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# Benchmarking an operational procedure for rapid risk assessment in Europe

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## *Abstract*

The development of methods for rapid flood mapping and risk assessment is a key step to increase the usefulness of flood early warning systems, and is crucial for effective emergency response and flood impact mitigation. Currently, flood early warning systems rarely include real–time components to assess potential impacts generated by forecasted flood events. To overcome this limitation, this work describes the benchmarking of an operational procedure for rapid flood risk assessment based on predictions issued by the European Flood Awareness System (EFAS). Daily streamflow forecasts produced for major European river networks are translated into event-based flood hazard maps using a large map catalogue derived from high-resolution hydrodynamic simulations. Flood hazard maps are then combined with exposure and vulnerability information, and the impacts of the forecasted flood events are evaluated in terms of flood prone areas, economic damage and affected population, infrastructures and cities.
An extensive testing of the operational procedure is carried out by analysing the catastrophic floods of May 2014 in Bosnia-Herzegovina, Croatia and Serbia. The reliability of the flood mapping methodology is tested against satellite-based and report-based flood extent data, while ground-based estimations of economic damage and affected population are compared against modelled estimates. Finally, we evaluate the skill of risk estimates derived from EFAS flood forecasts with different lead times and combinations of probabilistic forecasts. Results show the potential of the real-time operational procedure in helping emergency response and management.

## *1) Introduction*

Nowadays, flood early warning systems (EWS) have become key components of flood management strategies in many rivers (Cloke et al., 2013; Alfieri et al., 2014a). They can increase

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preparedness of authorities and population, thus helping reduce negative impacts (Pappenberger et al., 2015). Early warning is particularly important for cross-border river basins where cooperation between authorities of different countries may require more time to inform and coordinate actions (Thielen et al., 2009).

In this context, the European Commission has developed the European Flood Awareness System (EFAS) which provides operational flood predictions in major European rivers as part of the Copernicus Emergency Management Services. The service is fully operational since 2012 and available to hydro-meteorological services with responsibility in flood warning, EU civil protection and their network.

While early warning systems are routinely used to predict flood magnitude, there is still a gap in the ability to translate flood forecasts into risk forecasts, that is, to evaluate the possible impacts generated by forecasted events (e.g. flood prone areas, affected population, flood damages losses). Currently, flood impacts are generally evaluated considering static flood scenarios, either related to official maps issued by the competent authorities (EC 2007) or to synthetic events derived from current or future climatology (Alfieri et al., 2015), which implies some degree of manual interpretation of forecasts to delineate flood prone areas and define impacts. A few research projects are being developed where flood impact estimation is automated and linked to event forecasting (Rossi et al., 2015; Schulz et al., 2015; Saint-Martin et al., 2016), however to our knowledge these systems are still at experimental phase, and not yet integrated into operational EWS.

Indeed, the availability of real-time operational systems for assessing potential consequences of forecasted events would be a substantial advance in helping emergency response, and indeed flood impact forecasts are increasingly being requested by end users of early warning systems (Emerton et al., 2016; Ward et al., 2016). At local scale, impact forecasting may provide valuable information to alert local civil protection services and plan measures to increase preparedness, for instance monitoring and strengthening flood defences and planning evacuation measures. At European scale, the possibility to receive prior information on expected flood impacts would increase preparedness and response time of the Emergency Response Coordination Centre (ERCC), in order to plan and coordinate support for national emergency services.

In the present paper, we describe a methodology designed to meet the needs of EWS users and overcome the limitations mentioned so far. The methodology translates EFAS flood forecasts into event-based flood hazard maps, and combines hazard, exposure and vulnerability information to produce risk estimations in near-real time. All the components are fully integrated within the EFAS forecasting system, thus providing seamless risk forecasts at European scale.

To demonstrate the reliability of the proposed methodology, we perform a detailed assessment focused on the 2014 floods in the Sava River Basin in Southeast Europe. A large dataset for the evaluation and validation of the results has been collected, which consists of observed flood magnitude, flood extent derived from different satellite imagery datasets, and detailed post-event evaluation of flood impacts, economic damage assessment and affected population and infrastructure.

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The reliability of the flood mapping procedure is first assessed by assuming a "perfect" forecast, where flood magnitude is taken from real observations instead of EFAS predictions. The effect of flood defences failure is also taken into account. After that, we test the performance of the operational flood forecasting procedure, to evaluate the influence of different lead times and combination of forecast members.

## 2) Methodology

In this section we describe the three components which compose the rapid risk assessment procedure: 1) streamflow and flood forecasting; 2) event-based rapid flood mapping 3) impact assessment. Figure 1 shows a conceptual scheme of the step composing the methodology.

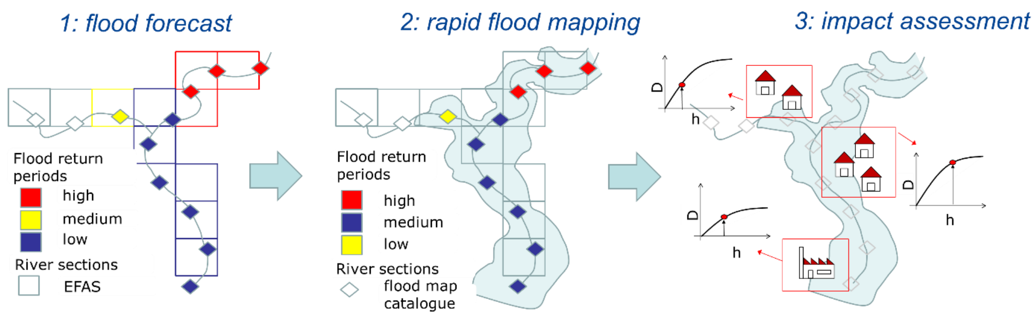


*Figure 1: conceptual scheme of the rapid risk assessment procedure*

The basic workflow of the procedure is the following:

- Every time a flood event is forecasted, we identify the river sections affected and local flood magnitude, (expressed as return period of the peak discharge);
- we identify areas which might be flooded using a the map catalogue, which contains all the flood prone areas for each river section and flood magnitude; these local flood maps are then combined to derive event-based hazard maps:
- Event hazard maps are combined with exposure information to assess affected population, infrastructures and urban areas, and economic damage.

The following sections provide a detailed description of each component.

### 2.1 The European Flood Awareness System (EFAS)

The European Flood Awareness System (EFAS) produces streamflow forecasts for Europe using a hydrological model driven by daily weather forecasts. We provide here a general description of the EFAS components, the reader is referred to the website (www.efas.eu) and to published

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literature for further details (Thielen et al., 2009; Pappenberger et al., 2011; Cloke et al., 2013; Alfieri et al., 2014a).

Hydrological simulations in EFAS are performed with Lisflood (Burek et al, 2013; van der Knijff et al., 2010), a distributed physically based rainfall-runoff model combined with a routing module for river channels. The model is calibrated at European scale using streamflow data from a large number of river gauges and meteorological fields interpolated from point measurements of precipitation and temperature. Based on this calibration, a reference hydrological simulation for the period 1990-2013 is run for the European window at 5 km grid spacing, and updated daily. This reference simulation provides initial conditions for daily forecast runs of the Lisflood model driven by the latest weather predictions, which are provided twice per day with lead times up to 10 days. To evaluate the magnitude of streamflow forecasts in every grid point of the simulation domain, these are compared with local discharge thresholds, statistically evaluated from the reference simulation (Alfieri et al., 2014a). In case thresholds are exceeded persistently over several forecasts, flood warnings for the affected locations are issued to the members of the EFAS consortium.

To account for the inherent uncertainty of the weather forecast, EFAS adopts a multi-model ensemble approach, running the hydrological model with forecasts provided by the European Centre for Medium Weather Forecast (ECMWF), the Consortium for Small-scale Modelling (COSMO), and the Deutscher Wetterdienst (DWD),

## *2.2 Database of flood hazard maps*

Linking streamflow forecast with inundation mapping is complex because inundation modelling tools are computationally much more demanding than hydrological models used in early warning systems, which currently prevent a real time integration of these two components. To overcome this limitation, in the present work we decided create a catalogue of flood inundation maps covering all the EFAS river network and linked to EFAS streamflow forecast.

The hydrological input for creating the map catalogue is derived from the stream flow dataset of the EFAS reference simulation, described in Section 2.1. The information is available on the EFAS river network at 5 km grid spacing for rivers with upstream drainage areas larger than 500 $km^2$. The streamflow data is downscaled to a high-resolution river network (100m), where reference sections are identified at regular spacing along stream-wise direction each 5km. Figure 2 shows a conceptual scheme of the two river networks. For each of these reference sections, a statistical analysis of extreme value analysis is applied to derive discharge values for several reference return periods (10, 20, 50, 100, 200 and 500 years), which are then combined with flow duration curves to produce flood hydrographs (see Alfieri et al., 2014b for a detailed description).

The hydrographs are used to run flood simulations at 100 m resolution in each river section using the 2D hydrodynamic model LISFLOOD-FP (Bates et al., 2010).

The 100m flood maps related to the same EFAS river section (i.e. pixel of the 5km river network) are merged together, to identify the areas at risk of flooding because of overflowing from a

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specific EFAS river section, and archived in the flood map catalogue. The merging is performed separately for each return period, in order to relate flooded areas with the magnitude of the flood event.

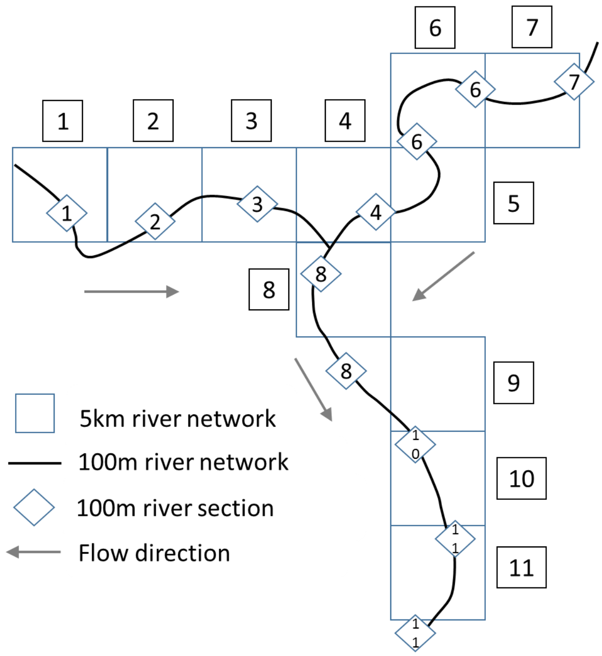


*Figure 2: conceptual scheme of the EFAS river network (5 km, squares) with the high resolution network (100m) and river sections (diamonds) where flood simulations are derived. The sections of the two networks related are indicated by the same number. Adapted from Dottori et al. (2015).*

## *2.3 Event-based mapping of flood hazard*

The database of flood hazard maps described in Section 2.2 is used to translate the information coming from EFAS discharge forecasts into event-based estimations of flood extent. Since the EFAS daily predictions are provided as an ensemble of forecasts, the procedure to identify flood prone areas and flood magnitude is also carried out in a probabilistic framework.

We first identify the maximum discharge predicted over the full forecasting period, calculated using the median discharge from ensemble forecasts at each river grid cell. The value is compared with the reference long-term climatology to calculate the return period.

Then, predicted streamflow is compared with the local flood protection level, and river grid cells where the protection level is exceeded are considered to activate the complete risk assessment procedure.

Flood protection levels are given as the return period of the maximum flood event which can be retained by the defence measures (e.g. dykes). The map of flood protections used is based on risk-based estimations for Europe developed by Jongman et al. (2014), integrated, where available, with the actual level of protection found from literature review or assessed by local authorities. Selected river cells are reclassified into classes according to the closest return period exceeded (10, 20, 50, 100, 200, 500 years) and the corresponding flood hazard maps are retrieved from the catalogue and tiled together. For instance, if the estimated return period is 40 years, the flood map for 20 years return period is used. Where more maps related to more river sections overlap (see Section 2.2), the maximum depth value is taken.

### 2.4 Flood impact and risk assessment

After the event-based flood hazard map has been completed, it is combined with the available information defining the exposure and vulnerability at European scale.
The number of people affected is calculated using the population map developed by Batista e Silva et al. (2012) at 100m resolution. A detailed database of infrastructures produced by Marín Herrera et al. (2015) is used to compute the extension of the road network affected during the flood event. The list of major towns and cities potentially affected within the region is derived from an internally developed map of major urban areas. The total extension of urban and built-up areas (differentiated between residential, commercial and industrial areas) and agricultural areas is computed using the latest update of the Corine Land Cover for the year 2006.
The land use layer is also used as asset exposure information to compute direct economic losses in combination with flood hazard variables (flood extent and depths) and depth-damage functions, following the approach applied by Jongman et al. (2012), Rojas et al. (2013) and Alfieri et al. (2015). The set of empirical damage functions derived for European countries by Huizinga (2007) have been elaborated to produce separate functions for the land use classes that are more vulnerable to flooding (residential, commercial, industrial, agricultural). To account for the variable value of assets within one country, damage values are corrected considering the ratio between the gross domestic product (GDP) of regions (identified according to the Nomenclature of Territorial Units for Statistics (NUTS), administrative level 1) and country's GDP. To enable the application of the methodology in all the EFAS domain, additional damage curves have been derived for countries not included in the original database, like Serbia and Bosnia-Herzegovina.
All the results computed during the risk assessment procedure are aggregated using the classification of EU regions of EUMetNet (the network of European Meteorological Services, www.meteoalarm.eu). The regions considered are based on the levels 1 and 2 of the NUTS classification, according to the EU country, with the advantage of providing areas of aggregation with a comparable extent.
In the operational system, the described procedure is fully integrated in the EFAS forecast analysis chain. When a new EFAS hydrological forecast becomes available, the risk assessment procedure is activated in those locations where predicted peak discharges exceeds the flood protection levels. When activated, the execution time depends on the extent and spatial spread of the potentially affected areas over the full forecasting domain. Even in case of flood events

occurring simultaneously in different European countries, the results of the analysis are delivered within one hour after the EFAS forecast runs are finished.

## *3) Benchmarking of the procedure*

In order to perform a comprehensive evaluation of the risk assessment procedure, it is important to evaluate each component of the methodology, namely, streamflow forecasts, event-based flood mapping, and the impact assessment. The skill of EFAS streamflow forecasts is routinely evaluated (Pappenberger et al., 2011) while impact assessment was successfully applied by Alfieri et al. (2016) to evaluate socio-economic impacts of river floods in Europe for the period 1990-2013. Here, the complete procedure is tested using the information collected for the catastrophic floods of May 2014, which affected several countries in Southeast Europe. In particular, we focus on the flooding of the Sava River in Bosnia-Herzegovina, Croatia and Serbia.

### *3.1 The floods in Southeast Europe in May 2014*

Exceptionally intense rainfalls from 13 May 2014 onwards following weeks of wet conditions led to disastrous and wide spread flooding and landslides in South-eastern Europe, in particular Bosnia-Herzegovina and Serbia. In these two countries, the flood events have been reported to be the worst for over 200 years. Over 60 people lost their lives and more than a million inhabitants were estimated to be affected, while the estimated damages and losses exceeded 1.1 billion Euro for Serbia and 2 billion Euro for Bosnia-Herzegovina (ECMWF, 2014; ICPDR and ISRBC, 2015). Critical flooding was also reported in other countries including Croatia, Romania and Slovakia. Serbia and Croatia requested and obtained access to the EU Solidarity Fund for major national disasters (EC 2016).
According to the technical report issued by the International Commission for the Protection of the Danube River and the International Sava River Basin Commission (ICPDR and ISRBC, 2015), the flood events were particularly severe in the middle-lower course of the Sava River and in several tributaries. The discharge measurements and estimations carried out between 14 and 17 May indicated that the peak flow magnitude exceeded the 500 years return period both in the Bosna and Kolubara rivers and in part of the Sava River downstream of the confluence with Bosna. Discharges above 50 years were observed in the Una, Vrbas, Sana and Drina rivers (Figure 3).

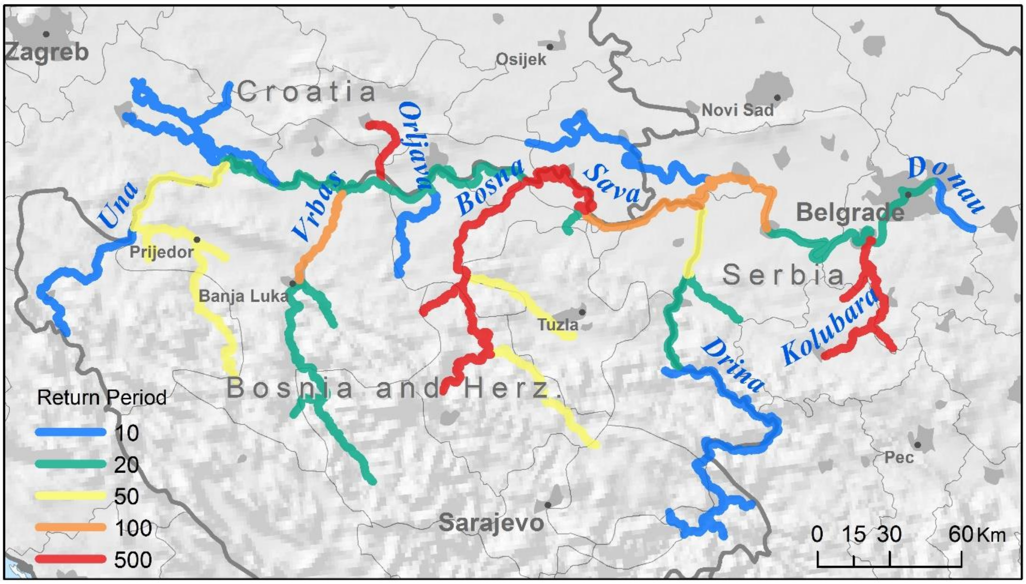


*Figure 3. Reconstruction of return period of peak discharges in Sava River basin (source: ICPDR and ISRBC, 2015).*

The lower reach of the Sava was less heavily affected because upstream flooding reduced peak discharges and hydraulic operations on the Danube hydraulic structures reduced water levels in the Danube (ICPDR and ISRBC, 2015). As a result, multiple dyke breaches occurred along the Sava River, and severe flooding occurred at the confluence of tributaries like Bosna, Drina and Kolubara due to the extreme discharges (Figure 4). In many areas, dykes were reinforced and heightened during the flood event to withstand the peak flow; also, additional temporary flood defences were built to prevent further flooding, and drains were dug to drain flooded areas more quickly. Other rivers in the area experienced severe flood events, such as the tributaries of the Danube Velika Morava and Mlava, in Serbia.

Table 1 reports a summary of flood impacts at national level for Bosnia-Herzegovina, Croatia and Serbia, retrieved from different sources.

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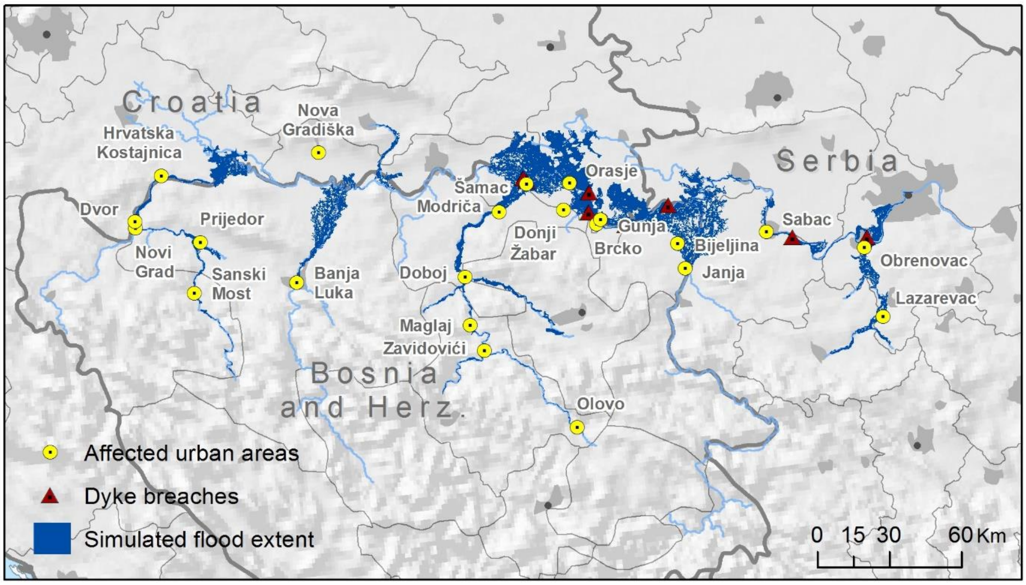


*Figure 4. Reconstruction of affected urban areas and dyke failure locations along the Sava River (sources: UNDAC, 2014; ICPDR and ISRBC, 2015). The flood extent of the reference simulation with the proposed procedure is also shown (see Section 3.2).*

| | Flooded area ($km^2$) | Casualties[1] | Affected population[1] | Evacuated population[1] | Economic impact (M€) |
|---|---|---|---|---|---|
| Bosnia-Herzegovina | 266.3[1]; 831[2] | 25 | 1.6 million | 90000 | 2040 |
| Croatia | 53.5[1] ; 110[3]; 210[4] | 3 | 38000 | 15000 | 300 |
| Serbia | 22.4[1] ; 221[3]; 350[5] | 51 | 1 million | 32000 | 1530[1] |

*Table 1. Summary of flood impacts at national level. Figures have been retrieved from the following sources: 1- ICPDR and ISRBC (2015); 2- Bosnia-Herzegovina Mina Action Center (BHMAC, Bajic et al 2015); 3– Copernicus EMS Rapid Mapping Service; 4- Wikipedia (2016); 5- GeoSerbia geoportal (2016).*

## 3.2 Evaluation of the flood hazard mapping procedure

We considered in our analysis the river network of the Sava River basin, where some of the most affected areas are located and for which detailed information is available from various reports.

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To evaluate the skill of the flood hazard mapping procedure, we used observed flood magnitudes (Figure 3) to identify the return period of peak discharges and thus select the appropriate flood maps. In addition, we used the information on flood protection level and dyke failures to select only those river sections where flooding actually occurred, either because of defence failures or exceeding discharge. The resulting flood hazard map will be named from now on as "reference simulation". Such a procedure excludes the uncertainty due to the hydrological input from the analysis, focusing on the evaluation of the flood hazard mapping approach alone. In other words, the test can be seen as an application of the procedure in case of a single, deterministic and "perfect" forecast. The resulting inundation map is displayed in Figure 4.

It is important to note that a margin of uncertainty remains because of the emergency measures taken during the event. In several river sections of the Sava River, the flood defences were actually able to withstand discharges well above their design value, thanks to timely emergency measures such as the heightening and strengthening of dykes. Moreover, the preparation of temporary flood defences in the floodplains helped to protect some areas which would have been otherwise flooded. A further issue of the methodology is that, where flood protections are exceeded, flooding can occur on both river banks, while in case of dyke failure flooding is usually limited to one side where protection level is lower. This has not been corrected and therefore the results are affected by this limitation.

The flood events in the Sava River have been mapped by several agencies and institutions using both ground observations and satellite imagery (see UN SPIDER 2014 for a complete list). The most comprehensive flood maps were developed by the Copernicus Emergency Management System (EMS) using Sentinel-1 data (EMS, 2014), and by NASA using MODIS Aqua (2014). For Serbia, the Republic Geodetic authority has acquired and processed further satellite images, which are available on the geoportal GeoSerbia (2016).

Despite this large amount of data sources available, the evaluation of the simulated flood extent is not straightforward. All the available images have been acquired during the flood recession (from 19 May onwards), while flood peaks in flooded areas where observed between 15 and 17 May 15 and 17. Therefore, several areas which have been reported as flooded in the available documentation are not included in the detected flood footprints, which results in a significant difference between satellite-detected and reported flood extent from ground surveys (see Table 1). On the other hand, EMS satellite maps are designed to produce a low rate of false positive errors, therefore they can be considered as a "lower limit" for the real flood extent. Finally, it has to been considered that the available sources of information report for each country different extents of flooded area, as can be seen in Table 1.

In order to take into account these issues, we first compare the total simulated and reported flood extent, considering all the available reported data. Then, we evaluate the agreement between satellite-derived and simulated flood extent using the hit ratio H (Alfieri et al., 2014b). The index measures the extent of observed flooded area included into estimations and it is defined as:

$$H = (Fm \cap Fo)/(Fo\ ) \times 100 \qquad (1)$$

where $Fm \cap Fo$ is the area correctly predicted as flooded by the model, and $Fo$ is the total observed flooded area. As a further element, we compare the number of urban areas (cities, towns and villages) which were reported as flooded in existing reports.

### *3.2 Evaluation of forecast-based flood maps*

To evaluate the overall performance of forecast-based flood mapping, we considered the EFAS forecasts issued on 12 and 13 May for the Sava river basin, that is, immediately before the occurrence of first flood events on 14 May. We first applied the procedure described in Section 2.3 to derive peak discharges and the estimated return period using the median of the EFAS ensemble forecasts. To provide an indication of the possible range of risk scenarios, we produced additional flood hazard maps with the same procedure considering the 25 and 75 percentiles of discharge.

The forecast-based flood hazard maps are evaluated against the reference simulation, comparing the river sectors and the urban areas (or municipalities) at risk of flooding. Note that no direct comparison against observation-based flood maps has been carried out, because forecast-based maps cannot account for defence failures or strengthening.

### *3.3 Evaluation of the flood risk assessment*

Inundation maps derived from the reference simulation and flood forecasts have been used to compute the flood impacts in terms of number of affected people, affected major towns and cities, and economic damage.

The results are compared with the available impact estimations both at national and local level. For Serbia and Bosnia-Herzegovina, the national figures reported in Table 1 are referred to the total impact given by river floods, landslides and pluvial floods, therefore they cannot be directly compared with methodology results. As such, the comparison has been done only for Croatia and for a number of municipalities (e.g. Obrenovac in Serbia) where impacts can be attributed to river flooding alone.

The figures of affected population simulated with the observation-based flood scenario are also useful to test the reliability of the population map used as exposure dataset. Similarly, damage estimations coming from the observation-based scenario provide an indication of the reliability of depth-damage curves for the study area.

As done for the flood hazard maps, forecast-based risk estimations are evaluated against the observation-based estimations, comparing both population and damage figures. Note that other variables produced by the operational procedure (e.g. roads affected, flooded urban and agricultural areas) could not be tested due to the lack of observed data and therefore are not discussed here. To add a further term of comparison, affected population has been computed using Copernicus-EMS flood footprints.

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## 4) Results and discussions

The results of the validation exercise are shown and discussed separately for each component of the procedure.

### 4.1 Flood hazard mapping

Table 3 reports the observed flood extent data from different sources and the simulated extent derived from the reference simulation (.i.e. the mapping procedure applied on discharge observations). Table 4 reports the scores of the hit ratio H for a number of flooded river sections, together with a comparison of towns flooded according to simulations and observation.

| **Country** | Flood extent (km$^2$) | | | |
|---|---|---|---|---|
| | Simulated | Satellite | Reported by ICPDR-ISRBC | Reported (other sources) |
| ***Bosnia - Herzegovina*** | 995 | 339 | 266.3 (1) | 831 (2) |
| ***Croatia*** | 919 (319) | 110 | 53.5 (1) | >210 (3) |
| ***Serbia*** | 582 | 221 | 22.4 (1) | >350 (4) |

*Table* 3. *Comparison of observed and simulated flood extent data at country scale. Satellite flood extent is referred to Copernicus EMS maps. The value between parentheses for Croatia is based on a modified simulation, as explained in the text. Reported flood extent has been retrieved from the following sources: 1- ICPDR and ISRBC (2015); 2- BHMAC(Bajic et al 2015); 3- Wikipedia (2016); 4 – GeoSerbia geoportal (2016).*

| **Affected areas** | **Hit ratio** | **EMS flooded area (km$^2$)** | **Affected towns and cities** |
|---|---|---|---|
| Bosna River | 90.6% | 58.46 | Maglaj, Doboj, Modriča |
| Sava River between confluences with Bosna and Drina | 63.9% | 134.76 | Orašje, Šamac, Donji Žabar, Brcko, Gunja, (Zupanja), Bijeljina |
| Sava River between confluences with Drina and Kolubara | 83.7% | 405.43 | Sabac, Obrenovac, Lazarevac |
| Total | 79.9% | 598.65 | |

Table 4. *Scores of the hit ratio H for a number of flooded river sections, and affected towns and cities. Names between parentheses refer to towns and cities wrongly predicted as flooded, otherwise towns and cities have been correctly predicted as flooded.*

As expected, the simulated flood extent is significantly larger in all the cases than the satellite extent (see Table 3), given the delay between flood peaking time and time o image acquisition mentioned in Section 3.2. For Serbia in particular the flooded area detected from Copernicus and GeoSerbia maps are both smaller than the simulation. Also, flood extent indicated in the ICPDR and ISRBC report is consistently lower than values from both simulated and satellite maps.
For Bosnia-Herzegovina, the simulated value is close to the reported flood extent published in a report by Bajic et al. (2015). For Croatia, the flood mapping methodology is largely overestimating both the satellite-based and reported flood extents. The main reason is that flooding on the left side of Sava was limited due to the reinforcing of river dykes in the area close to the city of Zupanja, which could contain the reported 500 years return period discharge despite having been designed for a 1 in 100 year event. In fact, all the left bank of Sava in this area was reported as areas at risk in case of a failure of flood defences, and only the emergency measures taken prevented more severe flooding (ISRBC, 2014). We performed an additional flood simulation excluding any failure on the river left bank between the Bosna confluence and Zupanja, and in this case we found a total flood extent of 319 $km^2$. Although this value is larger than for satellite maps, it is close to the extent reported by other sources.
Regarding Table 4, the scores of the H index indicate that the mapping procedure can correctly detect most of the flooded areas, although with the partial exception of the lower Sava area. In particular, the great majority of towns reported to have been flooded are correctly detected by the simulations, with only few false alarms (e.g. the already mentioned Zupanja).
When looking at the results it’s important to keep in mind the limitations of the procedure. As mentioned in Section 2.3, the mapping procedure is able to reproduce only maximum flood depths, and the dynamic of the flood event is not taken into account. This means that processes like flood wave attenuation due to inundation occurring upstream cannot be simulated, and possible flood mitigation measures taken during the event are not considered as well. Furthermore, due to the DEM coarse resolution, flood simulations do not include small scale topographic features like minor river channels, dykes and road embankments.

### *4.2 Flood risk assessment*

Tables 5 and 6 show a summary of the simulated flood impacts on population (based on the reference simulation), compared with estimates both at local scale and aggregated at national scale. Note that we compare simulated population impacts with figures of evacuated population because the reported estimates of affected population included also people affected by pluvial floods and landslides, as well as indirect effects like energy shortage and road cuts. On the other hand, it is important to remember that the figures of evacuated population are not equivalent to directly affected population (i.e. whose houses were actually flooded). In some areas, evacuation was taken as a precautionary measure, even if flooding did not eventually occur.

| Country | Evacuated population (reported) | Affected population (satellite) | Affected population (simulated) |
|---|---|---|---|
| Bosnia-Herzegovina | 90.000 | 51.010 | 215.200 |
| Croatia | 27.255 | 5.758 | 57.000 |
| Serbia | 32.000 | 13.699 | 29.800 |

*Table 5. Comparison of evacuated population and affected population estimated from satellite and simulations in Bosnia-Herzegovina, Croatia and Serbia (source: ICPDR and ISRBC, 2015).*

| Administrative area | Country | Evacuated population (reported) | Affected population (estimated) |
|---|---|---|---|
| Obrenovac municipality | Serbia | > 25000 | 17600 |
| Brod-Posavina county | Croatia | 13700 | 12800 |
| Osjek-Baranja county | Croatia | 200 | 1300 |
| Sisak-Moslavina county | Croatia | 2400 | 3300 |
| Požega-Slavonija county | Croatia | 2300 | 1500 |
| Vukovar-Srijem county | Croatia | 8700 | 39200 |

*Table 6. Comparison of evacuated population (reported) and affected population (simulated) in administrative areas in Croatia and Serbia (source: ICPDR and ISRBC, 2015; Wikipedia, 2016)*

As can be seen, results from the reference simulation match well figures reported for all the flooded counties of Croatia except for the Vukovar-Srijem County. This is due to the overestimation of flooded areas due to the emergency measures mentioned in Section 4.1. If these are taken into account and dyke failures are not included in this county, the affected population is reduced to 8600 people, extremely close to the reported figure. Some underestimation can be observed for Obrenovac municipality but the estimated figures still depict a major impact on the city. A possible reason is that the flood simulations are less reliable for urban areas, as the elevation data from SRTM is known to be less accurate in urban and densely vegetated areas (Sampson et al., 2015). It is worth noting that simulated and reported figures for affected people compare much better than for flood extent, which supports the hypothesis of a general underestimation of flood extent from satellite images.

For flood impacts related to monetary damage, the simulations for Croatia report a total damage of 653 M€, against a reported estimate of 298 M€. However, if the already mentioned overestimation of flooded areas is considered, then the estimate decreases to 190 M€. As mentioned in Section 3.3, damage figures Serbia and Bosnia-Herzegovina could not be used because available estimates aggregate damages from landslides and river and pluvial flooding.

The observed underestimation can be explained considering that the damage curves applied have not yet been calibrated for Bosnia-Herzegovina, Croatia and Serbia. On this point, previous applications in countries where established damage curves were available (e.g. Germany) led to results well in line with observations (Jongman et al., 2012; Alfieri et al., 2016). Also, estimated damages include only direct damage to buildings, while infrastructural damage is only partially accounted for (e.g. damage to the dyke system).

### *4.3 EFAS forecasts*

Figures 5 and 6 show the inundation maps derived using the median of ensemble streamflow forecasts issued on 12 and 13 May (that is, the standard procedure adopted for the operational procedure). In addition, Table 7 illustrates the outcomes of impact forecasts, compared to impacts obtained from the reference simulation. For 12 May, we considered predicted maximum streamflow values based on the $25^{th}$, $50^{th}$ and $75^{th}$ percentiles of the ensemble forecast. For 13 May only the $50^{th}$ percentile is considered. All of estimations are computed taking into account local flood protection levels.

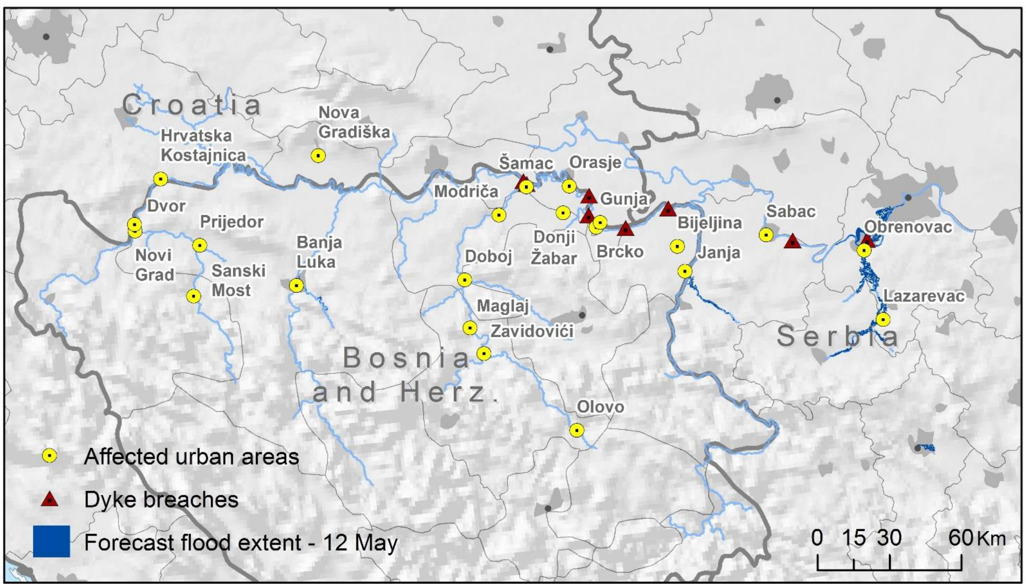


*Figure 5. Simulated flood extent based on 12 May forecast, with location of reported flooded urban areas and dyke failures.*

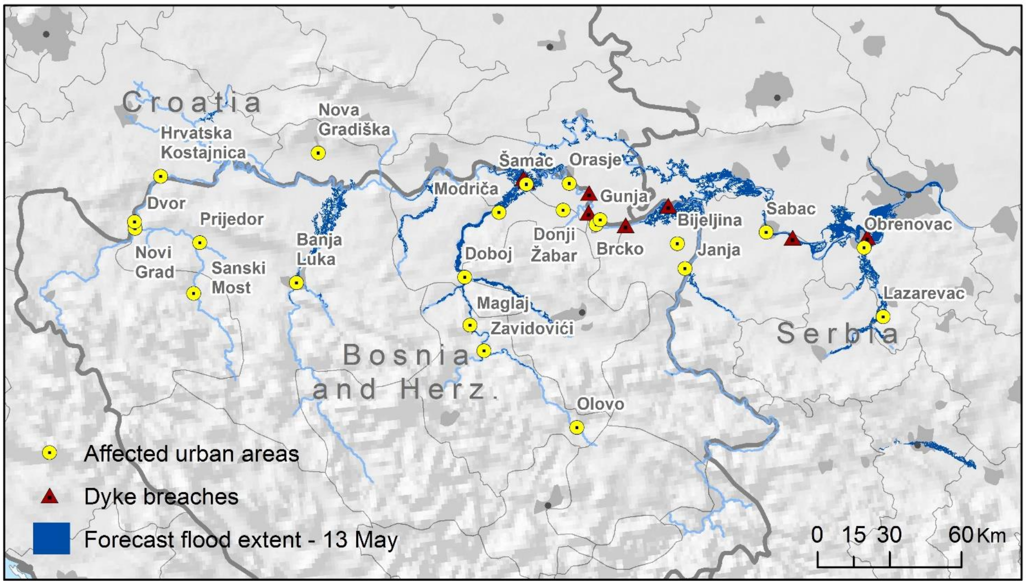


*Figure 6. Simulated flood extent based on 13 May forecast, with location of reported flooded urban areas and dyke failures.*

| Country | 12 May - 25 perc | 12 May 12 -50 perc | 12 May - 75 perc | 13 May - 50 perc | Reference |
|---|---|---|---|---|---|
| flood extent (km$^2$) | | | | | |
| Bosnia-Herzegovina | 0 | 5 | 196 | 509 | 995 |
| Croatia | 0 | 0 | 100 | 159 | 919 |
| Serbia | 91 | 187 | 385 | 658 | 582 |
| affected population | | | | | |
| Bosnia-Herzegovina | 0 | 5,225 | 20,458 | 100,665 | 215,176 |
| Croatia | 0 | 0 | 3,598 | 4,924 | 57,053 |
| Serbia | 2,793 | 6,012 | 15,120 | 27,732 | 29,758 |
| economic damage (million €) | | | | | |
| Bosnia-Herzegovina | 0 | 10 | 36 | 254 | 378 |
| Croatia | 0 | 0 | 41 | 54 | 653 |
| Serbia | 14 | 31 | 92 | 203 | 141 |

*Table 7. Comparison of forecasted flood impacts with the reference impact estimation.*

The simulated flood maps and the values displayed in Table 7 show that, while forecasts for 12 May are significantly far from the observations, the performance greatly improves after one single

day, when predicted impacts are very similar to the reference simulation for Serbia, even though for Bosnia- Herzegovina and especially Croatia there is still a significant underestimation. Nevertheless, the order of magnitude is already indicating a major flood risk for the predicted events, meaning that emergency responders could have used this estimation to plan and implement countermeasures, and monitor the situation. A further important result is that the location of forecasted flooded areas is mostly consistent with the reference simulation shown in Figure 3, with several urban areas already at risk of flooding in the map based on 13 May forecast (Figure 6).
Regarding the prediction based on 12 May forecast, it is worth noting that the use of 75$^{th}$ percentile results in estimations closer to the reference simulation (Table 7). Again, this is an important piece of information because it provides emergency responders with an early indication of the possible severe consequences of the upcoming flood.

## *5) Conclusions and next developments*

This paper presents the first application of an impact forecasting procedure which is fully integrated within a continental scale flood early warning system. The procedure has been thoroughly tested in all its components, and the results demonstrate the potential of the proposed approach. Comparison of reported and simulated flooded areas suggests that the methodology enables to identify areas at risk well in advance, which could help the planning of timely response measures (e.g. dyke strengthening, temporary road closure).
The methodology provided acceptable estimates of affected population, thus providing valuable information for the implementation of evacuation measures. Damage estimations are in the same order of magnitude of observed figures, albeit with a general underestimation. It should be considered, however, that the damage curves used for Bosnia-Herzegovina, Croatia and Serbia are curves that have been derived for other European countries rescaled to reflect local asset values. Further applications will allow to improve estimations by calibrating damage curves in different contexts and more countries.
When evaluating the outcomes, it is important to remember that, even in case of a risk assessment based on “perfect” forecasts and modelling, simulated impacts will always be different from actual impacts. As we have shown in the test case of the floods in the Sava River basin, unexpected defence failures can occur for flow magnitudes lower than the design level, thus increasing flood impacts. On the other hand, flood defences might be able to withstand greater discharges than the design level, and emergency measures can improve the strength of flood defences or creating new temporary structures. Finally, evaluating forecasted impacts is still complicated by the lack of standardized reporting of flood impacts, meaning that reported flood extents and damages can strongly deviate from the true extents and damages (as observed in the test case from the differences between the satellite and reported extents). As such, forecast-based risk assessment should be regarded as a flood scenario that can provide valuable information for

local, national and international authorities, complementing the standard information provided by flood early warning systems.

Since September 2016, the procedure is running in testing mode within the EFAS modelling chain and will be fully operational by the beginning of 2017. Besides the version currently in use and described in this paper, further modifications and alternative approaches for hazard mapping and risk assessment will be tested in the near future.

Currently, inundation forecasting is computed using the median of daily ensemble streamflow forecasts, but in principle the methodology can easily be adapted to produce additional flood scenarios considering different ensemble percentiles, thus taking into account less probable but potentially more severe flood scenarios (see the application described this paper). Alternatively, the uncertainty of meteorological predictions could be represented using probabilistic maps of flood extent as proposed by Di Baldassarre et al. (2010). The influence of lead time on flood predictions could also be assessed, for instance by setting a criterion based on forecasts persistence over a period to trigger the release of impact forecasts. All these alternatives will be tested in collaboration with the community of the EFAS users, to maximize the value of the information provided and avoid information overload which can be difficult to manage in emergency situations.

A further promising application is the possibility of using inundation forecast to activate rapid flood mapping from satellites, exploiting the Copernicus Emergency Mapping Service of the European Commission.

Finally, the proposed procedure will also be incorporated into the Global Flood Awareness System (GloFAS), which would allow to establish a near-real time flood risk alert system at global scale.

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## *Bibliography*

Alfieri L., Pappenberger F., Wetterhall F., Haiden T., Richardson D., Salamon P., 2014a. Evaluation of ensemble streamflow predictions in Europe, Journal of Hydrology, 517, 913-922

Alfieri, L., Salamon, P., Bianchi, A., Neal, J., Bates, P.D., Feyen, L., 2014b. Advances in pan-European flood hazard mapping, Hydrol. Process., 28 (18), 4928-4937, doi:10.1002/hyp.9947.

Alfieri L., Feyen L., Dottori F., Bianchi A., 2015. Ensemble flood risk assessment in Europe under high end climate scenarios. Global Environmental Change 35, 199–212.

Alfieri, L., Feyen, L., Salamon, P., Thielen, J., Bianchi, A., Dottori, F., and Burek, P.: Modelling the socio-economic impact of river floods in Europe, Nat. Hazards Earth Syst. Sci., 16, 1401-1411, doi:10.5194/nhess-16-1401-2016, 2016.

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

Batista e Silva F., Gallego J., and Lavalle C. (2013). A high-resolution population grid map for Europe. Journal of Maps, 9 (1), 16-28.

Burek, P., Knijff van der, J., Roo de, A., 2013. LISFLOOD, Distributed Water Balance and Flood Simulation Model Revised User Manual 2013. Publications Office, Luxembourg.

Cloke, H., Pappenberger, F., Thielen, J. and Thiemig, V. (2013) Operational European Flood Forecasting, in Environmental Modelling: Finding Simplicity in Complexity, Second Edition (eds J. Wainwright and M. Mulligan), John Wiley & Sons, Ltd, Chichester, UK. doi: 10.1002/9781118351475.ch25.

Copernicus Emergency Management Service - Mapping. Institute for the Protection and Security of the Citizen (IPSC), European Commission, Joint Research Centre (JRC). Accessed November 12, 2014. http://emergency.copernicus.eu/.

Di Baldassarre G, Schumann G, Bates PD, Freer JE, and Beven KJ. (2010). Floodplain mapping: a critical discussion of deterministic and probabilistic approaches. Hydrological Sciences Journal, 55 (3), 364–376.

Dottori F., Salamon P., Kalas M., Bianchi A., Thielen J., Feyen L., 2015. A near real-time procedure for flood hazard mapping and risk assessment in Europe. 36th IAHR World Congress 28 June – 3 July, The Hague, the Netherlands.

EC, 2016. List of EU Solidarity Fund Interventions since 2002, http://ec.europa.eu/regional_policy/sources/thefunds/doc/interventions_since_2002.pdf (accessed 15-9-2016).

EC, 2007. Directive 2007/60/EC of the European Parliament and of the Council on the assessment and management of flood risks. Official Journal of the European Communities, Brussels, http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32007L0060 (accessed 21-10-2016).

ECMWF, 2014. EFAS Bulletin April – May 2014. Available at https://www.efas.eu/efas-bulletins/1801-efas-bulletin-april-may-2014-issue-20143.html (accessed October 2015).

Emerton, R., Stephens, E.M., Pappenberger, F., Pagano, T.C., Weerts, A.H., Wood, A.W., Salamon, P., Brown, J.D., Hjerdt, N., Donnelly, C., Baugh, C.A., Cloke, H.L., 2016. Continental and global scale flood forecasting systems. WIREs Water 2016 (3) 391–418, doi:10.1002/wat2.1137.

Geoportal GeoSerbia, http://www.geosrbija.rs/ (accessed 21-10-2016).

Nat. Hazards Earth Syst. Sci. Discuss., doi:10.5194/nhess-2016-338, 2016
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Published: 24 October 2016


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Huizinga H. J. (2007). Flood damage functions for EU member states, HKV Consultants, Implemented in the framework of the contract #382442-F1SC awarded by the European Commission – Joint Research Centre.

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. Natural Hazards and Earth System Sciences. 12, 3733–3752.

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., Ward, P.J., 2014. Increasing stress on disaster-risk finance due to large floods. Nat. Clim. Change 4, 264–268. doi:http://dx.doi.org/10.1038/nclimate2124.

ICPDR – International Commission for the Protection of the Danube River and ISRBC – International Sava River Basin Commission2015. Floods in May 2014 in the Sava River Basin. https://www.icpdr.org/main/sites/default/files/nodes/documents/sava_floods_report.pdf (accessed 11-10-2015).

Marín Herrera, M., Batista e Silva, F., Bianchi, A., Barranco, R. and Lavalle, C., 2015. A geographical database of infrastructures in Europe. JRC Technical Report, JRC99274.

Pappenberger F., Thielen J., and Del Medico M. (2011). The impact of weather forecast improvements on large scale hydrology: analysing a decade of forecasts of the European Flood Alert System. Hydrological Processes, 25, 1091–1113. http://dx.doi.org/ 10.1002/hyp.7772.

Pappenberger F., Cloke, H. L., Parker, D.J., Wetterhall, F., Richardson, D.S, Thielen, J., 2015. The monetary benefit of early flood warnings in Europe. Environmental Science &Policy 51, 278–291.

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

Rossi, L., Rudari, R., and the RASOR Team. RASOR Project: Rapid Analysis and Spatialisation of Risk, from Hazard to Risk using EO data. Geophysical Research Abstracts Vol. 18, EGU2016-15073.

Saint-Martin, C., Fouchier, C., Douvinet, J., Javelle, P., Vinet, F., 2016. Contribution of an exposure indicator to better anticipate damages with the AIGA flood warning method: a case study in the South of France. Geophysical Research Abstracts Vol. 18, EGU2016-10305-4.

Sampson, C.C., Smith, A.M, Bates, P.D., Neal, J.C., Alfieri, L., Freer, J.E., 2015. A High Resolution Global Flood Hazard Model. Accepted article in Water Resour. Res., doi: 10.1002/2015WR016954.

Schulz, A., Kiesel, J., Kling, H., Preishuber M., Petersen G., 2015. An online system for rapid and simultaneous flood mapping scenario simulations - the Zambezi FloodDSS. Geophysical Research Abstracts Vol. 17, EGU2015-6876.Thielen J., Bartholmes J., Ramos M.H., and De Roo A. (2009). The European flood alert system – part 1: concept and development. Hydrology and Earth System Sciences 13, 125–140.

UNDAC - United Nations Disaster Assessment and Coordination Team, 2014. Mission to Serbia – Floods 18-31 May 2014, end of mission report.

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

Ward, P., Coughlan de Perez, E., Dottori, F., Jongman, B., Luo T., Safaie S., Uhlemann-Elmer S., 2016. The need for mapping, modelling and predicting flood hazard and risk at the global scale. In publication in: Global Flood Hazard: Applications in modeling, mapping and forecasting (Eds. Guy Schumann, Paul Bates, Giuseppe Aronica and Heiko Apel).

Wikipedia. Poplave u istočnoj Hrvatskoj u svibnju 2014 (accessed 21-10-2016).