What if the 25th October 2011 event that struck Cinque Terre (Liguria) had happened in Genova, Italy? Flooding scenarios, hazard mapping and damages estimation.

Francesco Silvestro[1*], Nicola Rebora[1], Lauro Rossi[1], Daniele Dolia[1], Simone Gabellani[1], Flavio Pignone[1], Eva Trasforini[1], Roberto Rudari[1], Silvia De Angeli[1,2], Cristiano Masciulli[3]

Dear Editor and Reviewers,

In the following we report the editor and reviewers comments with our replies in italic.

Since most of the modifications are text modifications we report, after the responses, a new version of the manuscript. We based the improvements on the comment's answers.

Along the text we highlighted in yellow the parts of the manuscript where major changes have been applied. Along the text even other modifications have been applied (for example: text modifications, figures modification, …etc).

We hope that the manuscript is now publishable in NHESS but we are open to introduce further improvements.

Best regards.

Referee 1

I have 2 requests: change 'stroke' to 'struck' in the title and elsewhere; correct some of the grammar in a very few places.

We changed stroke with struck as requested and we revise the grammar and typing. If it is necessary we will revise the manuscript with the help of a native English speaker.

Referee 2

Abstract: The abstract should be rewritten. In its present form it seems more an Introduction than an abstract. Parts of the abstract could be moved to the Introduction. After a very short introduction (one or two sentences) the abstract should be focused on the objective of the paper, cases study and methodology and results.

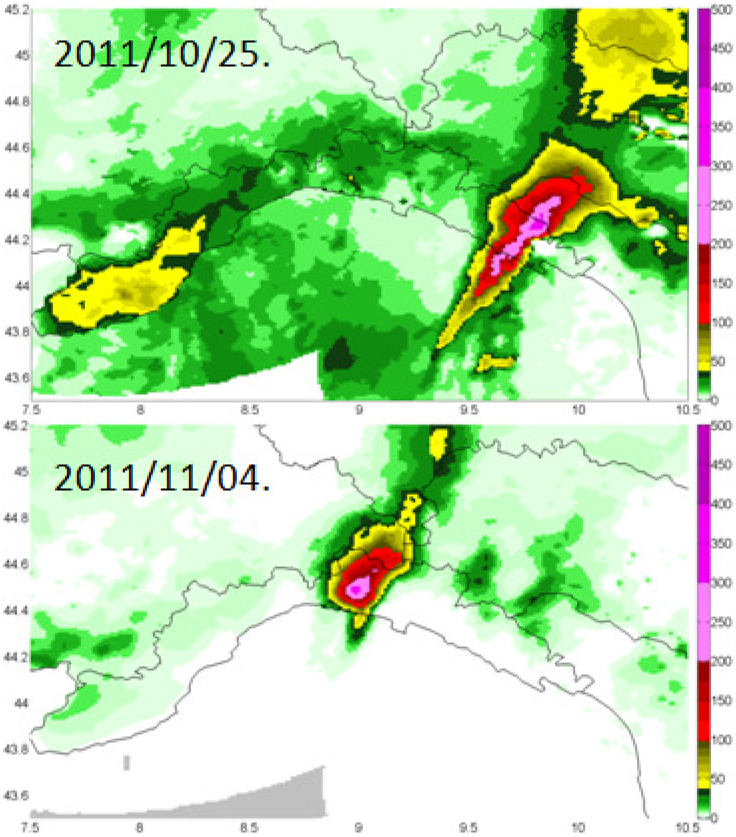
The abstract was rewritten as suggested by the reviewer and part of its first version was moved on the text of section 1. (pgg 3-4 lines 22-3)

Some parts of the Introduction should be moved to the methodology: P.4 Lines 15-23, P.5 Lines 1-8.

We moved part of the introduction to section 3. We left on section 1 only a brief explanation of the method we applied (pgg 9 lines 3-12)

It will be useful to have a better understanding of both events and the reason that justifies the exercise, to include some explanation about the October event that affected Cinqueterre in comparison with the November event that affected Genoa (maximum cumulated rainfall and hourly intensity, damages, relative discharge,…)

We added more details of the two events and a new figure in section 1 as requested (pgg 4 lines.4-15)



Section 2: Please, tell the main features of the Magra basin

In the presented application we do not do any hydrological evaluation on Magra basin and the focus is not the comparison of the effects of the two events. It appears to us a little bit out of the scope of the paper to insert in section 2 the description of that basin since there we described Bisagno creek which is the target area. In section 1 we mention Magra basin and its drainage area(pgg 4 line 16).

Anyway if the reviewer retains necessary inserting more characteristics we are open to do this.

Please, indicate where the Passerella Firpo level gauge is (Bisagno creek? Magra basin?).

We indicated that it refers to Bisagno creek (pgg 9 line 4)

Could you illustrate the example explained in page 13 with a figure?

The requested figure was added

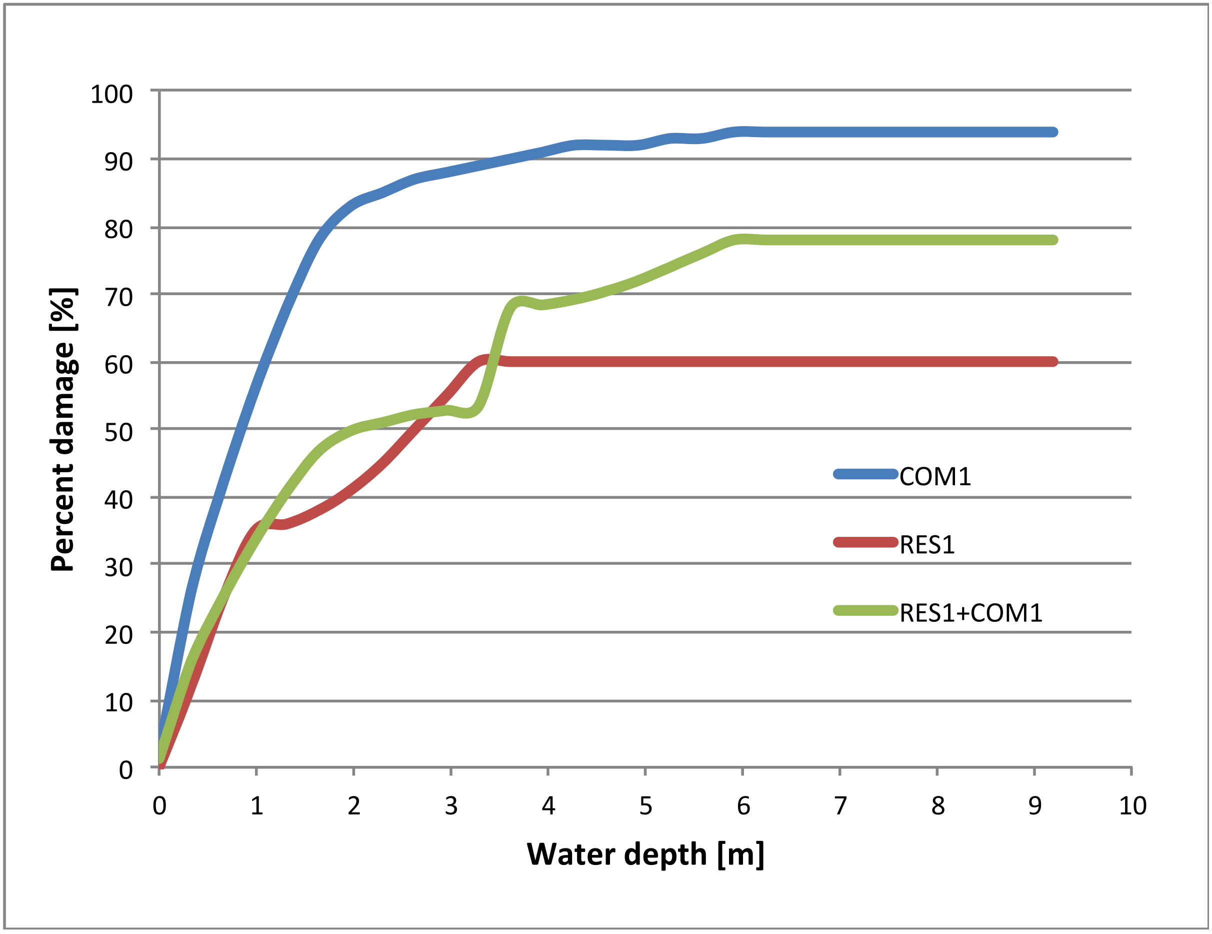


Figure 5: An example of mixed-use curve definition. The green curve corresponds to the flood vulnerability function for the content of a 2-storey building, with mixed commercial and residential use: specifically retail trade at ground floor and residential

at first floor. It is obtained by combining the 1-storey curve for generic residential (in red) with the 1-storey curve for retail trade (in blue). The yellow section of the graph represents the average height of the ground floor. The left part of the mixed curve is obtained by re-scaling the blue curve. For higher values of water level, the function increases proportionally to the values that the residential curves assumes (red) in the left part of the graph.

It is assumed that the value of the ground floor is equal to 60% of the whole (2-storeys) building.

Specific comments

P.2, Line 10: Separate the words “approach combines”

The sentence was moved and corrected

P.3. Line 2: There are some parenthesis and “O” that should be deleted.

We changed the sentence with “….and fast response of catchments with O(Area) 100 to 103 km2 (Quevauviller, 2014).”

P.3. Line 3: To define flash floods, I think it would be better to use other references, like www.nws.noaa.gov; Gaume and Borga, 2008 or Borga et al., 2008.

We added one of the references suggested by the reviewers

P.3. Line 20: Put a point between “authorities” and “Rebora”

P.3. Line 22: Put a point between “question” and “in fact”

P.4. Line 9: Put a point between “data” and “Buzzi”

P.4. Line 11: Put a point between “genesis” and “in addition” and a comma after this.

Ok, done

P.4. Line 19: Add “it” is downscaled

P.4. Line 21: Put a point between “experiment” and “in fact”

P.4. Line 22: “allows accounting”

Ok, done

P.4. Line 22: “allows accounting”

P.5. Line 2: “…large scale”

P.5. Line 21: Genova is also in Liguria. Then, it is better to write only (Liguria, Italy) after “Genova”.

P.7. Line 20: Substitute “here” by “where”

Ok, done

P.8. Lines 13-18: DV? RS? AF?

We changed the text trying to make it clearer.

P.8. Line 3. Please indicate for which hourly interval this precipitation was recorded. Which was the duration of the total event? When the precipitation event is moved to the Genoa catchment, is the time distribution the same?

We changed the text: “The rainfall field occurred from the 00:00 UTC of 25th October 2011 to the 00:00 UTC of 26th October 2011”

The time distribution is one of the variables of the downscaling procedure.

When the temporal aggregation scale is 60 minutes, the time distribution is the same of the observations.

When the temporal aggregation scale is 360 minutes, the time distribution is lost inside the 6 hours length aggregation time windows and it is generated by the downscaling algorithm.

P.8. Line 11 and P.9. Lines 6-10. If the RainFARM product is a downscaling product, why is necessary to aggregate the radar data and disaggregate it posteriorly?

Because in this way we can analyze the effects of changing the temporal and spatial structure of the precipitation but maintaining always the total volume.

This effect should be clear looking at Figure 5 (7 in the new version)

Example:

Spatial agg. 2km and Temporal agg: 1/6 hour. This is (almost) a rigid translation of the event in fact the streamflow scenarios are really similar

Spatial agg. 2km and Temporal agg: 3 hour. The temporal structure changes (not the total volume) and the streamflow scenarios are different

P.9. Line 1: RVs?

Mistake. Corrected with AFs

P.9. Line 9: “Continuum”

Corrected

P.10. Line 7: “hazards. It allows easily updating”

Ok

P.10. Line 18: EO?

Corrected

P.12. Line 7: “2005; Freire, 2010)”

Corrected

P.12. Line 10: Delete the initial letters of the authors’ name.

Corrected

P.13. Line 3: Please, include a reference for the HAZUS-MH database.

Ok inserted

P.14. Line 16: Please, use the super index format for the square meters.

Corrected

P.15. Line 5: Please, delete the initials ML.

Corrected

P.15. Lines 8-10: It seems that the verb lacks

The new sentence is “In order to compare possible impacts on population for different scenarios, four hazard zones (very high, high, moderate, low flood hazard) were defined based on the human instability in floodwaters.”

P.15. Line 15: Delete the word “where” in the parenthesis.

Corrected

P.15. Line 20: Replace $0<h<0.2$ by $h<0.2$; replace $h \geq 0.2$ m and $h < 0.5$m by $0.5>h\geq 0.2$m. Is there any reference for these thresholds? Please, define h (I suppose it is the water level in the inundated street)

P.16. Line 1: Replace h > 0 m and h<0.2m by h<0.2m; Replace h >0.2m 1 and h <0.5m by 0.2<h<0.5 m.

We changed the text as suggested and inserted the definitions of h and v some lines above :"…

that in flow conditions 0.5 < v < 3 m/s and 0.3 < h < 1.5 m (where v and h are the velocity and the water level in the inundated street)…".

The thresholds to differentiate high from very high hazard and moderate from low hazard are introduced based on experience. We modified the text in order to point out this fact "…Further thresholds (upper and lower) were introduced based on "expert judgement" in order to identify…"

DAI P.16. Line 20: Replace yrs. by y.

We used yrs to indicate "years" along all the manuscript since we used it in other published papers so we propose to maintain this nomenclature. If the reviewers retain this should be change we can modify it.

P.16. Line 22-P.17. Lines 1-3: Please, indicate in which gauge stations and regions the different peak flows were recorded. The 7th October event is not necessary "well-known for the reader. Please add a parenthesis with some information about it that justifies its importance.

In section 3.1 we stated that passerella Firpo on Bisagno creek is the reference section: "…The considered reference model section correspond to the location of Passerella Firpo level gauge on Bisagno creek, there the drainage area is 93 km2…"

Now we added on section 4.1: "…. Figure 5 shows the box plot of the 500 peak flows generated with FFF compared with the mean peak flow of the sample of 500 realizations represented by the blue diamonds for the reference model section on Bisagno creek..."

Regarding the event on 7th October 1970.

We removed "well-known" from the text as suggested. The importance is due to the large amounts of dead people, but probably is not important for the scope of this part of the paper. The reference in the text (Rosso 2014) describes the event.

P.17. Line 8: " as they are reported…"

Corrected

P.17. Line 21: Telemac-2D is a part of the Telemac-Mascaret?

Yes as already mentioned in section 3.2

P.17. Line 22: Replace Telecam by Telemac

P.17. Line 22: Replace the comma before “in” by a dot.

P.18. Line 6: Replace the comma before “for” by a dot.

P.18. Line 10: Replace the comma before “some” by a dot

Corrected

P.19. Lines 9-24: The paragraph is indented.

Corrected

P.19. Lines 16-18: The meaning of the sentence “some information…estimation” is not clear. Please, rewrite it

We changed the sentence with: “….Particularly binding was the fact that some information was available only for the considered are, we refer to the high resolution DEM and to some data needed to carry out the damage estimation.”

P.20. Line 11: Substitute Mln € by M€. I suppose that these quantities refer to the simulated event, but, please, remind it to the reader. Do the same change in p. 23.

Corrected and mentioned that the loss refers to simulated events.

P.21. Line 6: I suppose that the extension of the inundated area does not change due to the orography, but it will be better to add a comment to justify it.

The new secentence is:”This is due to the fact that the extension of the inundated area does not change significantly because of the topology”

P.22. Line 7: It will be better to say “the hypothetical rainfall event…” or something similar.

Modified as suggested

P.22. Line 21: UTC in capital letters

Corrected

P.22. Line 22: Replace persons by people.

Corrected

Figure 1: Please, show where the city of Genova is and the position of the radar.

The figure 1 was modified as requested

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Abstract

During the autumn of 2011 two catastrophic very intense rainfall events affected two different parts of the Liguria Region of Italy causing various flash floods. The first occurred in October and the second at the beginning of November. Both the events were characterized by very high rainfall intensities (> 100 mm/h) that persisted on a small portion of territory causing local huge rainfall accumulations (> 400 mm/6h).

Two main considerations were done in order to set up this work. The first consideration is that various studies demonstrated that the two events had a similar genesis and similar triggering elements. The second very evident and coarse concern is that two main elements are needed to have a flash flood: a very intense and localized rainfall event and a catchment (or a group of catchments) to be affected. Starting from these assumptions we did the exercise of mixing the two flash floods ingredients by putting the rainfall field of the first event on the main catchment struck by the second event that has its mouth in correspondence of the biggest city of the Liguria Region: Genova.

A complete framework was set up to quantitatively carry out a “what if” experiment with the aim of evaluating the possible damages associated to this event. A probabilistic rainfall downscaling model was used to generate possible rainfall scenarios maintaining the main characteristics of the observed rainfall fields while a hydrological model transformed these rainfall scenarios in streamflow scenarios. A subset of streamflow scenarios is then used as input to a 2D hydraulic model to estimate the hazard maps and finally a proper methodology is applied for damages estimation. This leads to the estimation of the potential economic losses and of the risk level for the people that stays in the affected area.

The results are interesting, surprising and in such a way worrying: a rare but not impossible event (it occurred about 50km away from Genoa) would have caused huge damages estimated between 120 and 230 million of euros for the affected part of the city of Genova, Italy and more than 17000 potentially affected people.

Key words: flash floods, hazard, extreme rainfall, damage estimation, risk, urban hydrology.

1 Introduction

Flash floods are one of the most disastrous natural hazards that affect citizens in many part of the world causing high risk for them and for their goods and activities. Many types of flash floods exist but in a great number of cases they are caused by very intense (i.e. 50-150 mm/h) and localized rainfall events that persist on the same area for hours (i.e. 4-12 hrs) causing large accumulation of precipitation and fast response of catchments with O(Area) 10^0 to 10^3 km^2 (Gaume and Borga 2008; Quevauviller, 2014). Many authors focused on the analysis of these events, their genesis and their ground effects (Amengual et al, 2007; Barthlott and Kirshbaum, 2013; Gaume et al., 2009; Marchi et al., 2009; Delrieu et al., 2006; Massacanad et al., 1998; Roth et al., 1996), and lot of research was carried out to improve their predictability in terms of rainfall with Numerical Weather Prediction Systems (NWPSs) (Buzzi et al., 2013; Fiori et al., 2014) and in terms of streamflow (Alfieri et al., 2012; Siccardi et al., 2005; Silvestro and Rebora, 2014; Versini et al., 2014) even referring to hydrological nowcasting techniques (Borga et. al, 2011; Liechti et al., 2013; Silvestro et al., 2015a)

During the autumn 2011 two flash floods struck the Liguria Region of Italy causing a total of 19 victims and a large amount of damages. The first flash flood occurred the 25th October 2011; it affected the Cinque Terre coastal towns of Monterosso and Vernazza on the Eastern Liguria Region and caused the flooding of Magra river. The second event occurred 9 days later, the 4th November, at about 50 km of distance and mainly affected the city of Genova with the flooding of Bisagno creek (see Figure 1).

Figure 1

They became two “school cases” studied by many scientists around the world during the last five years and they awaken the interest of the local authorities and of the civil protection actors regarding these type of calamities. Due to the large amount of damages and the numerous victims, they caused a general increase of the sensibleness of the citizens of the stricken areas regarding the natural hazards.

Both the events where characterized by very high rainfall intensities and a highly persistent localization. The V-shaped precipitation structure was observed in both cases, the rainfall cells were anisotropic with the dimension of major axis of 50-60 km oriented in the direction perpendicular to the coast and the dimension of minor axis of 5 to 15 km (see Rebora et al., 2013). The maximum hourly rainfall intensities measured by a gauge where around 160 mm during 4th November event and 150 mm during 25th October event, while the 24 hours accumulation where respectively around 500 and 540 mm. Figure 2 shows the maximum accumulated rainfall on 6 hours for the two events obtained merging the radar data from Italian national mosaic and gauge data with the algorithm described in Sinclair and Pegram (2005).

Figure 2

In both cases the effects in terms of discharge were important, the Bisagno creek (Area = 98 km^2) flooded the 4th of November reaching a peak flow with return period (T) around 30 yrs while Magra basin (Area = 1660 km^2) flooded the 25th of October reaching a peak flow with T around 50 yrs; in some small tributaries the peak flow had T larger than 100 yrs during both the events.

Silvestro et al. (2012) provided an hydrological description of the 4th November event highlighting the efficacy of the forecast approach adopted by the local authorities. Rebora et al. (2013) gave a detailed analysis of what happened based on a wide collection of observed data. Buzzi et al. (2013) conducted a series of experiments based on a Numerical Weather Prediction System (NWPS) to understand the genesis of the two events. Nardi and Rinaldi (2014) analyzed the changes in space and time of channel patterns in response to the major flood of the Magra basin during the 25th October event. Davolio et al. (2015) analysed the improvements in the flood forecast of the two events due to the horizontal spatial resolution increasing of a Numerical Weather Prediction System (NWPS) used to trigger a probabilistic flood forecast chain.Some of the authors of this work were involved as co-authors in many of the aforementioned manuscripts and recently a very simple but interesting question arose: what would have been the impacts if the storm event of 25th October had hit the city of Genova?

This is a reasonable question, in fact various authors (Buzzi et al., 2013; Rebora et al., 2013; Fiori et al., 2014) demonstrated that the two events had similar characteristics and a similar genesis. In addition many of the conditions that triggered the rainfall event were the same.

We tried to answer to this question by setting up a complete flood forecasting chain that combine a rainfall downscaling model, a hydrological model, a 2D hydraulic model and a methodology to estimate damages.

The rainfall downscaling model and the hydrological model are part of the flood forecasting framework presented in Silvestro et al. (2015b) and already employed to study the predictability of a flash flood event. The rainfall field observed on the 25th October 2011 on the east part of Liguria is artificially moved on the Bisagno creek following a probabilistic approach to generate possible streamflow scenarios.

In order to produce a damage assessment analysis, a sub-set of the streamflow scenarios are used as input to a 2D hydraulic model to estimate the related hazard maps and then, using information about exposure, an appropriate methodology is applied to estimate the potential damage and the risk level for the population. This latter is based on a standard approach but a series of novel elements was introduced in order to adapt the method to the particular study area.

Currently the planning and designing of structures and infrastructures which have the purpose of mitigating the flood risk is carried out based on the estimation of peak flow with a certain return period T (as an example in Italy the reference T is 200 yrs), but no indications on the evolution of the discharge event are provided. Given a return period, different assumptions concerning the evolution, duration of the event (shape of hydrograph, total volume, etc) can make a real difference in terms of impacts. The presented work demonstrates that quantitative indications on possible direct impacts can be obtained, at least in some cases, following a "worst case" scenario perspective based on real possible events. The presented approach is robust and it faces the problem in a probabilistic way giving possible flooding scenarios starting from a real precipitation event.

In this way a multi-disciplinary approach was implemented in order to answer to the initial scientific question that is: what if the 25th October 2011 event that struck Cinque Terre had happened in Genova (Liguria, Italy)?

The paper is organized as follows: section 2 describes the study area and the hydro-meteorological data set, section 3 shows the material and models used to carry out the experiments while in section 4 the results are reported, and finally the paper concludes in section 5 with the discussion and conclusions.

2 Hydro-meteorological data set and study area

Bisagno Creek is placed in the center of the Liguria Region in northern Italy (Figure 1), it drains a total area of approximately 98 km^2 and it is characterized by steep slopes due to the a mountainous topology given its proximity to the Apennines. The minimum and maximum elevations are 0 and 1100 m respectively, while the mean elevation is about

370 m. The majority of the Bisagno basin is covered with vegetation characterized by forest, meadows and brushes, but the last 10 kilometres of its riverbed are heavily urbanized; there are residential areas, factories and infrastructures which are exposed to a high risk of flooding. Along the last 1.5 kilometres, towards the mouth, the river flows under a cover.

The territory of Liguria is monitored by a meteorological network, named OMIRL – "Osservatorio Meteo-Idrologico della Regione Liguria". It is the official network managed by the Civil Protection Agency of Liguria Region and it is part of the Italian raingauge network managed by the Italian Civil Protection Department (Molini et al, 2009). This system provides rain gauge measurements with 5-10 minutes timesteps. The network counts a total number of about 200 instruments over the region reaching an average density of 1 rain gauge/40 km^2. Stations with other sensors (temperature, radiation, wind, air humidity, etc.) are present, even though their densities are lower than the rain gauges density.

Bisagno Creek is a very well instrumented/monitored catchment with a rain gauge density of about 1 rain gauge/10 km^2.

For the analyzed basin, level gauge data are available at the cross section Passerella Firpo, that has an upstream area of about 93 km^2. The level data is combined together with a rating curve in order to estimate the observed streamflow.

The Liguria Region (Figure 1) is covered by a Doppler polarimetric C-band radar, located on Mount Settepani at an altitude of 1386 m, that works operationally with 10 minutes scansion time (e.g. time interval when radar data are available). Rainfall fields are provided with 1x1 km spatial resolution.

3 Material and models

3.1 Flood Forecast Framework

The Flood Forecast Framework (hereafter FFF) is described in Silvestro et al. (2015b), and it is made by two elements: i) RainFARM (Rebora et al. 2006a, 2006b) which is a rainfall downscaling model used for generating an ensemble of precipitation fields that are consistent with large scale predictions issued by meteorological models (Laiolo et al., 2013) and/or by expert forecasters (Silvestro et al. 2011); ii) *Continuum* (Silvestro et al. 2013; Silvestro et al., 2015c) which is a continuous distributed hydrological model.

The setting and the parameters of the *Continuum* model are obtained from previous application (Silvestro et al., 2015b). The spatial resolution is 90 m and the temporal resolution is 10 minutes. The considered reference model section correspond to the location of Passerella Firpo level gauge on Bisagno creek, there the drainage area is 93 km^2. The model is run using meteorological observation from ground stations starting from 1th January 2011 in order to estimate the values of the state variables at the beginning of the event.

We supposed to know the total volume of precipitation at a certain large scale (Rainfall Volume: RV) deriving it by the observations.

The rainfall field occurred from the 00:00 UTC of 25th October 2011 to the 00:00 UTC of 26th October 2011 was estimated by the radar rainfall estimation merged with rain gauge data using the Conditional Merging (CM) technique described in Sinclair and Pegram (2005), This rainfall field is named “true rainfall field” (hereafter TRF). The algorithm is applied at hourly scale. The TRF is artificially moved in order to affect the Bisagno creek with the following approach: the point where the accumulated rainfall over 24 hours has the maximum value was made coinciding with the centroid of the basin (see Figure 3). The TRF is then aggregated at different spatial and temporal scales and finally it is downscaled to generate possible streamflow scenarios that affect the Genova city; this is to the knowledge of the authors, a quite novel way to set up a “what if” experiment. In fact, on one side it allows to use a real event (not built with standard methods based on the generation of synthetic events), on the other side it allows accounting for the uncertainties and possible variability of spatial and temporal patterns at small scales (i.e. 1-8 km, 10-60 min) of a rainfall field with a certain volume of precipitation and a certain spatial-temporal structure at larger scales (i.e. 8-30 km, 60-360 min)

Figure 3

The RainFARM parameters are estimated directly by the radar rainfall fields in order to determine the correct spatial and temporal characteristics of the rainfall event.

A domain (hereafter DV) of 32 x 32 km centered where the accumulated rainfall over 24 hours has the maximum value, was considered for computational reasons.

The TRF is aggregated on the DV at different time and spatial scales RS (from fine to coarse scales) obtaining an aggregated rainfall field (hereafter AF). The total volume of rainfall of AF is conserved and equal to the volume of TRF.

The spatial and temporal aggregation scales are chosen in order to account for the possible uncertainties related to the temporal and spatial distribution of the rainfall and to easily compute Fast Fourier Transform (FFT) (Rebora et al., 2006a):

Spatial Scales (km): 1, 2, 4, 8

Temporal Scales (min.): 10, 30, 60, 180, 360

The AFs are then disaggregated with RainFARM producing N equi-probable rainfall scenarios at the radar time and spatial resolution (1 km, 10 minutes) that are used to generate N equi-probable streamflow scenarios by the Continuum model (N=500).

For the sake of clarity we report the scheme of FFF in Figure 4

We can state that the analysis is mainly made by the following steps:

1. Aggregation of TRF on DV at fixed time and spatial scales (RS) obtaining AF
2. Downscaling AF on radar spatial and temporal resolution with RainFARM obtaining N equi-probable rainfall scenarios
3. Using the N equi-probable rainfall scenarios as input to Continuum to produce N equi-probable streamflow scenarios

Figure 4

3.2 Hydraulic model: TELEMAC-MASCARET

TELEMAC-MASCARET (http://www.opentelemac.org/) is an integrated suite of solvers for applications in the field of hydraulic modelling. It is managed by a consortium of core organizations. The suite contains different modules and in this work Telemac-2D is used. It solves the shallow water equations, also known as the Saint Venant equations, using the finite-element or finite-volume method and a computation mesh of triangular elements. It can perform simulations in transient and permanent conditions. This software has many fields of application and is widely used for both research and technical purposes. In the maritime sphere, particular mention may be made of the sizing of port structures, the study of the effects of building submersible dikes or dredging, the impact of waste discharged from a coastal outfall or the study of thermal plumes. In river applications, mention may also be made of studies relating to the impact of construction works (bridges, weirs, and tubes), dam breaks, flooding and transport of decaying or non-decaying tracers.

3.3 Damage estimation

Damage computations was carried out through the RASOR (Rapid Analysis and Spatialization Of Risk) platform (Rudari 2015, Koudogbo et al. 2014), which enables multi-hazard risk analysis for full cycle disaster management. RASOR integrates diverse data and products across hazards. It allows to easily update exposure data and to make scenario-based predictions to support both short and long-term risk-related decisions.

A conventional damage model, based on stage(m)-damage(%) vulnerability curves was implemented to compute building damage related to each flood scenario. Damage assessment considers physical and economic damage at structures and their content.

Besides physical and economic damage, an estimation of the population potentially involved in the area was also given. A simple downscaling methodology was implemented to obtain population distribution at building scale in areas with different hazard levels.

3.3.1 Exposure-building

Very detailed exposure data were obtained merging institutional information with Earth Observation-based (EO-based) and crowd-sourced geographic information and virtual surveys. Buildings were classified according to their occupancy class (usage), as required by the vulnerability model (see vulnerability paragraph below).

Official information from real estate registry and census (year 2011) were updated through high-resolution optical imagery and cross-compared with crowd-sourced dataset such as Open Street Map (http://www.openstreetmap.org). Inconsistencies found in the comparison of the two datasets were fixed thanks to field and virtual surveys.

Moreover, from real estate registry and census datasets it is impossible to distinguish mixed occupancy buildings. In fact, it is very common the case of buildings with commercial activities (like shops, stores, banks, etc...) at the ground floor and dwelling at upper floors. In the same way, no information was provided on the presence of basement. While this type of information might play a minor role for other hazards, in case of flood it is relevant as it changes the response of the building in terms of damage. In this case, field and virtual surveys were realized to recognize these features and classify them in new building classes. The whole process led to an accurate description of the assets in the areas affected by the flood. The original occupancy classes by HAZUS-MH database (www.fema.gov/hazus) distributed from FEMA (US Federal Emergency Management Agency) were extended as shown in Table 1.

Table 1

3.3.2 Exposure-population

Quantifying population exposure as a step for conducting spatially-explicit risk assessment requires to map the spatial distribution of population with adequate spatial-temporal resolution. Since natural hazards can affect urban areas in a very selective manner, only fine-scale population data can provide an accurate estimate of the affected population (Deichmann et al., 2011). Data on resident population (census tracts or global population data sources such as WorldPop - http://www.worldpop.org.uk/, Gridded Population of the World, and Global Rural-Urban Mapping Project by NASA, LandScan by UT-Battelle and United States Department of Energy) are not normally available at building scale. Moreover, due to its dynamic nature, the estimation of people presence in each building is quite complicated as it is affected by many variables, such as hour of the day, level of productivity in the area, main traffic patterns, etc.

In literature several methodologies are proposed to downscale population to fine scales, some examples are: choropleth method, areal interpolation method, dasymetric method, and statistical approach for population distribution in urban area (Bhaduri, et al., 2007; Holt et al., 2004; Langford et al., 2008; Wu et al., 2005; S. Freire 2010).

In this study, a top-down approach is employed to spatially disaggregate and distribute the population from official census and statistics for nighttime and daytime periods, by adapting the methodology proposed by Freire and Aubrecht (2012).

Population is split into three classes: night-time population (equal to the residential population); daytime residential population; and daytime worker and student population.

Total daytime population distribution results from the sum of the daytime population in their places of work or study and the population that remains at home during the day. The latter is obtained by multiplying the night-time distribution by the ratio of resident population who, according to official statistics by the National Statistics Institute (ISTAT, 2011), does not commute to work or school. Daytime population is then distributed into buildings, which are considered the main aggregation places; a buffer around the building is considered to take into account also of people which could be in the proximity of the building. Daytime residential population is then equally distributed among residential building storeys while daytime commuting workers and students are distributed into non-residential building storeys.

3.3.3 Vulnerability-building

A classical damage model, based on stage(m)-damage(%) vulnerability curves was implemented to compute losses associated to each flood scenario. HAZUS-MH database provides one of the most complete collections of stage-damage curves. Water depth-damage functions in the HAZUS library are separately provided for structure (load-bearing systems, architectural, mechanical and electrical components, and building finishes) and for content. Different curves are available for different occupancy classes.

Starting from this collection, several curves were added to take into account additional classes such as mixed occupancy (e.g. retail trade and residential) and presence of basement (see Table 1). In order to create curves for mixed occupancy and multiple storeys residential occupancy classes the following procedure was applied. The first part (from 0 to 3m) of the residential curve for one-floor building (RES1) from HAZUS is intended to be representative of each floor of a generic multi-story residential building. Under the assumption that each of the N floors represents, in percentage of damage terms, 1/N of the total building damage, for the construction of an N-story residential building it is necessary to sum this curve N times, taking care to weigh each addend by multiplying by 1/N. The same hypothesis and the same procedure apply to mixed-type buildings with commercial activities at the first floor (retail trade or restaurant, etc.) and apartments on the other floors: in this case, for the first floor, the first part of the curves for commercial building is used (e.g. COM1, COM8, etc.), while for each of the other floors the residential part of RES1 is summed (N-1) times. In this case different weights for different occupancy types can be used, as in general the value for commercial floors is bigger than the one for residential floors (Figure 5).

Figure 5

Figure 6 shows a comparison between three water depth – damage curves for content: retail trade (COM1) building [blue], mixed retail trade (COM1) at first floor & RES at second floor

[red], mixed retail trade (COM1) at first floor & residential (RES) at second and third floor [green].

Figure 6

The new set of curves covers all the possible types of buildings in the flooded area.

Physical damage obtained by application of stage–damage functions can be transformed into economic losses (ED) using replacement cost per square meter.

$$ED[€] = PD * A * RC * (n + b) \qquad (1)$$

where:

$PD\ [\%]$ is the physical damage

$A\ [m^2]$ is the area of the building footprint

$RC\ \left[\frac{€}{m^2}\right]$ is the replacement cost per square meter

n is the number of floors

$$b = \begin{cases} 0 & \textit{if the building has not a basement} \\ 1 & \textit{if the building has a basement} \end{cases}$$

Two different lumped replacement costs are assigned for structure damage and content damage: 500€/m^2 for structure replacement costs, and 400€/m^2 for content replacement costs. Those costs were derived considering typical damage caused by flood (replacement of floor, doors and window fixtures, sewage and electric systems, finishes, plaster, etc.) and the local market prices indicated by the regional authority (Unioncamere, 2014).

3.3.4 Vulnerability-population

Despite the enormous impacts of floods, there is relatively limited insight into the factors that determine the loss of life caused by flood events. In the literature several methods have been developed to assess the loss of lives due to flood events and to identify mitigation measures (DeKay, McClelland, 1993; Jonkman et al., 2008). In general these methods consist of a quantitative relationship between the flood characteristics (such as water depth, velocity) and the mortality in the flooded area.

In order to compare possible impacts on population for different scenarios, four hazard zones (very high, high, moderate, low flood hazard) were defined based on the human instability in floodwaters. In fact, practical experiments (Abt et al., 1989; Karvonen et al., 2000) show that in flow conditions $0.5 < v < 3$ m/s and $0.3 < h < 1.5$ m (where v and h are the velocity and the water level in the inundated street) the average human instability threshold in floodwaters corresponds to $hv = 1.35\ m^2/s$, (Jonkman et al., 2008). This is the threshold that differentiates the "high flood hazard" vs "moderate flood hazard" zones. Further thresholds (upper and lower) were introduced based on "expert judgement" in order to identify two other classes: "very high flood hazard" (very high water level and velocity) and "low flood hazard" (low water level and velocity). The resulting four flood hazard zones can be ranked as follows:

Very high hazard zone: if $hv \geq 5\ m^2/s$ and $v \geq 2\ m/s$

High hazard zone: if $h \geq 0.2\ m$ and $hv > 1.35\ m^2/s$

Moderate hazard zone: if $h < 0.2\ m$ and $hv > 1.35\ m^2/s$) or ($0.5 > h \geq 0.2\ m$ and $v > 1$ and $hv < 1.35\ m^2/s$) or ($h > 0.5\ m$ and $hv < 1.35\ m^2/s$)

Low hazard zone: if ($h<0.2m$ and $hv < 1.35\ m^2/s$) or ($0.5> h \geq 0.2\ m$ and $v < 1m/s$):

For each zone potentially affected, population is computed taking into account where the population is located during the day and the night at building level (see Exposure paragraph). This method can give useful indications especially in relative terms when comparing different scenarios.

4 Results

4.1 FFF

The results are shown using box plot representation. Figure 7 shows the box plot of the 500 peak flows generated with FFF compared with the mean peak flow of the sample of 500 realizations represented by the blue diamonds for the reference model section on Bisagno creek. Each panel refers to a different spatial RS (RSs), while on the x-axis the temporal RS (RSt) is reported (the case with RSs=1 km and RSt=10 minutes is obviously not considered since it corresponds to the resolution of the original field).

Figure 7

It is noticeable the fact that the Q_p varies from 1200 to 1800 m^3/s considering the 25% and 75% percentile of the box especially for spatial aggregations RSs 1 and 2 km, while the mean Q_p is between 1400 and 1600 m^3/s. This means that the considered rainfall field could lead to a peak flow with a return period T larger than 200 yrs, $Q(T=200 \text{ yrs}) \cong 1300$ m^3/s (Boni et al., 2007; Provincial Authority of Genoa, 2001). Just to have some terms of comparison: the 4th November 2011 flood led to a peak flow around 750-800 m^3/s (Silvestro et al., 2012), the 9th October 2014 major flood (Silvestro et al., 2015b) led to a peak flow around 1100-1200 m^3/s, the peak flow of the flood on 7th October 1970 was estimated around 1100 m^3/s (Rosso, 2014).

We considered the configuration with RSs=4 km and RSt=3 hrs in order to account for spatial and temporal uncertainty of rainfall pattern and to give a certain variability to the disaggregated rainfall fields, and to maintain a certain spatial-temporal coherence between RSs and RSt (Rebora et al., 2006b); we extracted the hydrographs that lead to the peak flows with 10, 25, 50, 75, 90 percentiles (hereafter perc10 to perc90), as they are reported in Figure 8.

Figure 8

The time series furnish important information. Firstly they confirm the severity of the possible streamflow scenarios (consider that given the current structural condition of the riverbed the flooding threshold is around 700 m^3/s); secondly they evidence that the flooding would have occurred between 12:00 and 16:00 UTC (14:00 to 18:00 local time) when the potential risk for human lives and goods were very high. In fact during that time window the city is in full activity: there is a lot of traffic due to people that uses means of transport for work, the shops and stores are open, kids and children exit from school.

4.2 Hydraulic model validation

The extent of hazard map was estimated using the hydraulic model Telemac-2D. The basic static input data used by Telemac-2D is a Digital Elevation Model (DEM). In this application a DEM with 1 m spatial resolution acquired by Light Detection And Ranging (LIDAR) technology was used; DEM information was integrated with a detailed description of the Bisagno riverbed derived by survey measurements done between August 2012 and June 2013. The aforementioned data were used to describe the topology of the area of the city of Genova affected by the Bisagno creek flooding events. The hydraulic model was set and calibrated to reproduce historical flooding especially the one occurred the 9th October 2014 (Silvestro et al., 2015b). For this latter a lot of data are in fact available together with a large number of field measurements that allowed to well estimate the magnitude of the flood in terms of both water level and extent (Figure 9).

The final setting of the model allows a good reproduction of the field post-event measurements Some mismatches are present and they are due to a non perfect reproduction of the real altitudes by the DEM in some areas, and by the fact that some features (for example basements) cannot be described with high detail but only in a parametric way.

Figure 9

4.3 Hazard mapping and damage estimation

This exposure dataset and the entire damage computation methodology presented in section 3.3 were validated referring to a recent urban flash flood, which occurred in October 9th, 2014 in Genoa (Silvestro et al., 2015b). In this event hazard and exposure-vulnerability models were computed separately and validated against observations and claims. As showed in paragraph 4.2 the maximum water depth values obtained by the hydraulic model were compared and validated with flood marks collected in the aftermath of the flood as described in section 4.2 (Figure 9). The total simulated damage was then compared and validated across the official damage assessment obtained through citizen claims and municipal authorities surveys (Trasforini et al., 2015). In that study, over 3000 refund requests for flood damage were processed and georeferenced, aggregated at building and neighbourhood scale to validate computed losses.

It must be remarked that damage at building structure and content does not represent the whole damage reported during the event. A relevant portion of total damage was due to cars parked in private and public parking and along the streets, to transport facilities (roads and train station), public sewage systems. These contributions are not accounted in the presented analysis.

The five streamflow scenarios identified in paragraph 4.1 (scenarios perc 10 to perc 90) were used as input to Telemac-2D and then the methodologies described in section 3.3 were applied to estimate the damage and the affected population.

An important hypothesis that was done and that needs to be noticed is related to the point where the flooding starts along the riverbed. It is in fact assumed to be constant for all the scenarios and coincident with the flooding point occurred during the benchmark event (9th October 2014 flash flood) used for validation, this is not rigorously correct but we needed to do this assumption for different reasons. Particularly binding was the fact that some information was available only for the considered area, we refer to the high resolution DEM and to some data needed to carry out the damage estimation.. All this leads to an underestimation of the total flooding area because the areas nearby the river branch upstream the considered point are not accounted.

The results are presented in Figure 10 to 12 where hazard maps are shown together with economic damage at building scale.

As can be easily seen the flooding affects a large heavily urbanized area, where several stores, offices, retail trade activities, schools and residential buildings are placed. The extent of the affected area weakly changes between perc10 to perc90 scenarios because of the topology of the city; anyway the water level in various areas changes dramatically increasing even of 2-3 meters. This is due to the increasing of flooding volumes and their accumulation on the depressed areas. This occurrence clearly leads to a different impact in terms of damage to goods and to a different level of risk for the lives of citizens.

In table 2 and 3 the estimation of economic damage is reported for each flooding scenario compared with the damage estimated for the 9th October 2014 flash flood, used as benchmark, during which a peak flow that correspond to a $100 < T < 200$ yrs was registered. Results are reported both as absolute values and percentage values and separating the damage to the structures from damage to the content. It is impressive that the total damage fort the simulated events ranges between about 141 M € and 232 M €, that in percentage means a range between 140 and 231 % of the 2014 event. Even the Perc10 scenario leads to a larger amount of damages in respect to the benchmark event notwithstanding the peak flows are comparable; this is probably due by a larger overbanking volume.

Table 2

Table 3

Table 4 reports the total affected population and their distribution on the areas at different level of risk. Population was distributed according to a day-time scenario (the hypothetical event would have occurred between 14:00 and 18:00 local time), considering that people can be found not only in dwellings but also in commercial and industrial buildings, schools, etc. (see paragraph 3.3.2 “Exposure-population”)

Table 4

Figure 13 to 15 show the maps with zones at different hazard level together with the affected population assigned to each building, while table 4 reports the total affected population and its distribution in zones with different level of hazard.

The total population that can be potentially affected by flooding is quite high (almost 19000 people) and does not significantly change from a scenario to another. This is due to the fact that the extension of the inundated area does not change significantly because of the topology. Clearly the percentage of people that can found themselves in areas at high or very high level of risk increases with the hazardousness of the scenarios (from Perc10 to Perc90), because of the different water levels and different flow velocities. This fact is evidenced both by Figures 13 to 15 and by the table 4.

5 Discussion and conclusion

The presented work analyses the consequences of a hypothetical but realistic event in Genova city located in correspondence of the mouth of Bisagno Creek, Liguria Region, Italy. This approach aims at quantifying impacts of possible real events in a "worst case" perspective. This is accomplished considering the rainfall field occurred during a real flash flood event at about 50 km of distance and transferring it over the target catchment following a robust and novel methodology based on the work presented in Silvestro et al. (2015b). The motivations that drove this kind of analysis can be found reading various papers (Buzzi et al., 2013; Delrieu et al., 2006;Rebora et al., 2013; Silvestro et al., 2012; Silvestro et al., 2015b) which show that this kind of very intense rainfall structures can potentially strike, more or less indifferently, a large portion of the Liguria Region Coast.

The rainfall field was used as input to a Flood Forecast Framework made by a downscaling model and an hydrological model in order to account for uncertainties related to the spatial and temporal structure of the rainfall pattern and to generate an ensemble of possible streamflow scenarios; a subset of these streamflow scenarios was then used to feed a hydraulic model in order to simulate the hazard maps. These latter are then used to estimate the damages with a proper methodology developed within the RASOR FP project (Rudari 2015; Koudogbo et al., 2014) .

The results of the experiments can be summarized as follows:

1) The hypothetical rainfall event lead to a very low frequent and extreme flood event on Bisagno creek, the peak flow at the section Passerella Firpo (located in the city of Genova) is around 1400-1600 m^3/s that correspond to a return period T larger than 200 yrs.
2) Peak flows of the aforementioned magnitudes are realistic and possible even if in living memory they never occurred. This is not a commonplace result. In fact, generally, these high flow values (T>200 yrs) are the result of statistical analysis of observed/simulated annual maxima time series with reduced length N (with N < 50-100 values) so very uncertain. The experiment generates such streamflow magnitude using a real rainfall event and considering a realistic soil moisture as initial condition of the study area.
3) The flooding of Bisagno creek in correspondence of the city of Genoa leads to a large inundation area with water level even higher of 2-3 meters in the centre of the city. The large volume of flooding produces large accumulation in the streets especially in depressed area

4) The over banking occurs between 12:00 and 16:00 UTC (14:00 to 18:00 local time) which is a time window really dangerous with a large number of people that can be potentially affected by the inundation
5) The estimated damages to the structures and their content is between 141 and 232 M of euro that means 140 to 231 % of the benchmark event, that was caused by a peak flow with 100 yrs < T< 200 yrs.
6) The population potentially affected is roughly between 17000 and 19000 units, with a distribution in the areas at high and very high hazard level which ranges between 3600 and 7700 units. This is a conservative estimation since the applied methodology does not completely account for people that live out of the affected area, but can access the area during their daytime activities.

These results show how devastating could be an event of such a magnitude and they highlight the need of augmenting the resilience of the city and of its population. Sophisticated and state of the art Early Warning Systems (EWS) as well as nowcasting techniques (Silvestro et al., 2011; Berenguer et al., 2005) are already operational in the study area as well a Civil Protection system that is able to act on the territory (Brandolini et al., 2012). Anyway we have to consider that EWS can fail especially in the exact localization of the event (Silvestro et al., 2015b, Buzzi et al., 2013) and that a Civil Protection system is effective when the population is able to translate the Alert and Warning messages in tangible behaviors and actions. The preparedness and correct information of the population is a basic prerequisite to save lives and try to reduce the loss of goods: people (especially who live or work in areas at high risk) should know exactly how to behave in case of event avoiding such actions that increase their risk. Moreover, even if in the case of a (purely hypothetical) perfect EWS, which enables Civil Protection to issue prompt alert messages and saves all the population, the level of damage would be huge anyway, causing large problems to the economy of city. With this respect, retrofitting measure aimed to reduce vulnerability (i.e. some small investments such as rails for stoplogs) can be useful in order to reduce the damages, especially in those areas were water level do not reach very high values. These interventions can be really effective until structural measures are completed and they can be useful to manage the residual risk once structural interventions are done. In the specific case, a series of structural measures, designed to avoid flooding driven by peak flows with T≤200 yrs are planned for the next years. (http://cartogis.provincia.genova.it/cartogis/pdb/bisagno/bisagno/documenti/PianoInterventi.pdf).

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6 tables

LABEL	OCCUPANCY CLASS	
RES1	Single Family Dwelling	**RESIDENTIAL**
RES2	Mobile Home	
RES3A	Multi Family Dwelling - Duplex	
RES3B	Multi Family Dwelling – 3-4 Units	
RES3C	Multi Family Dwelling – 5-9 Units	
RES3D	Multi Family Dwelling – 10-19 Units	
RES3E	Multi Family Dwelling – 20-49 Units	
RES3F	Multi Family Dwelling – 50+ Units	
RES4	Temporary Lodging	
RES5	Institutional Dormitory	
RES6	Nursing Home	
COM1	Retail Trade	**COMMERCIAL**
COM2	Wholesale Trade	
COM3	Personal and Repair Services	
COM4	Business/Professional/Technical Services	
COM5	Depository Institutions (e.g. bank)	
COM6	Hospital	
COM7	Medical Office/Clinic	
COM8	Entertainment & Recreation (e.g. restaurants and bar)	
COM9	Theatres	
COM10	Parking	
IND1	Heavy	**INDUSTRIAL**
IND2	Light	
IND3	Food/Drugs/Chemicals	
IND4	Metals/Minerals Processing	
IND5	High Technology	
IND6	Construction	
AGR1	Agriculture	**AGRICULTURE**
REL1	Church/Membership Organization	**RELIGION/NON-PROFIT**
GOV1	General Services	**GOVERNMENT**
GOV2	Emergency response	
EDU1	Schools/Libraries	**EDUCATION**
EDU2	Colleges/Universities	
COM1+RES	Residential with retail at ground floor	**MIXED**
COM5+RES	Residential with bank at ground floor	
COM8+RES	Restaurant and bar	

Table 1 Original HAZUS building occupancy classes (grey) and derived mixed occupancy classes (yellow).

	Perc10	Perc25	Perc50	Perc75	Perc90	2014 event
Economic Damage at structure [M €]	42.7	53.7	59.3	67.3	73.6	29.7
Economic Damage at Content [M €]	97,9	121.9	134.5	148.6	158	70.4
Total Damage [M €]	140.6	175.6	193.8	211.9	231.6	100.1

Table 2: economic damage estimated for the considered flooding scenarios compared with damage estimated for the event on 9th October 2014.

	Perc10	Perc25	Perc50	Perc75	Perc90	2014 event
Economic Damage at structure in respect 2014 event [%]	144%	181%	200%	227%	248%	100%
Economic Damage at content with respect to 2014 event [%]	139%	173%	191%	212%	224%	100%
% Total Economic Damage with respect to 2014 event [%]	140%	175%	194%	212%	231%	100%

Table 3: Ratio between damage estimated for the considered flooding scenarios and damage estimated for the event on 9th October 2014

Scenario	Total [units]	Low Hazard [units]	Moderate Hazard [units]	High Hazard [units]	Very High Hazard [units]
Perc10	17360	3085	10705	3520	50
Perc25	18255	2390	11175	4400	290
Perc50	18440	2140	10475	5195	630
Perc75	18645	1975	10005	5675	990
Perc90	18805	1890	9205	6360	1350

Table 4: population potentially affected by the different flooding scenarios and their distribution on the zones with different levels of risk. The total is estimated summing the population of the Low, Moderate, High and very High Risk zones.

7 Figures

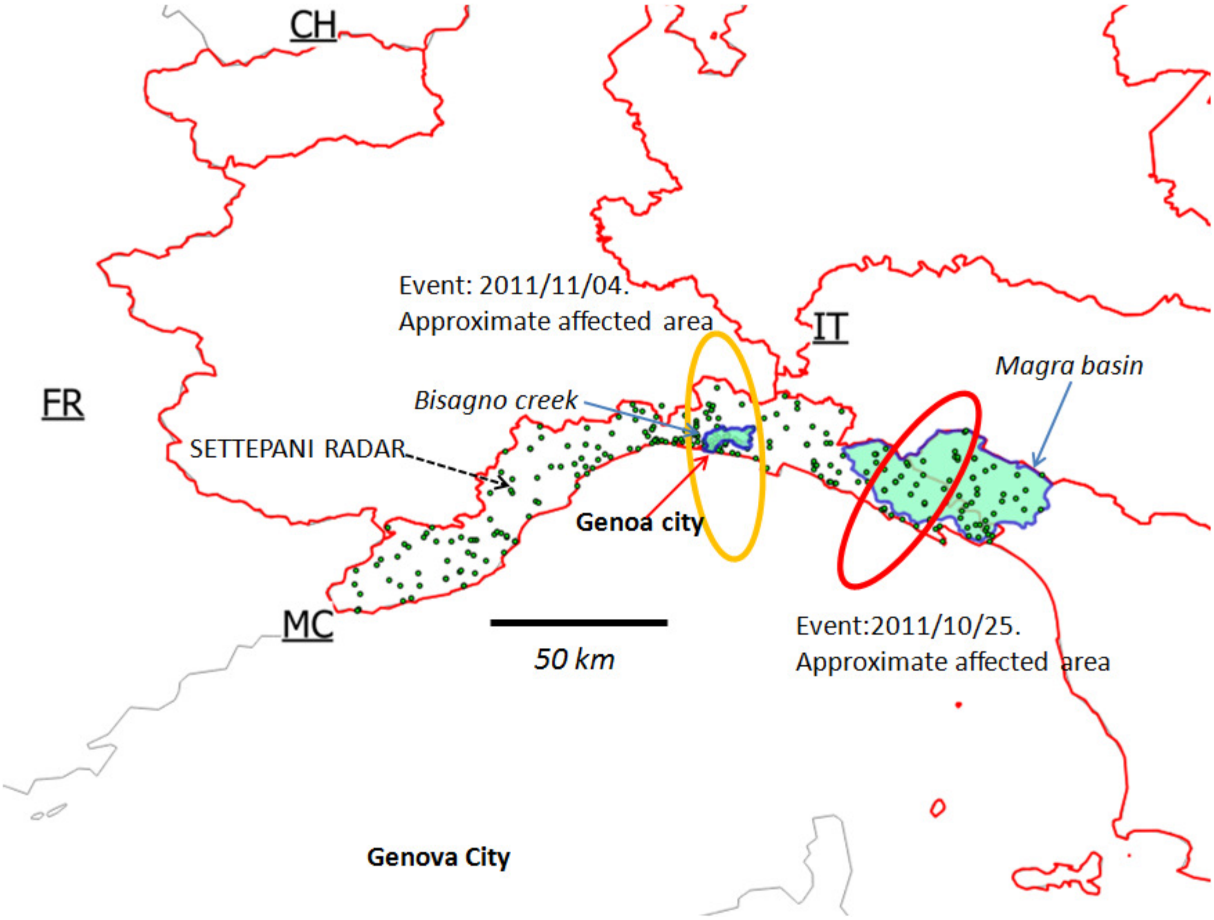


Figure 1: Main areas struck by the two intense events occurred between October and November 2011 (red and yellow ellipses). The watermarks of the Bisagno creek and of the Magra basin are reported in blue, the green dots are the rain gauges of the regional network. Red lines represent the North West Italian regions.

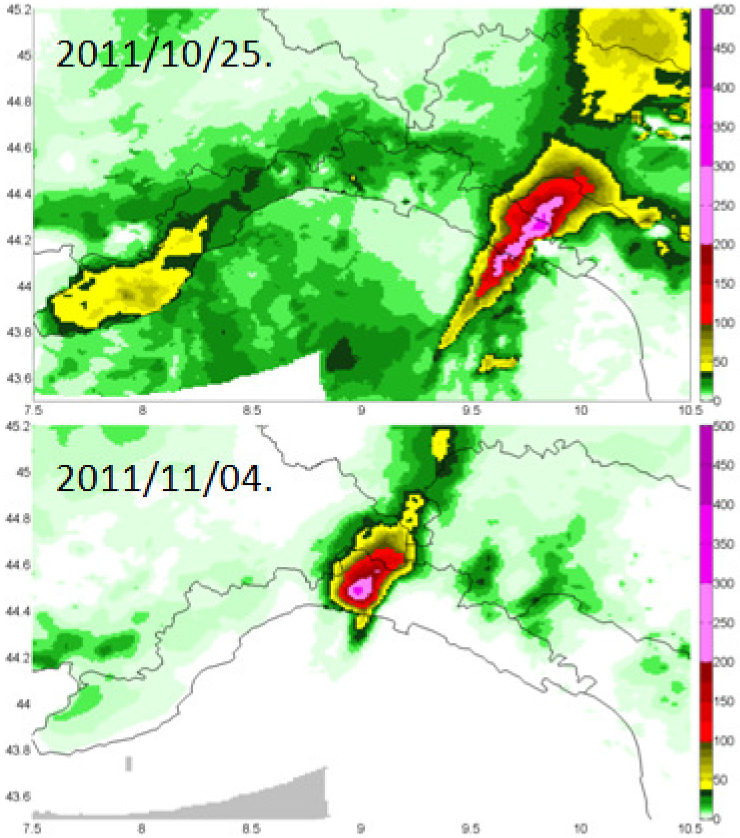
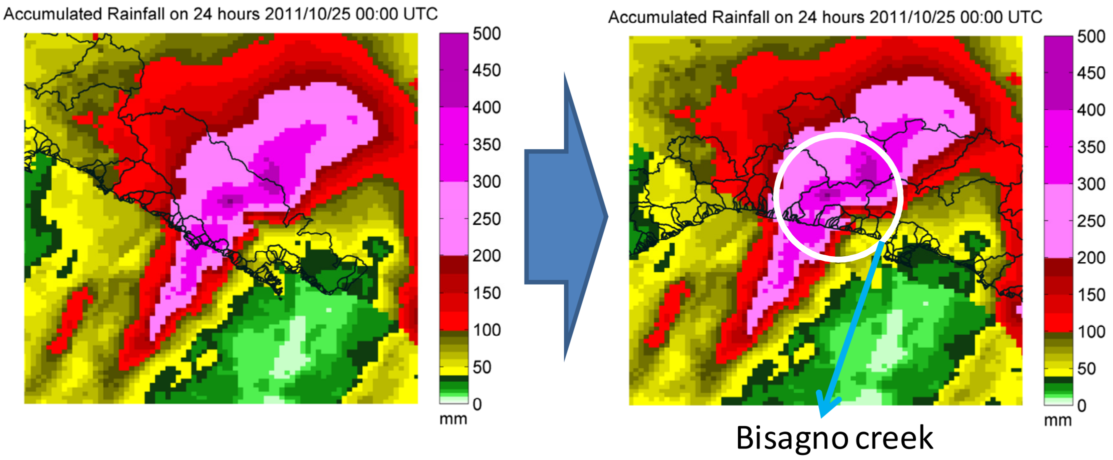


Figure 2: Comparison of the 6 hours maximum accumulated rainfall (mm) for the events on 2011/10/25 (top panel) and on 2011/11/04 (bottom panel).



Accumulated Rainfall on 24 hours 2011/10/25 00:00 UTC

Accumulated Rainfall on 24 hours 2011/10/25 00:00 UTC

Figure 3: 2011/10/25, accumulated rainfall on 24 hours. Left panel, observed rainfall field; right panel, hypothetical rainfall field obtained by the rigid translation of the observed rainfall field from the original position to the Bisagno creek.

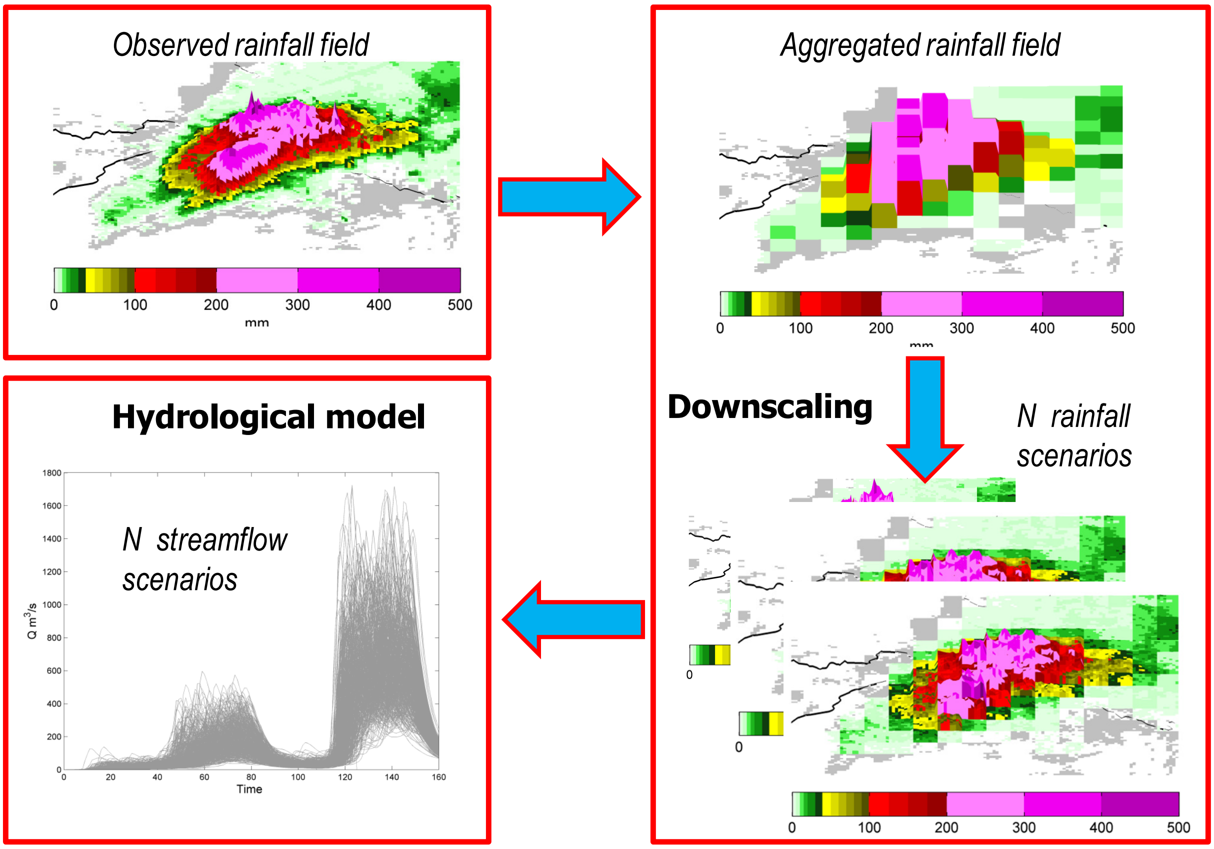


Figure 4: Schematization of the Flood Forecast Framework made by a downscaling model and a hydrological model. In this application the rainfall field is the one reported in figure 2.

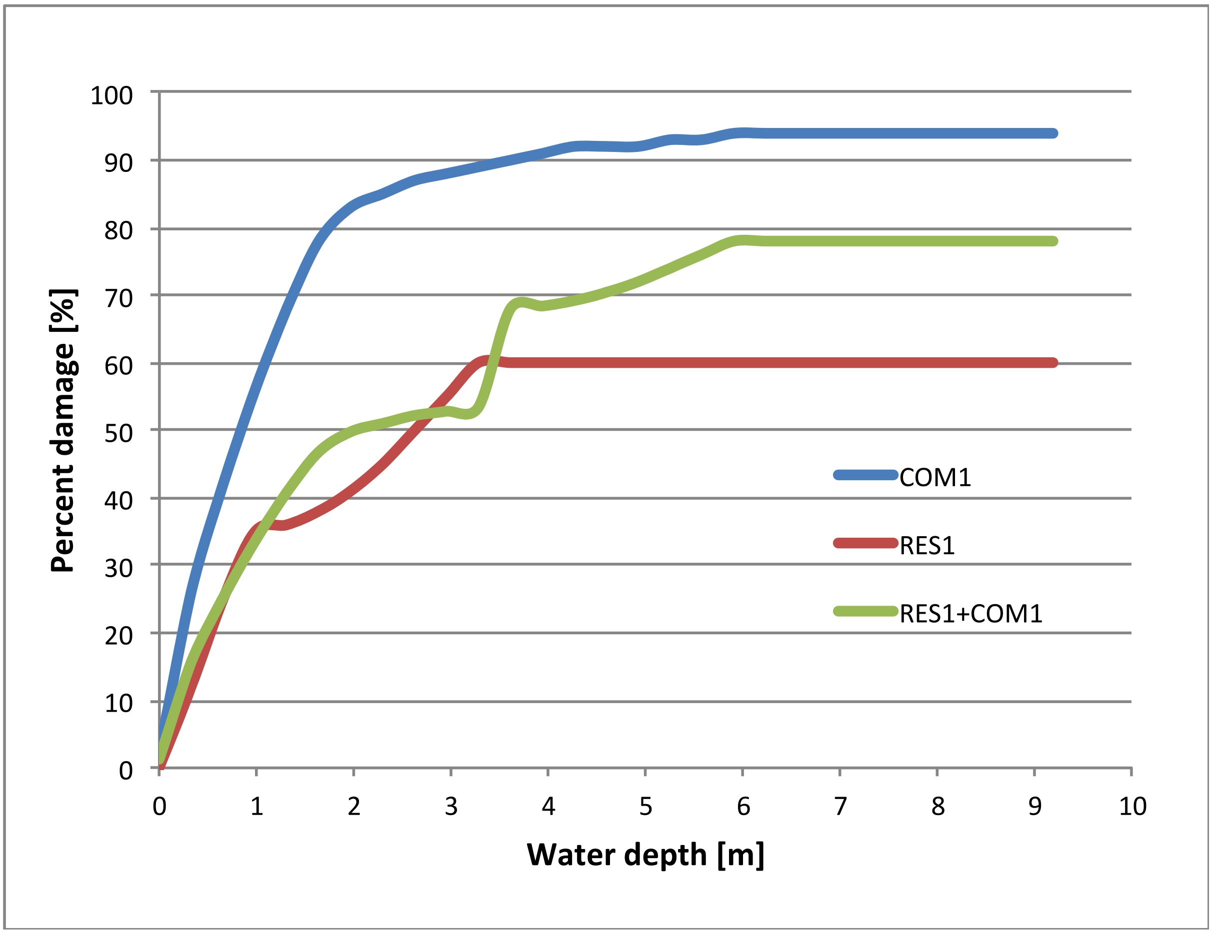


Figure 5: An example of mixed-use curve definition. The green curve corresponds to the flood vulnerability function for the content of a 2-storey building, with mixed commercial and residential use: specifically retail trade at ground floor and residential at first floor. It is obtained by combining the 1-storey curve for generic residential (in red) with the 1-storey curve for retail trade (in blue). The yellow section of the graph represents the average height of the ground floor. The left part of the mixed curve is obtained by re-scaling the blue curve. For higher values of water level, the function increases proportionally to the values that the residential curves assumes (red) in the left part of the graph.

It is assumed that the value of the ground floor is equal to 60% of the whole (2-storeys) building.

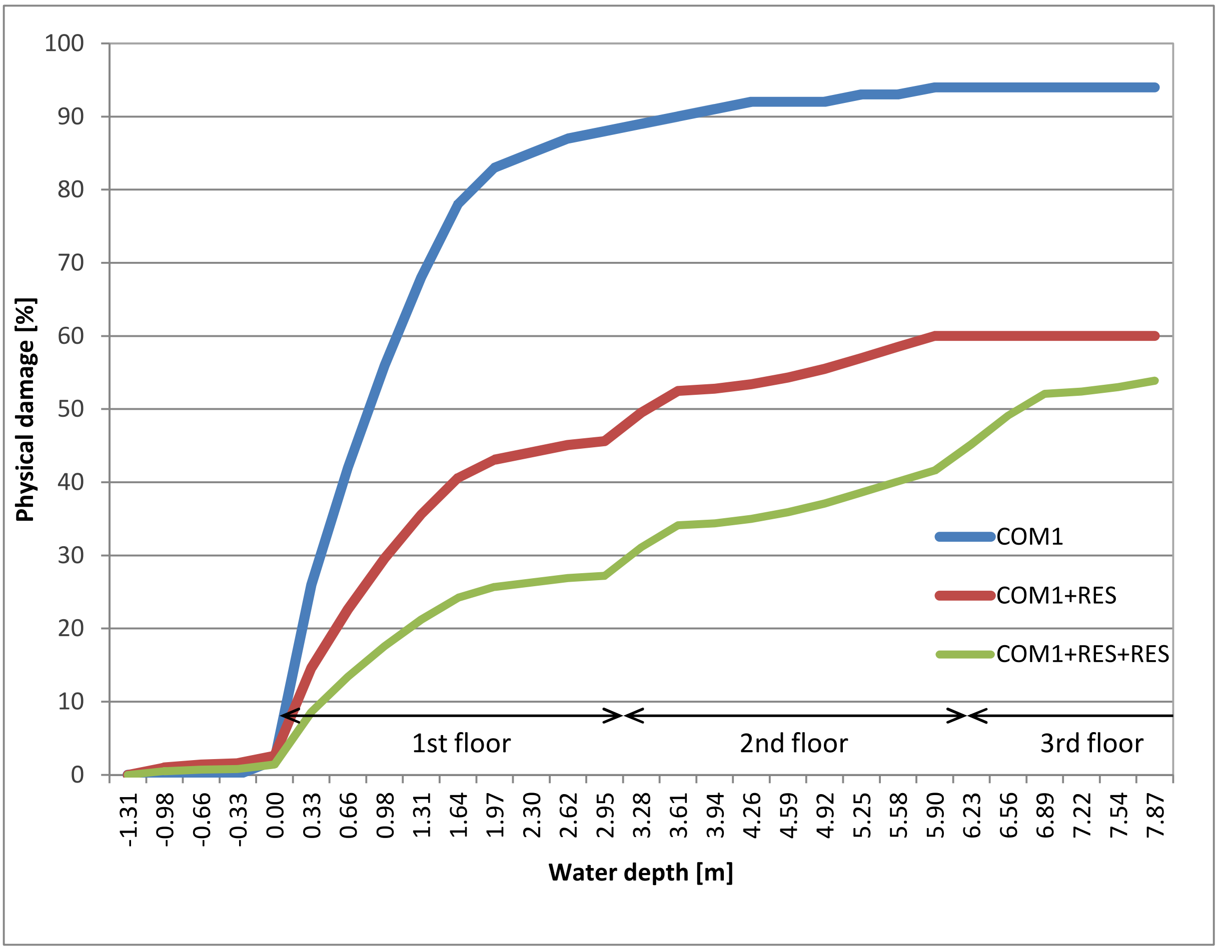


Figure 6: Comparison between water depth – damage curves for content: retail trade (COM1) building[blue], mixed retail trade (COM1) at first floor & RES at second floor[red], mixed retail trade (COM1) at first floor & residential (RES) at second and third floor[green].

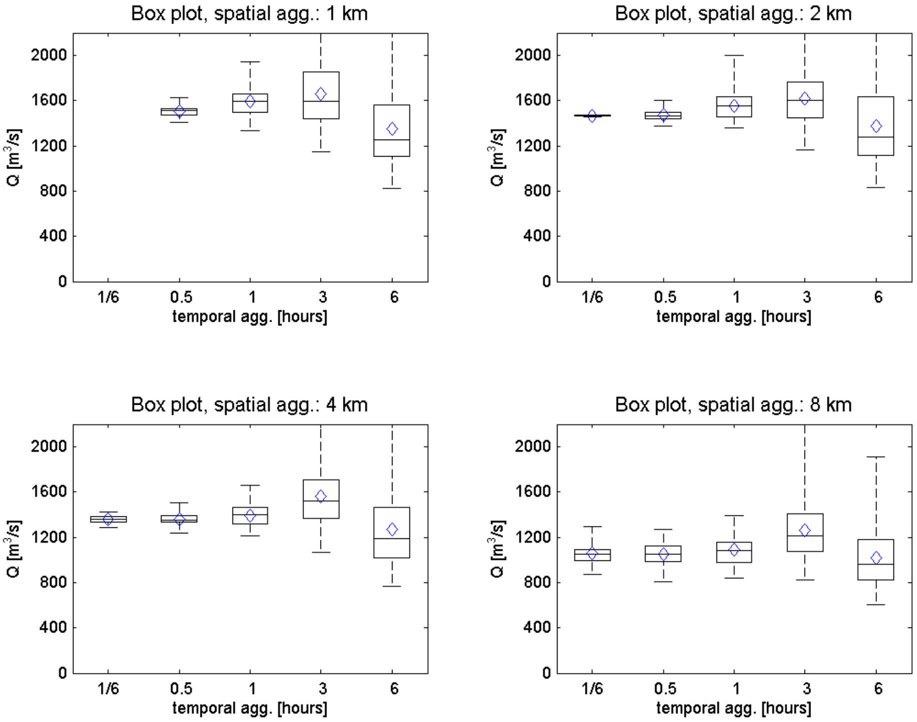


Figure 7: Passerella Firpo reference section, Area: 93 km^2. Box plot of the peak flow generated by the FFF. On Y axis the peak flow is reported, on X axis the temporal aggregation scales (RSt) are reported. Diamonds represent the peak flow of the reference hydrograph. Each sub-panel shows results for a different spatial aggregation scale (RSs).

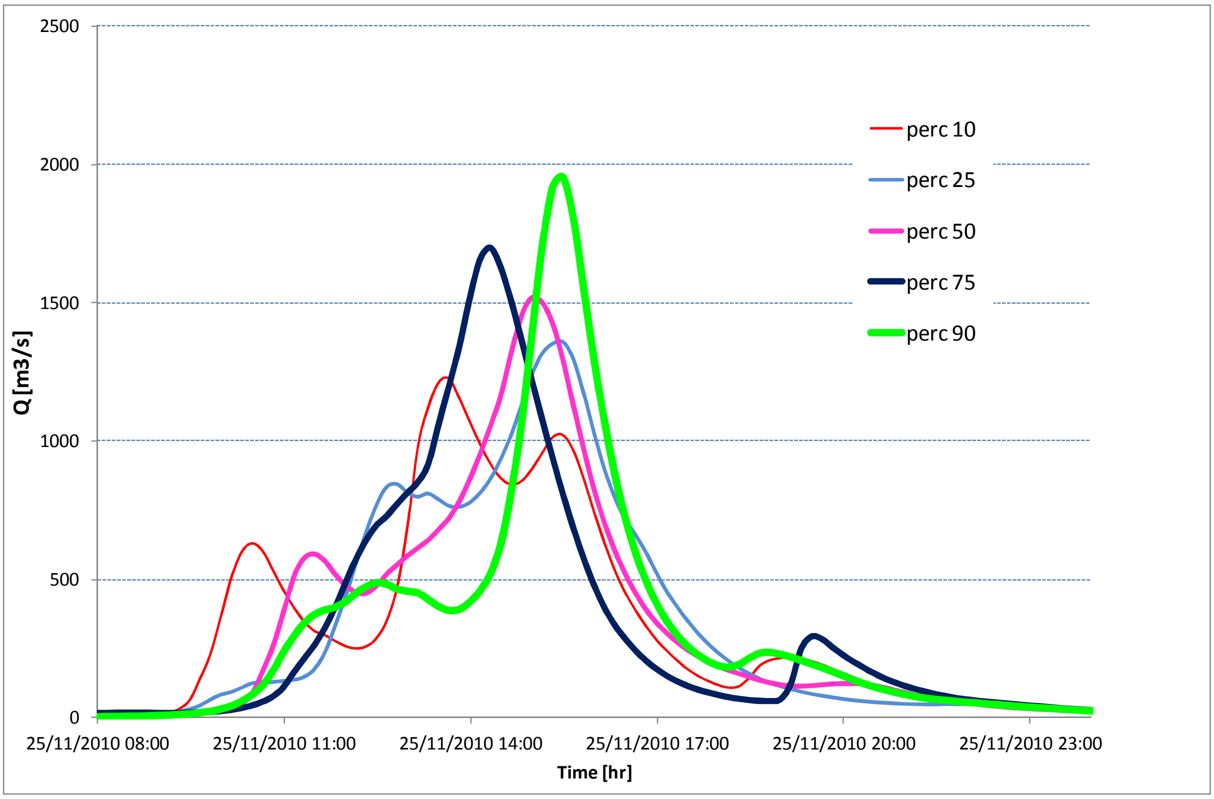


Figure 8. Streamflow scenarios derived by RSs=4 km and RSt=3 hrs. The hydrographs that lead to the peak flows with 10, 25, 50, 75, 90 percentiles were extracted.

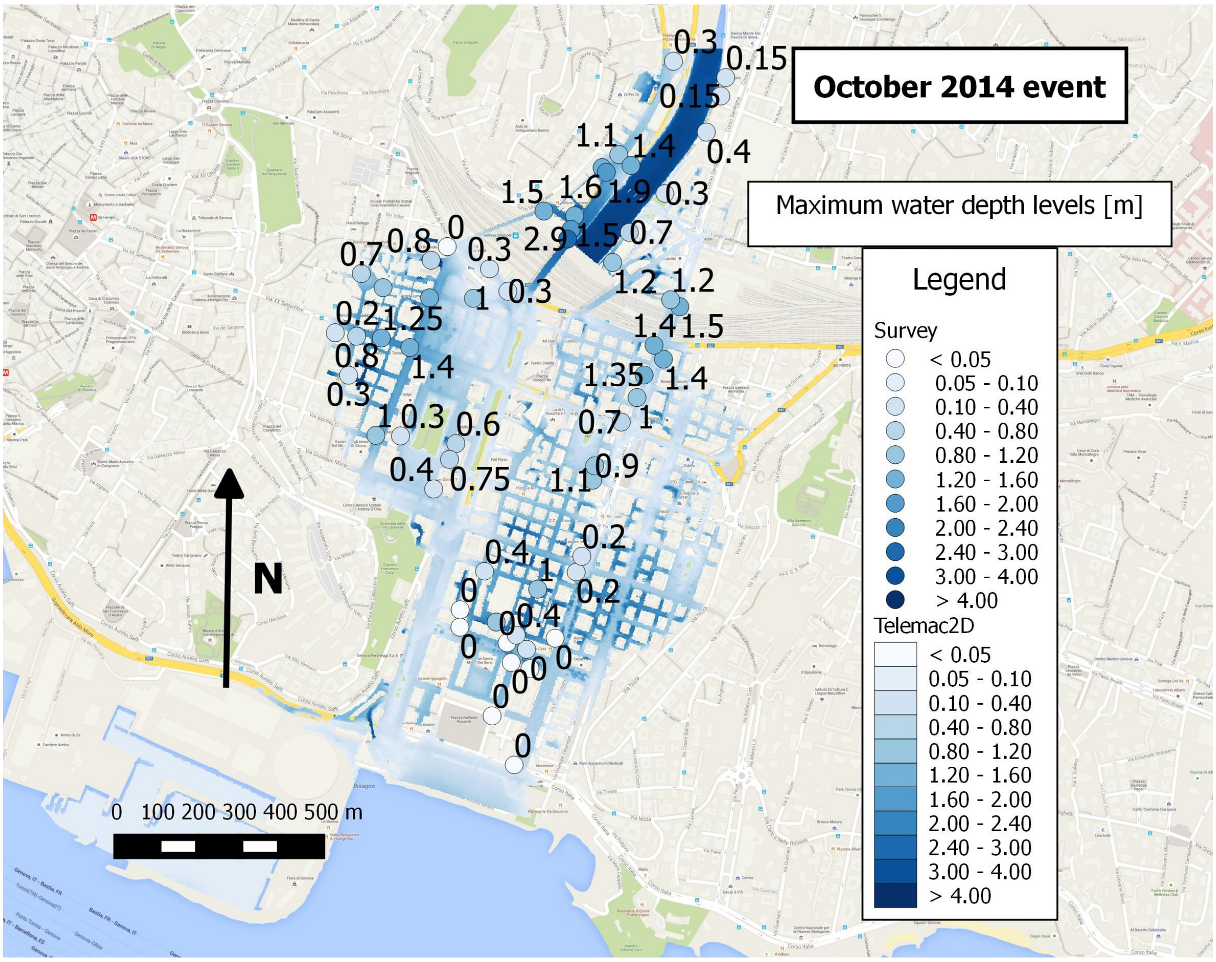


Figure 9. Center of Genova city. Flood occurred on 9th October 2014. Comparison of the maximum flooding extent obtained through Telemac-2D and the field observations. The model was set in order to obtain the best fit between modeling and observations.

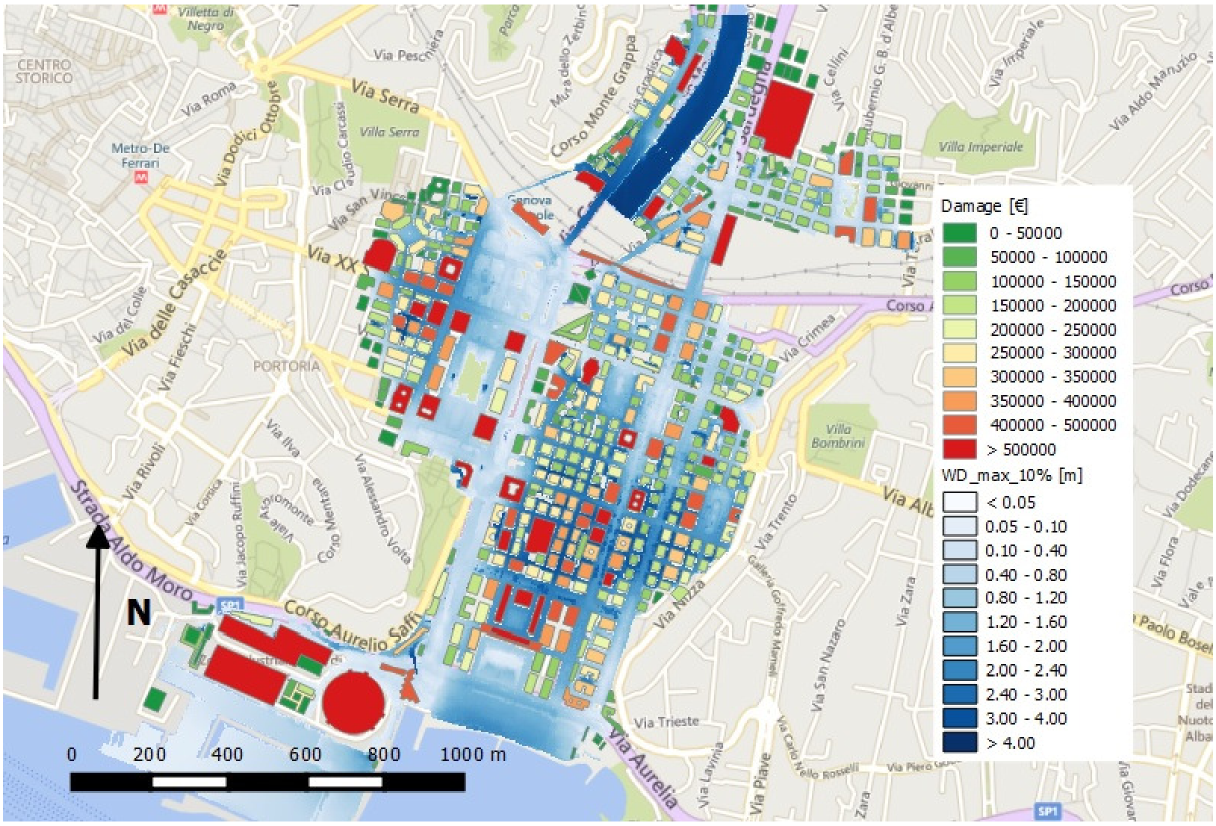


Figure 10: Perc10 scenario, inundation map and damage estimation. In blue scale the water level is reported. The damage is estimated at building scale in euro, the color scale ranges from low damage (green) to high damage (red).

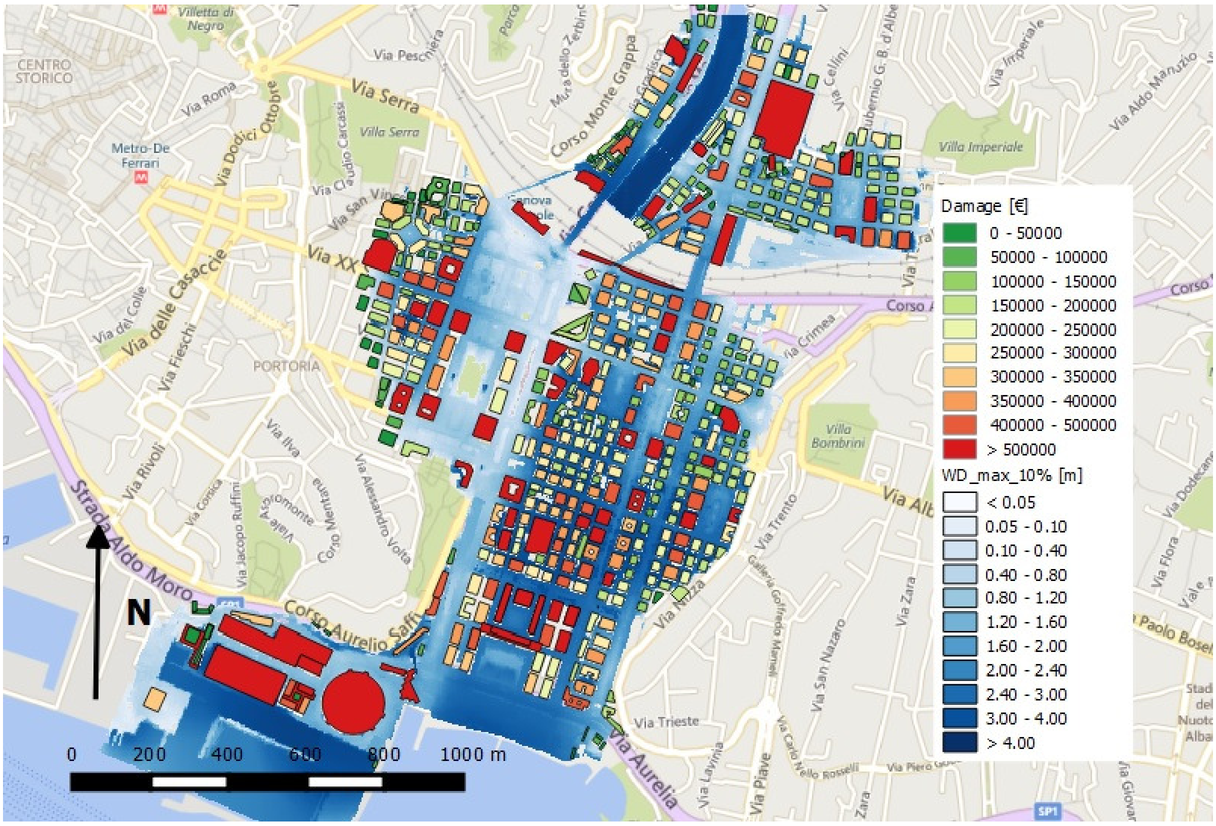


Figure 11: Perc50 scenario, inundation map and damage estimation. In blue scale the water level is reported. The damage is estimated at building scale in euro, the color scale ranges from low damage (green) to high damage (red).

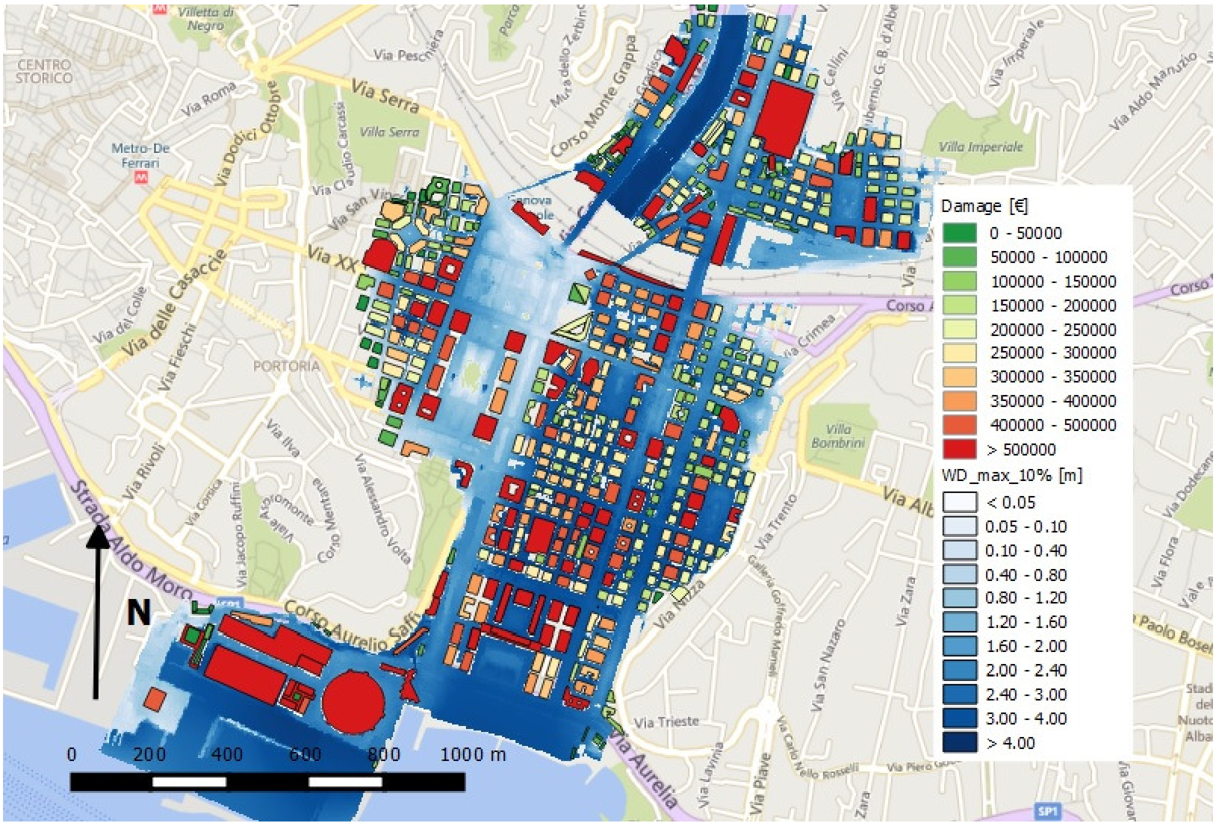


Figure 12: Perc90 scenario, inundation map and damage estimation. In blue scale the water level is reported. The damage is estimated at building scale in euro, the color scale ranges from low damage (green) to high damage (red).

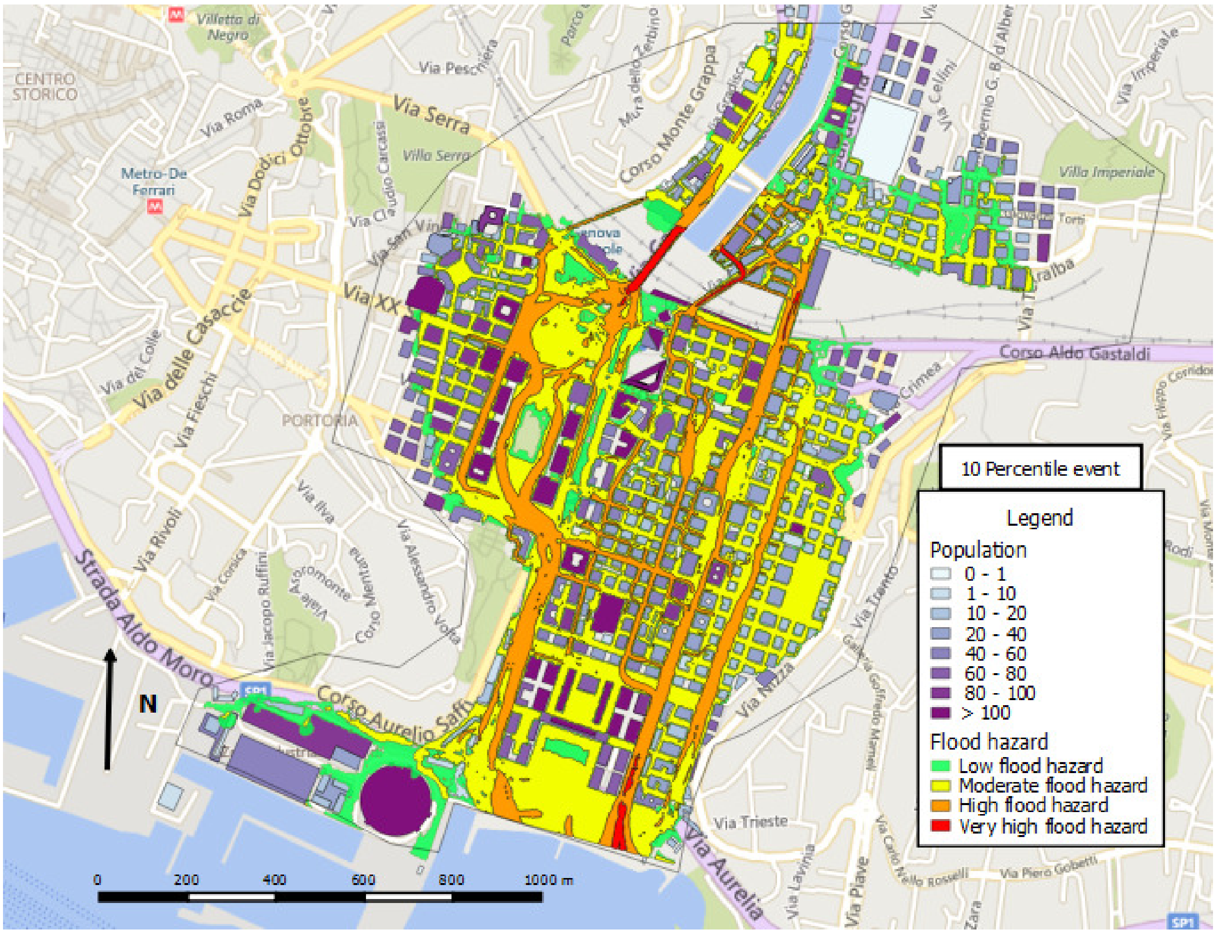


Figure 13: Perc10 scenario, hazard level map compared with population potentially involved assigned to each building.

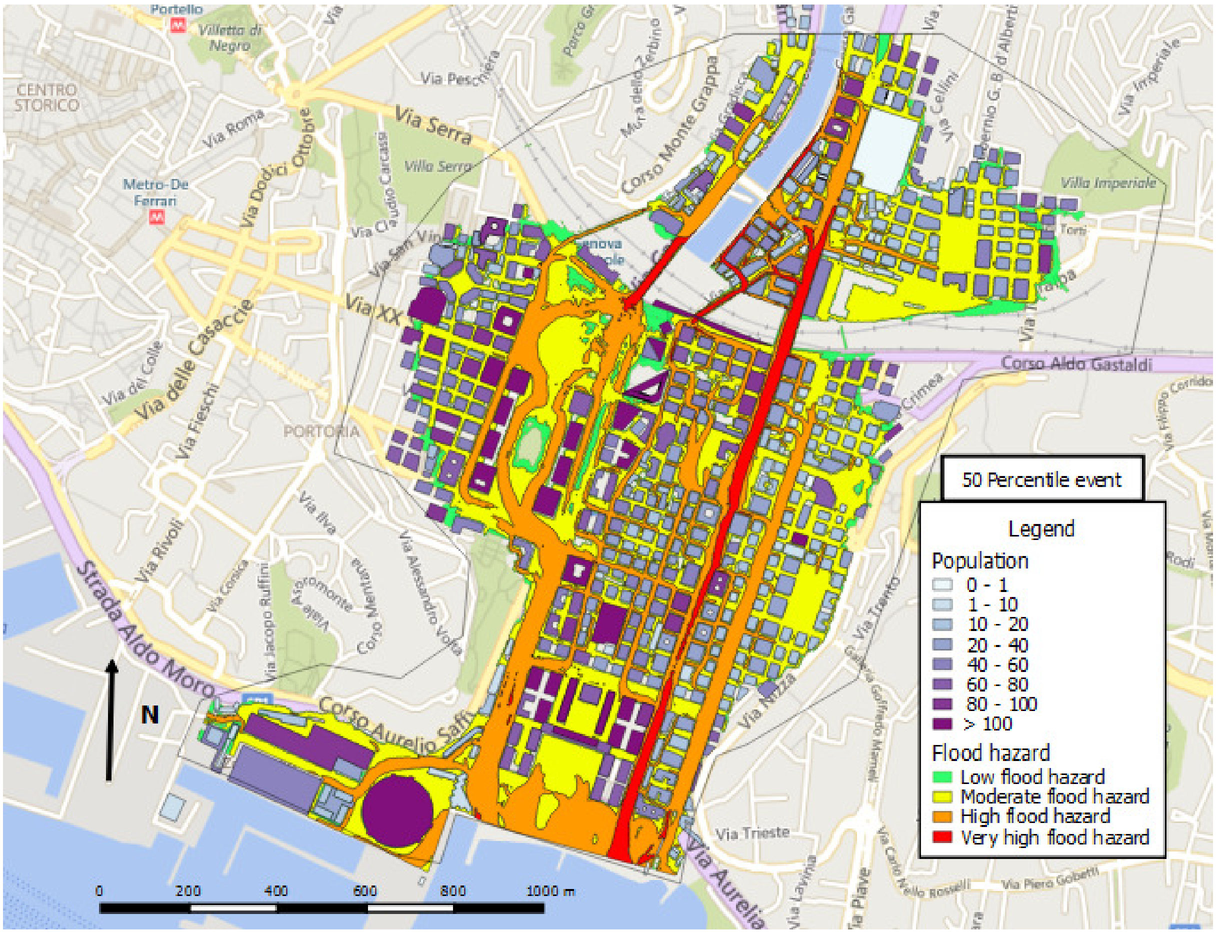


Figure 14: Perc50 scenario, hazard level map compared with population potentially involved assigned to each building.

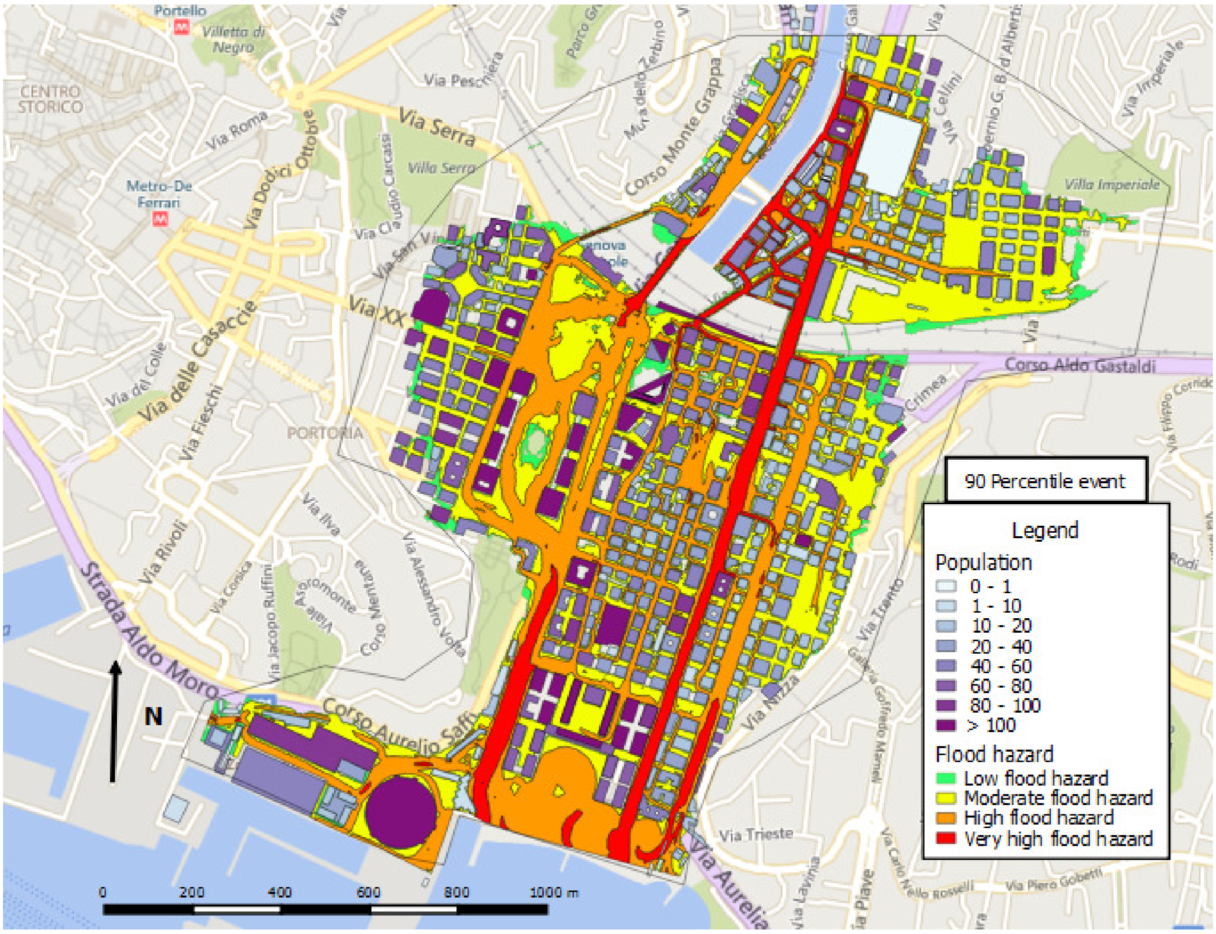


Figure 15: Perc90 scenario, hazard level map compared with population potentially involved assigned to each building.