vulnerability to river floods and the global benefits of adaptation, P. Natl. Acad. Sci. USA, 112, E2271–E2280, doi:10.1073/pnas.1414439112, 2015.

Kamari, J., Alcamo, J., Barlund, I., Duel, H., Farquharson, F. A. K., Florke, M., Fry, M., Houghton-Carr, H. A., Kabat, P., Kaljonen, M., Kok, K., Meijer, K. S., Rekolainen, S., Sendzimir, J., Varjopuro, R., and Villars, N.: Envisioning the future of water in Europe – the SCENES project, E-WAter, European Water Association (EWA), 1–28, 2008.

Koivumäki, L., Alho, P., Lotsari, E., Käyhkö, J., Saari, A., and Hyyppä, H.: Uncertainties in flood risk mapping: a case study on estimating building damages for a river flood in Finland, J. Flood Risk Manage., 3, 166–183, doi:10.1111/j.1753-318X.2010.01064.x, 2010.

Kron, W.: Flood Risk = Hazard Values Vulnerability, Water Int., 30, 58–68, doi:10.1080/02508060508691837, 2005.

Lugeri, N., Kundzewicz, Z. W., Genovese, E., Hochrainer, S., and Radziejewski, M.: River flood risk and adaptation in Europe – assessment of the present status, Mitig. Adapt. Strat. Glob. Change, 15, 621–639, doi:10.1007/s11027-009-9211-8, 2010.

Maione, U., Mignosa, P., and Tomirotti, M.: Regional estimation of synthetic design hydrographs, Int. J. River Basin Manage., 1, 151–163, 2003.

Merz, B., Kreibich, H., Schwarze, R., and Thieken, A.: Review article "Assessment of economic flood damage", Nat. Hazards Earth Syst. Sci., 10, 1697–1724, doi:10.5194/nhess-10-1697-2010, 2010.

Munich Re: Natural catastrophes 2013: Analyses, assessments, positions, Munich, available at: http://www.munichre.com/site/corporate/get/documents_E435413367/mr/assetpool.shared/Documents/0_Corporate_Website/_Publications/302-08121_en.pdf (last access: 14 June 2016), 2014.

Neal, J., Villanueva, I., Wright, N., Willis, T., Fewtrell, T., and Bates, P.: How much physical complexity is needed to model flood inundation?, Hydrol. Process., 26, 2264–2282, doi:10.1002/hyp.8339, 2012.

Ntegeka, V., Salamon, P., Gomes, G., Sint, H., Lorini, V., Thielen, J. and Zambrano-Bigiarini, M.: EFAS-Meteo: A European daily high-resolution gridded meteorological data set for 1990-2011, available at: http://publicationsjrceceuropa.ourtownypd.com/repository/handle/111111111/30589 (last access: 3 June 2014), 2013.

Pappenberger, F., Dutra, E., Wetterhall, F., and Cloke, H. L.: Deriving global flood hazard maps of fluvial floods through a physical model cascade, Hydrol. Earth Syst. Sci., 16, 4143–4156, doi:10.5194/hess-16-4143-2012, 2012.

Pappenberger, F., Wetterhall, F., Albergel, C., Alfieri, L., Balsamo, G., Bogner, K., Haiden, T., Hewson, T., Magnusson, L., de Rosnay, P., Muñoz Sabater, J., and Tsonevsky, I.: Floods in Central Europe in June 2013, ECMWF Newslett., 136, 9–11, 2013.

Penning-Rowsell, E. C.: A realistic assessment of fluvial and coastal flood risk in England and Wales, Trans. Inst. Br. Geogr., 40, 44–61, doi:10.1111/tran.12053, 2015.

Rodriguez, E., Morris, C. S., and Belz, J. E.: A global assessment of the SRTM performance, Photogram. Eng. Remote Sens., 72, 249–260, 2006.

Rojas, R., Feyen, L., and Watkiss, P.: Climate change and river floods in the European Union: Socio-economic consequences and the costs and benefits of adaptation, Global Environ. Change, 23, 1737–1751, doi:10.1016/j.gloenvcha.2013.08.006, 2013.

Sampson, C., Smith, A., Bates, P., Neal, J., Alfieri, L., and Freer, J.: A high-resolution global flood hazard model, Water Resour. Res., 51, 7358–7381, doi:10.1002/2015WR016954, 2015.

Schröter, K., Kunz, M., Elmer, F., Mühr, B., and Merz, B.: What made the June 2013 flood in Germany an exceptional event? A hydro-meteorological evaluation, Hydrol. Earth Syst. Sci., 19, 309–327, doi:10.5194/hess-19-309-2015, 2015.

Schumann, G. J.-P., Neal, J. C., Voisin, N., Andreadis, K. M., Pappenberger, F., Phanthuwongpakdee, N., Hall, A. C., and Bates, P. D.: A first large-scale flood inundation forecasting model, Water Resour. Res., 49, 6248–6257, doi:10.1002/wrcr.20521, 2013.

Swiss Re: Sigma preliminary estimates: natural catastrophes and man-made disasters in 2013 cost insurers worldwide USD 44 billion, Zurich, available at: http://media.swissre.com/documents/nr_20131218_sigma_Nat_Cat_2013_EN.pdf (last access: 14 June 2016), 2013.

te Linde, A. H., Bubeck, P., Dekkers, J. E. C., de Moel, H., and Aerts, J. C. J. H.: Future flood risk estimates along the river Rhine, Nat. Hazards Earth Syst. Sci., 11, 459–473, doi:10.5194/nhess-11-459-2011, 2011.

Thielen, J., Bartholmes, J., Ramos, M.-H., and de Roo, A.: The European Flood Alert System – Part 1: Concept and development, Hydrol. Earth Syst. Sci., 13, 125–140, doi:10.5194/hess-13-125-2009, 2009.

UNISDR: UNISDR Terminology on disaster risk reduction, United Nations International Strategy for Disaster Reduction (UNISDR), Geneva, Switzerland, 35 pp., 2009.

van der Knijff, J. M., Younis, J., and de Roo, A. P. J.: LISFLOOD: A GIS-based distributed model for river basin scale water balance and flood simulation, Int. J. Geogr. Inf. Sci., 24, 189–212, 2010.

Vogel, R. M. and Fennessey, N. M.: L moment diagrams should replace product moment diagrams, Water Resour. Res., 29, 1745–1752, 1993.

Ward, P. J., Jongman, B., Weiland, F. S., Bouwman, A., van Beek, R., Bierkens, M. F. P., Ligtvoet, W., and Winsemius, H. C.: Assessing flood risk at the global scale: model setup, results, and sensitivity, Environ. Res. Lett., 8, 044019, doi:10.1088/1748-9326/8/4/044019, 2013.

Wind, H. G., Nierop, T. M., De Blois, C. J., and De Kok, J. L.: Analysis of flood damages from the 1993 and 1995 Meuse floods, Water Resour. Res., 35, 3459–3465, doi:10.1029/1999WR900192, 1999.

Winsemius, H. C., Van Beek, L. P. H., Jongman, B., Ward, P. J., and Bouwman, A.: A framework for global river flood risk assessments, Hydrol. Earth Syst. Sci., 17, 1871–1892, doi:10.5194/hess-17-1871-2013, 2013.

Winsemius, H. C., Aerts, J. C. J. H., van Beek, L. P. H., Bierkens, M. F. P., Bouwman, A., Jongman, B., Kwadijk, J. C. J., Ligtvoet, W., Lucas, P. L., van Vuuren, D. P., and Ward, P. J.: Global drivers of future river flood risk, Nat. Clim. Change, 6, 381–385, doi:10.1038/nclimate2893, 2016.

Zambrano-Bigiarini, M. and Rojas, R.: A model-independent Particle Swarm Optimisation software for model calibration, Environ. Model. Softw., 43, 5–25, doi:10.1016/j.envsoft.2013.01.004, 2013.

Zurich: Risk Nexus, Central European floods 2013: a retrospective, available at: http://www.zurich.com/_/media/dbe/corporate/docs/whitepapers/risk-nexus-may-2014-central-european-floods-2013.pdf (last access: 14 June 2016), 2014.