

Article

The RainBO Platform for Enhancing Urban Resilience to Floods: An Efficient Tool for Planning and Emergency Phases

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Abstract: Many urban areas face an increasing flood risk, which includes the risk of flash floods. Increasing extreme precipitation events will likely lead to greater human and economic losses unless reliable and efficient early warning systems (EWS) along with other adaptation actions are put in place in urban areas. The challenge is in the integration and analysis in time and space of the environmental, meteorological, and territorial data from multiple sources needed to build up EWS able to provide efficient contribution to increase the resilience of vulnerable and exposed urban communities to flooding. Efficient EWS contribute to the preparedness phase of the disaster cycle but could also be relevant in the planning of the emergency phase. The RainBO Life project addressed this matter, focusing on the improvement of knowledge, methods, and tools for the monitoring and forecast of extreme precipitation events and the assessment of the associated flood risk for small and medium watercourses in urban areas. To put this into practice, RainBO developed a webGIS platform, which contributes to the “planning” of the management of river flood events through the use of detailed data and flood risk/vulnerability maps, and the “event management” with real-time monitoring/forecast of the events through the collection of observed data from real sensors, estimated/forecasted data from hydrologic models as well as qualitative data collected through a crowdsourcing app.

Keywords: web-based platform; early warning system; vulnerability simulations; flood risk maps; rainfall estimates; microwave links; CML; crowdsourcing; sensible targets

1. Introduction

Climate change affects the water cycle by intensifying it and this can change the magnitude, frequency, and timing of river floods in areas of the planet [1] such as some parts of Europe [2]. In particular, Blöschl et al. [3,4] by analyzing a pan-European database over the past five decades found clear patterns of change in flood timing in Europe due to changes in climate. However, the increasing trend of disasters due to floods in Europe is due also to non-climatic drivers, such as continued socio-economic growth, which induces population growth, economic wealth, and unplanned

urbanization. Furthermore, the projected change in frequency of discharge extremes in Europe is likely to have a large impact on the flood hazard, e.g., current 100-year flood peaks are projected to double in frequency within three decades [5].

The Floods Directive 2007/60/EC [6] published by the European Commission (EC), driven from the rising of human and economic losses of natural hazards, such as floods in Europe, aims to enhance the prevention, preparedness, protection, and response to flooding events and to increase the awareness of risk prevention measures within society. The early warning systems (EWS) are mentioned in this Directive as a relevant part of this disaster risk management cycle to support effective preparedness towards floods. Hence, it is fundamental for the European Member States to better identify the risk and occurrence of river floods and to better monitor the vulnerability of the society in order to establish effective early warning systems.

The usage of EWS as a useful tool to prevent damage, enhance the resilience of a society from natural hazards has been highlighted in the recent global policy treaties for climate change and disaster risk reduction in the last decade (e.g., the Paris Agreement in Articles 7 and 8 and the Sendai Framework for Disaster Risk Reduction in Priority 3 and 4). Furthermore, several success stories have shown that major EWS developments have been carried out due to technological advances (e.g., better forecasts made possible from radar nowcasting, ensemble weather models, high-resolution satellite data, more effective communication and sharing of information) [7–11]. Early warning systems can have a significant positive cost/benefit ratio in both disaster risk reduction and climate change adaptation [8,11–13]. In addition, the 2030 Agenda for Sustainable Development [14] has endorsed early warning systems as an essential action to be financed for protecting lives and property, thus contributing to sustainable development [15].

Early warning systems are defined by the United Nation Office for Disaster Risk Reduction (UNDRR) as “integrated system of hazard monitoring, forecasting and prediction, disaster risk assessment, communication and preparedness activities systems and processes that enables individuals, communities, governments, businesses and others to take timely action to reduce disaster risks in advance of hazardous events.” All these activities need to be coordinated in specific areas under interest and across multiple levels of governance to work effectively and to provide input in short times.

The challenge is to develop and implement early warning systems for any kind of scale of river catchments and especially for small catchments with a drainage area of a few hundred square kilometers that can be subjected to flash floods causing large amounts of damage in the urban context.

General review studies have discussed advances in river flood and river flash flood monitoring/forecasting and confirm the great hydrological challenge in developing and implementing an efficient early warning system despite the reliability of forecasts having increased due to the efficient integration of meteorological and hydrological modeling capabilities in the last years, especially in the developed countries [16,17].

Alfieri et al. [7] reviewed the current European operational warning systems for water-related hazards (e.g., river floods and coastal floods, flash floods, debris flows, mudflows, rainfall-induced landslides) due to severe weather conditions. This study identified those EWS including a weather prediction component to detect extreme events with considerable lead time, which can support early preparedness and effective disaster risk reduction. Further work is needed to better exploit the benefits provided by such systems [7].

Acosta-Coll et al. [18] conducted a systematic review to define the adequate structure of EWS for pluvial flash floods in urban areas. They identified the need for people-centered EWS with fail-safe systems able to guarantee the dissemination and communication of timely alerts during rainfall events. For doing so, the amount of rain and the water level need to be monitored and processed in real-time through the ultrasonic or radar sensors, which are more suitable for these applications. Finally, Acosta-Coll et al. [18] divided the EWS into four structures: “Disaster Risk Knowledge,” “Forecasting,” “Dissemination and Communication of Information,” and “Preparedness and Response.”

The presence of large complicated areas with barriers blocking, stormwater flow, insufficient drainage capacity, or the vicinity of a river, along with population growth and climate change impacts makes the urban areas highly vulnerable to flash floods. Reliable EWS for flash flood forecasting in urban watersheds are challenging and need special attention to the overall control of all components to reduce potential severe losses and as well are key for more effective and coherent implementation of existing European Union (EU) policies on disaster risk reduction and climate change adaptation [19,20].

Finally, recent European projects started to find new solutions for adapting to intense river floods in urban areas by addressing the different aspects of monitoring and forecasting. The EU Interreg project URBAN-PREX (monitoring, forecasting, and development of online public early warning systems for extreme precipitation and pluvial floods in urban areas in the Hungarian–Serbian cross-border region) [21] supported, as components of online public early warning systems for citizens and public authorities, the implementation of monitoring precipitation networks through rain gauges in urban areas in the Hungarian–Serbian cross-border region. On the other hand, the EU Interreg project RAINGAIN [22] used radar technology to provide high-resolution estimates of rainfall in cities to forecast pluvial floods in test urban sites in the UK, Netherlands, Belgium, and France. The EU FP7 project STAR-FLOOD (STrengthening And Redesigning European FLOOD risk practices: Towards appropriate and resilient flood risk governance arrangements) [23] aimed to improve the implementation of flood risk strategies in urban areas which are vulnerable to pluvial floods in different European countries (UK, Sweden, Poland, Netherlands, Belgium and France) by designing policies for an appropriate and resilient flood risk governance. Among its different outcomes, this project highlighted the need for further improving systems for forecasting, warning and emergency responses for urban floods that are proactive, risk-based and use collaborative approaches, for instance by optimizing the use of ICT (apps).

The need to improve the EWS and emergency communications related to flood risk in urban areas has been addressed from the EU Horizon 2020 project FLOOD-serv (Public FLOOD Emergency and Awareness SERvice) [24]. This project aimed to develop a collaborative platform that links citizens, public authorities, and other stakeholders and to enable the public to be warned in due time to reduce the adverse effects of floods.

Taking into consideration past studies and experience, the project RainBO focuses on the improvement of knowledge, methods and tools for the monitoring and forecast of extreme precipitation events and the assessment of the associated flood risk for small and medium watercourses in urban areas.

RainBO, funded by the EU Life Program, is a follow-up of the BLUEAP (Bologna Local Urban Environment Adaptation Plan for a Resilient City) LIFE project and T-Rain, a Climate-KIC (Knowledge and Innovation Community) project, in terms of implementing a reliable service based on big data coming from cellular networks.

The partners within the RainBO project, under the coordination of Lepida scpa (the in-house company of the Emilia-Romagna Region in charge of planning and implementing telecommunication infrastructures and IT services), comprise Arpae SIMC (the HydroMeteoClimate Service of the Regional Agency for Prevention, Environment and Energy of Emilia-Romagna is involved), the municipality of Bologna, MEEO (a small and medium enterprise with expertise in remote sensing and Commercial microwave links technology) and NIER (a consulting company with expertise on environmental analysis and risk evaluation).

The present article aims to describe the RainBO project and its main outcome: a webGIS (Geographic Information System) modular platform addressed local administrations to provide information from observed data, forecasts, and models before and during extreme events of precipitation in vulnerable river basins. On the platform, weather data are collected from traditional and innovative monitoring systems, weather forecasts are gathered from existing meteorological models whereas hydrological forecasts are provided by operational and newly developed models. The platform has been tested on two Italian urban areas, as detailed in the following.

The structure of the article is as follows: Section 2 describes an examination of existing data and useful models for the purposes of the RainBO platform, and afterward, the innovative methodologies developed within the project are explained. In Section 3, the platform and the main results achieved during the project are then presented, with a description of its main structure, databases, and modules. Finally, remarks for further developments are described.

2. Materials and Methods

2.1. Study Areas

The application of the RainBO platform is performed on two test areas, the cities of Bologna and Parma, located in the Emilia-Romagna region, Italy. The climatic features referred to 1991–2015 period for these two cities are shown in Table 1 [25].

Table 1. Annual climatic features of Bologna and Parma (reference climate: 1991–2015).

Variable	Bologna	Parma
Minimum temperatures (unit: °C)	9.88	8.76
Maximum temperatures (unit: °C)	19.27	19.14
Mean temperatures (unit: °C)	14.59	13.95
Precipitation (unit: mm)	775.7	795.3

Both these urban areas are crossed by watercourses: the Ravone creek flows through Bologna, the Parma river flows through Parma (Figure 1).

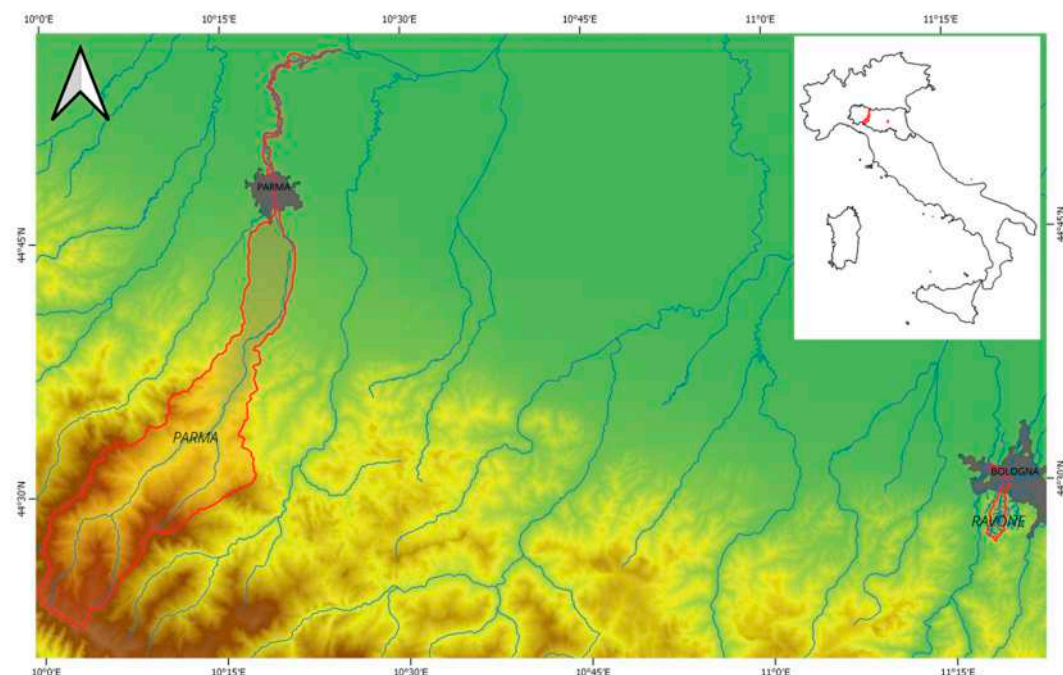


Figure 1. Study areas of the RainBO project.

As shown in the figure, the catchment of the Ravone creek is small, whereas the catchment of the Parma river is medium-large. The different sizes of the catchments are reflected in two different modeling approaches of the hydrologic forecasts, as explained below.

It is worthy to mention that each hydraulic section of the Emilia-Romagna catchments has three specific thresholds/levels of alarm: yellow threshold/warning, orange threshold/pre-alarm and red threshold/alarm. These thresholds are site-specific and defined according to Civil Protection purposes

for public safety, taking into account the geometry of the hydraulic section of the watercourse and the statistical distribution of historical recordings.

2.1.1. Ravone Catchment

The Ravone catchment, together with the Aposa catchment, is the largest river basins at SW of Bologna. They flow from the hills directly across the central part of the city. The upper part of the Ravone catchment is characterized by hills and steep slopes, with a prevalent vegetation coverage (grass, shrubs, and forest) and partial urbanization in the stream valley. In contrast, the lower portion is flat and densely urbanized, the drainage network is mainly artificial, and the watercourse is connected with the main urban drainage system in a critical spillway crosspoint, flowing in a culvert underneath the city's urban area before joining the Reno river. The length of the natural reach of the Ravone is approximately 4 km covering an area of 6 km².

The Ravone catchment has been chosen as a study area of RainBO because, as recorded in historical data, the response of the catchment to extreme rainfall past events caused significant damages. For instance, during a flood that occurred on July 22nd, 1932, a victim and severe damages to streets and houses in the Southern part of the city were recorded [26].

The catchment is equipped by an existing monitoring network (Figure 2), including a weather station 500 m far from the Ravone catchment equipped with a rain gauge on S. Luca hill where data have been collected since the early 1930s. To integrate the available dataset and to better monitor the Ravone catchment, in 2014 a second rain gauge was installed at the catchment upstream end of mount Paderno and a water level gauge was installed at the culvert entry of the Ravone creek (Figure 3).

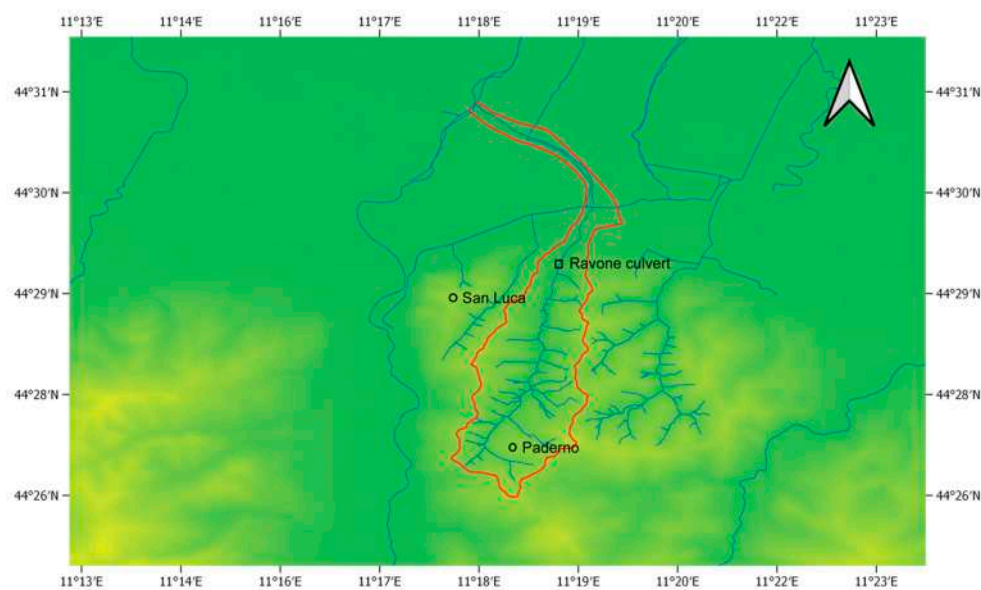


Figure 2. Map of existing monitoring network on the Ravone area. The circles are the rain gauges, the square is the water level gauge.



Figure 3. The entry of the culvert of the Ravone creek where the water level gauge is installed and the alarm thresholds are highlighted.

2.1.2. Parma Catchment

Parma river is the main river flowing through a homonymous city in Emilia-Romagna; it starts from Mount Marmagna at 1842 m.a.s.l. and flows in an N-NE direction joining the River Po near the city of Colorno as the right tributary. Usually, the hydrological responses for these basins are characterized by high discharges in the spring and autumn and low discharges in the summer.

The small catchment area and the steep part of the valley give high hydrological response during severe storms, generating, under particular conditions, flash flood events. Its major tributary is the Baganza River which has a very similar course and joins the main river on its left in the city of Parma (Figure 4).



Figure 4. Baganza river in Parma after the October 2014 event.

The available monitoring network for the Parma basin is composed of 15 rain gauges, 11 thermometers, and 6 water level gauges, these sensors are sufficient for the application of the RF Model, hence, no other installation was required (Figure 5).

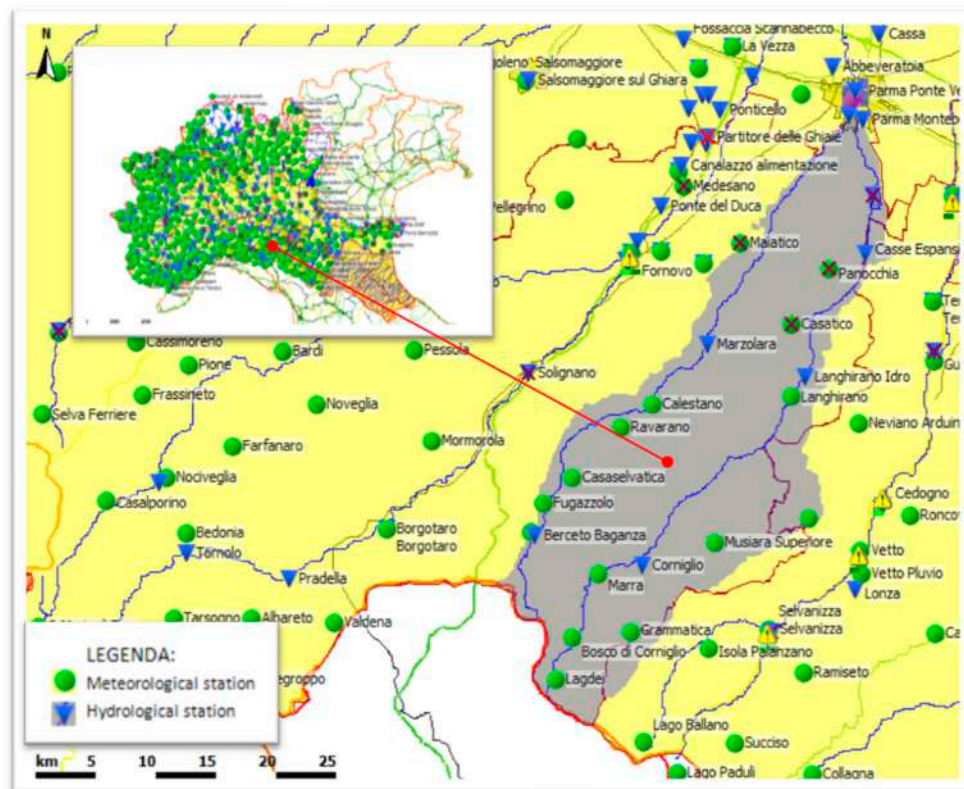


Figure 5. Parma-Baganza basin and monitoring network.

2.2. Background of the RainBO Project

The existing data and models at the beginning of the project identified as necessary for the development of the RainBO platform are described.

2.2.1. Territorial Data

According to the existing national and regional guidelines for the planning of Civil Protection, the following maps on the Emilia-Romagna region are available:

- Regional technical cartography (CTR) 1:5000 updated in 2013 with the topographic database (TIFF format)
- Ortho-photo Agea2014 (TIFF format) resolution 50 m
- Digital Surface Model Agea2008 (TIFF format) resolution 5 m × 5 m
- Digital Terrain Model Agea2008 (TIFF format) resolution 5 m × 5 m
- River catchments from numerical data 1:10.000 (shapefile format)
- Toponymy (shapefile format) 1:5000

These data are projected in the WGS84 UTM32N reference system.

2.2.2. Hazard, Vulnerability, and Risk Maps

To set up a tool for the management of flood risk in the Member States of the European Union, the main legislative reference is the Floods Directive [6]. In the directive, the hydraulic risk is the product of the hazard and potential damage at a specific event:

$$R = P \times E \times V = P \times Dp, \quad (1)$$

where:

- P (Hazard): it is the probability of occurrence, within a certain area and in a certain time interval, of a natural phenomenon of assigned intensity
- E (Exposure): it represents people and/or assets (structures, infrastructures, etc.) and/or activities (economic, social, etc.) exposed to a natural event
- V (vulnerability): the degree of capacity (or incapacity) of a system/element to resist at the natural event
- Dp (potential damage): it is considered as the degree of foreseeable loss following a natural phenomenon of a given intensity, the function of both value and vulnerability of the exposure
- R (risk): expected number of victims, injured persons, damage to property, cultural assets e environmental, destruction or interruption of economic activities, as a result of a natural phenomenon of assigned intensity

Emilia-Romagna Region has developed the Flood Risk Management Plan (FRMP), to be compliant with the Floods Directive [6] and Legislative Decree 49/2010, which requires these flood risk management plans to include measures to reduce the probability of flooding and its potential consequences and to address all phases of the flood risk management cycle but in particular the prevention, the protection, and the preparedness. As the causes and consequences of floods are different in the different member states of the Community, the Management Plans take into account the specific characteristics of the territories and propose specific objectives and measures tailored to the needs and priorities.

The FRMP of the Emilia-Romagna Region is represented by three projects, one for each hydrographic district (Po River, Northern Apennines, and Central Apennines).

Existing hazard maps represent the potential extent of flooding caused by watercourses (natural and artificial) with reference to three scenarios (rare floods, infrequent, and frequent) colored with three different shades intensity of blue, depending on the frequency of flooding as follows:

- rare floods of extreme intensity: return time up to 500 years from the event (low probability)
- infrequent floods: return time between 100 and 200 years (average probability)
- frequent floods: return time between 20 and 50 years (high probability)

The hazard maps from the Floods Directive are available on the whole Italian territory. They constitute the reference hazard maps for the computation of hydraulic risk and, for the purpose of the RainBO project, they have been selected on the study areas of Bologna and Parma.

Moreover, for the Bologna study case, in addition to the reference hazard map where the Ravone and other small streams are not included, a specific map for the Ravone creek is available [27]. This has been obtained through scenarios of flood analysis [28].

The existing vulnerability maps from the Floods Directive have been clipped on the study areas of Bologna and Parma. It should be noted that these reference maps do not consider in detail population distribution issues, as well as risk maps, as a consequence. In particular, to define the expected damages of a flood, the Directive suggests including the following main items:

- urban areas and urban expansion areas
- industrial and technological areas
- environmental heritage and cultural assets of significant interest
- presence of critical infrastructures such as transport, communication, utility networks
- presence of public and private services: sports plant, recreational facilities, accommodation facilities

The risk maps indicate the presence of potentially exposed elements (population involved, services, infrastructure, economic activities, etc.) which fall within floodable areas by means of a classification in 4 risk categories, represented by a color scale: yellow (moderate or no risk), orange (medium risk), red (high risk), purple (very high risk).

Existing risk maps from Floods Directive, created by the integration of hazard maps and vulnerability ones, identify static situations and do not take into account urban territory resilience peculiarity. In this case, risk maps have also been selected for the study areas of Bologna and Parma.

2.2.3. Historical Events

A catalog of historical events from 1981 is available for the Parma and Reno, including the Ravone catchment. A historical event is defined as the exceedance of at least one pre-alarm threshold. For each event, the involved catchment, the exceeded thresholds of water level gauge, as well as the description of the flooded area are recorded.

Moreover, where available, for each event further information (i.e., the number of people evacuated, dead or wounded people, emergency state—if requested, the possible assessment of economic damages) were collected. Moreover, the reports for all the events that occurred in Emilia-Romagna are available [29].

2.2.4. Observed Meteorological Data

A complex infrastructure for environmental monitoring and for an early-warning system is based on the integration of different data from many sources. The hydro-pluviometric network of Arpae collects data from rain gauges, thermometers, and water level gauges on the Emilia-Romagna region (Figure 6).

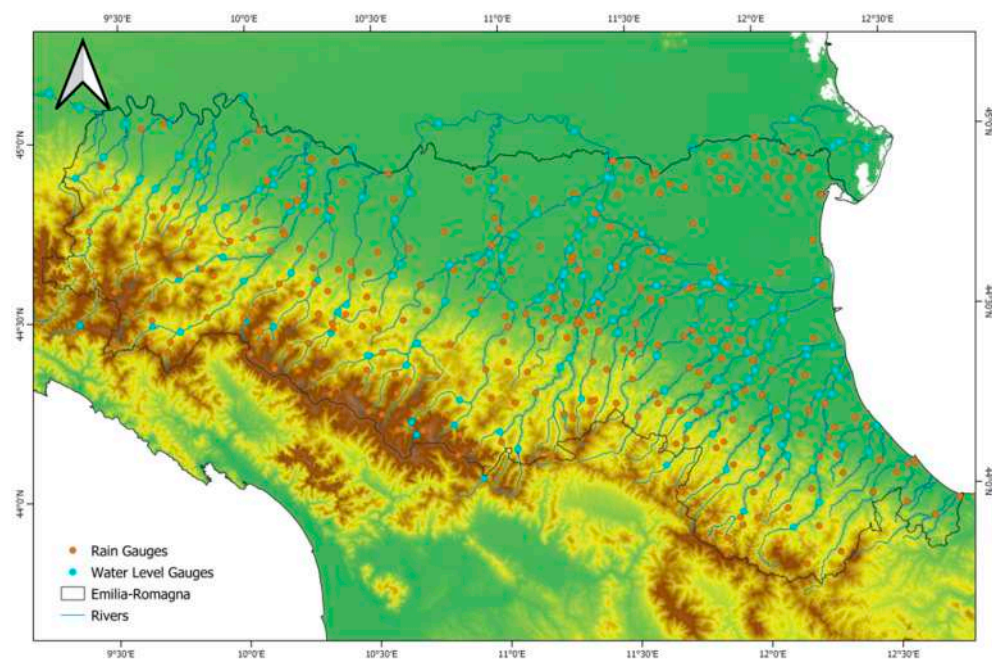


Figure 6. The hydro-pluviometric network of Emilia-Romagna.

For the RainBO purposes, the key variables are water level gauges (242 sensors) and rain gauges (282 sensors). Data coming from the hydro-pluviometric monitoring system are available on the Arpae ftp server. These data are acquired from the network every 15 min, the units are millimeters (mm) for precipitation and meters (m) for water level. In general terms, the series starts from 2003, the historical series for some sensors start from 1980.

These data are integrated into the Sensornet platform through a web service. Sensornet is the Internet of Things Platform of the Emilia-Romagna Region, that collects data and information from thousands of sensors distributed on the territory and builds a digital map over time [30].

The development of the RainBO platform implied also the empowerment of the monitoring network in critical areas not properly covered by sensors such as the Ravone catchment. For this reason, new monitoring sensors were installed in the Ravone area:

- a new real-time water level gauge has been installed in the upper part of the river basin
- a new weighing rain gauge has been located in a public property on the right side of the valley

These new monitoring sensors installed in the Ravone area are aimed at measuring environmental variables to be collected in the RainBO platform and at monitoring the Ravone creek with a high degree of accuracy.

2.2.5. Forecast Meteorological Data

The COSMO-LAMI forecasts provided by Arpa-SIMC are available on an open data platform as GRIB files over Emilia-Romagna [31].

Meteorological COSMO-LAMI forecasts are based on the operative non-hydrostatic limited-area atmospheric COSMO (Consortium for Small-scale Modelling) model, nested on the ECMWF (European Centre for Medium-Range Weather Forecasts) operational global forecast. This system is developed and maintained by the homonymous European consortium, and managed by Arpa-SIMC on the basis of the LAMI (Limited Area Model Italia) agreement. The forecast is issued twice a day (00 and 12 UTC) with a time range of 72 h on a regular 5×5 km grid covering the Mediterranean area.

2.2.6. Estimated Data

Commercial microwave links and radar data are estimated data, essential for the purposes of RainBO in order to monitor precipitation events.

The microwave links based on the rainfall monitoring system is an innovative but already tested technology, exploiting the microwave links used in commercial cellular communication networks (so-called commercial microwave links, CML).

Conventional rain gauges are not so effective during intense precipitation as their operating principle is based on mechanical tilting parts, which makes their measurements unreliable during this type of phenomenon. Rain gauges provide point-like measurements of the amount of rain fallen within the instrument sampling area, cumulated on time intervals, usually ranging from one minute to one day, with well known instrumental [32] and representativeness [33] limitations.

A relatively new and independent approach to the estimates of precipitation at the ground became available in the last decades with the broad diffusion of CMLs for cellular communication: integral precipitation content along a line path between two antennas can be estimated by measuring the attenuation of the microwave signal along the same path [34].

Heavy rain causes electromagnetic signal attenuation (from the transmitting antenna to the receiving one) and, subsequently, path-averaged rainfall intensity can be retrieved from the signal's attenuation between transmitter and receiver by applying, almost in real-time, a rainfall retrieval algorithm.

A distributed monitoring system can be developed by using received signal level data from the massive number of CMLs used worldwide in commercial cellular communication networks.

The first studies on this technology were concentrated on algorithms for spatial-temporal interpolation [35] from the joint analysis of multiple CMLs. The great potential of CMLs for ungauged regions was demonstrated by the Burkina Faso application [36]. In 2012, Overeem [37] demonstrated that processing algorithms are capable of providing real-time rainfall maps for an entire country, in this case, the Netherlands.

With regard to radar data, an existing dataset on Emilia-Romagna is based on hourly precipitation estimates obtained from the merger of the regional radar network managed by Arpa-SIMC. This network is composed of two C-Band systems, one located at San Pietro Capofiume (Bologna) and the other in Gattatico (Reggio Emilia). Every 5 min during precipitation events, the radars provide reflectivity data that are processed by several algorithms. The reflectivity value is correlated to the precipitation intensity. Reflectivity data are provided by Arpa-SIMC in open data [38].

For the RainBO project, an ad hoc stream was triggered for the automatic and periodic distribution of both reflectivity maps and hourly precipitation maps on the ftp server provided by Lepida, according to the RainBO project goals. Sent images are a merge of the two systems (reflectivity radar maps and accumulated hourly precipitation). Every new capture of the reflectivity (the frequency of observations is related to the weather conditions at the time) generates a merged image, which is then sent to the Lepida ftp server.

2.2.7. Crowdsourcing

A platform addressed to provide information for planning and management of extreme events and flash floods in urban areas should comprise also observations and contributions from citizens. These types of data, usually collected by means of applications, are a source of additional information during ongoing events but they are also conceived in order to engage and raise awareness of citizens. In this regard, the system Rmap [39] is a participatory monitoring and exchange system promoted by Arpa-SIMC, based on open hardware and software infrastructures, to collect and share meteorological data gathered by citizens between public and private institutions.

The Rmap application is mainly addressed to users and citizens with meteorological domain expertise and collects automatically the weather data in a WMO (World Meteorological Organization) binary data software (Binary Universal Form for the Representation of meteorological data—BUFR) through dedicated devices based on open hardware and free software. The weather information data can also be uploaded manually by expert users by using an on-line application, but the graphical user interface is not conceived as a smart tool for the general public.

It defines a set of standards for meteorological data sensing (security, reliability, elaboration) and for the transmission data system (transmission protocols, data formats, metadata formats, etc.).

The Rmap project has been promoted by Arpa-SIMC for some years, as it is an interesting project with the objective of defining methods, protocols, and formats to collect and share environmental data. The project is also promoted by Arpa Veneto, Cineca and the Computer Science Department of the University of Bologna and the RaspiBO network.

The Rmap system was taken into consideration because of this robust partnership and the relevant effort spent in its standardization.

The Rmap project adopts indeed a scientific approach based on standards defined by the WMO, in particular using their elaboration and classification process.

2.2.8. Models

The models used for the development of the RainBO services are:

- CRITERIA-1D
- CRITERIA-3D
- RANDOM FOREST

CRITERIA-1D [40,41] is a one-dimensional model developed by Arpa simulating the soil water balance, nitrogen balance, and crop development. The model is usually applied to agricultural case studies, nonetheless one of its main outputs (i.e., soil moisture) is a crucial variable for hydrological purposes. The CRITERIA-1D model simulates soil water movement by using a simplified model (tipping bucket) or a numerical model. It requires as an input at least daily data of temperature and precipitation, soil features, and crop information.

CRITERIA-3D [42] is a physically-based model developed by Arpa that works at the catchment-scale and solves equations of surface and subsurface water flow in a three-dimensional domain. The hydrologic component is a dynamic link library integrated into the other Arpa software, implemented within a comprehensive model that simulates the physical processes occurring in the catchment: surface energy, radiation budget, snow accumulation and melt, potential evapotranspiration, plant development, and plant water uptake.

The two models are under development and they are available as open-source code [43].

After the flooding of the Parma and Baganza rivers in Parma on October 2014, caused by heavy rains, the Civil Protection Agency of the Emilia-Romagna region required Arpae to develop a hydrological simulation model capable of promptly evaluating in advance the probability of overcoming the alert thresholds, especially for rapid or flash flood events. The RANDOM FOREST (RF) algorithm, applied in a hydrological context, provides the probability of overcoming the alert thresholds of some observation points for basins at small and medium scales in the oncoming next 6–8 h.

The RF model was added beside the existent hydrological-hydraulic model applied in real-time into the Flood Early Warning System Emilia-Romagna (FEWS-EMR) to provide a fast and preliminary response during flash flood or extreme rainfall events in the Emilia-Romagna basins.

The model is an ensemble learning method that operates by constructing a multitude of decision trees at training time and outputting the mode of the classes (classification) or mean prediction (regression) of the individual trees. Each tree classifies the dataset using a subset of variables. The number of trees in the forest and the number of variables in the subset are hyper-parameters and, for this reason, they have to be chosen a priori.

The number of trees is in the order of hundreds, while the subset of variables is quite small, if compared to the total number of variables, in Figure 7. the final Random Forests tree generated for Parma River at Ponte Verdi is shown, all paths end with terminal node that contains the probability of exceedance for each H.T.A. (hydrometric thresholds alert).

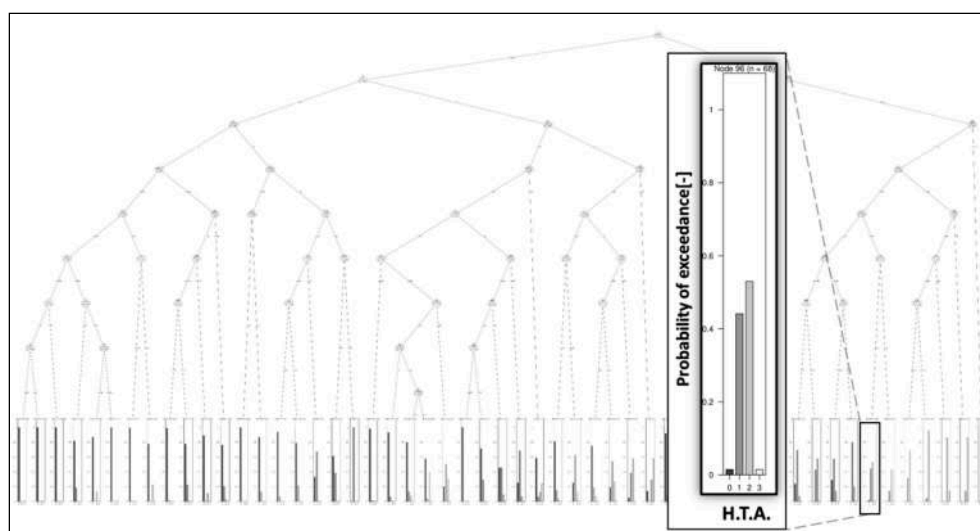


Figure 7. Random Forest tree generated for the main Parma River section (Ponte Verdi).

RF also provides a natural way to assess the importance of input variables (predictors). This is achieved by removing a variable at a time and assessing whether the out-of-bag error changes or not. If the out-of-bag error changes, the variable is important for the decision [44].

Model parameterization was performed using historical data (2003–2016), while recent data (2017–2019) are used for validation. Model parametrization was accomplished primarily by extracting historical events for each river section, hence defining the reference response time of the basin. This value was then used in the RF model, defining the maximum aggregation time for rainfall (Figure 8). For the RainBO project, the model was implemented using as input the same observed date used for the other Hydrological-Hydraulic model: observed mean hourly rainfall and discharge data.

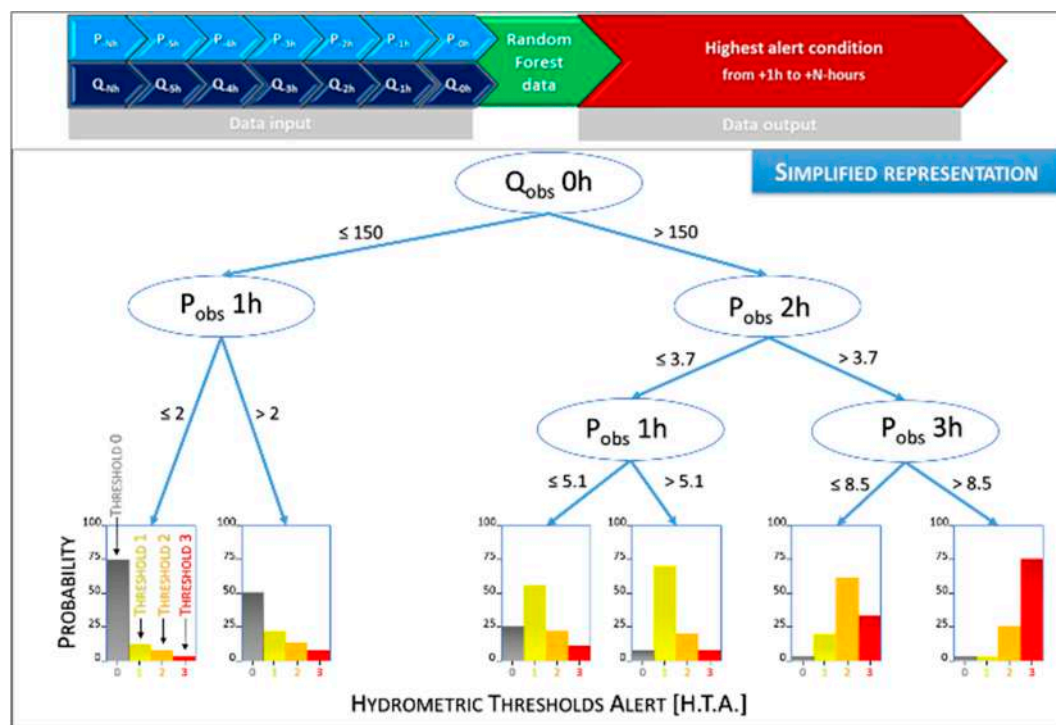


Figure 8. Random Forest model schematization. P_{obs} = observed mean hourly rainfall (unit: mm), Q = discharge (unit: m^3/s).

2.3. Foreground of RainBO Project: Innovation and Development

The development of the RainBO infrastructure started from existing data and models, then it focused on the application of new models specifically developed and new technologies, such as CML to enhance the monitoring systems during extreme events.

The project includes the development of a crowdsourcing web application for collecting and sharing information on the observed weather and its possible local effects/impact.

2.3.1. Commercial Microwave Links

The rainfall monitoring system proposed in the RainBO project exploits the Commercial Microwave links (CML or simply Microwave links—MWL) used worldwide in commercial cellular communication networks. Rain-induced attenuation and, as a consequence, path-averaged rainfall intensity can be retrieved from the signal's attenuation by applying, almost in real-time, a rainfall retrieval algorithm. The algorithm chosen for this purpose is the RAINLINK retrieval algorithm [37]. The code is an open-source R package available for free download on GitHub [45].

The implementation of the algorithm for the specific needs of the Italian test areas, as well as code debugging and improving, was carried out within the RainBO project.

To validate the algorithm, a dataset was provided by Vodafone Italia on Bologna and Parma urban areas from February 2016 to June 2016. Other (not commercial) microwave link data were supplied by Lepida to cover the Apennines area, from March 2016 up to date, providing near-real-time data.

During the project, the CML data validation on the Bologna area was performed by comparing the quantitative precipitation estimates (QPE) from CML, radar, and rain gauges.

Radar and rain gauges data were chosen for the validation because they are currently validated, used, and published by ARPAE in their operative meteorological services. It resulted that the coherence between CML and the other estimates is quite promising even if it requires a tuning activity to integrate the dataset with existing technologies (like rain gauges or radar).

Excellent results are achieved mainly in a convective event as shown in Figure 9. On 11 May 2016 precipitation occurred with a well-defined gradient in the West–East direction and some local maxima in the North–West and South–West part of the province. Microwave accumulation slightly underestimated the rainfall field while an overestimation is recorded in the non-adjusted radar. The adjustment procedure well calibrates radar data as displayed in the top right panel of Figure 9. Fine-scale structure of the daily amount is well detected in both remote sensing maps.

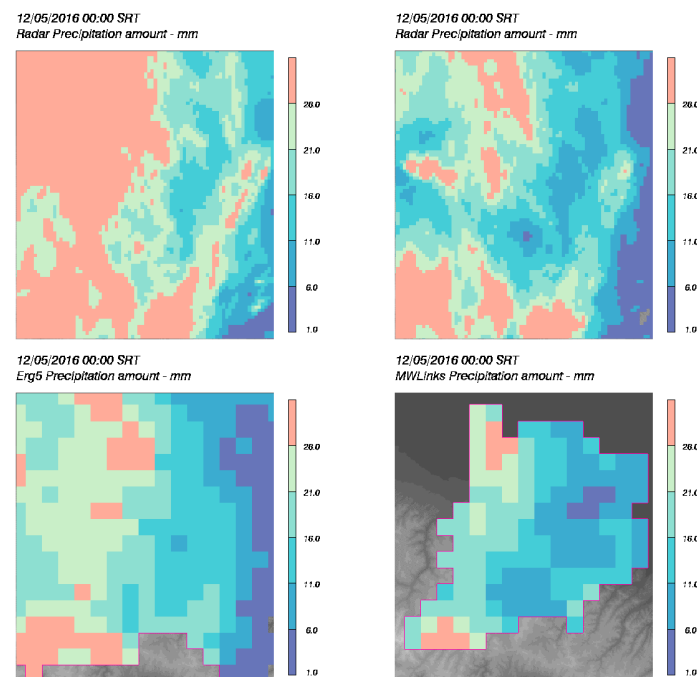


Figure 9. Quantitative precipitation estimates accumulated from 11/05/2016 00 UTC to 12/05/2016 00 UTC. (top left) Radar quantitative precipitation estimates (QPE), (top right) radar adjusted QPE; (bottom left) ERG5; (bottom right) microwave links QPE.

A qualitative analysis showed that the performance of the CLM estimate seems to increase in the second half of the analyzed period (May and June), mainly characterized by convective storms, even embedded in frontal patterns, where showers and heavy rain play an important role. As the microwave estimate is based on the attenuation that occurred in the link path, it is strongly related to rainfall intensity and the signal is, normally, stronger in the convective season. This behavior was confirmed by the quantitative analysis done by using statistical indicators that confirm a good rainfall estimation by CML data during summer and spring seasons. The validation has pointed out that CML estimation slightly underestimates precipitation occurrence both in spatial coverage and point amount, while radar adjusted has a complementary feature.

The precipitation monitoring infrastructure implemented during the RainBO project, based on the CML data, was called Rainlink4EMR (as the RAINLINK algorithm was applied to the Emilia-Romagna region) and a near-real-time module was implemented, which downloads the power attenuation raw data (CML data) from the Lepida telecommunication infrastructure and provides rainfall estimates on the midpoint of the links with a delay of a few minutes.

The validation study allowed us to achieve a first operational version of the related service, providing satisfactory reliability in monitoring convective events.

2.3.2. Crowdsourcing App

A crowdsourcing web application was implemented in RainBO to collect and display information regarding the observed current weather from expert users, as well as from people without any technical

skills. This webApp was created by means of a networking activity with the Rmap project [39] and, thus, it was called Rmap4RainBO.

The Rmap application is mainly addressed to users with meteorological domain expertise and collects automatically data coming from standard hardware devices and weather observation manually uploaded. The RainBO crowdsourcing application, called Rmap4RainBO, develops and improves the Rmap functionalities for the uploading and visualization of the observed weather and it keeps the WMO standard in the weather code. The RainBO crowdsourcing component, differently from the Rmap one, aims to address people without any technical skills so, as a consequence, it was developed as an intuitive and smart application that can be accessed through the RainBO project homepage [46].

The Rmap4RainBO application can benefit from the Rmap data and vice versa as the crowdsourcing information uploaded by citizens through Rmap4RainBO feeds the Rmap database.

Differently from the Rmap, the RainBO crowdsourcing webApp records the impacts, meant as effects of weather on the territory (damaged roads, fallen trees, ice on the road, etc.). The codes used to label the impacts were defined internally at the RainBO consortium as any official code was found on WMO standards; it represents a further innovative contribution by the RainBO project.

2.3.3. RainBO Vulnerability Model

The vulnerability module calculates the degree of vulnerability of exposed items over flood events.

The vulnerability reference maps do not consider in detail population distribution issues, whereas the vulnerability model developed for RainBO includes the presence of sensible targets in the territory (e.g., schools, nurseries, hospitals) and critical targets that can worsen a scenario reducing resilience, such as the fire brigade building.

To take into account in a realistic way the distribution of people on a territory, the developed algorithm considers different time frames: for example, the distribution of the population is supposed to be different in night hours (mainly in houses) with respect to working hours (mainly in workplaces). In a similar way, during morning time, students and teachers are supposed to be in schools, while during the afternoon school users decrease, and during the night no one is supposed to occupy these target buildings.

Vulnerability maps calculated by the vulnerability module are based on territorial data collected on the platform. Moreover, the maps, in summary, are calculated as a function of:

- time frame
- resident population distribution (based on land use—Copernicus, Urban Atlas 2012)
- employees distribution of industrial, commercial and agricultural sectors (based on land use—Copernicus, Urban Atlas 2012)
- users of sensible targets
- presence of critical targets as institutional site and first aid structures that could reduce the resilience of a territory, if they are involved by emergency events
- presence of critical targets such as industrial areas and utility networks, which could produce a domino effect if they are involved by emergency events

The platform provides 32 vulnerability maps (20×20 m grids in raster format), corresponding to 32 reference time frames.

This information is useful not only to compute more realistic vulnerability maps but also because it can be used by the early warning module. Through these data, the priority of targets to be warned during an ongoing emergency can be identified.

2.3.4. Hydrologic Forecast for Small Catchments

One of the main activities of the project has been the development of a model of the hydrological forecast for small basins, by using Ravone as a test case.

Within the available dataset (from 2014 to 2018) of observed water level at the culvert entry there are not events that exceed the alarm threshold. For this reason, CRITERIA-3D model has been used to simulate scenarios in order to assess the effects of severe rainfall events potentially able to exceed the alarm threshold (Figure 10), starting from initial conditions of soil moisture corresponding to the most remarkable event within the dataset (recorded on March 25th, 2015). The scenarios include three possible precipitation sum (70, 85, and 100 mm per event) with two possible event lengths (9 or 14 h) and two possible precipitation hyetographs (triangular and trapezoidal). These choices correspond to a discretization of the precipitation intensities recorded during the most remarkable past events (including the event recorded in 1932) when water level gauges were not installed. Thus, 12 possible precipitation scenarios on the Ravone catchment have been simulated with the CRITERIA-3D model. This discretization is a compromise between the need to simulate as many cases as possible and to run simulations within an acceptable computational time.

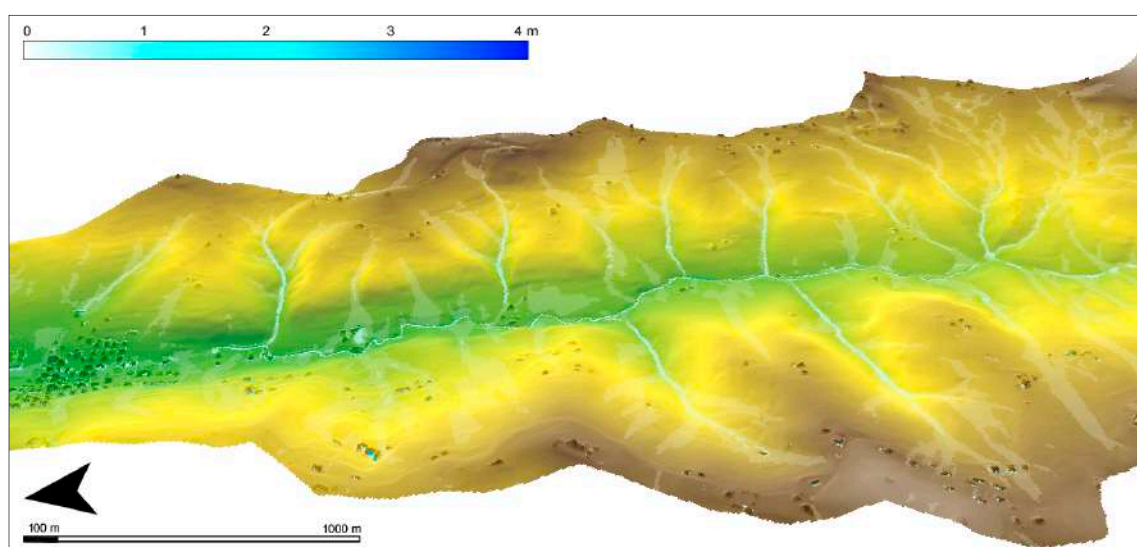


Figure 10. CRITERIA-3D simulation of the surface water flow on the Ravone catchment during a rainfall event. The color scale represents the surface water level (unit: m).

The water levels simulated by CRITERIA-3D have been integrated with observed data. On the resulting dataset, a statistical analysis has been performed, taking into account water levels, precipitation and soil moisture (defined as water holding capacity, see below for further details). As a result, a significant logistic regression between these variables has been identified.

The hydrological forecast is based on this regression using as input the forecast of precipitations of the COSMO-LAMI model, presenting the best available resolution in open data and calibrated on the study area. In order to include the spatial variability of the event, the computation is performed on the Cosmo grid cell containing the prevailing area of the Ravone catchment and on the 8 neighboring cells.

To validate the forecast algorithm, a hindcast analysis using the COSMO-LAMI forecasts for the period 2015–2016 was carried out. The analysis showed that the maximum intensity of precipitation forecast on the area is mainly underestimated, with an average underestimation of approximately a third of the observed value. To compensate for this underestimation, that could be cause missing alarms, the operational dataset used as input for the hydrologic forecast is integrated with a second forecast series where the maximum hourly intensity of precipitation is increased by 33%.

Therefore, an ensemble of forecast scenarios of precipitation is produced and an ensemble of the hydrological forecast is derived. The statistical distribution of this output is computed to provide a boxplot of the hydrological forecast.

In addition to the precipitation, the crucial variable for the hydrological forecasts is the soil moisture of the catchment. We decided to use an estimated value of this variable instead of measured one because

it has the advantage that it is not affected by sensor lacking or failures and local peculiarity. To estimate the soil moisture for catchments of small dimensions as Ravone, it is possible to assess the mean soil moisture of the area by means of a mono-dimensional soil water balance model, as CRITERIA-1D. For the development of the algorithm for the forecasts of exceeding the hydrometric threshold, a new output variable named water holding capacity (WHC) has been added to the CRITERIA-1D model. WHC provides the maximum amount of water the soil can retain before the runoff starts, given the current conditions of soil moisture. For the Ravone study case, CRITERIA-1D is set with the parameters of the prevailing soil on the catchment (silty loam) and the parameters of prevailing crop coverage in the area (fallow); the WHC index is computed on the upper soil layer (30 cm). Weather data (daily temperature and precipitation) used as input are the values of the analysis grid ERG5 on the Emilia-Romagna region.

3. Results and Discussion

The main output of RainBO has been the integration of the data and models described in the Materials and Methods encapsulated in an organic platform [47], as presented in the next paragraph.

3.1. The RainBO Platform

The RainBO platform consists of the following key elements:

- database containing monitoring, territorial, and historical data
- software modules, which are the platform intelligence
- graphic interface, which is the platform output

One of the most important features of the platform is the database containing the monitoring data, whose functionality is to integrate data collected from different monitoring infrastructures, both conventional and unconventional, as well as forecast data, hydrological, and meteorological models, and estimated ones.

In particular, the implementation of an advanced monitoring infrastructure within the RainBO Life project consists of the integration of these types of data:

- real sensors data (e.g., weather stations)
- “virtual sensors” data, not associated with observed measurements from physical sensors, but obtained indirectly through the estimation of correlated data or from simulation models
- forecast data, provided by simulation models

This structure allows us to monitor extreme precipitation events, their evolution, and to generate early warnings. It is worthy to mention that the concept of “virtual sensor” allows us to integrate information from observed and not observed data sources, georeferencing them with the same reference system and synchronizing them over time.

The integration of these new virtual sensors into the RainBO platform has been accomplished in a simple way, using the same data model defined for the physical sensors, without any extension or specialization and providing the platform with an enhanced monitoring infrastructure.

The territorial database hosts both the input data and the output data coming from the processing of the application modules, as well as, obviously, the data necessary to describe the territorial characteristics.

The RainBO platform architecture has been designed according to the following attributes:

- open: each module exposes standard interfaces (web services) to ensure system generality and replicability as well as interoperability and integration with other platforms
- centralized: each DB is centralized and enables data sharing, managed, and updated by different users

- scalable: each module is developed so as to be implemented on different machines
- modular: the platform is formed by individual modules ensuring more flexibility, maintainability over time, as well as platform evolution as each module can evolve or be replaced independently from each other
- configurable: each module is configurable, i.e., the operating parameters must be read from the table and not written in code

RainBO platform has been conceived according to two operational modes:

1. Planning support
2. Event management

Both the modes display a time bar with different time ranges according to the selected operational mode: the menu bar for the planning support mode refers to historical events whereas the menu bar for the event management mode refers to monitoring data (from -24 h to $+72$ h), in addition to menu bars and GIS maps specifically for each mode (Figure 11).

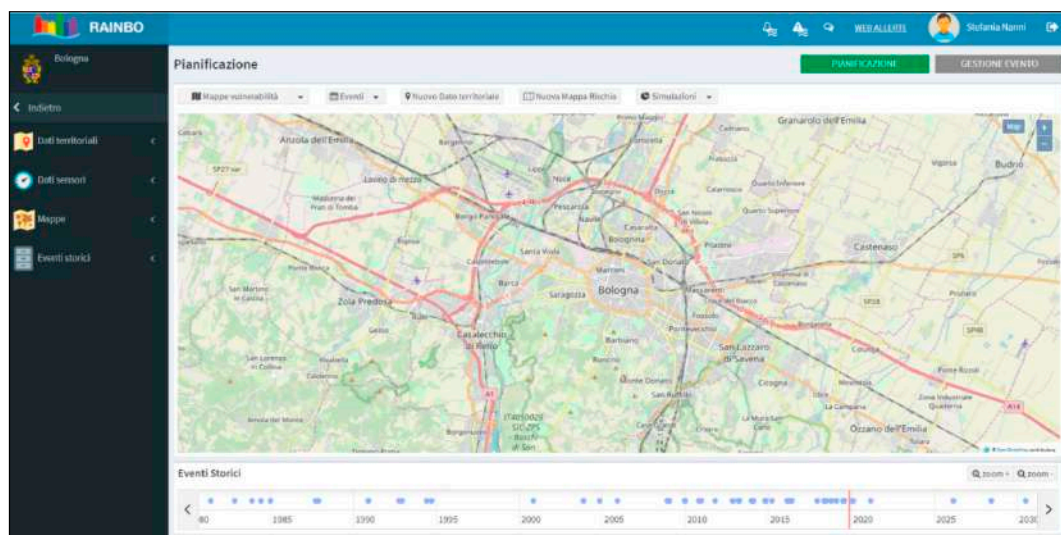


Figure 11. The opening screen of the RainBO platform interface in the planning support mode. On the left bar the thematic maps can be selected and displayed, on the bottom time bar the blue circles, corresponding to historical events, can be clicked and displayed on the map. The two buttons (green and gray) on the upper right corner allows switching from planning support mode to event management mode.

3.2. Territorial Data

To collect territorial data, the data model was defined according to the existing national and regional guidelines for civil protection emergency plans. It requires the mapping of all the critical, sensible, and strategic items, flood maps, river and territory maps (e.g., land use, network infrastructures, buildings, factories, parks).

The territorial database of the RainBO platform contains the existing data listed above: basic regional maps, hazard maps from the Floods Directive, and territorial data at municipality level (e.g., hospitals, schools, emergency areas). The territorial database also contains the maps resulting from the vulnerability module elaborations.

The definition of the spatial data model required an important standardization work to specify its structure, name, and format, to define a standard at the implementation level, both for the RainBO platform and as a reference for data coming from third-party systems.

For instance, the attributes to be provided for schools are the location, the polygon of the area, the number of students, employees and disabled persons, the number of floors of the building, the contacts of the school manager, including the phone numbers. The set of this information, as will be explained below, is necessary both to define the degree of vulnerability of critical sites, but also for the set up of the early warning system.

3.2.1. Hazard, Vulnerability, and Risk Maps

The RainBO platform includes reference hazard maps as:

- hazard maps deriving from the Floods Directive: they represent the potential extent of flooding caused by (natural and artificial) watercourses or by sea, with reference to three scenarios (rare floods (P1—L), infrequent (P2—M) and frequent (P3—H)) represented with three different shades of blue, where the decrease of frequency of flooding corresponds to the decrease in intensity of color. The Floods Directive hazard maps derive from the national hydro-geological management plan (PAI) and they are available for the main basins
- hazards maps from specific hydraulic model/studies for small basins, not included in the Floods Directive maps
- historical events maps that are maps of the flooded areas due to past events. These maps represent an important source of additional information to compare reference maps listed before and real ground effects expected in case of an event.

Concerning these maps, Figure 12a shows the hazard map related to the Parma river in the city of Parma from the Floods Directive. Figure 12b shows the same map integrated with the flooded area during the flood of October 13, 2014. This additional information extends the standard risk area to a secondary one.

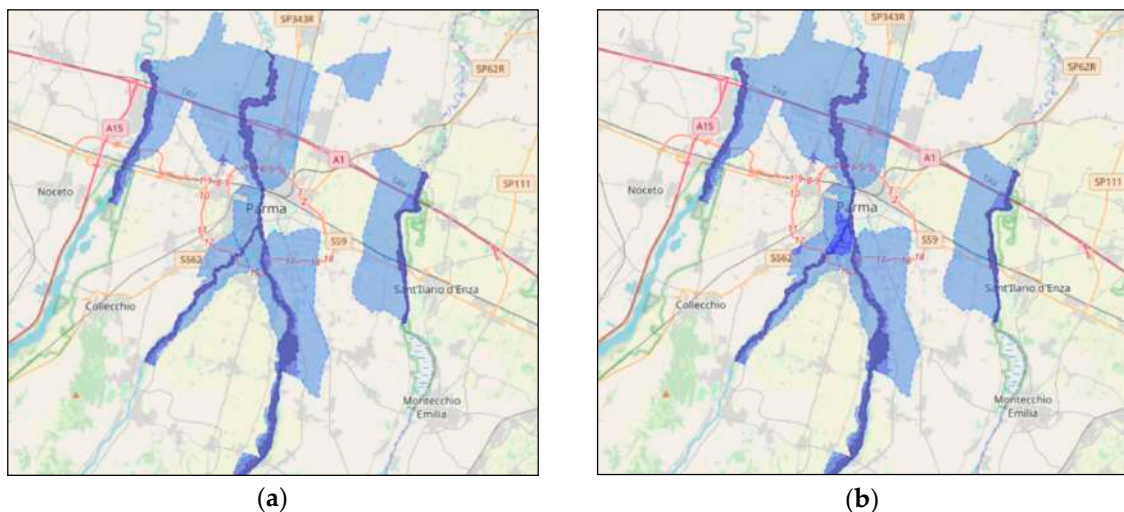


Figure 12. (a) Parma River hazard map from Floods Directive; (b) Parma River hazard map integrated with the flooded area of October 2014. The color from light blue to dark blue shows three different level of hydraulic hazard: P1—L (Low probability of floods or extreme event scenarios), P2—M (infrequent floods: return time between 100 and 200 years—medium probability), P3—H (frequent floods: return time between 20 and 50 years—high probability).

Figure 13 shows the hazard map related to the Reno River in the city of Bologna from the Floods Directive, integrated with the additional hazard map for the Ravone creek.

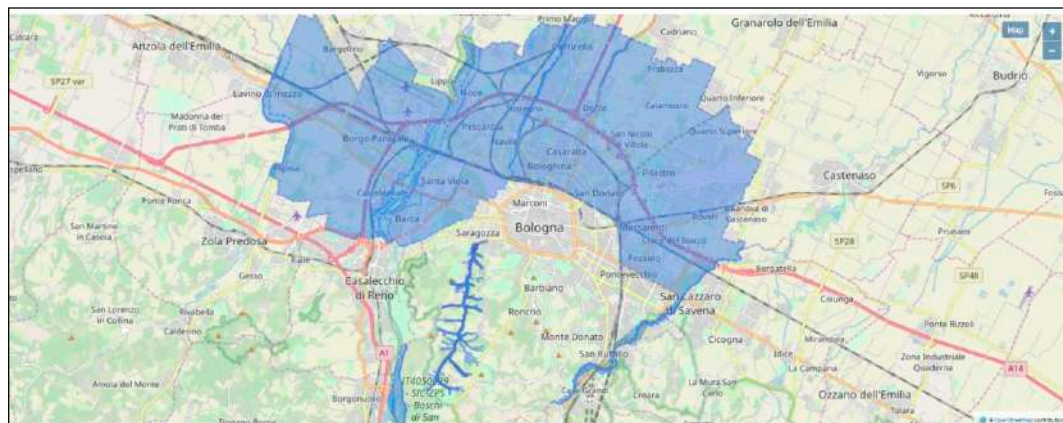


Figure 13. Reno River and Ravone creek hazard map. The color from light blue to dark blue shows three different level of hydraulic hazard: P1—L (low probability of floods or extreme event scenarios), P2—M (infrequent floods: return time between 100 and 200 years—medium probability), P3—H (frequent floods: return time between 20 and 50 years—high probability).

The vulnerability module calculates the degree of vulnerability as described in Section 2.3.3. As a result, 32 vulnerability maps, corresponding to 32 predefined time frames, are produced.

Furthermore, vulnerability maps are a support for territorial planning in prevention and preparedness stages also according to the regional law of December 21, 2017, n.24, which requires the preliminary assessment of the risk, and therefore of the vulnerability, with respect to different types of events, including the hydraulic one, for the purpose of defining the regional urban plan.

In case of an ongoing event, or forecast event, the RainBO platform can select and make available the vulnerability map of the corresponding time frame, providing support for its management.

In more detail, the main difference between the 32 vulnerability maps concerns the distribution of residents, workers, and users of sensible targets during the whole day. By way of example, during the night sensible targets, workplaces, and facilities are usually closed, therefore it is supposed that most of the population are in residential areas. As a consequence, in the vulnerability map referring to this time frame, the urban residential areas are represented in red, whereas during the morning of a working day these areas are green; during the night frame, also sensible targets as schools, gyms, or museums are green areas, whereas during opening hours these areas are red.

Figure 14 shows the vulnerability map of an area of the city of Bologna corresponding to a working day at 4 a.m. The vulnerability level shown in the following pictures is:

- Red for high vulnerability, which means the presence of many people in the grid cell.
- Orange is medium-high vulnerability
- Yellow is medium vulnerability
- Green is low vulnerability, due to the presence of few people in the grid cell

As a result, the RainBO platform provides also the corresponding 32 risk maps. In case other up-to-date or detailed hazard maps (besides the Flood Directive maps) are available, the platform allows us to specify the hazard map on which the risk can be calculated.

As described above, RainBO risk maps based on the vulnerability maps are more detailed and focused on the distribution of sensible and strategic targets and on the time depending presence of citizens in an urban area, with respect to Floods Directive data.

As a result, in case of a forecast event, the risk map, derived from the combination of the hazard map (now from the Floods Directive) and the vulnerability map (selected according to the time frame by the timing of forecast alert between the 32 maps of default) could better support decision-makers to prioritize the warning from the red areas to the green ones.

Moreover, in the planning phase, the capacity of the software to calculate new risk maps from vulnerability maps can support municipal technical and planning offices to evaluate territorial planning choices, as a preventive measure.



Figure 14. Vulnerability map at 04:00 of a working day. In the color legend, green (“vulnerabilità 1”) is low vulnerability, yellow (“vulnerabilità 2”) is medium vulnerability, orange (“vulnerabilità 3”) is medium-high vulnerability, red (“vulnerabilità 3”) is high vulnerability.

Figure 15 shows the risk map at 4:00 a.m. of a working day related to the Ravone creek, produced by using the hazard map of the catchment integrated within the RainBO platform and not included in the Floods Directive.

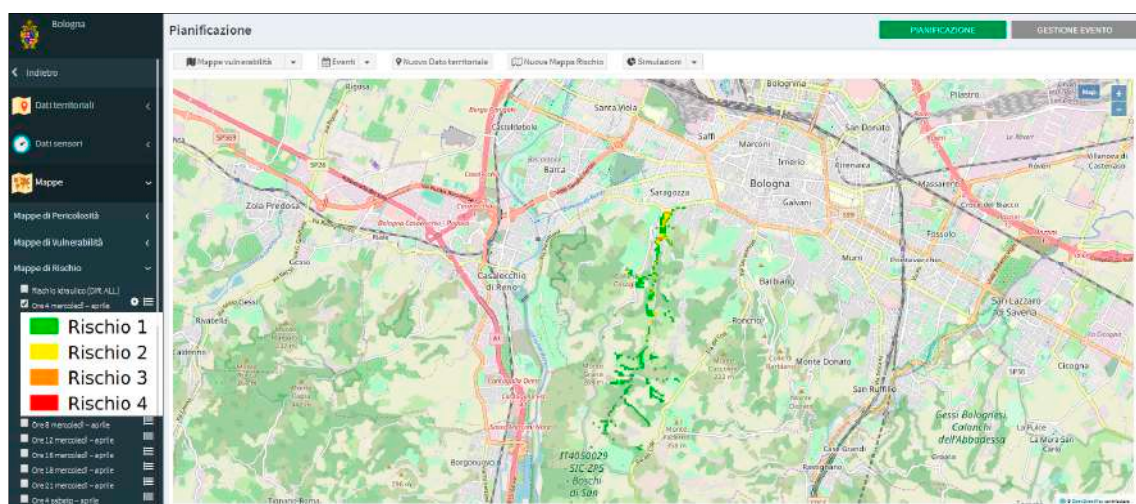


Figure 15. Risk map at 04:00 of a working day referred to the Ravone creek. In the color legend, green (“rischio 1”) is low risk, yellow (“rischio2”) is a medium risk, orange (“rischio3”) is medium-high vulnerability, red (“rischio3”) is high risk.

3.2.2. Historical Events

RainBO platform integrates a database where the most significant past flood events on test catchments provided by Arpaie are stored. This database is aimed at collecting meaningful information for the management of future events. The time bar allows us to identify and explore the flood events in the planning support mode. The most important information linked to the event (e.g., data catchment

of interest, the exceeded threshold of water level gauge, the description of flooded area uploaded on the platform as vectorial data) are highlighted in one view Figures 16 and 17.

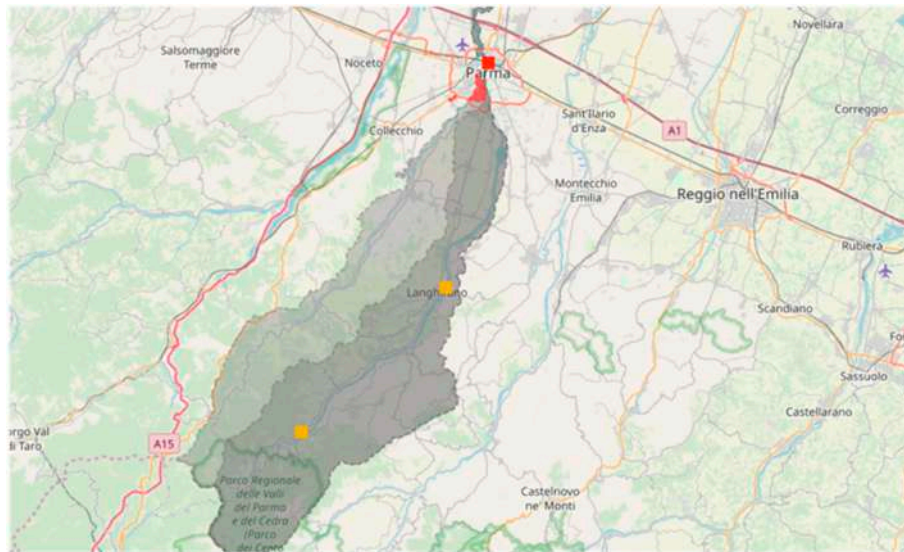


Figure 16. Past flood event on the Parma catchment. The colored squares represent past events where the red (alarm) and orange (pre-alarm) thresholds were exceeded.

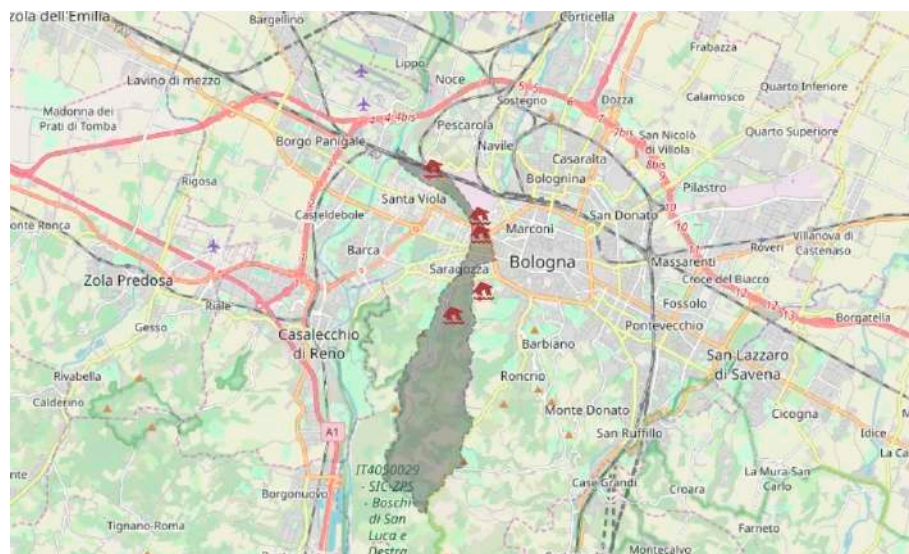


Figure 17. Map of critical points referred to an extreme event occurred on 2015, March 25th in Ravone catchment. The house icons represent the points where damages due to extreme events are recorded.

3.3. Observed, Forecast, and Estimated Data

With regard to the observed data, the RainBO platform collects data from heterogeneous sensors: inclinometers for landslide monitoring, rain gauges, and water level gauges for hydro-pluviometric monitoring of the Arpae network (including the new monitoring stations installed for the RainBO project), inductive-loop detectors for traffic monitoring. The RainBO platform integrates more than 1500 sensors of different types and technologies (Figure 18).

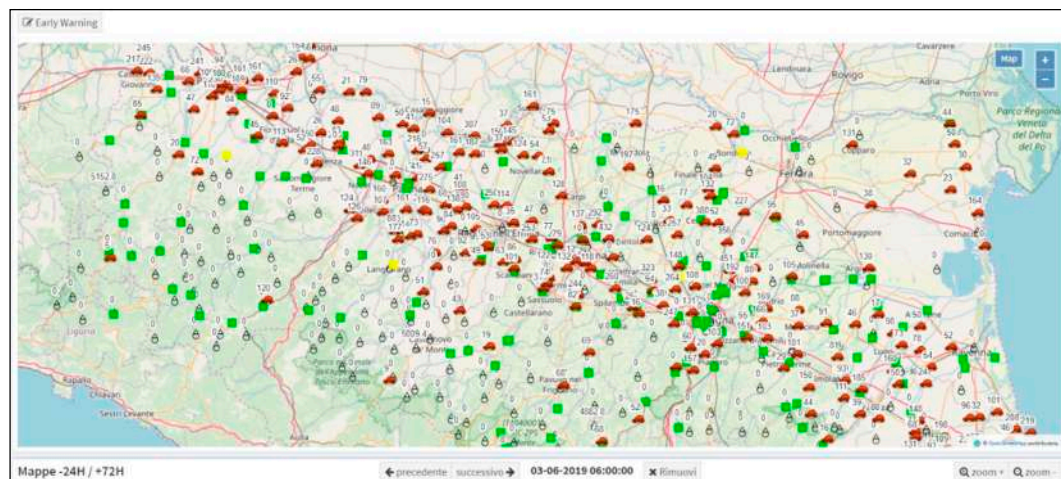


Figure 18. RainBO sensors of observed data: water level gauge (rectangles), rain gauges (drops), and traffic data (cars).

Precipitation forecast maps of the COSMO-LAMI model (Figure 19) are available in a specific section of the platform. Forecasts are summed on 3 h and can be displayed by means of the time bar until the following 72 h.

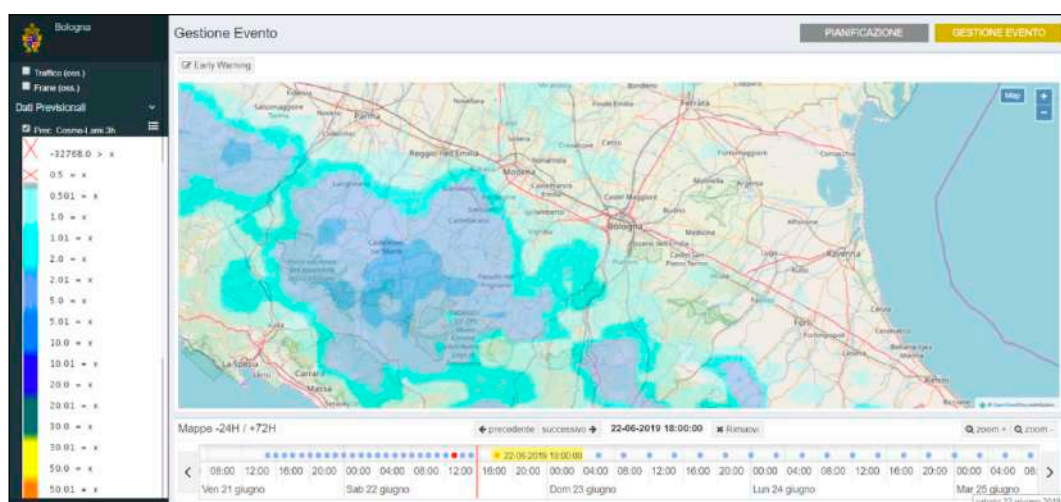


Figure 19. Map of the COSMO-LAMI precipitation forecast. The left-sided color legend represents the quantity of precipitation forecast (unit: mm).

With regard to the estimated data, the system displays maps of radar reflectivity (Figure 20) and radar-estimated precipitation. These two variables are directly related. The hourly maps of these variables can be explored using the time bar for the previous 24 h and it allows the monitoring of ongoing events.

Concerning CMLs, the RainBO platform integrates 73 microwave virtual sensors, corresponding to the midpoint of radio links on the Lepida wireless network (Figure 21).

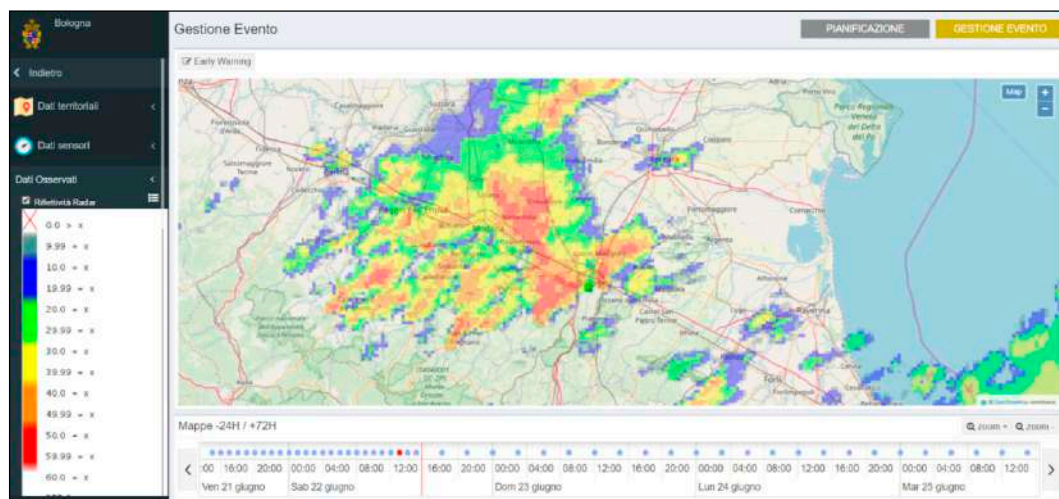


Figure 20. Map of radar reflectivity, a proxy variable to estimate precipitation. The left-sided color legend shows the scale of reflectivity (unit: dBZ).

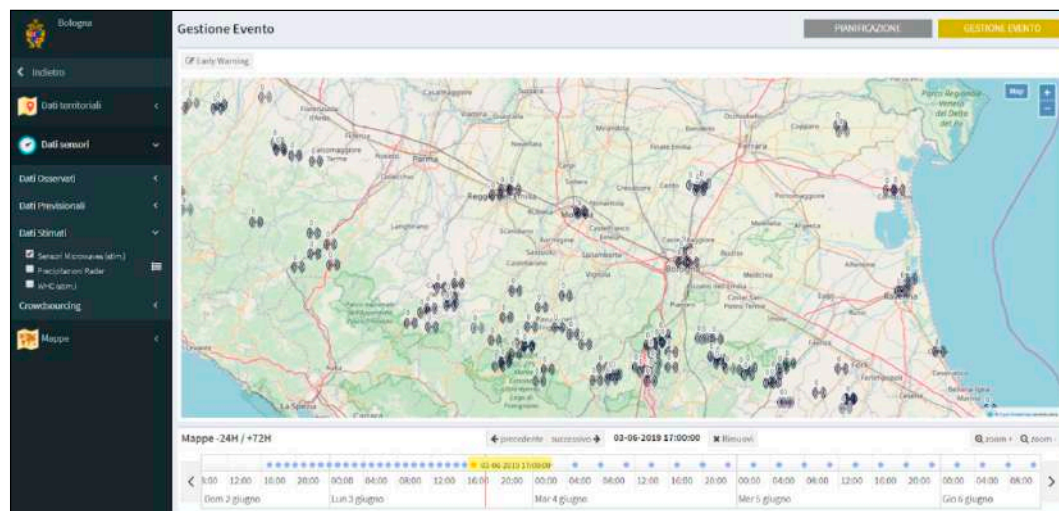


Figure 21. Virtual sensors of precipitation estimated by commercial microwave links (CMLs). The radio wave icons represent the midpoint of radio links on the Lepida wireless network.

3.4. Hydrologic Forecast

RainBO platform provides the forecast of exceeding critical thresholds on the two test catchments, the River Parma for the Parma municipality and the creek Ravone for Bologna municipality. The forecast refers to specific hydraulic sections of the catchments: the culvert entry for Ravone creek, Ponte Verdi, and Ponte Nuovo hydraulic sections for the Parma River.

The forecast covers different time ranges, 6 h for the Parma and 72 h for Ravone, as it is produced by different forecast models, as explained before. In the following, two examples of the RainBO Platform functioning in Event management mode during two extreme events are presented. With regard to the Bologna pilot case, during the afternoon of May 18th, 2019, the Ravone creek exceeded the warning threshold with two water level peaks of 0.82 m at 14 UTC and 0.69 m at 17 UTC.

The water level forecast at the culvert of Ravone issued by the RainBO platform on the morning of May 17th (Figure 22a) matched with the observed values: the exceeding of warning threshold was foreseen with a low probability to exceed the pre-alarm threshold. However, the timing of the event was not correctly forecasted. The hydrological model uses as input the COSMO-LAMI model

that forecasted the precipitation peak during the early morning, whereas it occurred about 8 h later. Therefore the hydraulic forecast shows the same time shift. (Figure 22b).

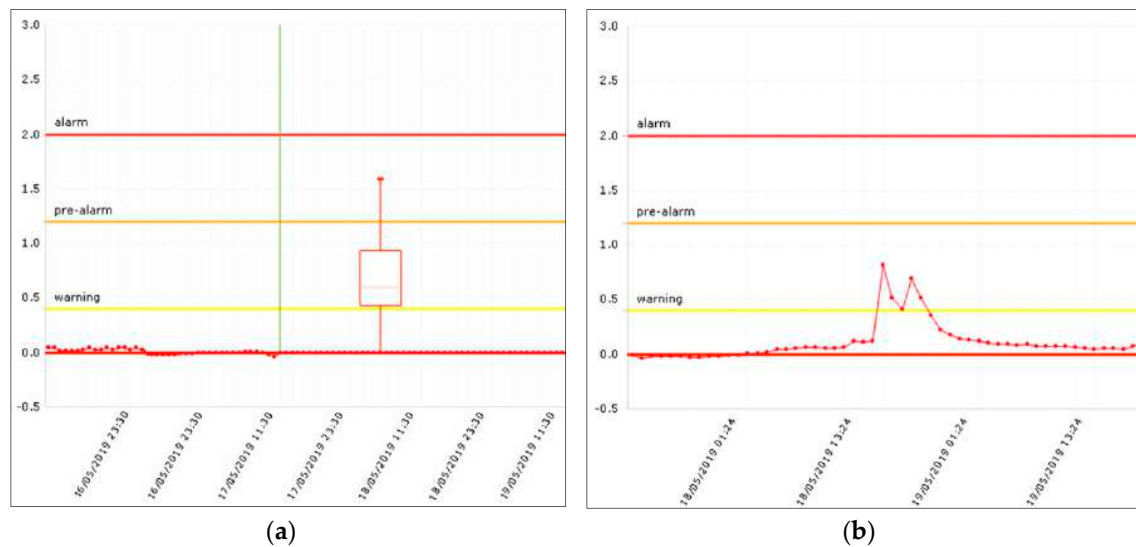


Figure 22. (a) Operational forecast of the maximum water level (m) at the culvert entry of Ravone delivered by the platform on the morning of May 17th, 2019. The green line is the moment of the forecast, on the left, the red dots are the observed data, on the right, the boxplot is the forecast distribution. The box of boxplot represents the interval between the 25° and 75° percentile, the tails are the 5° and 95° percentiles; (b) water level (m) observed at the culvert entry of Ravone, as displayed on the RainBO platform in the event management mode.

Concerning the Parma case study, in 2017, December 12th, the Parma river basin was interested in an intense and prolonged rainfall event, starting from the 14:00 UTC of the 10th of December a weak rainfall interested the basin till the day after when the rainfall started growing in intensity and space. The peak in terms of mean area rainfall was at midnight on December 11th with about 8 mm/hr (Figure 23).

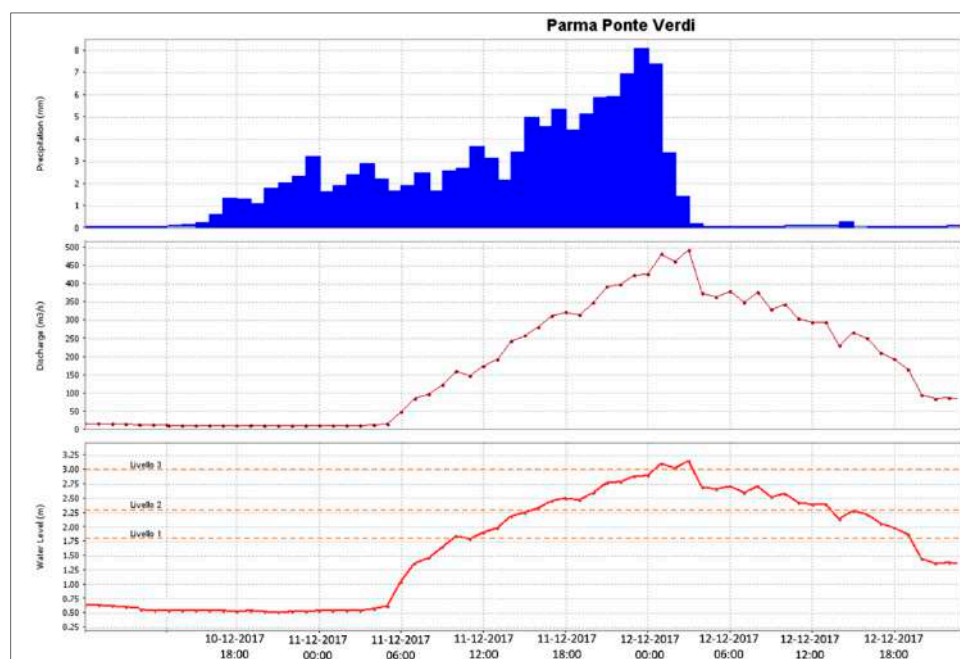


Figure 23. Mean rainfall, discharge, and water level during the December 2017 event.

Looking at the riverside we observed, at 05:00 UTC, the first raise of levels in the river Parma at Ponte Verdi with a level 1 threshold crossing event on the same day at 11:00 UTC. Levels raised continuously in the next hours due to the prolonged rainfall in the basin, reaching the threshold 2 at 16:00 UTC and a peak of 3.14 m (meter above local reference) at 03:00 UTC of the 11th of December, and at the same time, the rainfall in the basin ended with a total amount of mean area rainfall for the entire event of about 116 mm.

The forecast probability generated by the RF model during this event is shown in Figure 24. We can notice that all threshold reached a high probability, between 90–100%, this is obviously related to the high level reached by the river during the event, but we can also consider the forecast lead time provided by the model, in fact, if we look at Table 2, we can find a good consistency between probability and observed effects few hours later, especially for threshold 3 where at 18:00 UTC the probability raise from 12% to 44%, and lately at 20:00 reached a 73%, about 6 h before the effective threshold crossing event, observed at 02:00 UTC (red color).

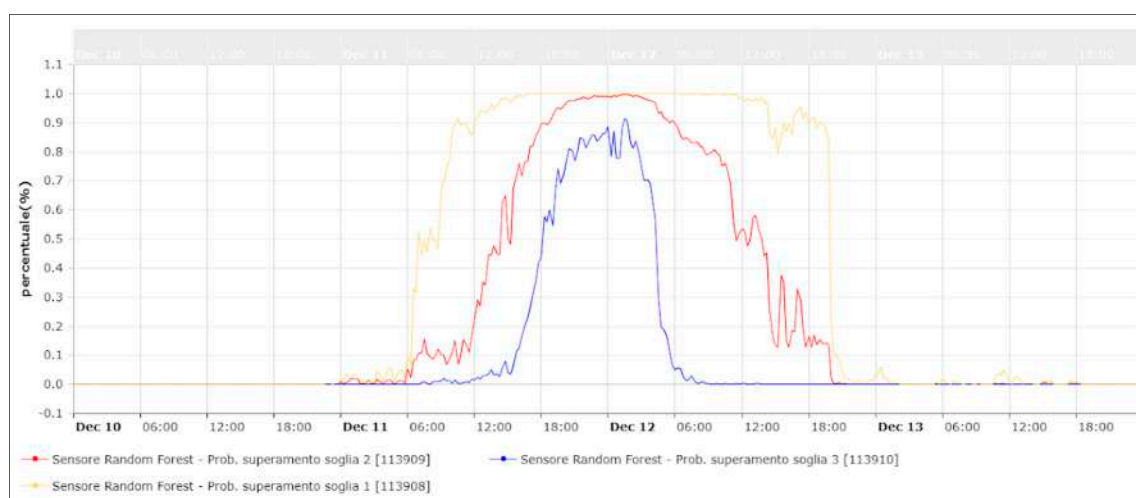


Figure 24. RainBO platform RF results for the Parma River during the event of December 2017.

Table 2. Threshold crossing probability for each level (Green < Threshold 1, Yellow < Threshold 2, Orange < Threshold 3, Red > Threshold 3).

Thr/hrs	07:00 A.M.	08:00 A.M.	09:00 A.M.	10:00 A.M.	12:00 A.M.	02:00 P.M.	04:00 P.M.	06:00 P.M.	08:00 P.M.	10:00 P.M.	00:00 A.M.	02:00 A.M.	03:00 A.M.
1	52	54	67	87	90	96	100	100	100	100	100	100	100
2	11	10	10	11	22	45	76	90	96	99	99	99	99
3	0	0	1	0	1	4	12	44	73	81	89	83	74

3.5. Early Warning Module

An early warning module was developed in the RainBO platform in order to identify the expected scenario as a function of monitoring, forecast and vulnerability maps. A filtering and signaling system allows to select and group essential information useful for the users during extreme events.

In more detail, in the event management mode, two specific icons conceived for early warning are included. The icons are highlighted if a warning occurs. The first icon refers to ongoing events (alert is triggered by observed data of threshold exceeding recorded by water level gauges), whereas the second icon refers to forecasts (alert is triggered by hydrologic models).

In the presence of an alert, a specific dashboard is opened by clicking on the reported event. The dashboard includes only the essential and useful information for the Event management, as the list of catchments where critical thresholds are exceeded (Figure 25), the link to the corresponding charts (Figure 26), the vulnerability map corresponding to the current or forecast scenario.

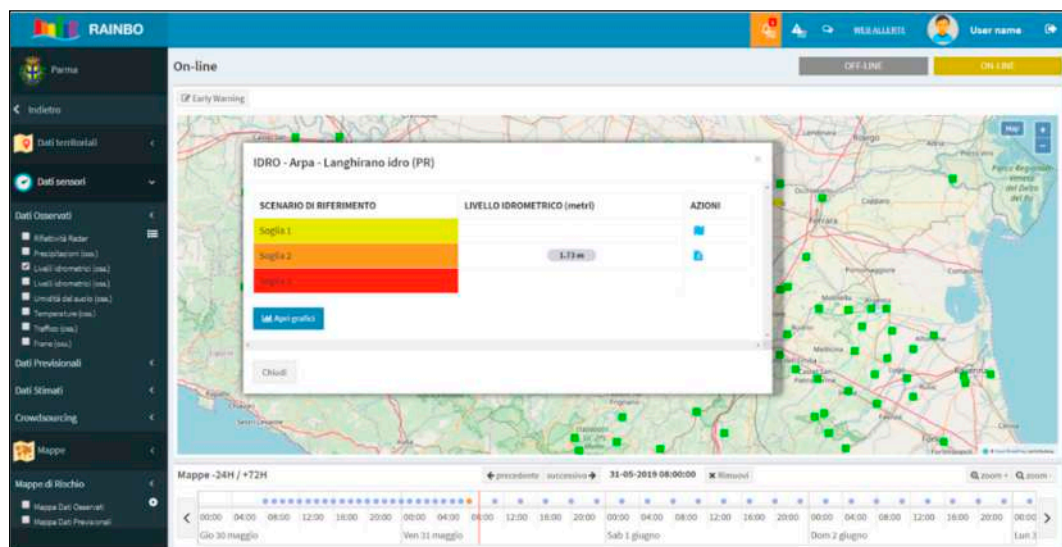


Figure 25. Alert of an ongoing event. The icon on the right side of the platform is highlighted and the dashboard displays the information connected with the event.



Figure 26. Example of charts of water level gauge and its alarm thresholds.

Furthermore, in the event management mode, a specific tool allows selecting an area of interest where critical targets and sensible targets (with users) are listed, so that reference persons can be identified in order to contact them (Figure 27).



Figure 27. Critical sites list and corresponding information displayed by selecting an area of interest.

3.6. Discussion

In general terms, the flood risk in urban areas can be reduced through the implementation of planning, and monitoring and forecasting phases. These activities are related to different time scales and can be supported through a tool that uses multiple information collected and which can display them easily.

The RainBO platform integrates meteorological and territorial data in time/space and provides a holistic interface for the planning phase and disaster risk reduction, allowing to prevent impacts of flood events and reduce the residual risk during their occurrence.

As flooding in urban areas in Europe is increasing, European projects tackled this issue in urban environments with different features. The EU Interreg project URBAN-PREX aimed at monitoring/forecasting and developing online public EWS for extreme precipitations and pluvial floods in urban areas. URBAN-PREX focused on precipitation monitoring by means of rain gauges located in urban areas and precipitation forecasts.

With respect to this project, the approach of RainBO includes further modules that deal with the planning, monitoring, and forecasting phases. Maps of hazard, vulnerability, and risk are available in the planning phase; data and innovative technology such as CML have been included to monitor precipitation events in the monitoring phase; finally, there is a very clear focus on specific hydrological modeling in the forecasting phase.

Another EU Interreg project named RAINGAIN sought to obtain detailed rainfall data at an urban scale, to predict urban flooding and to implement the use of rainfall and flood data in urban water management practice. In this case, radar technology is used to provide estimates of rainfall in time and space in cities.

RainBO provides estimates of precipitation from different sources such as rain gauges, radar data and CML, and provides a forecast of precipitation from a limited area meteorological model. These data related to precipitation are integrated with other processes (e.g., hydrological modeling) and with territorial data useful before and during the event.

Furthermore, the EU FP7 project STAR-FLOOD aimed to improve the implementation of flood risk strategies in urban areas by building appropriate and resilient flood risk governance. This project stressed the need to have proactive and risk-based systems for forecasting, warning and emergency responses for urban floods that also need to use collaborative approaches. Therefore STAR-FLOOD is more focused on the planning phase, whereas RainBO comprises also a consistent part devoted to forecasting and event management.

Finally, the EU Horizon 2020 project FLOOD-serv aimed to develop a collaborative platform among citizens, public authorities and other stakeholders, which enable alerts in due time to reduce

the adverse effects of the floods. In this regard, it is worthy to mention that the RainBO platform is addressed only to decision-makers; decision-makers of a municipality can support both territorial planning and early warning systems through this platform.

RainBO platform has the added value of combining in only one integrated tool territorial data, historical data, real-time monitoring, a crowdsourcing system, hydraulic models for small creeks and medium rivers and the early warning system.

The strengths of the project both in terms of the development of new products and enhancements of existing ones are:

- Vulnerability map calculation module (for hydraulic risk purposes)
- Integration of observed, estimated, and predicted data
- Hydrological simulation model for small basins

Moreover, a first operational level has been defined for a rainfall monitoring system based on CML and it consists of satisfactory reliability in monitoring convective events, mainly during the summer and spring seasons.

4. Conclusions

The RainBO platform is open, centralized, scalable, modular and configurable; it means that it can include various data and models in a different time and space scale, providing an opportunity of replicability and scalability in other geographical and administrative contexts and also for different purposes.

Furthermore, the effectiveness of the RainBO platform has been confirmed by the other municipalities in the Emilia-Romagna Region (i.e., Cento, Comuni della Val Samoggia, Anzola dell'Emilia) keen to demonstrate this platform.

Some limitations of the RainBO platform are to be mentioned:

- The platform is addressed to decision-makers but not to citizens (the citizens can only send information through crowdsourcing)
- The hydrologic models used within the platform have to be calibrated and validated if applied in different river basins, therefore they are not easily replicable in other contexts
- A very large amount of information can be challenging to manage

From a future perspective, the extension of this platform can be foreseen in other urban areas due to the diffusion of open data. As an increasing number of territorial open data is now available, one of the benefits of the platform is also the convergence on the same hub of these data organized in a functional and rational way.

The specific features of this platform allow the upload of datasets provided from international programs (e.g., Copernicus) to supply the lack of local information or infrastructures.

Another future development could be the re-engineering of the platform with a simplified set of information, conceived for the citizens of specific urban areas.

In the future, an effort should be made to enhance the robustness of this platform, i.e., improving the operational functioning of the monitoring and forecasting phases.

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References

1. IPCC. *IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX)*; Cambridge University Press: Cambridge, UK, 2012.
2. EEA. *Climate Change, Impacts and Vulnerability in Europe—An Indicator-Based Report*; EEA: Copenhagen, Denmark, 2017.
3. Blöschl, G.; Hall, J.; Parajka, J.; Perdigão, R.A.; Merz, B.; Arheimer, B.; Čanjevac, I. Changing climate shifts timing of European floods. *Science* **2017**, *357*, 588–590. [CrossRef] [PubMed]
4. Blöschl, G.; Hall, J.; Zivkovic, N. Changing climate both increases and decreases European river floods. *Nature* **2019**, *573*, 108–111. [CrossRef] [PubMed]
5. Alfieri, L.; Burek, P.; Feyen, L.; Forzieri, G. Global warming increases the frequency of river floods in Europe. *Hydrol. Earth Syst. Sci.* **2015**, *19*, 2247–2260. [CrossRef]
6. EU, Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the Assessment and Management of Flood Risks. 6.11. 2007, pp. 27–34. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32007L0060> (accessed on 26 November 2019).
7. Alfieri, L.; Salamon, P.; Pappenberger, F.; Wetterhall, F.; Thielen, J. Operational early warning systems for water-related hazards in Europe. *Environ. Sci. Policy* **2012**, *21*, 35–49. [CrossRef]
8. UNEP. *Early Warning Systems: A State of the Art Analysis and Future Directions*; UNEP: Nairobi, Kenya, 2012.
9. UNFCCC. *Adoption of the Paris Agreement*; UN Framework Convention on Climate Change: Bonn, Germany, 2015.
10. UNISDR. *Sendai Framework for Disaster Risk Reduction 2015–2030*; United Nations: Geneva, Switzerland, 2015.
11. UNDRR. *Global Assessment Report on Disaster Risk Reduction*; United Nations: Geneva, Switzerland, 2019.
12. Golnaraghi, M. *Institutional Partnerships in Multi-Hazard Early Warning Systems*; Springer: Berlin/Heidelberg, Germany, 2008; pp. 1–8.
13. Bouwer, L.; Papyrakis, E.; Poussin, J.; Pfuertscheller, C.; Thieken, A. The costing of measures for natural hazard mitigation in Europe. *Nat. Hazards Rev.* **2014**, *15*, 04014010. [CrossRef]
14. UN. *Transforming Our World: The 2030 Agenda for Sustainable Development*; United Nations: New York, NY, USA, 2015.
15. UNISDR. *Disaster Risk Reduction and Resilience in the 2030 Agenda for Sustainable Development*; United Nations: Geneva, Switzerland, 2015.
16. Hapuarachchi, H.A.P.; Wang, Q.J.; Pagano, T.C. A review of advances in flash flood forecasting. *Hydrol. Process.* **2011**, *25*, 2771–2784. [CrossRef]
17. Jain, S.K.; Mani, P.; Jain, S.K.; Prakash, P.; Singh, V.P.; Tullos, D.; Kumar, S.; Agarwal, S.P.; Dimri, A.P.A. Brief review of flood forecasting techniques and their applications. *Int. J. River Basin Manag.* **2018**, *16*, 329–344. [CrossRef]
18. Acosta-Coll, M.; Ballester-Merelo, F.; Martinez-Peiró, M.; De la Hoz-Franco, E. Real-Time Early Warning System Design for Pluvial Flash Floods-A Review. *Sensors* **2018**, *18*, 2255. [CrossRef] [PubMed]
19. EU. *Establishing the Urban Agenda for the EU ‘Pact of Amsterdam’*. Agreed at the Informal Meeting of EU Ministers Responsible for Urban Matters on 30 May 2016 in Amsterdam, The Netherlands; EU: Brussels, Belgium, 2016.
20. UN. *New Urban Agenda*; United Nations: Geneva, Switzerland, 2017.
21. URBAN-PREX–Interreg Project. Available online: <http://www.urban-prex.org/> (accessed on 18 November 2019).
22. RAINGAIN–Interreg Project. Available online: <http://www.raingain.eu/en/interreg-ivb-north-west-europe-programme-1> (accessed on 18 November 2019).
23. STAR-FLOOD FP7 Project. Available online: <https://www.starflood.eu/> (accessed on 18 November 2019).
24. FLOOD-SERV Horizon 2020 Project. Available online: <http://www.floodserv-project.eu/> (accessed on 18 November 2019).
25. Climatic Tables of Emilia-Romagna. Available online: https://www.arpae.it/dettaglio_generale.asp?id=4143&idlivello=1591 (accessed on 26 November 2019).
26. Grazzini, F.; Dottori, F.; Di Lorenzo, M.; Spisni, A.; Tomei, F. *Nubifragi e Rischio Idraulico Nella Collina Bolognese: Il Caso Studio del Torrente Ravone*; Public Report of Arpa; Arpa: Bologna, Italy, 2013.
27. Bracaloni, A. *Analisi del Rischio Idraulico in Ambiente Urbano: Il Caso del Torrente Ravone a Bologna*. Master’s Thesis, University of Bologna, Bologna, Italy, 10 March 2016.

28. Dottori, F.; Grazzini, F.; Di Lorenzo, M.; Spisni, A.; Tomei, F. Analysis of flash flood scenarios in an urbanized catchment using a two-dimensional hydraulic model. In Proceedings of the International Association of Hydrological Sciences, Bologna, Italy, 4–6 June 2014.
29. Technical Reports of Hydro-Meteo Events in Emilia-Romagna. Available online: https://www.arpae.it/documenti_find.asp?parolachiave=sim_rapportoradar&cerca=si&idlivello=64 (accessed on 18 October 2019).
30. Nanni, S.; Mazzini, G. Advanced Infrastructure for Environmental Monitoring and Early-Warning System Integration, Sensor Networks. In *International Conference on Sensor Networks*; Benavente-Peces, C., Cam-Winget, N., Fleury, E., Ahrens, A., Eds.; Springer Nature: Basel, Switzerland, 2019.
31. Numerical Weather Forecasts of Emilia-Romagna. Open Data of ARP AE. Available online: https://dati.arpae.it/fa_IR/dataset/previsioni-meteorologiche-numeriche-emilia-romagna (accessed on 18 October 2019).
32. Lanza, L.; Stagi, L. Certified accuracy of rainfall data as a standard requirement in scientific investigations. *Adv. Geosci.* **2008**, *16*, 43–48. [CrossRef]
33. Porcù, F.; Milani, L.; Petracca, M. On the uncertainties in validating satellite instantaneous rainfall estimates with raingauge operational network. *Atmos. Res.* **2014**, *144*, 73–81. [CrossRef]
34. Casicci, L.; Ioiò, C.; Pecora, S. An operational system for the Po flood forecasting in Italy. In Proceedings of the 7th International Conference on Hydroinformatics, Nice, France, 4–8 September 2006.
35. Zinevich, A.; Messer, H.; Alpert, P. Frontal Rainfall Observation by a Commercial Microwave Communication Network. *J. Appl. Meteorol. Climatol.* **2009**, *48*, 1317–1334. [CrossRef]
36. Doumounia, A.; Gosset, M. Rainfall monitoring based on microwave links from cellular telecommunication networks: First results from a West African test bed. *Geophys. Res. Lett.* **2014**, *41*, 6016–6022. [CrossRef]
37. Overeem, A.; Leijnse, H.; Uijlenhoet, R. Country-wide rainfall maps from cellular communication networks. *Proc. Natl. Acad. Sci. USA* **2013**, *110*, 2741–2745. [CrossRef] [PubMed]
38. Radar Meteo. Open Data of ARP AE. Available online: <https://dati.arpae.it/dataset/radar-meteo> (accessed on 18 October 2019).
39. Rmap Participatory Monitoring and Exchange System. Available online: <http://rmap.cc/> (accessed on 18 October 2019).
40. Marletto, V.; Ventura, F.; Fontana, G.; Tomei, F. Wheat growth simulation and yield prediction with seasonal forecasts and a numerical model. *Agric. For. Meteorol.* **2007**, *147*, 71–79. [CrossRef]
41. Tomei, F.; Antolini, G.; Bittelli, M.; Marletto, V.; Pasquali, A.; Van Soetendaal, M. Validazione del modello di bilancio idrico CRITERIA. *Ital. J. Agrometeorol.* **2007**, *1*, 66–67.
42. Bittelli, M.; Tomei, F.; Pistocchi, A.; Flury, M.; Boll, J.; Brooks, E.S.; Antolini, G. Development and testing of a physically based, three-dimensional model of surface and subsurface hydrology. *Adv. Water Resour.* **2010**, *33*, 106–122. [CrossRef]
43. CRITERIA-3D. Open Source Code of ARP AE. Available online: <https://github.com/ARPA-SIMC/CRITERIA3D/wiki/CRITERIA3D> (accessed on 18 October 2019).
44. Breiman, L. Random Forests. *Mach. Learn.* **2001**, *45*, 5. [CrossRef]
45. RAINLINK Retrieval Algorithm Open Source Code. Available online: <https://github.com/overeem11/RAINLINK> (accessed on 30 October 2019).
46. Crowdsourcing App Rmap4RainBO. Available online: <https://partecipa.RainBOLife.eu> (accessed on 30 October 2019).
47. RainBO Platform. Available online: <http://webgis.rainbolife.eu/prototipo/01-tempo-di-pace.html> (accessed on 18 October 2019).

