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Looking Forward from the Past: Assessing the Potential Flood Hazard and Damage in Polesine Region by Revisiting the 1950 Flood

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Summary

River floods are a common natural hazard in Europe, causing high mortality and immense economic damage (EM-DAT 2009). Human-induced climate change will alter intensity and frequency of extreme weather events, hence flood risk (IPCC 2012). While large-scale assessments of flood risk dominate (Genovese, et al. 2007), the knowledge of the effects at smaller scales is poor or incomplete, with few localized studies. The approach of this study starts from the definition of the risk paradigm and the elaboration of local climatic scenarios to track a methodology aimed at elaborating and combining the three elements concurring to the determination of risk: hydrological hazard, value exposure and vulnerability. First, hydrological hazard scenarios are provided by hydrological and hydrodynamic models, included in a flood forecasting system capable to define "what-if" scenario in a flexible way. These results are then integrated with land-use data (exposure) and depth-damage functions (vulnerability) in a GIS environment, to assess the final risk value (potential flood damage) and visualize it in form of risk maps. In this paper, results from a pilot study in the Polesine area (Po river basin) are presented, where four simulated levee breach scenarios are compared. This technique is of great interest to decision makers who are interested in gaining knowledge about possible direct losses from river flooding events. It can also be an important tool to guide decision making and planning processes, to help them understand how to reduce risk to river flood events. As future perspective, the employed methodology can also be extended at the basin scale through integration with the existent flood warning system to gain a real-time estimate of floods direct costs.

Keywords: Flood Risk/Damage Assessment, Hydrological-Hydrodynamic Modelling, Climate Scenarios, Historical Flood Reassessment, Po River Basin District, Polesine Region (Rovigo Province)
JEL Classification: Q25, Q54

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Looking forward from the past: assessing the potential flood hazard and damage in Polesine region by revisiting the 1950 flood event

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Abstract

River floods are a common natural hazard in Europe, causing high mortality and immense economic damage (EM-DAT 2009). Human-induced climate change will alter intensity and frequency of extreme weather events, hence flood risk (IPCC 2012). While large-scale assessments of flood risk dominate (Genovese, et al. 2007), the knowledge of the effects at smaller scales is poor or incomplete, with few localized studies. The approach of this study starts from the definition of the risk paradigm and the elaboration of local climatic scenarios to track a methodology aimed at elaborating and combining the three elements concurring to the determination of risk: hydrological hazard, value exposure and vulnerability. First, hydrological hazard scenarios are provided by hydrological and hydrodynamic models, included in a flood forecasting system capable to define "what-if" scenario in a flexible way. These results are then integrated with land-use data (exposure) and depth-damage functions (vulnerability) in a GIS environment, to assess the final risk value (potential flood damage) and visualize it in form of risk maps. In this paper, results from a pilot study in the Polesine area (Po river basin) are presented, where four simulated levee breach scenarios are compared. This technique is of great interest to decision makers who are interested in gaining knowledge about possible direct losses from river flooding events. It can also be an important tool to guide decision making and planning processes, to help them understand how to reduce risk to river flood events. As future perspective, the employed methodology can also be extended at the basin scale through integration with the existent flood warning system to gain a real-time estimate of floods direct costs.

Keywords: Flood risk/damage assessment, Hydrological-hydrodynamic modelling, Climate scenarios, Historical flood reassessment, Po River Basin District, Polesine region (Rovigo province)

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Looking forward from the past: assessing the potential (future) flood hazard and damage by revisiting the 1950 and 2000 flood events

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1. INTRODUCTION

The frequency of flood events in Europe shows an increasing trend (Genovese, et al. 2007) for both average and major flood events. Two years of the past decade (2000 and 2002) are among the worst in the timeframe, with 2002 having the highest rate of damage of the series. This upshift in the amount of losses is in line with the measures of extreme meteorological damages carried worldwide by IPCC; economic losses (normalized with inflation rates) in the past ten years are ten times higher than 1960-1970 period (IPCC, 2001). However, other factors strongly influence the total risk value, such as changes in socio-economic exposure (e.g. urban expansion along riversides).

The IPCC (2012) also concluded that the occurrence of future extreme flood events are very likely to increase scale: events with a 100-year return period may occur more frequently by the end of 21st century. However, drawing an hypothetical scenario without any change in the meteorological forcing, losses would increase indifferently in the future due to socio-economic changes, such as higher population, improved pro-capita wealth and living standards: all factors which heighten the exposure value (Barredo 2009).

A recent study (Legambiente & Dipartimento della Protezione Civile 2011) conducted by the Ministry of Environment in all Italian regions estimates that almost 3.5 million people (6% of the Italian population) are present in hydrological risk areas every day. ISPRA (2009) estimated the costs of hydrogeological disasters in Italy between 1951 and 2009 as exceeding € 52 billion. To tackle the hydrogeological emergencies of 2010 alone, a total of € 650 million have been allocated (Legambiente & Dipartimento della Protezione Civile 2011). For the 20th century and thereafter (1900-2008), period for which available information is more reliable, Salvati et al. (2010) list some 2,321 flood events, while referring to the last 59 years, the value is 1,654. During the period 1996–2010, the emergency situation due to the hydrogeological disasters was declared 245 times.

The aim of this paper is to estimate the impacts of climate change on the magnitude and frequency of extreme flood events in the Po River basin, and to understand how these impacts will qualitatively and quantitatively reflect in terms of direct socio-economic risk.
The study will focus on a pilot case study located in Polesine (Rovigo province), with the purpose of extending the methodology to the whole river basin in future research. The estimated projections of hydro-climatic change in the river basin will be used as starting

conditions for a hydro-meteorological model run provided by ARPA-SIM (Hydro-Meteorological Service of Regional Environmental Agencies) to simulate the effects of an extraordinary discharge event on a flood scenario, producing a potential value of Hazard for each climatic scenario. This Hazard value will be compared with Exposure and Vulnerability values through GIS elaboration to estimate the direct socio-economic Risk (economic losses) potentially occurring in the pilot case study area during each scenario. The Risk outputs of different scenarios are conclusively compared. We strongly believe that this technique is of great interest to decision makers who are interested in gaining knowledge in a short time about possible direct losses from river flooding events. It can also be an important tool to guide decision making and planning processes, to help them understand how to reduce risk to river flood events.

The paper is structured as follows: Section 2 describes the case study area in terms of hazard profile and socio-economic drivers of risk. The November 1951 and October 2000 flood events are put in relation with their socio-economical impacts. Section 3 explains the methodological framework and tools employed to calculate the risk. Section 4 presents the results and discuss them. Section 5 provides conclusions and an annex with the risk maps.

2. CASE STUDY AND REFERENCE EVENTS

2.1. The Po river basin and the Polesine region

With 71.000 km^2 (~24% of the state territory), the Po River Basin District (PRBD) is the largest single-river basin in Italy, and the economically most important one. It is home to almost 17 million (~28% of the national population), spread in 8 regions, 13 provinces and 3.210 municipalities (on average 22 sq.km large, 5.000 inhabitants). More than one third of the Italian industries are located in the basin area, producing about 40 per cent of the national *gross domestic product* (GDP). More than a half of the basin area (~56 per cent) is agricultural land. Agriculture in the so called "food valley" produce about 35 per cent of the national agricultural output (AdBPo 2006).

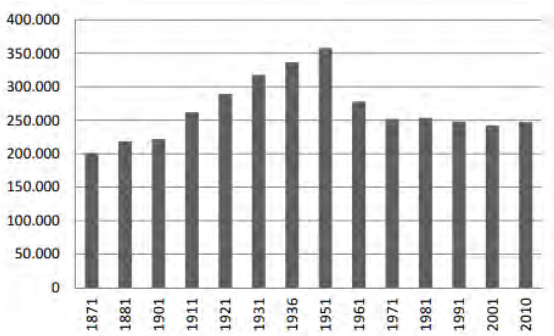


Figure 1. *Population development in the Polesine region since 1871. The graph shows no significant changes since the 70s and a sharp drop in the 50s as a result of the exodus in the aftermath of the 1951 flood.*

Polesine region (PoR) denotes an area located between the final sections of the two largest Italian rivers Po and Adige, until their outlets to the Adriatic Sea. The ~1930 sq.km large area, formally a part of the *Fissero-Tartaro-Canalbianco* (sub)basin, comprises 50 municipalities of the Rovigo province. To the north and south the PoR is delimited by Po and Adige embankments, making the area analogous to a large polder. Agriculture is the dominant land use. Around 2.000 km of canals and 80 water pumps facilitate water drainage from the territory that used to be marshes and wetlands. This system is strongly stressed during intense precipitation events, causing the risk of flooding from the inner network. Moreover, the sea level rising adds supplemental pressure to the dewatering system. In fact, the drainage of the basin is completely artificial. The water stages in Po and Adige are often up to several meters higher than the surrounding areas, the elevation of which is often lower than at sea level. The PoR is exposed to land subsidence (~5 mm/year). Prior the land reclamation and river embankment, the PoR had been regularly affected by large floods, the worst of which were felt in 1951 after a levee failure (see section 2.2). Between 1952 and 1966, the PoR experienced 20 river and coastal floods. Since then, the methane extraction stopped to slow down the land subsidence, and the river levee had been heightened to reduce the flood risk.

Some 250.000 people live in Polesine (according to the 2011 census), 50.000 of whom in the province capital town Rovigo. The population density (138 inhabitants per sq.km) is much lower than the regional (268 inh./sq.km) and national (201 inh./sq.km) average. The population growth has been very slow since the population drop in the aftermath of the 1951 disaster (Figure 1). According to the ISTAT (2010) the population will remain stable or decline, while the proportion of those with age higher than 65 years (old age dependency) will increase (Regione Veneto 2009). This PoR maintained dominant agricultural character and benefited marginally from the accelerated industrialization over 70s and 80s, compared to the rest of the North-Eastern Italy.

2.2. *Reference historical flood events*

The highest river stages in the at the basin closure (Pontelagoscuro) were recorded in November 1951 (10.300 mc/sec), November 1994 (8.750 mc/sec), October 2000 (9.750 mc/sec), November 2002 (8.100 mc/sec), and April 2009 (7.700 mc/sec) (ARPA 2009). During the 1994 and 2000 floods the discharge levels in the higher-upstream sections of the river were higher because part of the flood peak had been unloaded before reaching Pontelagoscuro. Table 1 shows discharge levels during the 1951, 1994 and 2000 events, ordered per station from upstream.

Station	*Max discharge during flood events (m^3/sec)*		
	1951	**1994**	**2000**
Isola Sant'Antonio	-	10,500	10,500
Becca	11,250	11,500	11,200
Piacenza	12,800	11,055	12,240
Cremona	-	11,300	11,850
Boretto	12,100	10,400	11,900
Borgoforte	11,800	11,000	11,800
Pontelagoscuro	10,300	8,750	9,750

Table 1. *Comparison between flood discharges during four flood events (AdBPo 2005).*

For the scope of this analysis, we have chosen two: the 1951 flood of Polesine [51-PE] and the 2000 flood of Piedmont [00-PT].

The 00-PT event was exceptional not only for the highest (since instrumental records) maximum discharge but also for the duration of the peak flow. The event is used as a benchmark by the River Basin Authority (RBA) to define the objectives of future hydrological risk management (AdBPo 2008).

Project SIMPO previously employed the 51-PE as a reference for flood modeling. Peak discharges, numerically augmented by 10 per cent, have been used to evaluate potential breaks in the embankments (AdBPo 2007). While the number of the ruptures in the embankments caused by each flood event is decreasing, the extent of flooded areas increased specially in the downstream sections (Mantova, Ferrara and Rovigo provinces). This is clear through comparison of the 51-PE and 00-PT events. In 1951 the river reached the highest stages in the last section, in 2000 some of the flood water was discharged in the mid-section, and by doing so easing the damage in the downstream part (AdBPo 2005).

Therefore, we use the 00-PT as a reference event for the hazard assessment and for extreme climate event projections, whereas the 51-PE event is instrumental for understanding the potential losses and vulnerability.

2.2.1. 00-PT event

From 13th to 16th of October 2000, a series of extreme precipitation events hit Italy's Northwest, causing floods and landslides along the Po river and main tributaries. The torrential rain exceeded in some places 700 mm in 60 hours. The Po river's discharge registered record levels (almost 10.000 cbm/s never recorded before higher upstream from the basin's closure), with estimated return period of 200 years and higher (Figure 2). The communities of the Piedmont, Valle d'Aosta and Liguria regions were affected particularly hard, but floods were registered also in Lombardy, Emilia Romagna and Veneto. At some places precipitation of up to 740 mm in just four days were recorded. The EM-DAT International Disasters Database indicates 25 casualties, population affected of 43,000 and overall direct economic damage amounting to 8 billion USD in 2000 values (EM-DAT 2009).

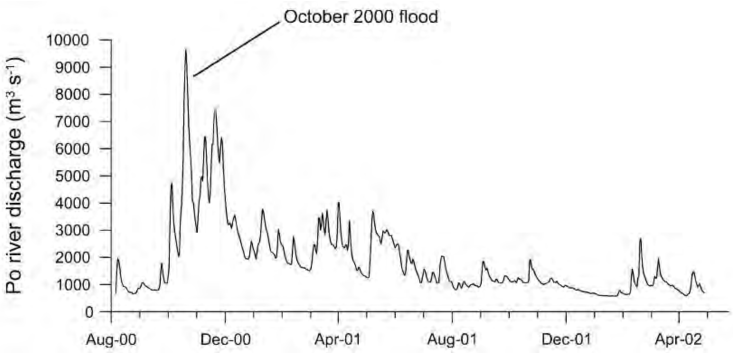


Figure 2. *Discharge graph from August 2000 to April 2002, showing the peak discharge during the extreme event in October.*

The flood caused significant structural damage, lifelines interruption, environmental damage and social hardship. Several important urban centers were flooded, buildings and key infrastructure damaged, bridges destroyed, electricity and water supply interrupted, road and railway network impaired, river banks eroded, water quality deteriorated etc. In the Piedmont region alone, the event devastated more than 25 per cent of the territory causing damage to infrastructure and property topping 1 billion Euro (Regione Piemonte 2000). The flood affected more than 700 municipalities and almost all largest cities including Turin, the capital of the region. All economic sectors were impacted, directly through structural damage or indirectly by business interruptions. There was a high risk of industrial accidents as a consequence of the flood (ANPA 2002, ARPA Piemonte 2003). To a large extent, the available studies address the structural damage inflicted by the flood, and the costs of aftermath recovery and (future) risk mitigation. The estimation of the costs of the final repair, from damages provoked by the extreme event, for the Valle d'Aosta Region have been quantified by the regional institution as 329 million Euro (Regione Autonoma della Valle d'Aosta 2001-2002). In the Piedmont Region, the estimated recovery costs amounted to 2,881 million Euro, split up as follow: 26 per cent for local infrastructures; 10 per cent for provincial infrastructures; 64 per cent for intervention of hydraulic restoration and hydro-geological intervention. Total expenses borne by the regional administration amounted to 786.5 million Euro (Regione Piemonte 2000).

2.2.2. *51-PE event*

The disastrous event which affected the lower fraction of the Po River in November 1951 exceeded all previously registered events in the river section between Ticino confluence with Po and to the basin's outlet, inundating some 1.000 sq.km of land. The discharge levels reached a peak of 12.000 cm/s (river level 4.28m). The most affected regions were Veneto, Emilia Romagna and Piedmont, but also Lombardy and Liguria were concerned (Marchi, Roth e Siccardi 1995, AdBPo 2009).

The structure and morphology of the Po riverbed and embankments had been unaltered since the beginning of the century, so the explanation for such extraordinary flood must be found in the distribution, intensity and duration of the precipitation preceding the event, and in the unfortunate coincidence of flood waves from the river tributaries. Starting from November 8th, constant and intense rainfalls were registered over the whole basin. The total amount of rain was 214 mm over 7 days (30.6 mm per day), triggering high peak of discharge in almost all alpine and Apennine tributaries; their flood waves converged together in the main river branch causing a fast increase in the Po water level. On Monday 12th, after the Ticino confluence (Ponte della Becca, near Pavia), the Po River reached the top discharge level at all the stations, starting to flood the lowlands. Two breaches near Parma and Reggio were not sufficient to reduce the peak flow discharge. On Wednesday 14th a flood wave coming from the tributary stream Crostolo broke the levees few hundred meters from the confluence point, inundating the town of Gualtieri and reinforcing again the Po river flow. Before reaching Pontelagoscuro station, in Malcantone (Occhiobello municipality, Rovigo province), the left embankment was overtopped by the water from the first hours of the day and collapsed around 8 p.m., followed by other two levee failures (Bosco and Vallice di Paviole, RO) between 14th and 15th, for a total length of the rupture of 736 m causing a flood lasting for about 20 hours (fig 3). Though this breaches, over 8,000 m^3

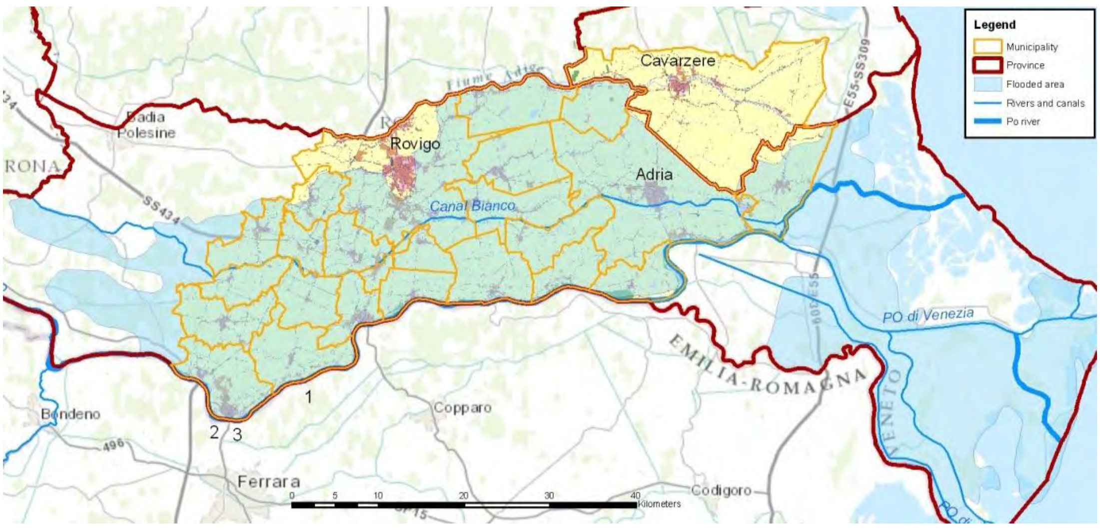


Figure 3. *Flood expansion during the 1951 event in Polesine (Rovigo Province). The numbers show the three breaks in the embankments system.*

of water flowed out of the river and crushed on the plain which is 5-6 meters below the embankments, inundating in 11 days about 1,000 km^2 in Polesine lowland (Rovigo province) with 2-3 m depth water. Rovigo, Adria, Cavarzere and Loreo were evacuated and completely flooded on November 19^{th}. Also part of Mantova and Venice provinces were reached by the water. Finally, on November 20^{th}, the flood wave discharged in the Adriatic Sea (Turitto 2004, Marchi, Roth e Siccardi 1995, Lastoria, et al. 2006, AdBPo 2009).

This catastrophic event caused 100 casualties and an estimated total damage of € 206.59 million (uninflated), equal to 3.7216% of 1951 GDP (Lastoria, et al. 2006). Compared to an inflation rate of 2.434% (up to year 2000), it is equal to € 5,235 million in 2000 value (calculated through ISTAT index's revaluation converter using a factor of 25.3403). 38 municipalities were involved, with 900 houses destroyed, 160,000 people evacuated, and important damages to the country economy, with dead cattle and fields covered by sediments. 60 km of embankments were damaged, and 52 bridges were destroyed (Turitto 2004). The description of this event is useful to be reviewed as historical record of the hazard in the area, but the produced impact may be lower if compared with an actual potential damage, since the socio-economic conditions has probably changed in the last 60 years. While the 1951 flood hit a majority of cultivated, rural land, the same event occurring today may affect a much developed area, with more infrastructure and higher social and economic value and, consequently, the present exposure potential needs to be fully evaluated.

3. METHODOLOGY

3.1. Climatic projections

To reduce the uncertainty with respect to the spatial variability concerning the downscaling of global climatic models (GCMs), some "ensemble" techniques between different model chains have been used. European Commission projects STARDEX (STARDEX 2005) and ENSEMBLES (Van der Linden e Mitchell 2009) aimed at this goal. Statistical and deterministic tools were employed to regionalize climatic data from the European macro-scale models to derive the climate change scenarios for Emilia Romagna. Both dynamical downscaling adapted to regional climate models and statistical downscaling models (SDMs) were employed to provide high-resolution climate change scenarios (Cacciamani, Tomozeiu, et al. 2007). Coherently with the RCM HIRHAM models (Dankers e Feyen 2008), the temperature signal obtained from project STARDEX ((Van der Linden e Mitchell 2009, STARDEX 2005) is homogenous for most of Europe, with a maximal increase of 1.5-2 °C, and the precipitation trend shows dissimilarity between northern and southern Europe: increasing in north-east and decreasing in south-west (figure 4). Results from different models used in the ensemble are comparable with modest variability throughout Europe, which imply a strong credibility (Cacciamani, Pavan e Tomozeiu, Cambiamenti climatici, impatti e adattamento 2010).

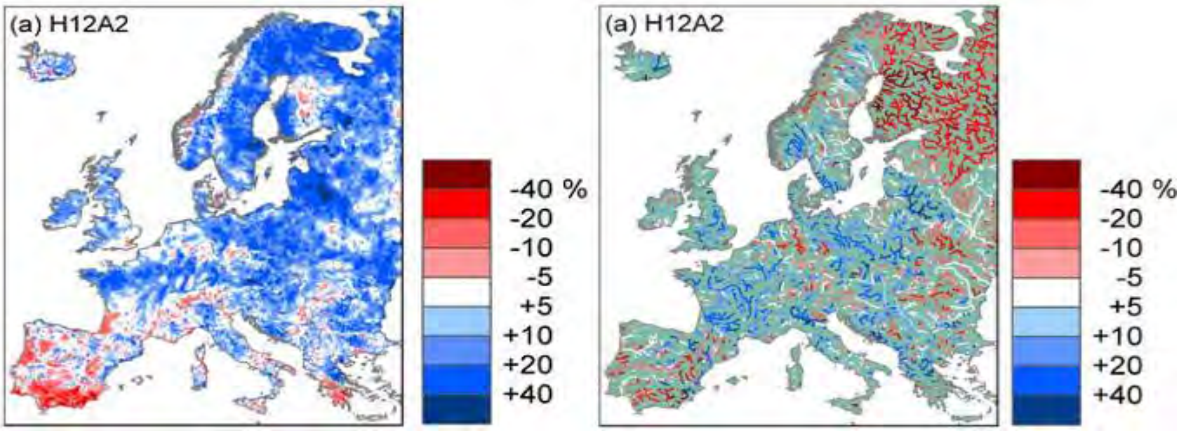


Figure 4. *RCM HIRHAM simulation of variation in the annual 5-day accumulated rainfall(a) and 100-years discharge levels (b) for scenario A2 and B2 (2071-20100). Values are compared to a 30-year average control run (1961-1990) (adapted from Dankers, et al., 2008).*

For Emilia Romagna, results about temperature are expressed as probability density function (PDF) for 2021-2050. Considering the shift in the distribution of the values, an increase in temperature measures (both minimal and maximal) are expected for all seasons, with an average shift of +2/+2.5 °C. The minimum temperature increases more than the maximum during autumn and winter (+2 °C), while the maximum temperature increases more in spring (+3 °C) and summer (+5 °C). Summer heat waves will be stronger and with longer duration, while winter freezing days will be reduced up to 40 days (Cacciamani, Pavan e Tomozeiu, Cambiamenti climatici, impatti e adattamento 2010, STARDEX 2005). There is no quantitative data reported about precipitation change, but scenarios indicate a marked decrease in winter (-10%) and summer (-20%) rainfall, while a slight increase in autumn precipitation is expected. Furthermore, rainfall magnitude during short-time extreme events are "very likely to increase" during spring-summer, alternated with longer and more frequent droughts (Cacciamani, Pavan e Tomozeiu, Cambiamenti climatici, impatti e adattamento 2010, STARDEX 2005, Tomei, et al. 2010).

3.2. Hazard characteristics VS value at risk

Four main parameters are defined for this step:

<u>Flood characteristics (Hazard value)</u>: among all flood parameters such water speed, inundation area, duration and water depth, the last one carries the strongest influence on damage magnitude, while the others are rarely taken into account. The dominant approach, as suggested by Merz et al. (2010), employs depth-damage functions. Flood discharges, extent and depth can be calculated by means of 1D-2D models and simple GIS functionality. A combination of hydrological and hydraulic models has been employed for the definition of our scenarios.

Hydrological model: DHI-Mike11 NAM Rainfall-Runoff

1D hydrodynamic model: DHI-Mike11 HD

2D hydrodynamic model DHI-Mike21 HD

Different scenarios have been generated from these models, with different starting hypothesis drawn on the basis of the climatic forecasting background discussed previously. Firstly, flow dynamic discharge scenarios have been made both for unvaried conditions (present) and for climate change conditions (future) by means of 1D modeling over the whole Po basin, taking into account the main tributary streams. Secondly, the same model have been used to produce some rupture scenario and their relative outgoing discharge hydrographs, which have been employed as inputs for the 2D model elaboration of inundation of the floodplain. The propagation of the flood is mainly regulated by the topography of the area. A 10 meters grid DEM (Digital Elevation Model) has been aggregated to 200 meters grid and used to simulate the flooding propagation. The loss of information from this aggregation process is tolerable and do not compromise the representation of the process. The inner canals of the floodplain (such as Canalbianco, Adigetto and Ceresolo) are not considered as streams contributing to the flood, but rather their embankments are accounted in the topography as they act like obstacles, adjusting the direction of the flood. They still can be surmounted if the water reaches their top height.

To obtain realistic discharge scenarios, observation data of the October 2000 event have been used to define the base scenario in the period 10-18 October. Climate Change conditions already reviewed have been discussed with the experts from the ARPA-SIM ("hydro-meteorological service") and applied on this base scenario to produce two future discharge scenarios: +10% rainfall on the base event (2021-2050 scenario) and +30% rainfall on the base event (2071-2100 scenario). Four different rupture scenarios have been derived from these discharge scenarios, supposing a failure of the left embankments caused by erosion at Occhiobello, near Pontelagoscuro station. This rupture scenario resembles the reference event of 1951. The rupture length extension is 200 meters for three scenarios, while the last scenario figures a 400 meters break. Table 5.2 summarizes all the scenarios elaborated by ARPA-SIM. The spatial resolution (grid cell) of the simulation results is 200x200 meters, as obtained from the DEM. The output is a raster file where each pixel represents one cell of the grid.

Scenarios	*Definition*	*Rainfall rates (compared to 2000 event)*	*Rupture*
Discharge scenarios	Base scenario	+0%	
	2021-2050	+10%	
	2071-2100	+30%	
Rupture scenarios	Base scenario	+0%	200 m
	2021-2050	+10%	200 m
	2071-2100	+30%	200 m
	2071-2100	+30%	400 m

Table 2. *Summary of different flood scenarios elaborated by ARPA ER.*

To have an inclusive view of the maximal hazard value in the whole area, envelope curves of maximal depth have been used to summarize all the timeframes of each scenario simulation in one summed-up frame, which is then used to represent the whole scenario in the risk calculation.

Assets at risk (Exposure value): Land-use data about the number and typology of affected properties can be obtained from pre-existing data sources. Regional web-database (Regione Veneto 2009) provides with a detailed datasets about land-use in GIS format (vector). Regional land-cover datasets (2006) have a resolution of 1:10,000, with the smallest homogeneous area equal to 0.0025 km². There are 62 land-use categories, divided in 5 hierarchic levels. For the purposes of this research, several classes are aggregated together to identify some main categories: urban areas (continuous and discontinuous), industrial-commercial areas and agricultural areas. Classes are listed in Table 3. Forest and semi-natural areas, wetlands and water bodies are other main categories which are not taken into account in the impact assessment.

Urban surface	*Agricultural surface*
• Continuous urban fabric (density >50%) • Discontinuous urban fabric (density <50%) • Industrial and commercial • Mine, dump and construction sites • Other artificial areas	• Arable land (maize, cereals, soya, beet, sunflower) • Permanent crops (fruit trees, vineyards) • Pastures

Table 3. *Aggregated land-use categories which are significant for the analysis.*

The resulting aggregated land-use layer is converted to raster for comparison with the hazard layer. To avoid losing too much information, the grid cell resolution measures 50x50 meters, that means four times more detailed compared to the hazard raster. Unlike land-use units, which are geographically identified on the maps through GIS layers, population and vehicle statistics are available only in text form. Therefore, the analysis of these data requires a slightly different approach. For each municipality, the total amount of inhabitants is divided over the total area of urban fabric to obtain a density of population for km² of residential buildings. This distribution of population is then compared with the amount of flood-covered area to attain a coarse estimation of the exposed value, ignoring the sparse houses which are not mapped. Regarding the private vehicles, their density over population for each municipality is obtained from official statistics (Automobile Club Italia 2009). The distribution of vehicles over the territory is assessed through simple correlation between population and vehicles density, assuming that all the vehicles are parked near the owners' houses (urban fabric). The resulting data is compared with the hazard extension, to assess the number of involved vehicles per depth categories over urban fabric areas.

Value of assets at risk: the value of elements at risk must be assessed on the basis of available statistical data or approximating land-use values from similar studies. These values are then integrated in the absolute depth-damage functions for each category to estimate the absolute damage. Assets values are then merged with land-use categories via GIS to obtain a layer showing the value concentration in €/m². Additional data from statistic sources such as population density, average per capita income, etc. can also be integrated to improve the description of land-use value. Maximal damage values for each land-use category in Italy are obtained from HKV Consultants (2007). Other discretional categories taken in account are vehicles, furniture and agricultural products. The average value of vehicles in Italy (2011) is obtained from private statistics (autoscout24.it), while the value of furniture and agricultural products is accounted as a part of the damage share for their respective land-use categories. The eventual absence of products due to seasonality is discussed separately.

Susceptibility of assets at risk (Vulnerability value): using a set of previously developed absolute damage functions, only land-use data are required. Each land-use category needs its own damage function. Generally, damage curves can be roughly described as:
$Damage = a \times \sqrt{depth}$ with "a" being the parameter dependent on the category.
Absolute depth-damage functions have been developed by HKV consultants (2007) for each European country on the basis of empirical data previously collected in other studies. These functions comprise two damage indicators: a damage ratio between 0 and 1, relative to the maximum damage for each category, and an absolute damage estimate expressed in €. The water depth range from 0 to 6 meters, where 6 is the maximum damage level (damage ratio = 1). These functions are obtained as averages of empirical functions previously redacted in nation-specific researches carried out in Europe. They take in account five land-use categories (including inventories), chosen to cover at least 80% of the total damage. The total damage values are calculated on the basis of economic characteristic specific for each country, deduced from Eurostat and Worldbank data. These values are then actualized to 2007 and harmonized using the average national annual inflation rate (equal to 0.3 for 2000-2010 in Italy). Table 4 summarizes the average functions for each land-use category. Damage amounts can be further translated into Purchasing Power Parities (PPP). The conversion factor for Italy is equal to 0.87 (1 PPP $ = 0.87€) (rates from data.un.org).

Water depth (m)	***Damage factor***				
	Residential buildings including inventory	*Commercial and Industrial including inventory*	*Agriculture including products*	*Transport infrastructures (roads and railroads)*	*Cars*
0	0	0	0	0	0
1	0.4	0.3	0.55	0.42	0.5
2	0.6	0.55	0.75	0.65	1
3	0.75	0.75	0.85	0.8	1
4	0.85	0.90	0.95	0.9	1
5	0.95	1	1	1	1
6	1	1	1	1	1
	Maximum damage value (€/m²)				***(€/n)***
	618	475	0.63	20	14,450

Table 4. *Depth-damage factors and maximal damage for each category (adapted from HKV Consultants, 2007).*

3.3. Economic assessment

The results are usually highly spatially diverse, so it is better to represent them in geographic terms. The final risk map represents the value of the potential socio-economic damage in monetary terms for each flood scenario, with a spatial resolution of 50x50 meters. It must be specified that this map shows the damage as occurring simultaneously in the whole area. The methodological approach described in this chapter is summarized in table 5.

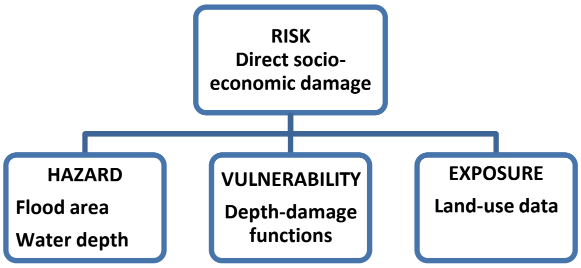


Figure 5. *schematic representation of the flood damage evaluation process.*

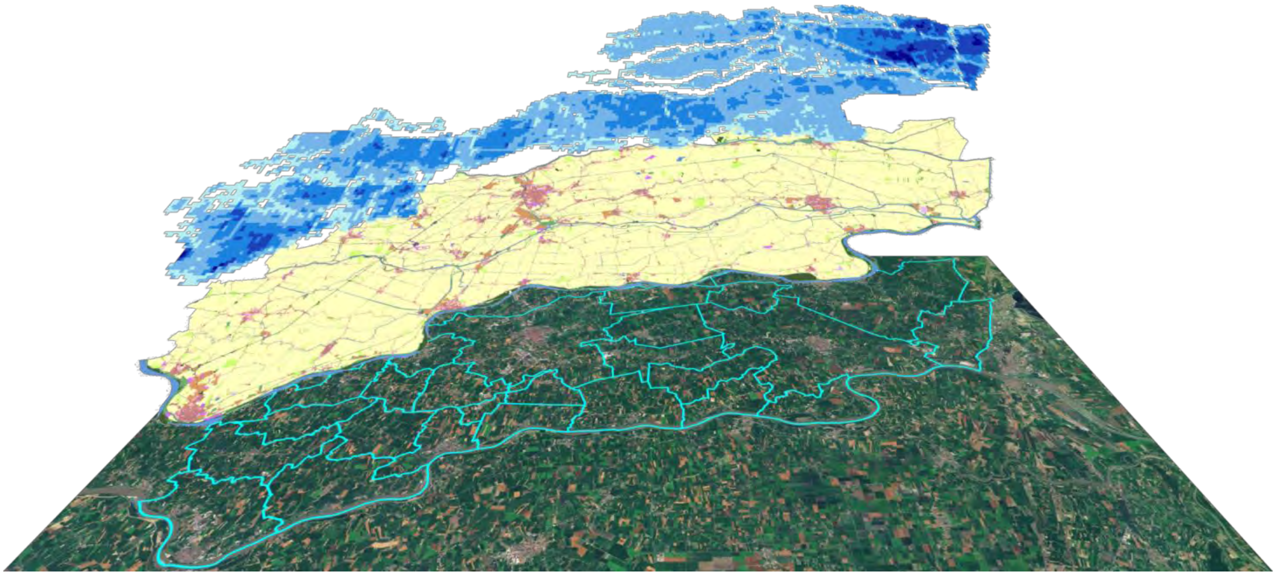


Figure 6. *visual representation of overlay operation in ArcGIS environment.*

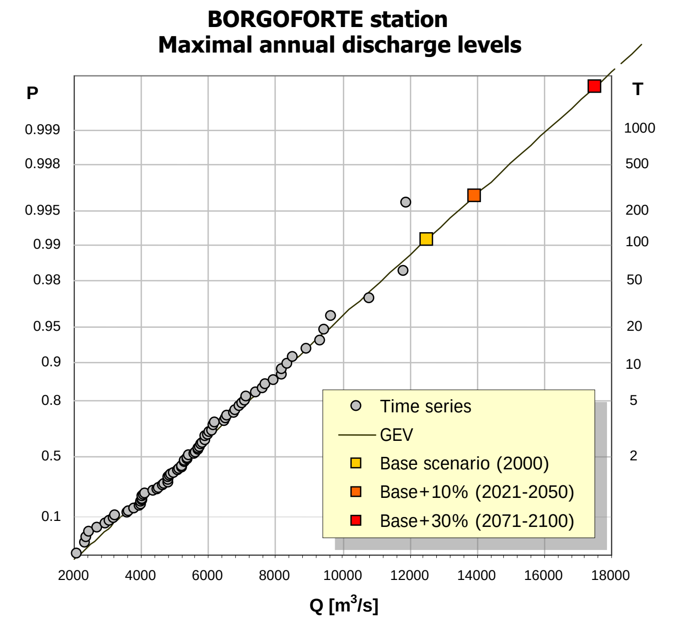
Step 1	**Approach and data requirements**	• Meso-scale (province, municipalities) • Flood scenarios and characteristics • Aggregated land-use data • Approximate values for land-use categories • Damage functions
Step 2	**Damage categories considered**	• Land-use categories • Furniture • Cars • Agricultural products
Step 3	**Flood characteristics**	• 4 different flood scenarios • Area • Depth
	Land-use data	• Regional GIS dataset: 4 aggregated categories • ISTAT: population and vehicles numbers
	Determination of values of assets	• Transfer from previous studies
	Damage functions	• 5 depth-damage functions (matched with damage categories) transferred from previous studies
Step 4	**Damage calculation and presentation**	• ArcGIS overlay and spatial analyst • Shapefile data and maps

Table 5. *Summary for damage evaluation approach.*

4. RESULTS AND DISCUSSION

4.1. Discharge scenarios

The output of the model previously described provides with the characteristic of the hazard for each scenario. The rupture in the embankment system is located in Occhiobello, like in the 1951 event. The choice of the same rupture scenario as in the reference events is motivated by the fact that, in this sector of the basin, the mitigation system already reached its structural limit, and therefore it cannot be increased with further intervention. This means that the embankments height will more likely remain the same in future decades. Other mitigation measures are not taken into account in the discussion. Also, the influence of the mechanical drainage system (waterpumps) is not accounted to assess the flood outflow. Its slow action would probably affect only the duration of the flood event in some areas, but not its intensity. The discharge time series 1924-2010 for the Po station of Borgoforte have been analyzed by ARPA-SIM through the Generalized Extreme Values (GEV) distribution (Jenkinson 1955). This distribution summarizes all the Gumbel, Frechet and Weibull distributions. The shape of the probability distribution has been then summarized through the L-moments method (Hosking 1990). Figure 7 presents the adapted probabilistic Gumbel distribution of the time series, which is employed to calculate the frequency (expressed as return time) of the events in our scenarios.



Scenarios	*Max discharge (m^3/s)*	*Return time (years)*
2000 (Base scenario)	12,500	110
2021-2050 (Base +10%)	14,000	270
2071-2100 (Base +30%)	17,500	>1,000

Figure 7. *Gumbel distribution of discharge flow for the three discharge scenarios at Borgoforte station.*

4.2. Rupture scenarios

Full maps for each levee breach scenarios can be found in the Annex. The Canalbianco embankments represents an obstacle for the further extension of the flood in the base scenario and in the 2021-2051 (Base +10%) scenario, while in the 2071-2100 (Base +30%) scenario this barrier is not sufficient to stop the flooding towards northern municipalities, involving the urban areas of Adria, Cavarzere and part of the Rovigo discontinuous urban fabric. Because the Polesine area is mechanically drained lowland surrounded by higher embankments, it behaves like a bowl, allowing the water to increase its depth until the height limit of the barriers is surpassed. After that, the flood is allowed to flow out covering a wider extent of floodplain and thus reducing its depth. The eastern section of the depressed basin (-1/-2 a.s.l.) is separated from the coastal area by the canal Brondolo, where embankments are some meters high over the floodplain. In none of our simulations this canal have been surmounted, thus avoiding the flood to reach the urban areas of Rosolina, Porto Viro and Chioggia, which are situated at circa 0/1 meters a.s.l. and would present an important exposed value either as urban, touristic and fish-farming area.

4.3. Exposure: Area affected

The total area of involved municipalities measures 868.5 km^2. The base scenario involves some 277.36 km^2 (32%), engaging just few towns (Occhiobello, Bottrighe and part of Polesella, Loreo and Adria urban fabric) in addition to sparse residential areas, with a maximum water depth of 3 meters; the 2021-2050 scenario has the flood spreading over 355.36 km^2 (41%), engaging the whole towns of Santa Maria Maddalena, Loreo and half of Adria urban fabric with a maximal depth of 4 meters; the 2071-2100 scenario covers 507.56 km^2 (58%), reaching Cavarzere and the outskirts of Rovigo, achieving a 5 meters depth in the eastern part of the basin; finally, the 2071-2100 scenario with the 400 meters breach simulation covers 590.08 km^2 (68%), engaging several minor towns in addition to the area covered by the previous scenarios, and increasing the maximal water depth in many areas. As already pointed out, the Polesine region is mainly agricultural. In the impact area, 63.7% of the territory is employed for agriculture, corresponding to 86% of artificial areas. Forest, wetlands and water bodies are excluded from the discussion, since they do not carry any significant flood-prone value. Agricultural products are mainly from arable land (maize, other cereals and soy) with few scattered permanent cultures (fruit trees, vineyards and others). Residential buildings, which have the higher value density, account for just 6% of the total. Industrial and commercial activities are not widespread, accounting for just 2% of the artificial coverage. The transport network in the exposed area is mainly constituted of second and third order roads, but two important first-order transport ways are heavily exposed to the flood: the Padova-Bologna A13 highway and the Padova-Bologna railroad, which is served by hi-speed trains (Intercity and Eurostar). The A13 highway is exposed in the section between Rovigo and Occhiobello (20 km north-south) to an average flood depth of 2.5 meters, while the railroad follows a longer path (around 45 km) through Polesella and Canaro, so being exposed for a higher percent (from 70% to 90% depending on the scenario) of the total section to an average of 3 meters depth water. Both transport ways are not significantly elevated over the floodplain level. Discretional values such as agricultural products and private vehicles need to be discussed separately. Our flood scenario is ideally placed during the first or second week of October, similarly to the October 2000 event. At this time, arable crops have been usually harvested already in Polesine, except in case of extraordinary rainy weather in September. However, this period is sensible for sowing cereal crops such wheat, oat and barley. We can therefore argue that an October flood would be more impacting on cereal crops that have been just sowed, compromising the next year's yield.

For what concerns cars, the amount of private vehicle strictly reflects the distribution of population density among the 25 municipalities, with Rovigo being the larger urban area, and thus the most populated (51,872). Adria and Cavarzere municipalities follows, with 20,549 and 15,005 respectively, while Occhiobello is forth with 11,315 (ISTAT, 2008). The remaining municipalities do not have large towns, but instead a low-density urban fabric, widespread over the agricultural area. However, the urban area of Rovigo is for the most not interested by the flooding in any scenario, so the higher exposure of population and vehicles is located in Adria and Cavarzere municipalities.

4.4. Estimated impacts: population affected and economic damage

Full maps representing the damage classes for each flood scenario can be found in the Annex. The resolution of the risk layer pixel is 50x50m. The range of damage classes have been calculated through approximated Jenks' natural breaks classification, which minimize the average deviation from each class mean, but maximizing the deviation from the other classes. The calculation of the damage related to each land-use categories have been carried out in ArcGIS environment, employing the damage functions already presented. For the urban fabric, which is not purely residential, a mixed function is used: the fabric is considered as composed of 25% commercial use and 75% residential use, since the ground floors of buildings may be occupied by commercial activities, especially in towns. For each scenario, an assessment of the total damage is accomplished multiplying each damage class with the consistent total area. Damage is expressed in million € at the 2000 value for each scenario. Potential inflation taking place in future scenario is impossible to calculate, so it has not been taken into account for normalization. The percentage of damage among the land-use categories is compared to their corresponding coverage area in fig. 8. The total population of 161,864 is distributed for the most over a total urban area of 47.61 km^2, corresponding to a density of 3,400 people over urban km^2. For each municipality the amount of flooded urban area is multiplied by the local density. Municipalities' values are summed resulting in a value of exposed population for each scenario. The distribution of vehicles closely resembles the population spread over each municipality. The damage function for private vehicles is employed over their distribution using a maximal value of 14,450 € to assess the total damage induced by flooding.

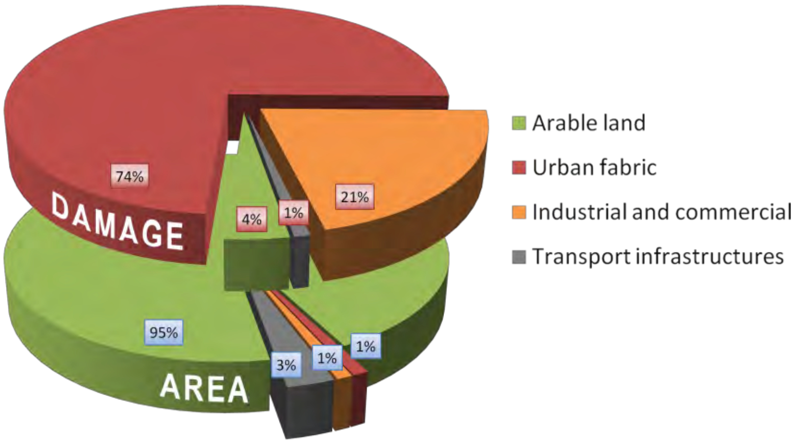


Figure 8. *Comparison between covered area and related damage for land-use categories in the Base Scenario.*

Scenarios	*Affected area (sq.km)*	*Affected urban area (sq.km)*	*Exposed population*	*Flooded vehicles*	*Vehicles damage (mil Euro)*	*Total damage (mil Euro)*	*Total damage (mil PPPs USD)*
2000 (Base scenario)	277.36	7.77	23,255	13,804	128.106	3,133	3,601
2021-2050 (Base +10%)	355.36	11.52	35,733	21,120	216.128	4,956	5,696
2071-2100 (Base +30%)	507.56	17.29	54,067	32,209	362.861	8,083	9,291
2071-2100 (Base +30%) 400 m	590.08	22.21	70,132	41,744	507.896	11,079	12,734

Table 6. *Total flooded area, urban flooded area, amount of population exposed to the hazard, flooded vehicles and their corresponding damage cost, and comprehensive damage for each flood scenario.*

4.5. Estimation of total damage

Finally, table 6 is drawn summing up the results from both land-use categories and vehicles, approximating to the integer. The third column show the same values converted in $ PPPs (conversion factor = 0.87). The percentage of damage spread among the damage categories is represented in fig. 9 for all scenarios.

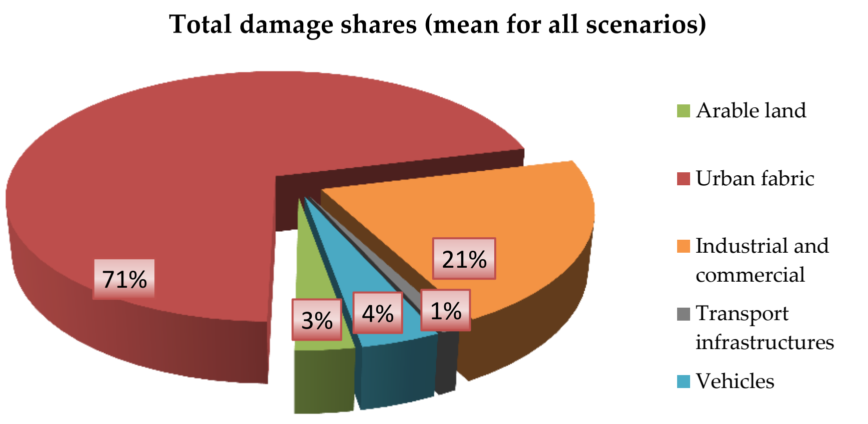


Figure 9. *Percentage of damage related to each land-use category and vehicles for the mean rupture scenario.*

The relative shares of damage do not differ much when comparing the four scenarios, showing how the increase in flood hazard level is constantly distributed among all the categories. This observation may be useful to roughly assess other hypothetical scenarios without running the whole analysis.

The arable land area covers the most of the exposed area in terms of surface, but because of its low maximal value it accounts for just 2-4% of the total damage. This share is even lower considering just the cereal production (20% of the total crops), which would be probably the only impacted crop according to the seasonality. Roads and railroads are also not significant in the total share, with just 1%. However, the A13 highway and the Padova-Bologna railway are two main arteries connecting highly developed areas, which likely means that a huge indirect impact would be caused by this negligible direct damage. Industrial-commercial (20-21%) and urban fabric (71-72%) hold the biggest shares of damage from hazard, despite the low shares of covered surface (roughly 1% and 3%). The damage assessment of the four potential scenarios can be compared with the reference events of the 1951 and 2000 to gain a denotative appreciation of both the physical and the economical scale of the event, using the same monetary measure ($PPPs updated to 2000 value). Table 7 summarizes the characteristics of each event.

Flood event	*Peak river discharge at Borgoforte (m^3/s)*	*Estimated damage (mil $ PPPs)*	*Affected population*
REFERENCE EVENTS			
1951	11,800	6,000	170,000
2000	11,800	8,000	43,000
SIMULATED EVENTS			
2000 (Base scenario)	12,500	3,601	23,255
2021-2050 (Base +10%)	14,000	5,696	35,733
2071-2100 (Base +30%)	17,500	9,291	54,067
2071-2100 (Base +30%) 400 m	17,500	12,734	70,132

Table 7. *Comparison between reference events and simulated flood scenarios considering flood discharge rates, total economic damage and affected population.*

Regarding the physical indicator of peak discharge, it must be highlighted that simulated events do not take in account any former outpouring of water before the rupture area. This practical approximation may be unrealistic and exaggerate the actual amount of water reaching the rupture. In fact, ARPA experts confirm that discharge values higher than 13,000 m^3/s would probably cause some flood scenario in previous sections of the basin, allowing to reduce the water load downstream.

The estimation of population exposure is based on the actual census (2008). Trends about population growth in Polesine are flat or slightly negative since 1951, suggesting that the real future scenarios may not change much compared to the simulations. This observation can be extended to the urban and economic development scenarios, which are strongly dependent on the population rates: as already pointed, also the primary sector has a flat or slightly negative trend in the whole eastern part of the basin. However, the comparison of estimated risk with registered damage of previous events is hindered by the fact that only a portion of the total damage categories is considered in the analysis of simulated events. In fact, the total cost of damage estimated on reference events includes much more sources of loss, but their share on the total is not indicated and it is therefore impossible to produce an item-by-item comparison with the potential scenarios. Accordingly to this, the estimation of potential damage has to be considered as a conservative approximation of the full cost of the flood. Another important distinction must be made taking into account the existent Early Flood Warning System by ARPA, which gives a reliable forecasting and a timely warning should therefore be expected for any kind of important event. This would lead to an important saving of costs by reducing the exposed value (for example the private vehicles) and by the execution of hazard mitigation measures (for example preventive controlled flooding) by the Civil Protection and other authorities.

Many other variables simply cannot be easily assessed in the long period, for example the subsidence of the area. If the methane gas extraction would be re-activated for any reason dependent on future socio-economic macro scenarios, the flood risk in the Polesine area would certainly increase by a large amount. In case of consistent changes in the socio-economic conditions, the analysis needs to be redrawn including the new variables. The uncertainty related to the results of the assessment is likely to be high due to the simplified assumptions on the development of the hazard scenarios and the choice of the damage categories. That is, the final uncertainty sums up the numerous sources of approximation on the three components of the risk paradigm and it is hardly evaluable without a tangible comparison with factual data about the forecasted event.

5. CONCLUSIONS

This research evaluated the prospective economic impact of four different climate-driven flood scenarios over the Polesine region. Risk maps have been produced as spatial interpretation of potential losses to help policy makers evaluate the priority of actions when developing adaptation policies. The quantification of total impacts to flooded land use classes and exposed vehicles can be found in Table 6, but it has to be considered as a rough estimate of maximal losses affecting the case study area.
Future climate change is likely going to positively influence the intensity and frequency of extreme flood events. However, the risk related to this increased hazard will be strongly dependent on both socio-economic conditions and anticipatory capacities. The integrated analysis of hazard, exposure and vulnerability values in GIS environment can provide a valuable approach to achieve a fast evaluation of potential damage regarding the most important categories of direct damage to help high-level decision making, without being much data-intensive and time-consuming. Moreover, after the pilot study, this methodology can be easily extended to larger parts of the basin using the same tools. They can be easily integrated in an automated chain model connected to the Early Flood Warning System to gain an appraisal of potential risk right after the meteorological forecasting. However, a calibration and validation of the model would be needed to assess and reduce uncertainty, which is still not measurable at this time. In addition to this, more complex and comprehensive statistical indicators about socio-economic trends in the impact area would be needed to correctly evaluate the changes in the exposure value for future scenarios. To obtain more consistent results, further research should focus on coupling a macro-economic probabilistic to this semi-deterministic model, assessing indirect damages and the full impact of an event over the GDP. The inclusion of a specific loss-of-life model is also a possible option to complete the framework of cost categories. Moreover, the reliability of the European depth-damage curves on the national scale is still to be assessed: it would need a specific national study to validate the scale of simulated losses in comparison with registered data from past flood events.

A final note concerns the inclusion of the Polesine area in the PAI document, since its development and safety is heavily connected to the measures adopted in the rest of the Po River basin. At the moment, different land-reclamation authorities manage this hybrid basin, but its general plan for the reduction of hydrological risk is not included either in the main basin plan or in the Delta plan. The inclusion of this area as effectively part of the Po River basin should be taken into account by river authorities.

ANNEXES

Exposure and risk maps are shown for each climatic scenario. Please note that total damage in the risk maps only refers to land use classes, without considering vehicles. Total damage can be found in Table 6.

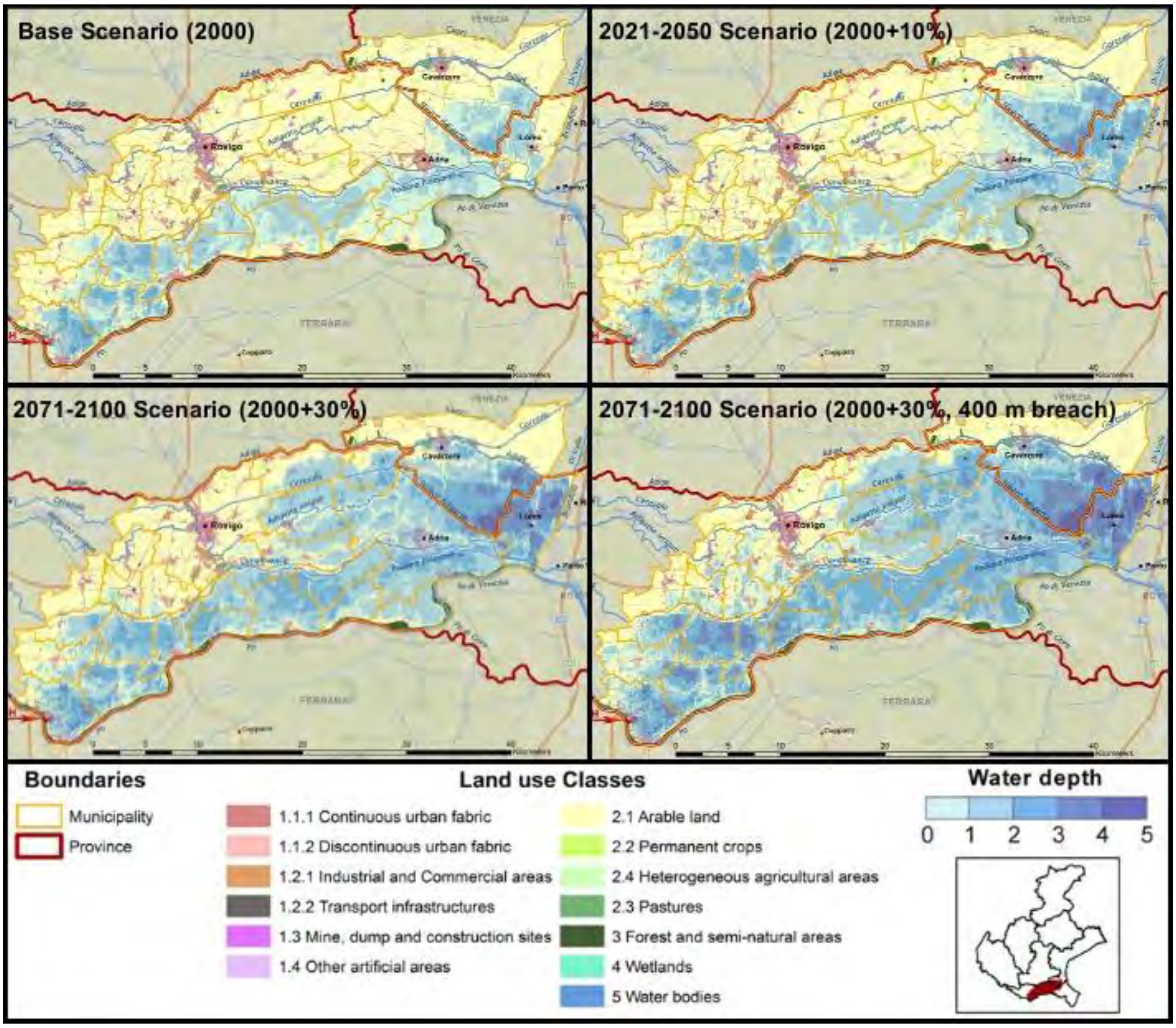
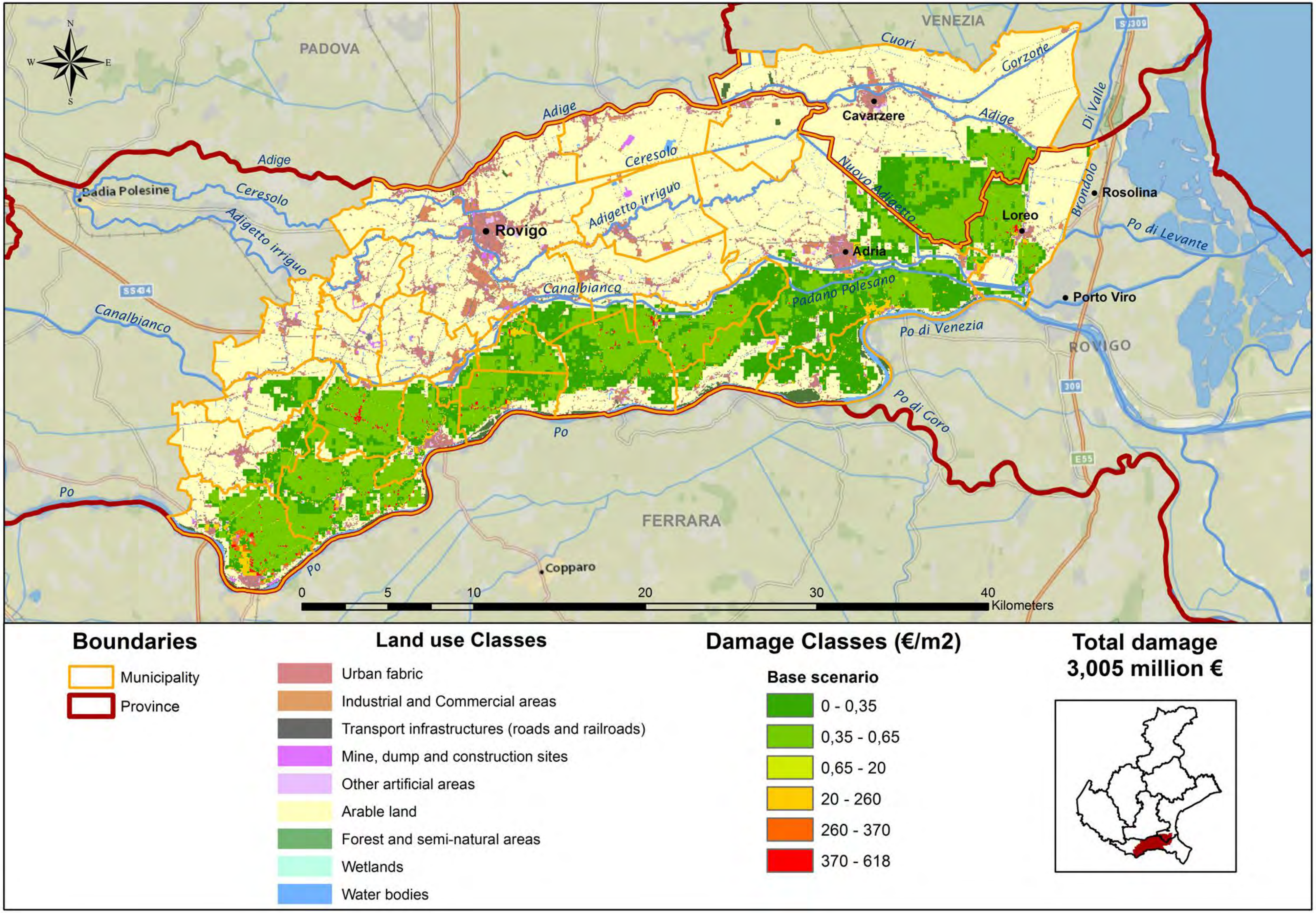
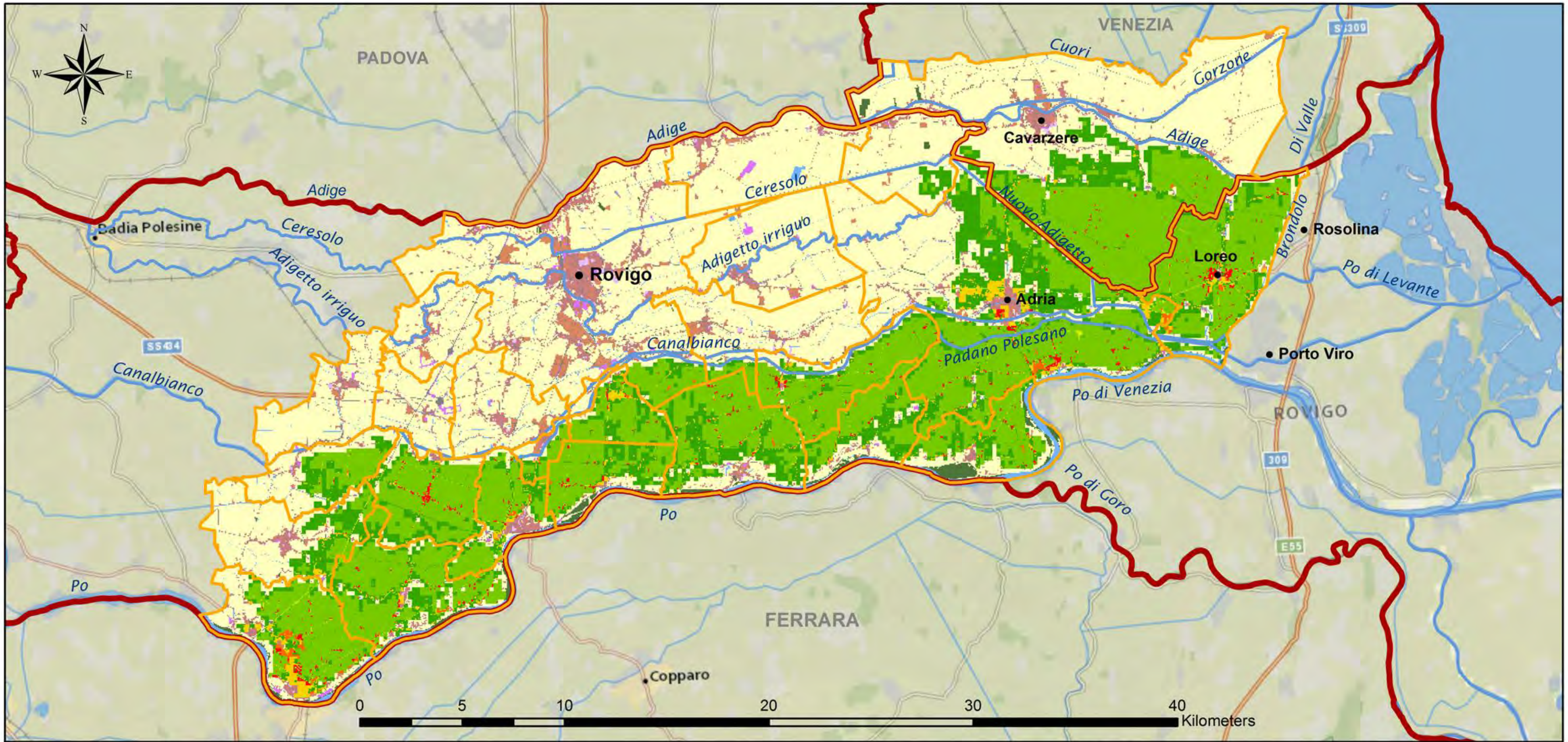


Figure 10. *Geographical representation of the four flood hazard scenarios.*

Damage assessment – Base scenario (2000) – 200 meters breach



Damage assessment – 2021-2050 scenario (2000 +10%) – 200 meters breach



Boundaries

- Municipality
- Province

Land use Classes

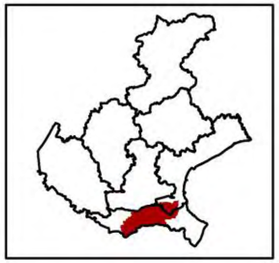
- Urban fabric
- Industrial and Commercial areas
- Transport infrastructures (roads and railroads)
- Mine, dump and construction sites
- Other artificial areas
- Arable land
- Forest and semi-natural areas
- Wetlands
- Water bodies

Damage Classes (€/m2)

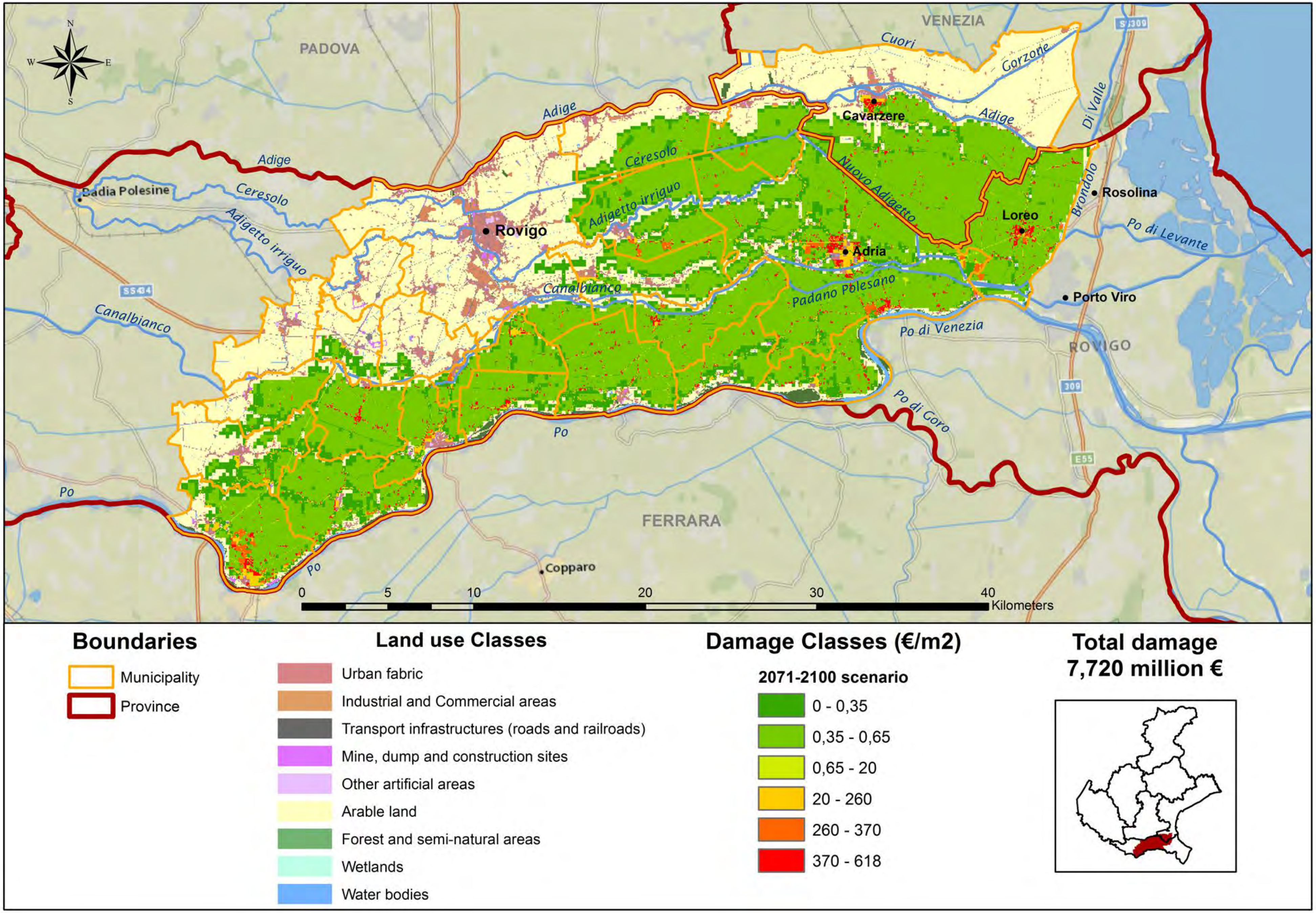
2021-2050 scenario

- 0 - 0,35
- 0,35 - 0,65
- 0,65 - 20
- 20 - 260
- 260 - 370
- 370 - 618

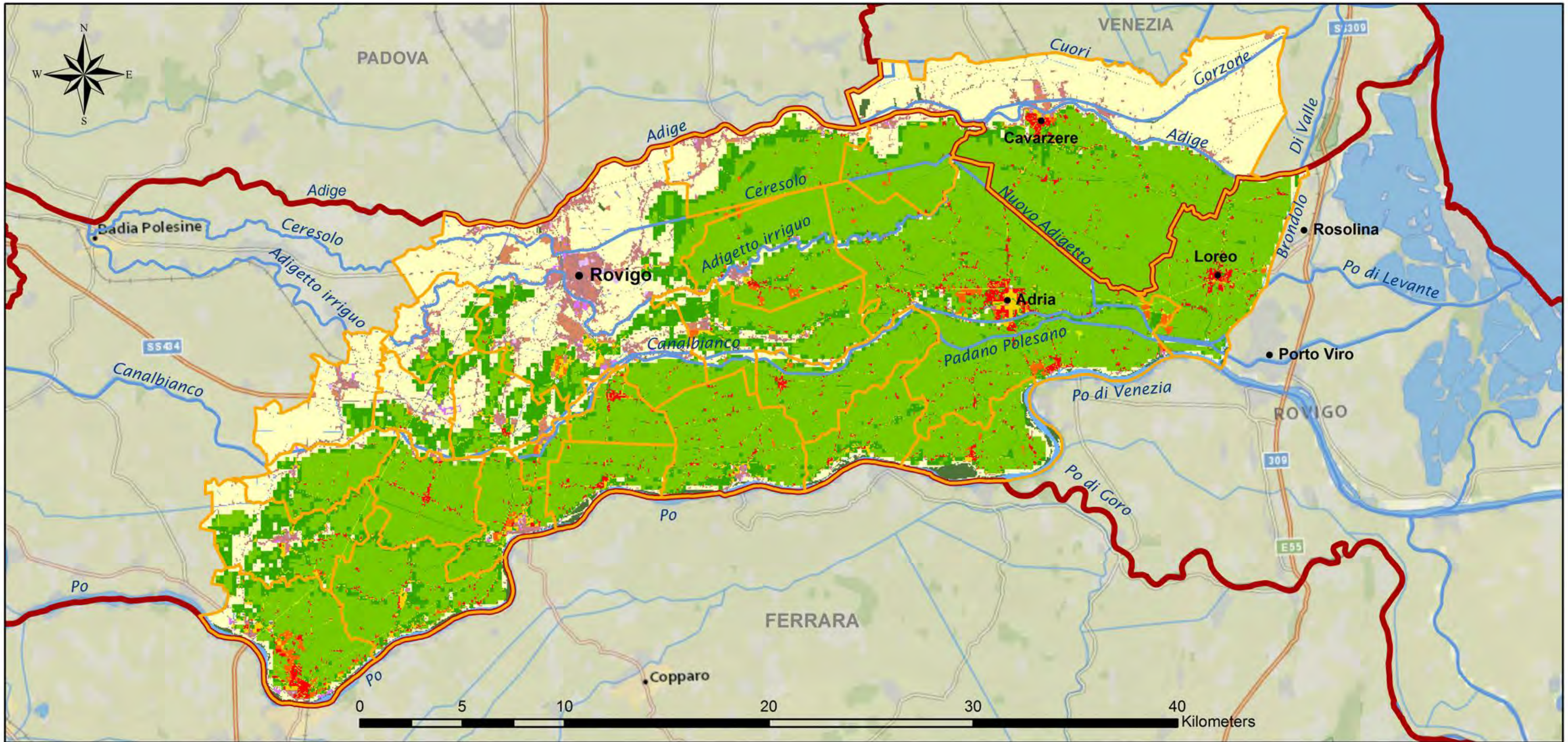
Total damage
4,740 million €



Damage assessment – 2071-2100 scenario (2000 +30%) – 200 meters breach



Damage assessment – 2071-2100 scenario (2000 +30%) – 400 meters breach



Boundaries

- Municipality
- Province

Land use Classes

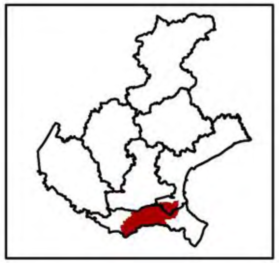
- Urban fabric
- Industrial and Commercial areas
- Transport infrastructures (roads and railroads)
- Mine, dump and construction sites
- Other artificial areas
- Arable land
- Forest and semi-natural areas
- Wetlands
- Water bodies

Damage Classes (€/m2)

2071-2100 400m scenario

- 0 - 0,35
- 0,35 - 0,65
- 0,65 - 20
- 20 - 260
- 260 - 370
- 370 - 618

Total damage
10,571 million €



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