



# **FLOOD RISK ASSESSMENT IN THE PO RIVER BASIN UNDER A CLIMATE CHANGE SCENARIO**

by

**Mattia Amadio  
825260**

*Environmental Sciences*

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Supervisors  
Prof. Gabriele ZANETTO  
Prof. Stefano SORIANI

Co-Supervisor  
Prof. Carel DIEPERINK

## Abstract

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River flooding is the most common natural disaster in Europe, causing deaths and huge amount of economical losses. Disastrous flood events are strictly related to extreme meteorological conditions; therefore, climate change is expected to have an important influence over the intensity and frequency of major floods. While approximated large-scale assessments of flood risk scenarios have been carried out by the European Joint Research Center, the knowledge of the effects at smaller scales is poor or incomplete, with few localized studies. Also, the methods are still coarse and uneven. 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. Through the integration of these elements in a GIS environment, results are drawn for a pilot study in the Polesine area, where four simulated breach scenarios are compared. The outcomes of the analysis may be instrumental to authorities to increase the knowledge of possible direct losses and guide decision making. 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 hazard; Risk assessment; Po River basin; Climate change; Disaster management.

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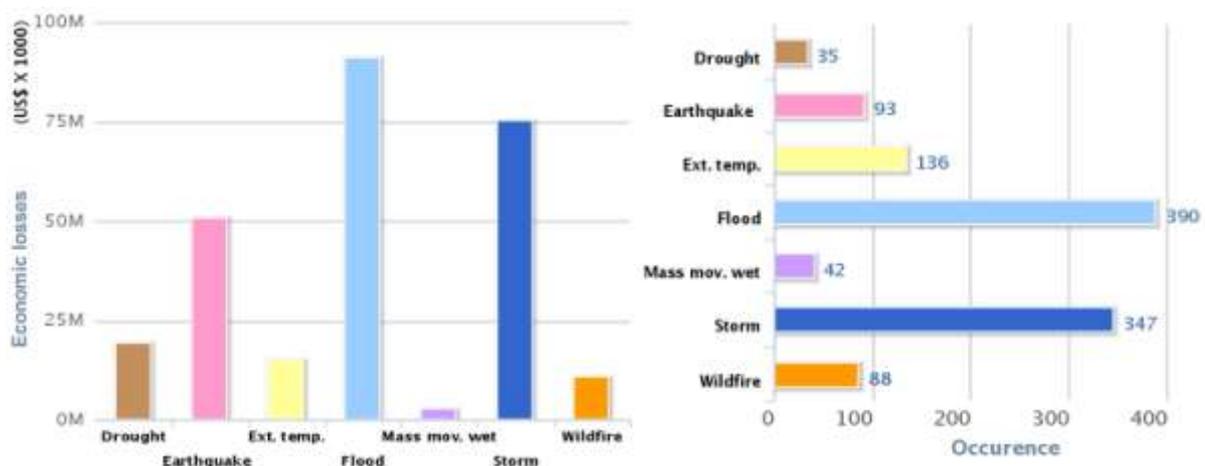
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# 1. Introduction

## 1.1. The main project: PREEMPT

Floods can have different categorizations. They can be caused by high tide, storm surge, overflow or breaks of embankments, dam failure, or extreme precipitation with impeded outflow. All these events share a common consequence, that land is temporarily submerged where this normally does not or should not happen. In Europe, floods of different kinds are the most common type of disastrous events, and they account for the biggest share of damage inflicted by natural disasters, both on economic terms and life threat (fig. 1.1) (EM-DAT, 2009).



**Figure 1.1:** Statistics about natural disasters losses and frequency in Europe for the period 1980-2008. In both cases, flood is the top category (data from EM-DAT, 2009).

While the trend of non-climatic disasters does not show radical changes, weather-related events such as floods, droughts and storms are substantially increasing in the last decades. Just in Europe, the number of disastrous events per year has doubled from 1980s to 1990s (European Environmental Agency, 2004).

The modern flood risk management approach acknowledges that, most of the times, floods cannot be stopped from occurring, and places emphasis on how to reduce hardship and vulnerability of risk-prone communities. This approach is also shared by the European Union Flood Risk Management Directive (2007/EC/60), which state that flood management plans need to consider first the harmful potential of floods, and then identify tangible measures to

reduce exposure and sensibility to floods, while improving risk governance. However, an effective prevention needs an accurate knowledge of what values are at stake, yet the knowledge about the past and potential disasters is all but erratic and incomplete. While macro-scale scenarios of climate change are commonly analyzed and diffused, little knowledge is available about the impact of these changes on the socio-economic parameters at the meso-scale.

The PREEMPT project run by Fondazione Eni Enrico Mattei (FEEM) sets to assist the relevant authorities to better appreciate the risks posed by droughts and floods. It complies with this objective by collecting the data about past disasters, filling-up the knowledge gaps about socio-economical losses, and by improving risk assessment methods and approaches in place. The knowledge collected or improved by this project will be instrumental to several EU policies such as Flood Risk Management Directive 2007/60/CE and to national plans to mitigate the natural hazard risk.

In Italy, given the rugged, mountainous topography, landslide-prone geological setting, and Mediterranean climate, large areas of the country are exposed to floods and landslides on one side, and drought and desertification on the other. For the 20th century and thereafter (1900-2008), the disaster records list some 2,713 landslide and 2,321 flood events (Salvati, et al., 2010). The costs of hydrogeological disasters in the period 1951-2009 exceeded € 52 billion. In 2010 alone € 650 million have been allocated to tackle the emergency situations.

This thesis, as contributive part of the broader PREEMPT project, aims to provide new knowledge about the potential damage that may occur in the next decades, assessing the expected flood risk in the Po River basin under a scenario of climate change. It will not take in account the whole hydrogeological processes contributing to risk, but instead it will focus only on flood events; analysis of other hydrogeological phenomena such as landslides or avalanches requires a wider and more complex framework.

## 1.2. Research objective

The aim of this research is to estimate the effects of climate change (considering both short-term and long-term timeframes) on the magnitude and frequency of extreme flood events in the Po River basin, and to understand how these effects 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 researches.

As first step (chapter 2), a theoretical framework is developed to identify and explain the main concepts, and to avoid ambiguity of terms; the notion of “hydrological risk” is defined on the basis of previous literature, and assessment methods are reviewed. Following, a profile of the hydro-geological risk is drawn for Europe and, with better detail, for Italy.

Secondly (chapter 3), the case study basin area is defined and described. Historical trends and representative flood events are identified as references, and their consequences and impacts are discussed. A limited pilot area is designated and focused.

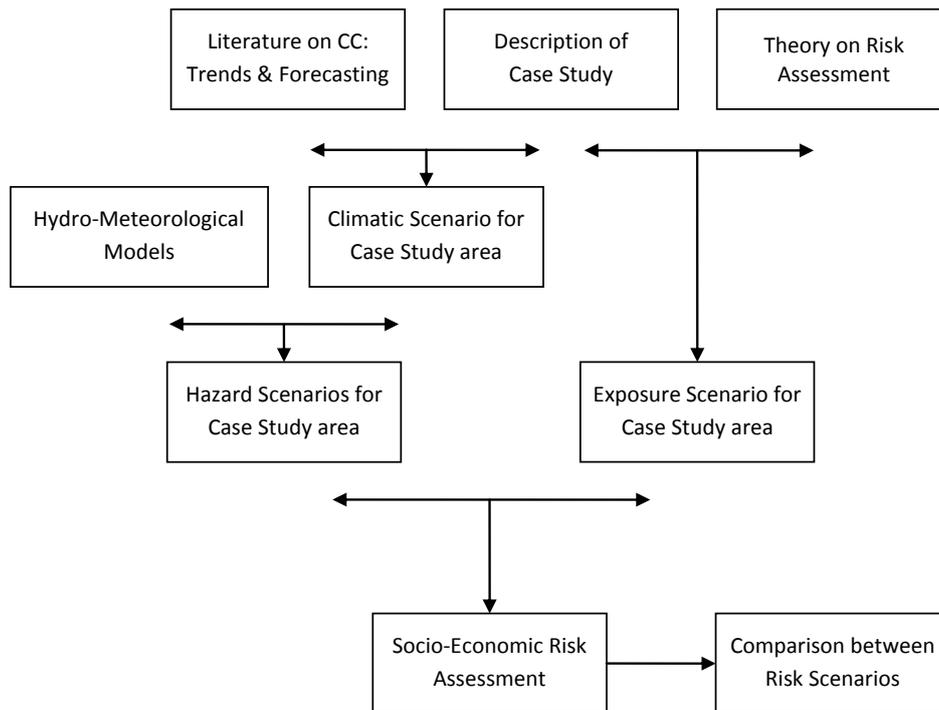
As last step of this part (chapter 4), we are going to review previous literature to gain descriptive knowledge about the processes occurring at the global European scale and in the case-study area: historical trends and climate change projections are collected and compared to establish some climatic scenarios.

The knowledge obtained from these first steps (chapters 2, 3, 4) will set the base data for the following experimental part (chapters 5, 6, 7), which aims to gain predictive knowledge.

Materials and Methods (chapter 5) are defined on the basis of the previously outlined theoretical framework and on the conclusions drawn from the review of the case study and the climatic scenarios.

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.

The 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. Here in fig. 1.2 the schematic flow chart of the research framework is presented.



**Figure 1.2:** Research framework.

### 1.3. Research question

The research provides an answer to the following question:

Which are the effects that future Climate Change will have on the magnitude and frequency of extreme flood events in the Po River basin, and how these effects will reflect in terms of socio-economic Risk for the specific Case Study area?

- Are extreme floods more likely to happen in the future due to Climate Change?
- How would be possible to assess the risk produced by future extreme events?
- Is the expected impact of future extreme events likely to be more important compared to reference events?

## 2. Theoretical Framework

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### 2.1. Terminology of Risk assessment

Definition of “risk” may vary in different research due to the field of application of the term. The “common sense” understanding of the concept is the notion which states that the risk connected to a particular hazard lies in the consequences caused by that particular hazard, and increase with both its frequency and severity; it is also clear that these consequences depend on what is exposed to the hazard and how much it is vulnerable to its damage (Fedeski, et al., 2007). This research will investigate a specific form of risk: the hydrological risk. A preliminary definition of the term “risk” is then necessary to avoid misunderstanding caused by some lack of uniformity in its use. To define risk, we also need to precisely explain the terms “hazard”, “vulnerability” and “exposure”. Moreover, a correct definition of “flood”, “damage” and “disaster” will help to have a better frame of the topic.

For the first terms, we will use the same operative definitions elected by Civil Protection and reported in the Plan for Hydrological Management (PAI). These definitions may slightly or majorly differ from other authors, especially whom not strictly regarding environmental disasters; however, the given definitions are shared by the International Disaster Database (EM-DAT, 2009).

- **Hazard (H)** is the probability of occurrence of a potentially damaging event in a fixed time range (t) and in a fixed area. It is related to the “return time” T which express the time span in which the event happen at least one time:  $H = 1 - \left(1 - \frac{1}{T}\right)^t$
- **Exposure (E)** (also “value at risk”) indicates the elements exposed to a certain hazard in a fixed area, and can be expressed either by the number of elements or by the collective economic value present in the territory. Sometimes it is also expressed as the probability for a certain element to be exposed to a fixed hazard in a fixed area. For the purpose of this research, E indicates the mean economic value (€/m<sup>2</sup>) for each category of settlements, infrastructures and activities in a fixed area, multiplied by the total area covered by each specific category. The quantification excludes the value of risk for lives threatening, as it is not monetizable, but it can be discussed separately.

- **Vulnerability (V)** is the degree of loss that a fixed element (people, buildings, infrastructure, and activities) would suffer from a certain hazard. This concept is the opposite of resilience, as it represents the territorial tendency to suffer damage from an event. It is expressed with a value between 0 and 1, where 1 means total loss.
- **Risk (R)** is measured through the combination of these variables:  $R = H \times E \times V$  (figure 2.1). It corresponds to the potential total damage that a specific event can cause in a fixed area in a fixed time.



**Figure 2.1:** Graphic representation of risk and its components (adapted from Crichton, 2001).

“Flood” is a form of natural hazard defined by International Commission on Irrigation and Drainage (ICID, 2011) as “a temporary condition of surface water (river, lake, sea) in which the water level and/or discharge rate exceed a certain value, thereby escaping their normal confines”; the act of “flooding” carries also its own definition: “the overflowing or failing of the normal confines of a river, stream, lake, canal, sea or accumulation of water as a result of heavy precipitation where drains are lacking or their discharge capacity is exceeded” (ICID, 2011). Floods can be identified as: “storm surges” when occurring along the coastal line of seas or lakes; “flash floods” when they are rapid local events occurring in a small area due to intense local rainfall; and “river floods” when they result from meteorological events over a large area (river basin) during several days, combined with seasonal snow melting. They can cover

hundreds of km<sup>2</sup> of floodplains, though their development is relatively slow compared with flash floods. As they are the subject of this research, when using the general term “Flood” we will reference to river flood. Floods of different scales share some measurable parameters: depth, extent, discharge rates, duration, and flow velocity. More generally, they can be identified with a value of “intensity”. Flood intensity is often expressed in terms of frequency as the “return period”, showing the probability of such magnitude of event to happen. A “100-year flood event” is a flood that has the statistical chance to happen one time over one century, or 1% of chance to happen in one year of the century.

“Disaster” is defined by economic terms as an event where the damage occurring in a territory exceeds the capacity of the society living in that territory to recover by its own means. This means that a similar event can be defined a “disaster” or not, depending on when and where it happens. International Disaster Database (EM-DAT, 2009) gives this definition: “Situation or event, which overwhelms local capacity, necessitating a request to national or international level for external assistance”; also: “an unforeseen and often sudden event that causes great damage, destruction and human suffering” (EM-DAT, 2009). A disaster depends on the amount of damages to properties (including the natural environment as a common property) and harm to people. Although natural disasters are caused by natural events, the hazard itself would not consist without the intersection with socio-economical parameters.

Dealing with the concept of “flood risk” implies to have a measure composed of both natural (H) and socio-economic parameters (E, V). The Hazard value for flood events depends on the hydro-meteorological conditions which affect the flow regime of the river. It is characterized by physical measures such as discharge, depth, duration, velocity (all of these can be summarized as “severity”) and frequency (Gendreau, 1999). Exposure and Vulnerability are often summarized into one parameter (often called again “Vulnerability”, leading to some ambiguity and misunderstanding), because both are expressed in economic terms. Together they indicate the total amount of damage that a certain area can suffer from a certain hazard. It is clear that the same element at risk can have different values of E and V depending on the season, the day of the week, or even the hour in which the event happens (e.g., the risk associated to a flooded school drastically change from lesson time to night time). Above all these factors, an early emergency warning drastically changes the E value by removing from hazard-prone areas part of the “value” (people, furniture) or allowing privates and authorities to activate in time some

protective counter-measures. All these variables must be taken into account when discussing the results of a risk assessment.

It is important to note that none of these parameters (H, E, and V) ever reach the zero value, so that their product R cannot be null: the “zero risk level” does not exist. This concept is now generally accepted by administrations, so that they no longer try to reach a “no risk” solution, but rather try to find an optimum in terms of acceptable risk: which kind of flood is acceptable and which one is not. The hydrological risk value can be expressed as the potential cost of the damage in a flood prone area with a quantitative economic value (€) (Fedeski, et al., 2007). Results of risk assessment are often summarized in form of a geographic index, such as a risk map. Flood risk mapping is becoming an essential tool for flood management and risk communication, and its redaction is required by the EU Flood Directive; from 2007, member states are requested to create both flood hazard and flood risk map. This approach allows authorities to optimally invest resources and reach a cost-effective risk management (Merz, et al., 2010). The index is obtained through a relative evaluation of semi-quantitative data: the distribution of different values is statistically analyzed to create aggregated classes of values which indicate the qualitative range of risk (AdBPo, 2005).

## **2.2. Assessment of hazard cost**

The contribute coming from a reliable and comprehensive cost assessment costs of natural hazards is of primary importance in the development of policies and decision making, which create strategies and measures to cope with natural hazards. The estimation of flood damages is gaining more attention for flood risk management in Europe, whilst the previous approach focused for the most on the hazard assessment part. In fact, actual policies shift their attention from reducing the probability and the intensity of flood hazards to a more comprehensive understanding of the risk over a certain period and the potential damage connected to it. Still, the methods for flood damage estimation are crude compared to flood hazard tools, and the available damage data are scarce (Merz, et al., 2010).

The CONHAZ project (Cost Of Natural HAZards), funded by the EU 7<sup>th</sup> Framework Program, provides a useful overview about the state-of-the-art in the assessment of socio-economic impact caused by natural disasters. It does so through the review of various articles about the

topic from different authors, therefore it has been used to draw a consistent framework about the assessment of hazard costs.

Flood damages have to be considered for the most as “act of men”, because they largely depend on the development of society along the river spaces. In other words, while the Hazard itself may depend fully on natural events, the Exposure and Vulnerability variables are determined by the choices of men in the use of soil. Schwarze, et al. (2011) highlight how the main approach in cost assessment by practitioners is all about direct costs, while available methods for assessing indirect or intangible costs are rarely applied. Ideally, all dimensions of damage (economical, social, psychological, political and environmental) should be included in flood risk assessment, but in practice some of these dimensions are seen of minor importance or they are neglected because the available methods do not provide reliable results.

First we need to outline the terminology regarding the cost categories, since literature presents various different interpretations about the topic. The following terms have been defined by CONHAZ project (Schwarze, et al., 2011):

- ***Direct tangible costs:*** damages inflicted to properties by physical contact with the hazard, such as damage or destruction of buildings, furnitures, infrastructures, etc. “Tangible” means that only monetizable objects are considered (e.g. loss of human life is excluded from this category).
- ***Losses due to business interruption:*** they include the damages occurring in the area directly affected by the hazard and caused by direct damages, such as the disruption of productive processes due to cut of lifelines. These losses can be considered as part of the direct costs or as primary indirects costs, even though their evaluation method differs from those used for both direct and indirect damages.
- ***Indirect costs:*** in this category are considered only losses which are not directly caused by the hazard itself but are induced by it through direct damage or business interruption, though they are one or more causal step further from it, such as negative economic feedbacks.
- ***Intangible costs:*** direct or indirect damage or destruction of elements that are not directly monetizable, such as environment, health, human life or cultural heritage.

- ***Mitigation and emergency measures costs:*** investments on the adaptation, mitigation and emergency measures adopted to cope with present or future risk. If these measures are successful, they can be the only cost of flooding.

### **Assessment methods**

The assessment of flood hazard can be applied on different spatial scales. Micro-scale assessment is based on single, disaggregated objects, such buildings or infrastructures; due to the huge amount of data and effort required for each element, the resulting assessment is usually limited to small communities or towns. Meso-scale assessment employs spatial aggregations such as land-use units, typically ranging from 1 to 10 km<sup>2</sup>. Macro-scale assessment works on larger aggregated elements, such as administrative units like municipalities, regions, or even countries. The choice of the assessment scale depends primarily on the spatial extent of the damaging event, but the scale classification does not have fixed boundaries and it often depends on the analyst preferences. However, the appropriate approach would be to set the spatial boundaries of the assessment according to those of the management policies involved, while possibly indicating, at least qualitatively, any impact overreaching the chosen administrative scale (Merz, et al., 2010).

Direct costs and losses due to business interruption are often assessed with a simplified approach which focuses on few parameters. Generally, depth and extent are the most important parameters for assessing direct losses, while duration is especially used for indirect losses and warning time is used for intangible losses (Genovese, et al., 2007). This is the reason why simple models such as depth-damage functions are used in most cases to assess flood damages. The potential damage is estimated with these functions comparing the susceptibility of the class at risk and the depth of the flood.

Merz et al. (2010) suggests a standardized step-by-step approach for this methodology:

1. Classification of elements at risk by pooling them into homogeneous classes.
2. Exposure analysis and asset assessment by describing the number and type of elements at risk and estimating their average value.
3. Susceptibility analysis by relating the damage share of the elements at risk to the flood impact.

(Merz, et al., 2010)

The elements in the risk-prone area (exposed value) are pooled into different classes of land cover and attached with a specific monetary value, and each class is evaluated estimating its elements in the same way. For example, the damage to the class “household” is assessed using the same susceptibility function for all the households in the class; these functions are specific for each land-use type and for each EU member state (HKV Consultants, 2007). This simple approach has become the standard for assessing urban flood damage, though it excludes many other parameters like water speed, flood duration, and occurrence time. The exposure data is commonly obtained crossing an inundation scenario with land-use data by means of a Geo Information System (GIS). To achieve quantitative results, land-use data need to include asset values for each element at risk (Merz, et al., 2010), possibly updated and standardized for each country according to their actual Purchasing Power Parities (PPPs) (Genovese, et al., 2007).

However, this methodology still shows some flaws. Simple functions are used to describe complex damaging processes; their validation is rarely carried out; related uncertainty is almost unknown or not expressed. Still, this methodology can be useful to carry a fast estimate of direct damages. It can be also linked with production losses through fixed rates of estimated primary indirect damages, but this approach may not be correctly applicable to measure the impact on some sectors such as agriculture, which strongly depends on the time of the occurring event (Schwarze, et al., 2011). However, economic damages to the agricultural sector are usually lower than losses occurring in urban areas, and often their estimation is rough if not completely neglected.

Assessment of economic costs of a higher casual order, such as secondary indirect costs, is more problematic. They span on a temporal and spatial scale that is often bigger than the one of the direct impact and their feedback effects can affect the national economy. There are two main approaches to estimate indirect flood losses: econometric approach and model-based approach. The first consist of a series of statistically estimated equations which represent the aggregate functioning of an economy. Through the analysis of statistical economic data they investigate any possible correlation between economic trends and disaster events, to guess a scale for assessing potential economic impacts of future floods. The weak point of this approach lies in the lack of available data; in fact, it would need time series data on a span of 10 years or more to build up a robust and useful interval of confidence. This fact makes their employment impractical on the regional scale, since this amount of data is often not available.

The model-based approach employs Input-Output models, Computable General Equilibrium models or hybrid models which mix the two types. Models analyze how direct and indirect economic flood damages affect economic performance indicators, such as the GDP. These kinds of models are usually limited to the macroeconomic (national) scale. Their utility has been questioned since decision makers usually needs information about the impact at the micro (city) or meso (catchment) scale, while on the other hand the economic effects tends to be completely absorbed in the national scale of industrialized countries. Furthermore, these models require high expertise but they carry a great amount of uncertainty due to the complexity of the phenomenon and the feedbacks involved (Schwarze, et al., 2011; Merz, et al., 2010).

Non-market costs are hardly included in the assessment of natural hazards. Multi-Criteria Analysis and Cost-Effectiveness Analysis are both used to include them in non-monetary terms, though their evaluation can give just a qualitative result which are hardly comparable. Mitigation costs can be also categorized as direct, indirect and intangible. However, just the structural implementation costs are usually considered for flood assessment (Schwarze, et al., 2011).

### **Uncertainty**

The aim of damage modeling is to gain a simplified, organized description of an event and use it to assess other similar potential events. This means that the model will be used in a different spatial and/or temporal context. Transfer in time would not be problematic in a stationary system, but even the vulnerability of risk-prone elements changes in time. Furthermore, the modern society changes at a fast pace, building new infrastructures and creating new vulnerabilities at high rate. Old households or enterprises are substituted by more valuable investments; communication and transportation structures lead to additional interlinkage, which leads to additional second-order effects. For these reasons, the transferability of the damage models to different spatial and temporal contexts carries a good degree of uncertainty which depends on the degree of similarity between the two situations: it increases with longer time and space distances, and it is hardly quantifiable. Therefore, model validation is rarely performed and the quality of the final estimate of damage is not evaluated.

Few attempts have been made to assess the relative weight of uncertainty in each phase of the risk analysis. Merz and Thielen (2009) concluded that the damage model contribution to the global uncertainty is low compared to the rates of uncertainty from flood frequency analysis and

inundation estimation. In conclusion, the dominant approach prefers to rely on simpler and faster methodologies, even if their limitations and the lack of precision and accuracy are well known. Most of the parameters influencing the damage rate are excluded in these models because of their heterogeneity in time and space, the difficulty to measure and assess them, and the lack of data about their quantitative contribution (Merz, et al., 2010).

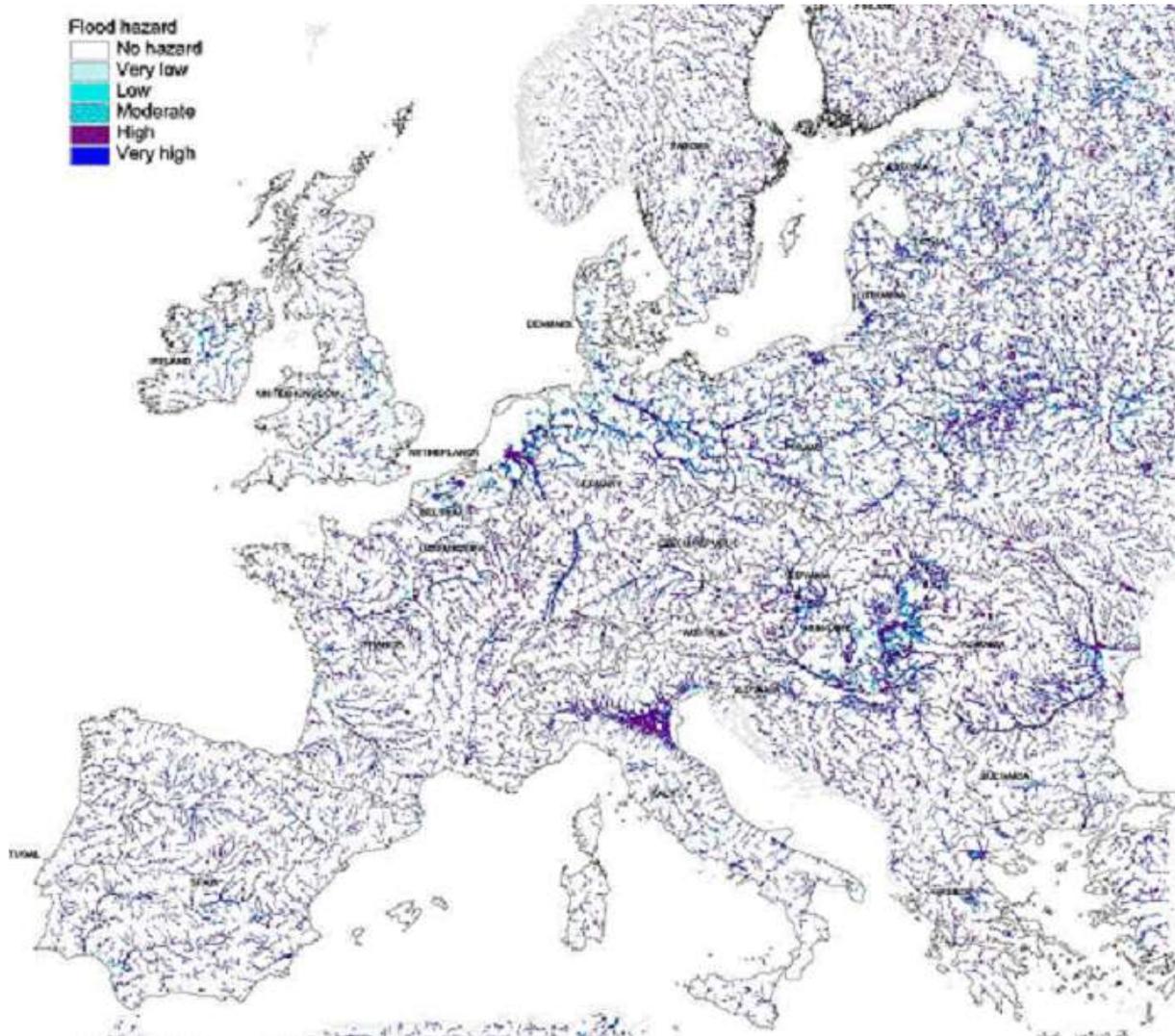
### 2.3. Flood risk in Europe

The Flood Risk in Europe is constantly monitored. The “Floods portal” was created by the Joint Research Centre (JRC) of the European Commission with the purpose to provide a European-scale overview of the present and future risk associated with flood events. The risk is quantified in terms of direct economic damage, while intangible values such as harm to people and loss of lives are not considered. This methodological choice is shared by the majority of European flood-risk studies. The reason for this is dual: first, the models for assessing the life risk in case of flooding are still rough and immature, due to the objective difficulty to account for all the variables involved in human fatalities; secondly, life threatening rates due to floods have become very low in the last decades in Europe, in comparison with global shares (fig. 2.2).



**Figure 2.2:** Human fatalities caused by major disaster events in the year 2000 (EM-DAT, 2009).

The JRC developed a continental map of flood-prone regions throughout the implementation of GIS-based tools, weather and discharge datasets and forecasting for future scenarios. The purpose is to quantify the potential losses to support the decisions by European Commission in its initiatives, like the European Flood Action Program or the Directive on the Assessment and Management of Flood Risks, through the analysis of extreme events triggered by the current climate and also the events expected from future climate change (EC Institute for Environment and Sustainability, 2010).

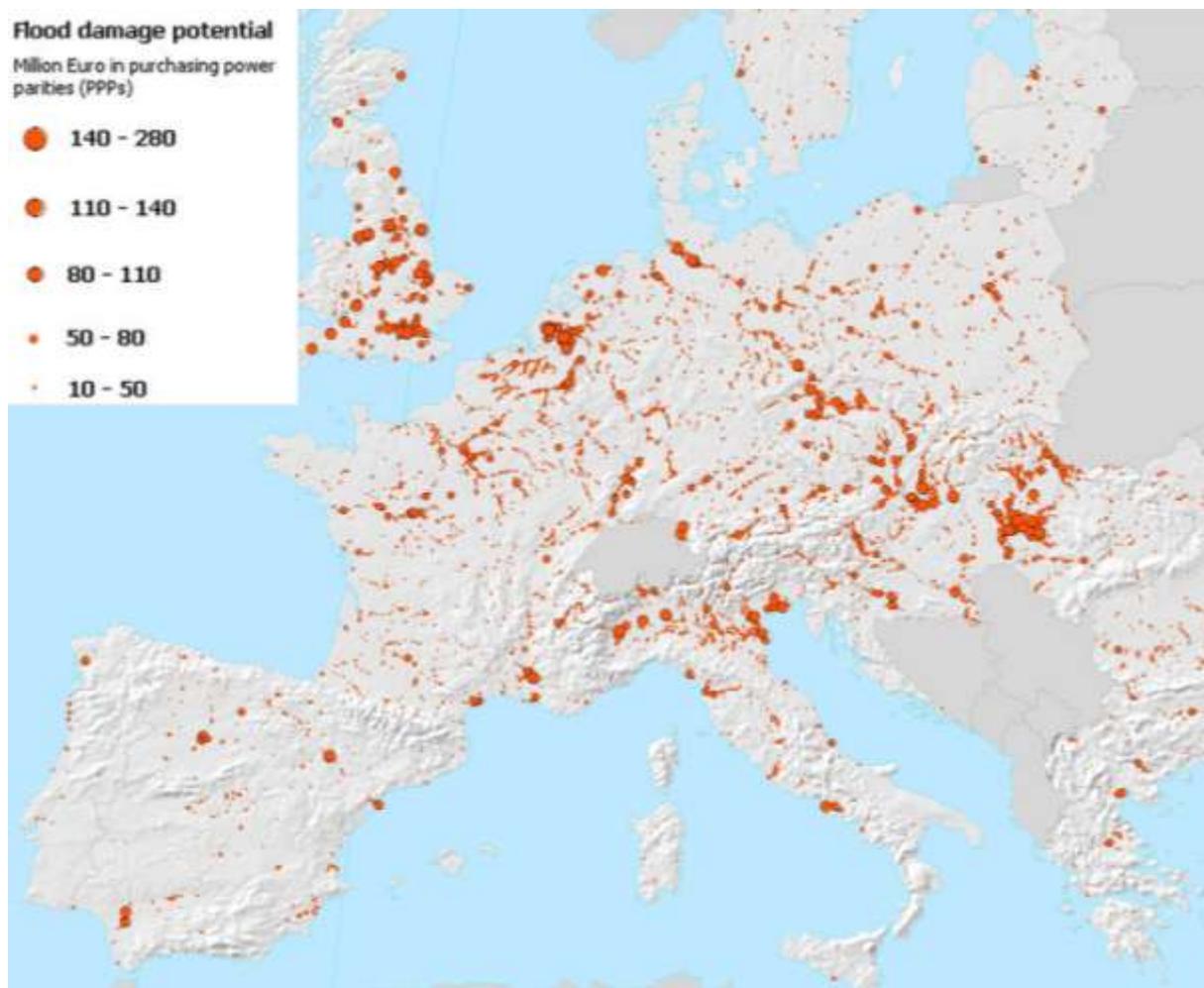


**Figure 2.3:** Flood hazard map of Europe by JRC: estimated extreme discharges to assess the potential flood risk (Genovese, et al., 2007).

To define flood risk areas, flood risk factors such as exposure and hazard are processed in form of geo-referenced datasets connected to land-use. Through the use of hydrological models and estimation of extreme precipitation events, the hazard factor is assessed for different time spans at the local scale (fig. 2.3). It must be highlighted that this hazard map was produced without considering any flood defense (Genovese, et al., 2007). Then, the obtained hazard value is compared with the anthropogenic factors which contribute to increase the risk connected with floods, such as exposure and vulnerability, though the application of depth-damage functions related to CORINE land cover classes (EC Institute for Environment and Sustainability, 2010). The results defined the map of maximum potential damage which is shown in figure 2.4, even though the scenario does not comprehend the contribution of protection measures. The map

explains in comparable terms (million € in Purchasing Power Parities) the amount of direct damage brought by extreme flood events among European countries.

Areas with higher potential damages include the final section of the Po river basin, mid-west of the Netherlands and the London area. These areas present a stronger risk associated with floods due to an higher value of exposure, caused by high population densities. On the other side, they involve a strong attention to flood protection measures (strategic plans, defensive structures, flood prevention, forecasting and mitigation system) which are totally neglected in the elaboration of results. This fact brings a massive inaccuracy to the study, probably exaggerating the impact of flooding in these areas.



**Figure 2.4:** Flood damage potential in million € in purchasing power parities for 100-years return period floods (EC Institute for Environment and Sustainability, 2010).

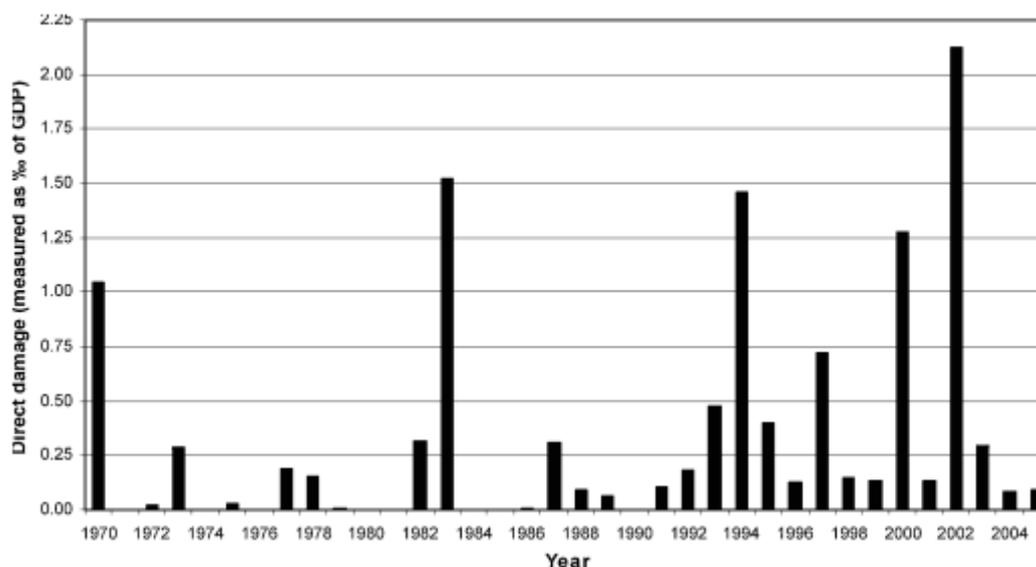
These conclusions are drawn also on the basis of previous studies on flood trends and correlated damages: Barredo (2006) produced a comprehensive analysis of major flood events in Europe

during the period 1950-2005, giving an estimate of the damage brought by these events. This research points out that the frequency of extreme events shows an increasing trend in the last part of the time series, as summarized in the table.

<i>Decade</i>	<i>Floods (overall)</i>	<i>Major floods</i>
1950-1959	11	5
1960-1969	7	5
1970-1979	21	6
1980-1989	33	7
1990-1999	64	15
2000-2005	104	9

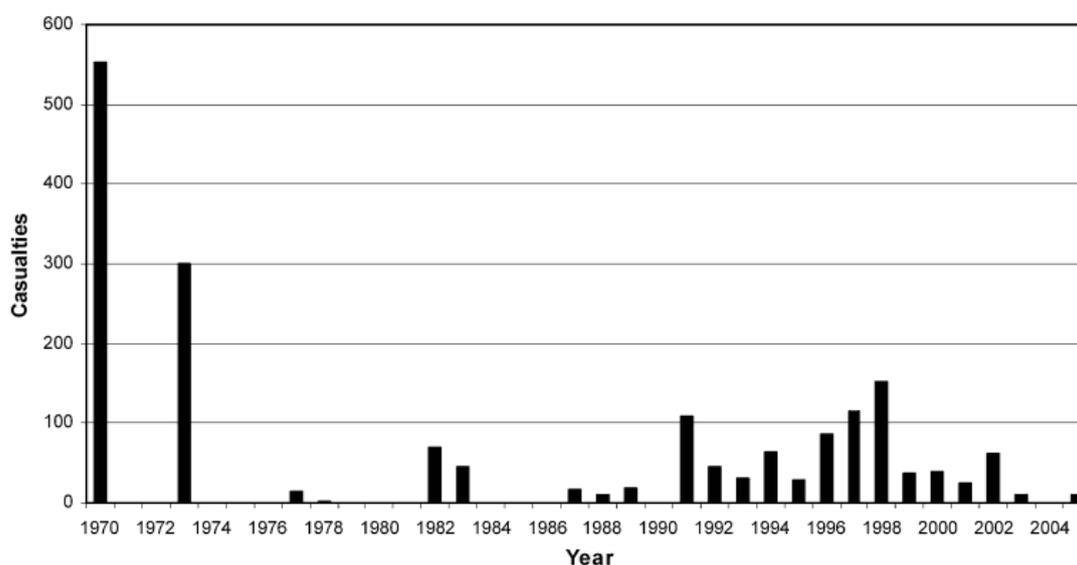
**Table 2.1:** Number of flood events and major floods in the EU for the period 1950-2005. “Major floods” are defined by the number of casualties (>70) or the amount of direct damage (>0.005% of the EU GDP). Adapted from (Barredo, 2006)

Figure 2.5 shows the direct damage produced by the 222 flood events registered in the time span. Both the frequency and the economic impact of floods show an increasing trend. In particular, 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 (2001): economic losses (normalized with inflation rates) in the past ten years are ten times higher than 1960-1970 period. Barredo do not draw any strict conclusion about the cause of this increment, stating it could be a consequence of a climatic trend or it can be caused by other factors, such as changes in socio-economic exposure (e.g. urban expansion along riversides).



**Figure 2.5:** Flood direct damage per year in Europe, measured on a comparison with EU GDP (Barredo, 2006).

On the other hand, the number of casualties produced by major events could be interpreted with a decreasing trend for Europe, although it is hard to prove it since casualties are very dependent of the single event (Fig. 2.6).



**Figure 2.6:** Casualties caused by floods per year in Europe (Barredo, 2006).

In a more recent research (Barredo, 2009) the same author concludes that there is no evidence to link flood losses with climatic change: drawing an hypothetical scenario without any change in the meteorological forcing, losses would increase indifferently due to socio-economic changes such as higher population, improved pro-capita wealth and living standards; all factors which

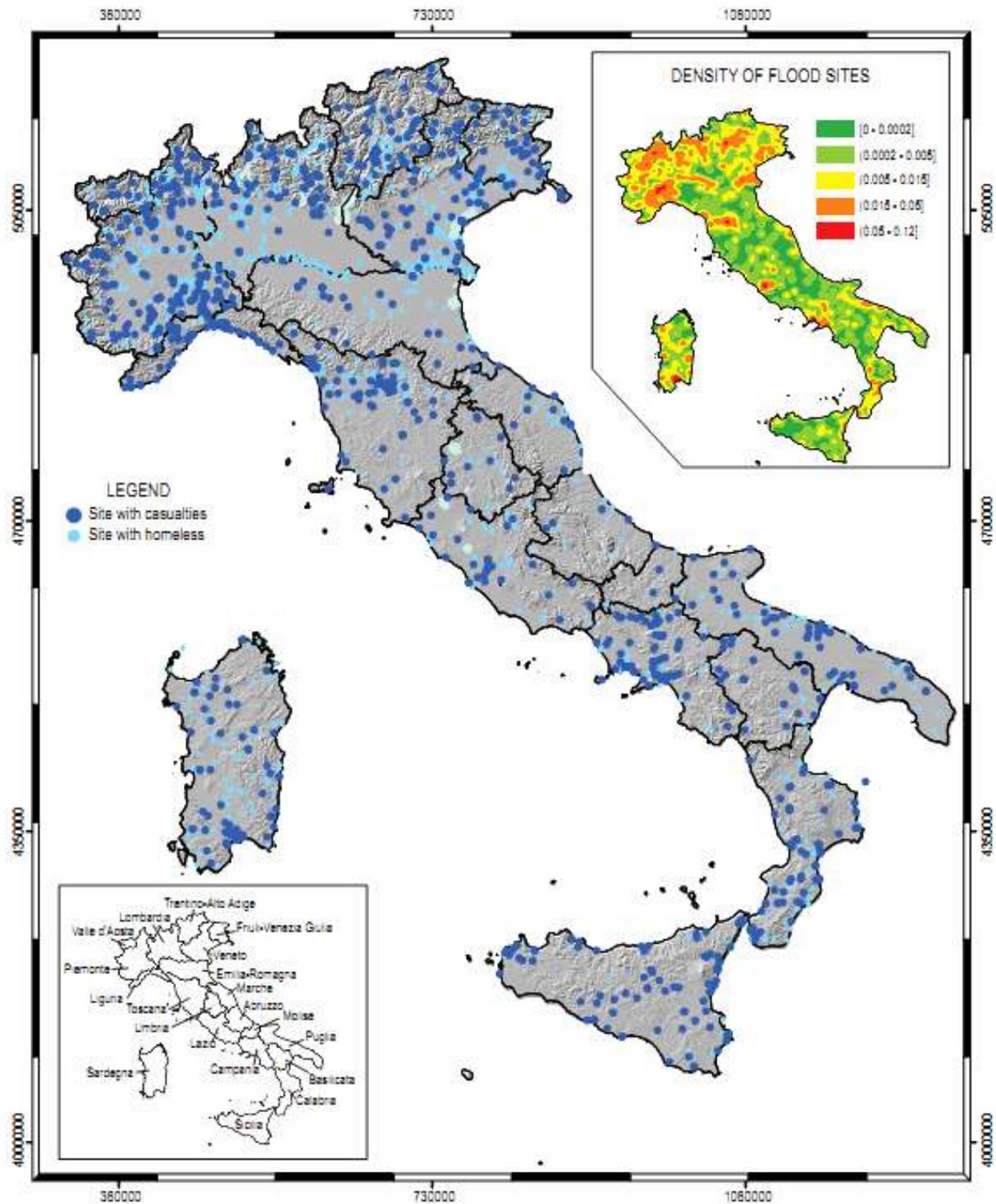
increase the exposure criteria. Effects of human modification in the morphology of the river basins are not taken in account. As a final note, the research does not exclude that future effects of climate change will affect the losses trend in a positive way.

## **2.4. Risk profile in Italy**

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, 2010).

Compared to droughts, the impacts of floods are more localized and easier to trace. Directly affected are public infrastructure (dikes, bridges, motorways, railway etc.), settlements, industrial plants, properties, and agricultural land. Industrial accidents triggered by floods may further amplify the risk and vulnerabilities of down-stream communities. The failure of lifelines leads to business interruption with wider knock-on effects on economy and social fabric of the basin area.

A recent study (Legambiente & Dipartimento della Protezione Civile, 2010) conducted on a subset (~30%) of the risk-prone municipalities provides a worrisome results. Some 82% communities reported the presence of dwellings, or even whole residential quarters, in the floodplains or areas exposed to landslides. Even worse, industrial facilities situated in risk-prone areas were reported in about a half of the cases. Last but not least, in some 19% of analyzed communities public structures such as hospitals and schools were built in the risk prone areas. The study estimates that some 3.5 million people (6% of the Italian population) are present in the risk areas every day.



**Figure 2.7:** The map shows the distribution of the 1836 sites affected by flood events having direct consequences on the population. The time span is 1959-2008. The map in the upper right corner summarizes the concentration of flood sites through 5 classes of density (adapted from Salvati et al., 2010).

For the 20th century and thereafter (1900-2008), period for which available information are more reliable, Salvati et al. (2010) list some 2,321 flood events, while referring to the last 59 years, the value is 1,654 (Table 2.2).

<i>Floods (1950 - 2008)</i>	
Length of period (years)	59
Deaths (a)	1,124
Missing persons (b)	90
Injured people (c)	1485
Fatalities (a+b)	1214
Casualties (a+b+c)	2699
Evacuees and homeless people	497,334
Largest number of fatalities in an event	84
Largest number of casualties in an event	341
Total number of events	1,654
Average number of fatalities per event	2.3
Average number of casualties per event	4.4

**Table 2.2:** Statistic of flood events in Italy for the period 1950-2008 (adapted from Salvati et al., 2010).

During the period 1996–2010, the emergency situation due to the hydrogeological disasters was declared 245 times; in 100 cases it was called in order to tackle the damage caused by intense precipitation followed by floods and landslides; in 49 cases for hydrogeological disasters; in 7 cases to stabilize large dams; and in 7 cases to tackle damage caused by extreme events.

In 2009, it was estimated that some € 84 billion were needed to make the territory safer. From this background, the resolution CIPE 83/2009 of 6 November 2009 assigned € 1 billion for the realization of the regional plans to reduce hydrogeological risks, an amount of money increased by additional € 1.2 billion from state or regional budgets.

## 2.5. Normative background

Italian hydrological risk legislation does not consist of a unitary and organic normative body, but it is spread among different laws concerning the various aspects connected with flooding hazard. Many of these sectorial laws had been often produced just after the occurrence of an emergency. The first was Law 183/89 about soil protection; then in the 1998 was Law 267, the so called Law Sarno, mandated after a disaster; and Law 365/2000, which followed the flood of Soverato.

Law 183/89 (then L.D.152/06 - art. 67 about PAI) established that the Basin Authorities have to adopt the Hydrological Management Plan (PAI) to identify hydrological risk areas; the plan developing process was sped up after the two big and very damaging disasters of Sarno (1998) and Soverato (2000). In Po River Basin PAI was approved by DPCM 24/5/2001; after that, the Delta of Po Watershed Management Plan (2008) and River Zones Watershed Management Plan have been both transposed into PAI.

The only existing link among these laws is traceable in Legislative Decree 152/06, the so-called “Environmental Code”, which transposes the first directive into Italian legislation and disciplines different aspects concerning hydrological risk in a dedicated part titled “Rules on soil protection and against drought, water pollution safeguard and water management”. The Decree established eight river basin districts (RBD), each governed by a river basin district authority (RBDA). In principle, the RBDA replaced the basin authorities mandated by the law 183/89, although as a result of the amendments 248/2007 and 13/2009, the former authorities continue to exist until the RBDA are fully operational (Balzarolo, et al., 2011).

The RBDAs are public bodies whose main task is to develop the River Basin Management Plan (RBMP) including the program of measures, a roadmap to the achievement of the environmental objectives in the river basin. Parts of the RBMP are the Water Management Plan and the Water Protection Plan introduced by the decree 152/06. Water District Management Plan was adopted on 24 of February 2010 (Balzarolo, et al., 2011).

Both the EU Water Framework Directive (WFD, 2000/60) and the Flood Risk Management Directive (FRMD, 2007/60/EC) have been transposed into national legislative systems and are being gradually implemented. The EU Flood Risk Management Directive (FRMD, 2007/60/EC) aims at the improvement of the knowledge about hydro-morphological processes connected with floods and the management of the associated risk; the objective is to reduce the damage caused by floods to human health, environment, cultural heritage and economic activities (AdBPo, 2009). It has been transposed into Italian legislation by the Legislative Decree 49/2010 which assigns to River Basin Authorities the task to comply with the three operative phases included in the Directive. The first phase prescribes to conduct a preliminary assessment of flood risk by 22 September 2011. As second phase, potential flood-prone areas are detected; before 2013 a map of potential flood hazard and risks has to be created, based on data, analysis and studies on the territory. Next deadline set in the FRMD for 2015 includes the

development of flood risk management plans to reduce the hazard probability and to mitigate the potential damage through the measures of prevention, protection and preparation (Balzarolo, et al., 2011; AdBPo, 2009).

## **2.6. Risk Governance in Italy**

The multi-level water-related risk governance in Italy includes Civil Protection, Authorities of Territorial Governance, River Basin District Authorities, the Land Reclamation and Irrigation Boards, and the Optimal Territorial Area Authorities (AATO). Civil Protection (CP) is assigned to a single organization, which in Italy is organized as a “National Service” that includes all means and actions taken to protect human lives, goods, settlements and the environment from damages or from the danger of damages deriving from natural calamities, catastrophes and other disastrous events (DPC, 2011). Established by the Law 225/92 and coordinated by the President of the Council of Ministers, the Service engages State administrations, Regions, Provinces, Municipalities, national and territorial public agencies, and other public and private institutions, including civil society organizations.

The main administrations involved in the governance of Po River basin are: Po River basin Authority (AdBPo), Interregional agency for the Po River (AIPO), Civil Protection Department (DPC), and the Regional Environmental Agencies of Valle d’Aosta (ARPA VdA), Piedmont (ARPA Piemonte), Lombardy (ARPA Lombardia), Emilia Romagna (ARPA ER) and Veneto (ARPAV). Moreover, a network of Functional Centers has been set up by Ministry Council Directive 27/02/2004 in order to provide the Civil Protection of a national warning system distributed over the whole territory. Its purpose is to monitor and measure the ongoing processes, forecast the potential events and their potential impacts on the territory.

After ten years from the application of PAI, the majority of interventions to protect and strengthen the embankments have been completed. Even though the Po River is embanked for 860 km in its main branch and for 1,420 km in its tributary branches, while constantly maintained and monitored, an absolute level of safety cannot be reached. As the theoretical formulation of risk suggests, the risk value is never null. This fact enlightens the importance of a better knowledge about the risk. The development of a reliable system for control, model and forecast the processes in the river basin plays a strategic role in providing this knowledge. For this reason, all the administrations involved in the basin governance signed an agreement to

develop this system, aimed at supporting the decisions of authorities which have the management responsibility during emergencies.

## **2.7. Flood Early Warning System**

The decision support system which provides information to the DPC Functional Centers is made up to supply a suitable forecasting system during real time applications. The flood early warning system is based on the forecasting signal provided by a chain of models joint together. The elements of the model chain match the following operational steps:

1. Measurement of meteorological and hydrological values through the monitoring network;
2. Developing of meteorological modeling (probabilistic + deterministic);
3. Developing of river modeling through triple-chain linked hydrological and hydrodynamic models (deterministic);
4. Evaluation of potential emergencies.

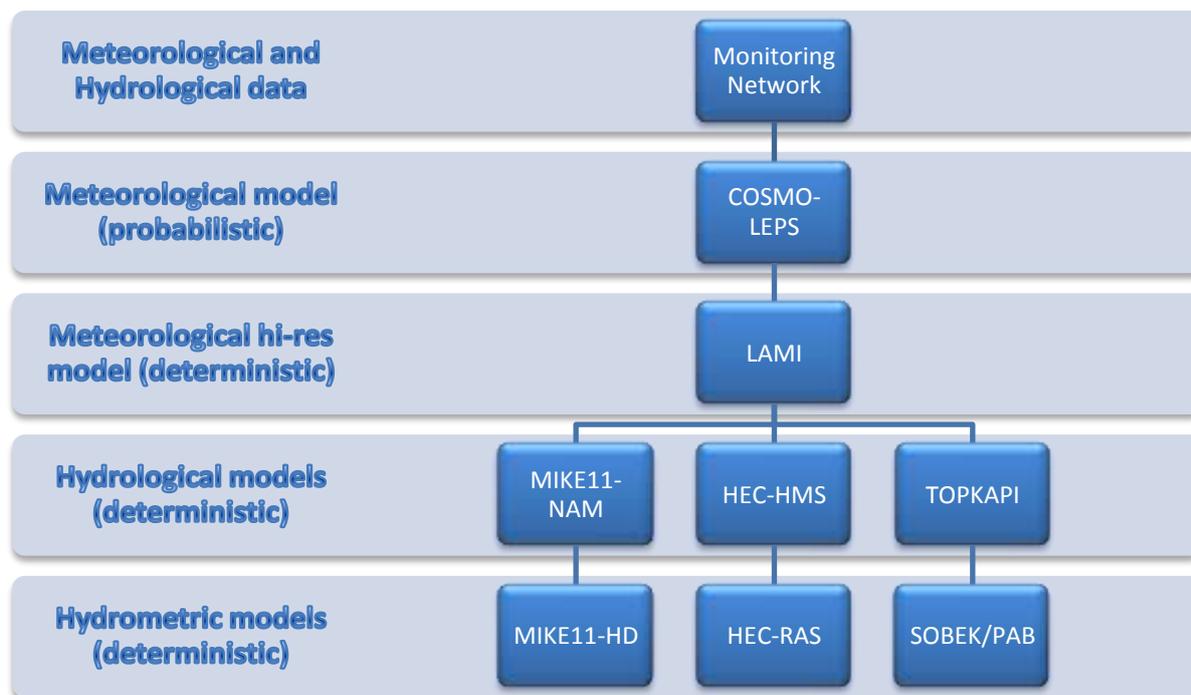
The Po River basin is monitored by a network of telemeters, thermometers, hydrometers and radars which provide the meteorological and hydrological deterministic input.

The COSMO-LEPS system (Limited-area Ensemble Prediction System developed by the Consortium for Small-scale Modelling) is based on the ECMWF (European Center for Medium-range Weather Forecast) EPS ensemble and it is maintained by ARPA-SIM. Through probabilistic approach it supplies both initial and boundary meteorological conditions for the subsequent high-resolution deterministic model LAMI (Italian Limited Area Model, developed by ARPA-SIM on the basis of LM model by Deutscher Wetterdienstse). LAMI runs twice a day for 72 hours with a spatial horizontal resolution of 7 km and 40 layers in the vertical, providing 132 hours of forecasting. These data determine the meteorological estimate and its uncertainty, which is the input for the next step of the process (Pecora, et al., 2006; Tibaldi, et al., 2007).

The river modeling consists of both hydrological and hydrodynamic models incorporated into a shell system, a modellistic environment by Delft-FEWS. They are organized in three parallel chains, each one composed of one hydrological model which provides the output for the linked hydrodynamic model. The parallel calculation of the same variable with different approaches is

necessary to reduce the experimental uncertainty which is inherent to this kind of tools (Tibaldi, et al., 2007).

The hydrological models include MIKE11-NAM, HEC-HMS and TOPKAPI, while the hydrodynamic ones are MIKE11 HD, HEC-RAS and SOBEK (Pecora, et al., 2006). The coupling of the model chain is displayed as a scheme in figure 2.8.



**Figure 2.8:** Schematic overview of the model chain used in the Flood Early Warning System.

MIKE11 NAM is a one-dimensional rainfall-runoff deterministic model developed by Danish Hydraulic Institute (DHI). It accounts for water storage in the catchment such as snow, surface water, root zone water and groundwater.

HEC-HMS is designed by US army engineers to simulate the precipitation-runoff processes of complex watershed systems. It consists of a deterministic model which includes parameters such as evapotranspiration, snow, the losses in precipitated water before runoff occur, the routing of the runoff, and finally the base flow.

TOPKAPI is a distributed, physically based model composed of three modules representing the soil components, the superficial runoff and the routing network. It represents flood curves starting from meteorological inputs and from morphological and physical characteristics of the hydrographical basin.

MIKE11-HD is another DHI model simulating flows and sediment transport in water bodies.

HEC-RAS is a one-dimensional flow simulation, again by US army engineers.

SOBEK (or PAB where SOBEK cannot be used) is a mono- and bi-dimensional modeling suite for the integral simulation of flood processes, developed by Delft Hydraulics (Pecora, et al., 2006).

The output generated by each of these modules can be mutually exchanged through a “general adapter software” which can convert the model formats. This can allow different run combinations to reduce uncertainty. When the final output is obtained from the models, its quality is evaluated through a three-step approach: validation, interpolation and transformation (Tibaldi, et al., 2007).

The whole system can run fully automatic or driven by the user. If automated, it can generate flood warning reports when a predefined limit threshold is exceeded and send them to the Civil Protection Functional Centers, together with an estimate of the uncertainty related to each module forecasting.

When driven by user, it can be configured to run the usual forecasting or it can be set to run a scenario. In that case, the initial pool of meteorological and hydrological data does not come from the monitoring network, but they are inserted by the user on the basis of the characteristic of the scenario. For example, some parameters (e.g. rainfall) from a registered event can be increased by a fixed percentage to simulate the consequence on the river discharge and potential floods.

## 3. Case Study

### 3.1. The Po River basin: general description

The river Po is the longest and most important river in Italy, with a length of 652 km from its source in Cottian Alps (at Pian del Re) to its delta discharging in the Adriatic Sea, north of Ravenna. It is also the largest Italian river, with an average discharge of 1,540 m<sup>3</sup>/s (before its delta), a minimum of 270 m<sup>3</sup>/s, and a maximum of 13,000 m<sup>3</sup>/s). It is fed by a main reticulum of 141 major water tributaries (>20 km of length), which measure 6,750 km in total (a partial list of them can be found in Table 3.1); it is also fed by the confluence of a ten time larger secondary reticulum of natural and artificial water bodies, irrigation and reclamation channels, for a total of ~50,000 km. In the Alpine area, 174 water reservoirs manage 2,803 billion m<sup>3</sup> a year, of which 143 artificial reservoirs for the hydropower production, controlling 1,513 billion m<sup>3</sup>, whilst natural lakes control another 1,290 billion m<sup>3</sup>. Furthermore the basin comprises circa 600 km<sup>2</sup> of glacier areas. The natural and artificial lakes in the basin regulate a volume of 1,858 million m<sup>3</sup> per year. The basin is structured in 28 principal sub-basins (Fig. 3.1), characterized by high variable discharge (AdBPo, 2006).

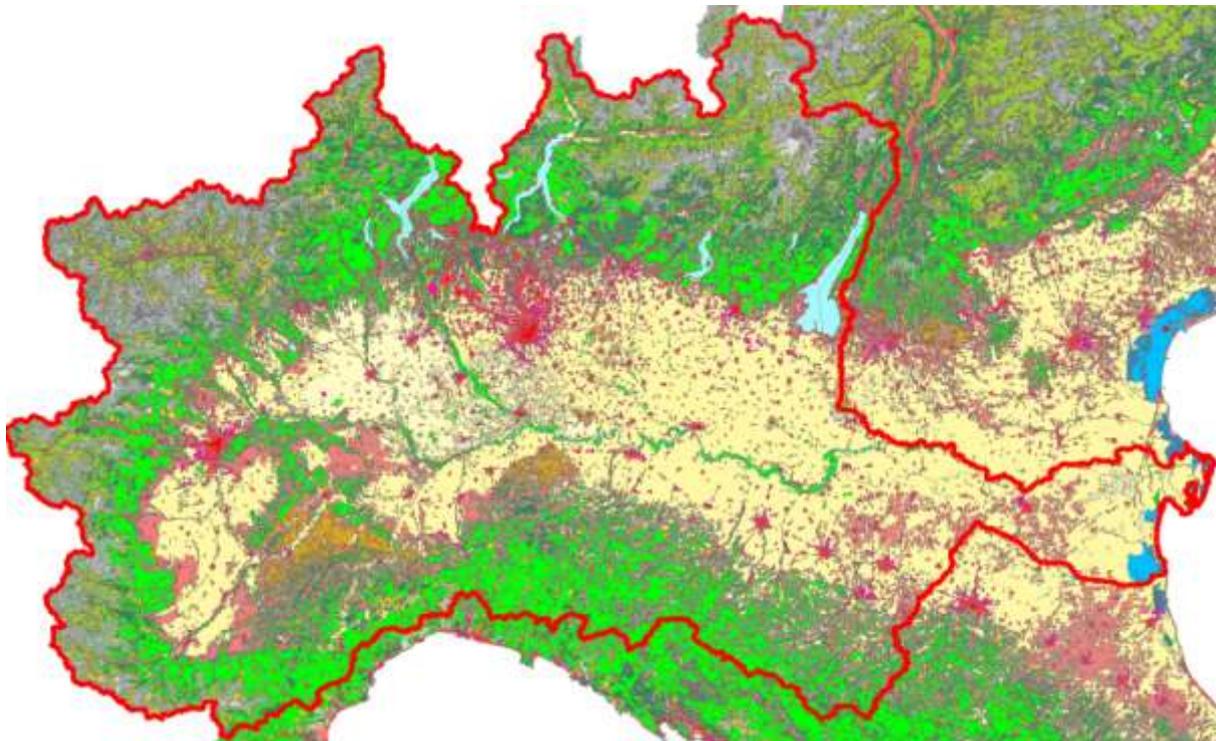
	<i>Main hydrographic network</i>	<i>Flow from</i>	<i>Length (km)</i>	<i>Area (km<sup>2</sup>)</i>	<i>% area of the main basin</i>	<i>Mean discharge (m<sup>3</sup>/s)</i>
1	Ticino	Lago Maggiore	112	153	12,2	350
2	Adda	Lago di Olginate	97	127	11,5	187
	sottolacuale					
3	Oglio	Lago d'Iseo	156	69	3,4	137
4	Tanaro	Ceva	190	146	4	132
5	Dora Baltea	Grand Eyvia	130	110	2,8	110
6	Sesia	Romagnano	77	78	3,8	70
		Sesia				
7	Mincio	Lago di Garda	73	49	5,9	60
8	Secchia	Castellarano	107	40	1,9	42
9	Lambro	Lago di Pusiano	119	35	2,6	40
10	Trebbia	Rivergaro	27	19	1,8	40
11	Panaro	Marano sul	92	24	1,4	37
		Panaro				
12	Stura di Lanzo	Lanzo Torinese	34	18	2,1	32
13	Taro	Fornovo di Taro	56	38	3,1	30
14	Scrivia	Serravalle	51	37	3,6	23

**Table 3.1:** List of the main tributaries in order of discharge magnitude (source: AdBPo, 2006).



### 3.2. Land-use: currents status and expected scenarios

More than a half of the basin area (~56%) is agricultural land. Agriculture in the so called “food valley” produce about 35% of the national agricultural output. Natural and artificial lakes in the basin regulate a volume of 1,858 million m<sup>3</sup> per year. There are 210 nature protected areas which represent 7% of the territory. Some 24% of the basin area is occupied by forests (AdBPo, 2006). The Corine Land Cover project (European Environment Agency, 2010) has revealed substantial changes over the period 2000-2006. At the country level, the artificial surfaces increased by 466 km<sup>2</sup> to a large extent on former agricultural areas (-450km<sup>2</sup>) and on forest and semi natural areas (-50 km<sup>2</sup>). On regional basis, the largest loss of forest and semi natural areas was recorded in Lombardy (-26km<sup>2</sup>), followed by Emilia Romagna (-18 km<sup>2</sup>). The largest increase of the artificial surfaces was observed in Veneto (78.72 km<sup>2</sup>), Lombardy (62.52 km<sup>2</sup>) and Emilia-Romagna (53.37 km<sup>2</sup>). In all regions, the new developed area was previously agricultural land, the latter declining by 78km<sup>2</sup> in Veneto, 29 km<sup>2</sup> in Emilia Romagna, and 36 km<sup>2</sup> in Lombardy. Through the employment of Corine Land Cover 2006 dataset it is possible to draw a map of the land-use, as in fig. 3.2.



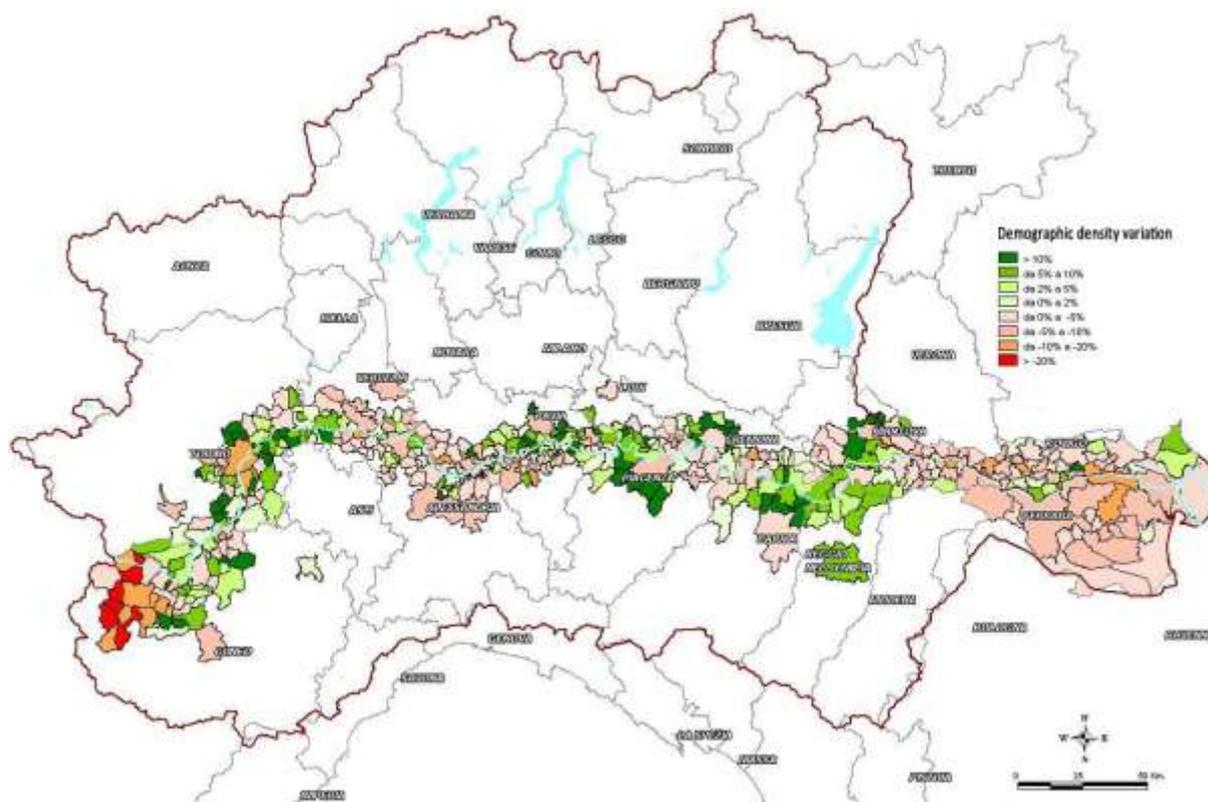
**Figure 3.2:** Land use map for the Po River basin obtained from Corine Land Cover 2006 dataset.

The changes in the land-use coverage depend on various variables, like demography, labor management, urbanization, use of resources, etc. Even though the urbanized areas represent just

5% of the total surface of the basin, their grow rate is rising faster than population growth or production rates, at the expenses of natural and rural areas. This growth happens with a sprawling dynamic of the residential and productive buildings, causing environmental consequences such as soil sealing, dismantling of some agro-touristic activities and devastation of the cultural landscape. The predominant productive point of view tends to consider the basin as a huge logistic platform for productive processes and connection with continental Europe. Environmental processes have a secondary importance in such a view. Still, the rural areas (woodland excluded) cover some 52% of the basin territory (AdBPo, 2008).

### **Demographic trends**

The trend registered from 1951 to 2001 shows a positive peak during the '70s (+12%) followed by a stabilization of the growth during 1991-2001. The 2001 census highlights a slight decrease (-0.2%). The two metropolitan provinces of Milan and Turin both show a sharp negative trend during 1991-2001 (-5% and -3.4% respectively). 64% of the total population of the basin lives in the lowland portion of the basin, in which the metropolitan cores are expanding their suburban districts defining two main areas: the northerner foothill Lombardy zone (48% of the basin population) and the southerner Emilia-Romagna zone (11% of the basin population). The lowland portion shows a decrease of -1.5% (mean annual value), while both the hill areas and the mountain areas slightly increased their population from 1991 (+0.8%) (AdBPo, 2008).



**Figure 3.3:** Variation in the demographic density along the Po river (1991-2001) (AdBPo, 2008).

The average demographic density in the basin ranges from 100 to 500 inhabitants for km<sup>2</sup>, with some lower peaks in the final part of the basin and in the delta area, as shown in figure 3.3. All the municipalities in the Ferrara and Rovigo province have a negative trend, with few sporadic exceptions (AdBPo, 2008).

### Economic trends

Through the ISTAT industry and service census for the period 1991-2001 (reported by AdBPo, 2008) it is possible to compare the employment rates in the primary, secondary, tertiary and touristic sectors. On the whole basin, the economic structure is stable with a positive trend, as shown in table 3.2. The secondary sector shows a slight decrease but it is compensated by an increase in the primary and tertiary sector. Also the touristic sector is slightly growing.

<i>Productive sector</i>	<i>1991</i>	<i>2001</i>
Primary	12,257	13,565
Secondary	654,794	602,624
Tertiary	920,765	1,094,855
Touristic	45,285	57,829
TOTAL	1,633,101	1,768,873

**Table 3.2:** Numbers of employed by sector for the two available years.

While in the western part of the basin the secondary and tertiary sectors have a strong role polarized in the major town (Torino, Alessandria, Pavia), the central part shows a positive trend for the primary sector, and again for the secondary and tertiary sectors in the main cities. The eastern part of the basin, from Ferrara province, has a negative trend for the primary sector but also a positive trend in the secondary. The touristic sector increases slightly from 1991 to 2001.

### **Future scenarios**

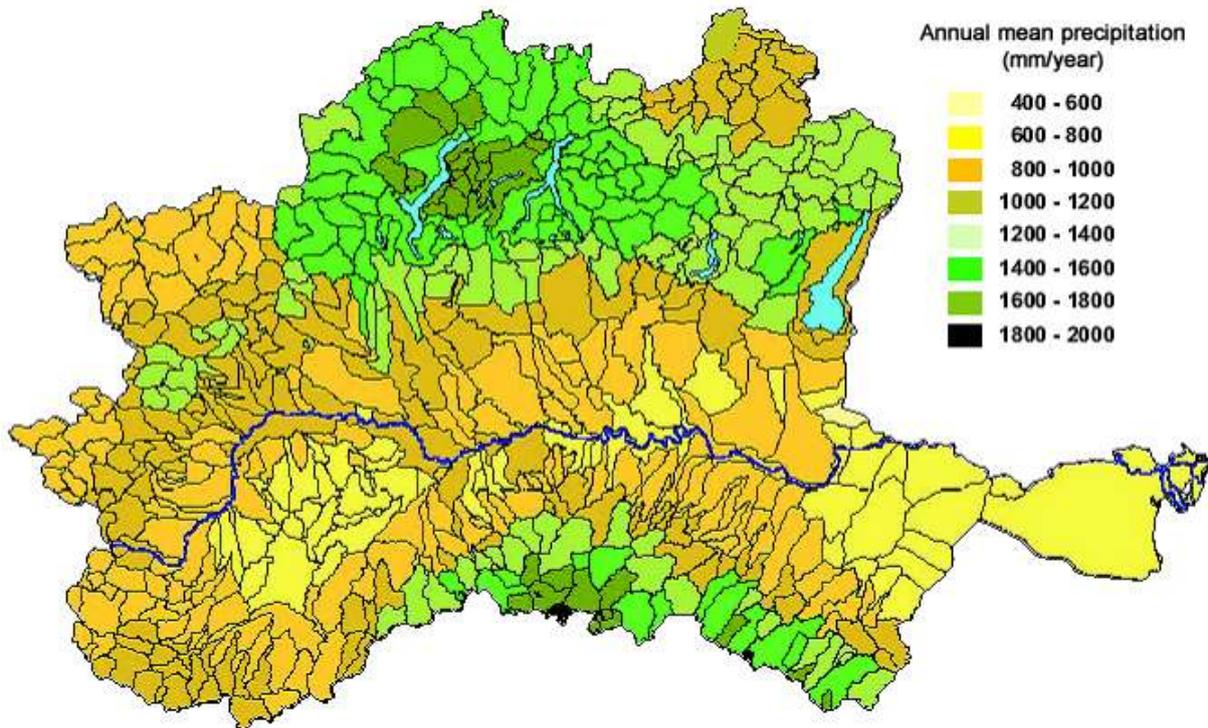
Two main future scenarios for the basin economy can be defined, as in Passino, et al. (2007).

If the European policies focus more on the competitiveness in the global market, the actual tendencies will be enforced and the concentration of activities will increase around the metropolitan core areas. So we should expect both a demographic and economic increase in the major cities, together with an extended suburban sprawl and a diffuse land cover by logistic activities and infrastructures supporting the production.

On the other hand, if European policies focus on a model oriented on the economic, social and territorial cohesion, the urban settlement scenario will be more polycentric compared to the actual trend. In this case, the basin will suffer less pressure, still maintaining his role in the national economy. However, this scenario is considered to be less probable (Passino, et al., 2007).

### **3.3. Climatic profile and Hydrogeological processes in the river basin**

The average annual precipitation over the basin is 1,200 mm. Figure 3.4 illustrates that the highest precipitation rates are found in nearly all Lombardy, some areas in Piedmont, and on the Ligure-Tosco-Emiliano Apennines. The low precipitations characterize the valleys Val di Susa, Valle d'Aosta, Valtellina and the downstream Po valley. The highest precipitation rates are concentrated around the great lakes situated at the base of the mountains some 2000-2500 m a.s.l (AdBPo, 2006).



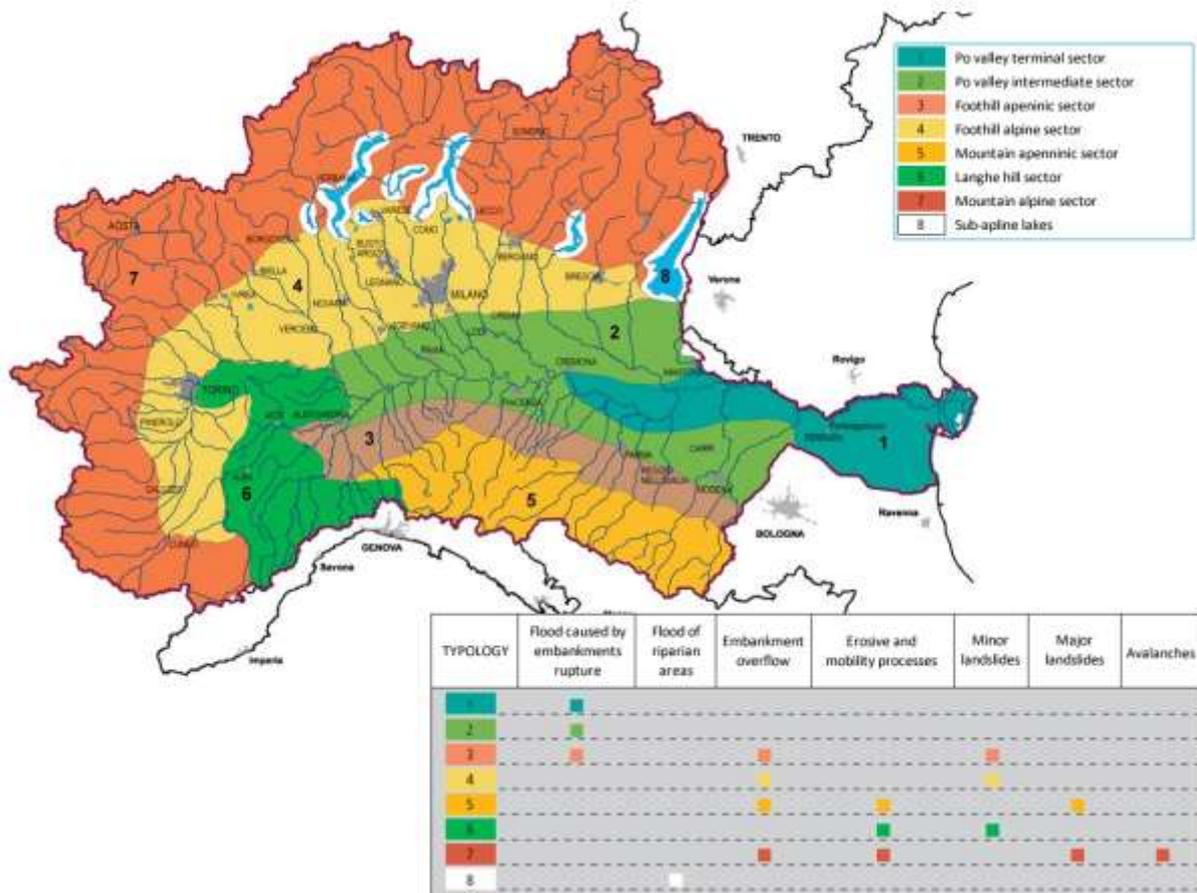
**Figure 3.4:** Annual mean precipitation in the Po river basin by mm/year range amounts (AdBPo, 2006).

In Lombardy, the average annual precipitation (~1,000 mm/yr) increases northwards in the Pre-Alpine hills up to 1,400 mm/yr and more (Ceriani and Carelli 2000). In Piedmont, the average annual precipitation ranges between 593 mm/year (Alessandria) and 982 mm/year and remain below the Italian average (970 mm/year) but approximately at the level of the Po plain (~760 mm). The exceptions are places such as Verbania which receive 1734 mm/year. The Val d'Aosta valleys receive some 500 mm/year but the precipitation increases up the mountain side. The average yearly precipitation in the region amounts to some 950 mm (AdBPo, 2006).

The current knowledge allows to identify some macro-areas within the Po river basin, which are characterized by large scale uniformity with regard to the prevailing processes of hydraulic and hydrogeological instability; some of these processes are specific and descriptive of these macro areas. In particular, the risk of flooding concerns: the plain areas along the main and the secondary hydrographic network, together with some associated erosive processes and sediment deposit; and the mountain areas, characterized by prevailing stream-like dynamic, also affected by processes of transport and storage of debris along the conoids.

Figure 3.5 describes the prevailing processes causing flood events for the homogenous areas. These processes are summarized by AdBPo (2010) as:

- proper flood events, caused by gradual and natural inundation of the flood plain;
- mobility processes in the riverbed, with erosion, transport and deposition of sediments;
- flooding processes related to an embankment rupture scenario.



**Figure 3.5:** Macro areas of the river basin with associated hazardous processes (AdBPo, 2009).

Each macro area is associated with some prevalent process:

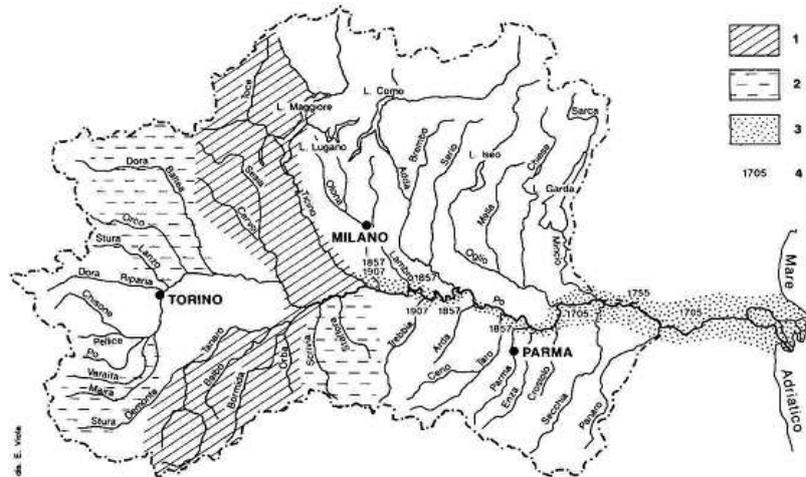
1. **Po valley terminal sector:** area of maximal expansion of the flood wave with a flood plain surface ranging from 3,000 to 10,000 km<sup>2</sup>. Events involve the main course and can be caused by embankment rupture and consequent progressive flooding of the plain. They can affect cities, towns and major infrastructures.
2. **Po valley intermediate sector:** area of expansion of the flood wave ranging from 1,000 to 3,000 km<sup>2</sup>. Events are often in the main course and can be caused by embankment rupture and consequent progressive flooding of the plain. They can involve cities, towns and major infrastructures.

3. ***Foothill apenninic sector:*** events caused by embankment rupture or river overflow. The available flood area is less than 1,000 km<sup>2</sup>. The events involve the Po apenninic tributaries.
4. ***Foothill alpine sector:*** fast flood events caused by water infiltration or river overflow, with associated landslides. The available flood area is less than 1,000 km<sup>2</sup>. The events involve the Po alpine tributaries.
5. ***Mountain apenninic sector:*** strong erosive processes along the streams with associated landslides.
6. ***Langhe hill sector:*** strong erosive processes along the main and secondary network, with associated landslides. Overflows and extensive flood events along the major tributaries.
7. ***Mountain alpine sector:*** strong erosive and transport processes along the secondary network, river overflow along the main network. Major landslides affecting stream flowing, fast avalanches.
8. ***Sub-alpine lakes:*** progressive flooding of riparian areas during flood events. Diffuse erosive and transport processes along the secondary network.

### **3.4. Flood typologies**

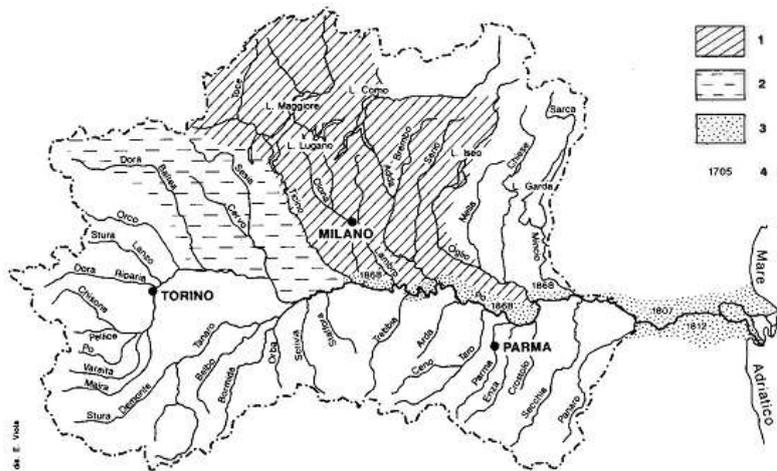
The hydrographic configuration of the Po river basin is made up of different types of streams, running through a variegated environment, from alpine lakes to low plains. This means that the hydrological regimes are quite different, which causes, during heavy rain events, a variety of flood situations along the water network. Information on historical floods is being used to define four major typical scenarios, based on the most frequent association of tributaries involved in flood events (AdBPo, 2005):

- First type (Piedmont):** this type of flood is mainly caused by the significant contributions of the Sesia, Ticino and Tanaro. The involved catchment area is the western or central-western part. Events of this type occurred in 1705, 1755, 1857, 1907, 1994 and 2000, all happened in autumn. See fig. 3.6.



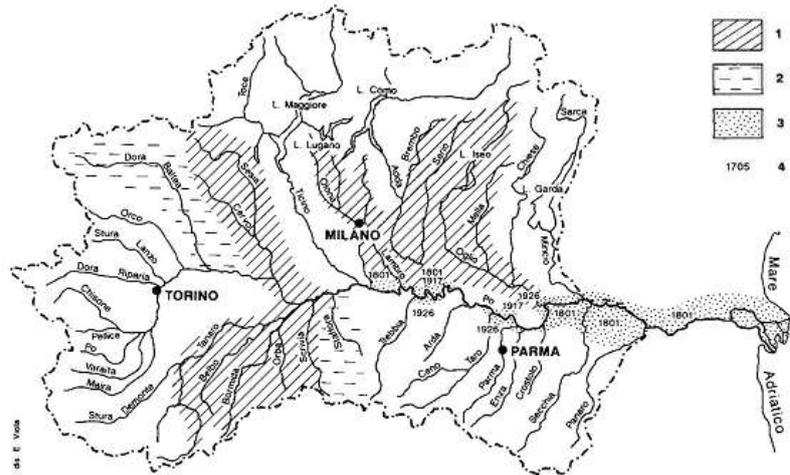
**Figure 3.6:** Basin areas involved in a Piedmont flood type. 1) Mainly involved basins; 2) Occasionally involved basins; 3) Flooded areas; 4) Flood year (AdBPo, 2005).

- Second type (Lombard):** the floods of the second type are due to the simultaneous participation of Ticino, Lambro, Adda and Oglio. The involved part of the basin is mainly in the central sector. Events of 1807, 1812 and 1868, all occurred during the autumn months, are assignable to this type of floods. See fig. 3.7.



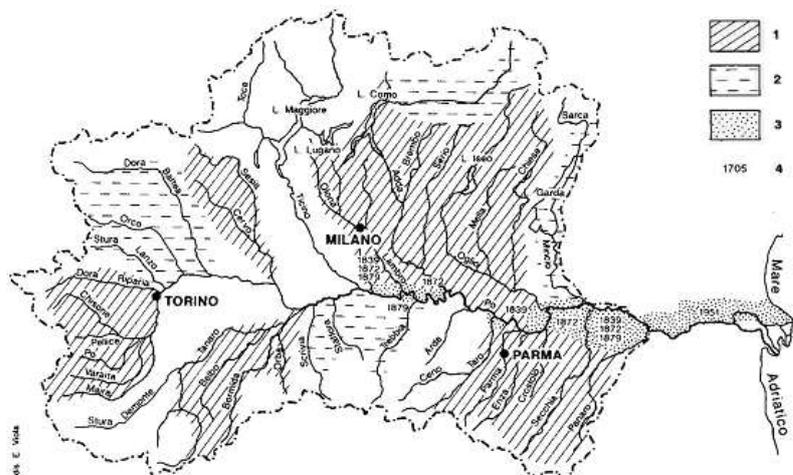
**Figure 3.7:** Basin areas involved in a Lombard flood type. 1) Mainly involved basins; 2) Occasionally involved basins; 3) Flooded areas; 4) Flood year (AdBPo, 2005).

- Third type (Piedmont-Lombard):** these floods happen thanks to the contributions from Sesia and Tanaro, the latter characterized by high flow rates because of the extraordinary contributions of Belbo, Bormida and Orba, and the significant contributions of Adda and Oglio, just below the maximum levels. Sometimes also Scrivia, Dora Baltea, Olona and Lambro simultaneously take part in the flood. In this type of event, the central and western alpine slopes are mostly involved. The floods of 1801, 1917 and 1926 all fall into this scenario. See fig. 3.8.



**Figure 3.8:** Basin areas involved in a Piedmont-Lombard flood type. 1) Mainly involved basins; 2) Occasionally involved basins; 3) Flooded areas; 4) Flood year (AdBPo, 2005).

- Fourth type (whole Po basin):** This remarkable type of flood arises from the contribution of a large number of streams of the Po river network. The initial flow contribution is systematically received by various groups of tributaries in the western sector, including the constant presence of Sesia and Tanaro. Further downstream, in the left side of Po, flooding of Olona and Lambro are usual, frequently associated with floods of Adda and Oglio; the floods of 1839, 1872, 1879 and 1951 are representative of such events. These all occurred in the autumn months, with the exception of 1879, which happened in the late spring. See fig. 3.9.



**Figure 3.9:** Basin areas involved in a whole-basin flood type. 1) Mainly involved basins; 2) Occasionally involved basins; 3) Flooded areas; 4) Flood year (AdBPo, 2005).

The exceptional nature of hydrometric heights along the Po, however, is not directly related to an absolute extraordinary flood of the various tributaries involved in the event. A crucial role is rather played by the coincidence of floods which, though moderate, join together in the main branch of the Po by numerous tributaries. The effects produced during each of these events are always been very serious, but the results were particularly disastrous during the 1951 flood: nearly 100,000 ha of plains near Rovigo (Polesine) were flooded in about 11 days.

### 3.5. Risk profile of the area

The basin surface which is prone to flood hazard is calculated as 3,517 Km<sup>2</sup>, which is the 5% of the total basin surface (MATTM, 2008). Table 3.3 summarizes the regional amount of territories prone to flood hazard in the most involved regions.

<i>Region</i>	<i>Flood hazard surface (Km<sup>2</sup>)</i>	<i>Total surface (Km<sup>2</sup>)</i>	<i>% of flood area surface (Km<sup>2</sup>)</i>
Emilia Romagna	1,818	22,186	8.2%
Piedmont	1,576	25,389	6.2%
Lombardy	1,232	23,862	5.2%
Valle d'Aosta	28	3,261	0.9%

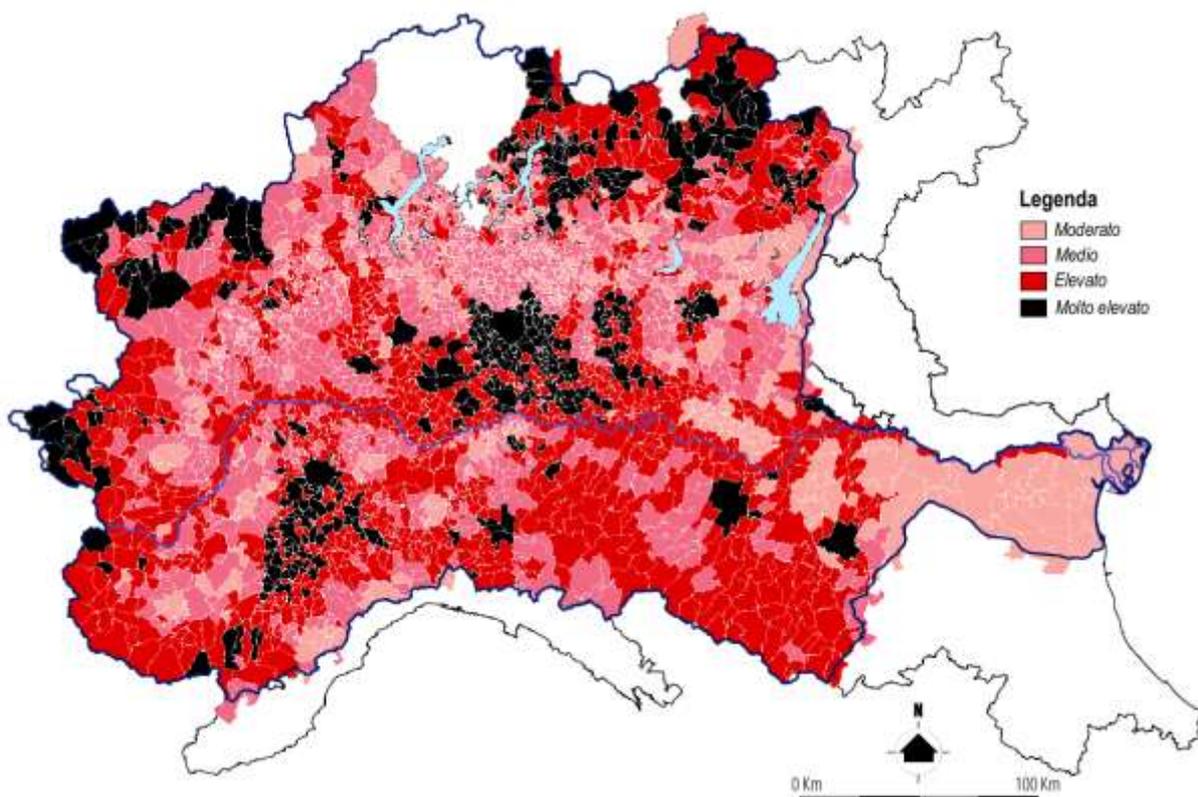
**Table 3.3:** Flood-risk prone territories compared in the basin Regions (adapted from MATTM 2008).

The river basin spreads over eight (out of twenty) Italian regions including Valle d'Aosta, Piedmont, Lombardy (all three entirely included in the basin area), Emilia Romagna (with about a half of the area included in the basin), Autonomous province of Trento, Veneto, Liguria and Toscana (marginally included in the basin area). Figure 3.10 gives a quick view of the distribution of flood risk through Italian regions.



**Figure 3.10:** Exposure to flood hazard in Italy as a percentage of the total regional area. FEEM elaboration on data by MATTM (2008).

Out of the four main regions extending over the river basin area, Emilia Romagna is the most risk-prone territory to floods in absolute (1,818 km<sup>2</sup>) and relative terms (8.2% of territory is prone to floods), because the Po River flows through heavily developed area with large damage potential. The floods along the main course and tributaries occasionally invade urban downtowns and cause casualties. Piedmont ranks second with about 6.2% of the territory being at high risk. Lombardy is among the six most-exposed regions to flood hazard in absolute terms, with some 5.2% of the territory being at high hydrogeological risk. Valle d'Aosta is marginally exposed to floods (1%).



**Figure 3.11:** Hydrogeological risk map for the Po River basin (AdBPo, 2001).

The Po River Basin Authority (AdBPo, 2001) created a hydrogeological risk map for the river basin (fig. 3.11), classifying the risk in four qualitative ranges:

- R1 – Moderate risk: marginal socio-economic damages.
- R2 – Medium risk: minor damages to buildings and infrastructures are possible, without endangering human lives or the performance of socio-economic activities.

- R3 – High risk: functional damages to building and activities are possible, safety of people is not granted. Building may not be usable and socio-economic activities are interrupted. The cultural heritage can be damaged.
- R4 – Very high risk: serious harm to people and human casualties are possible. Serious damage to buildings and cultural heritage, and destruction of socio-economic activities can happen.

This evaluation comes from the analysis of the maximal discharges in the basin compared to the actual embankment arrangement. Potential discharge amounts and their correlated return time has been evaluated through statistical models, as shown in table 3.4 for 20, 100, 200 and 500 years return times at the hydrometric stations in the lower section of the basin (AdBPo, 2001).

<i>Hydrometric station</i>	<i>Basin surface (km<sup>2</sup>)</i>	<i>Q20 (m<sup>3</sup>/s)</i>	<i>Q100 (m<sup>3</sup>/s)</i>	<i>Q200 (m<sup>3</sup>/s)</i>	<i>Q500 (m<sup>3</sup>/s)</i>
Po a Becca	36,770	9,290	12,190	13,600	15,050
Po a Piacenza	42,030	8,970	11,550	13,000	14,100
Po a Cremona	50,726	10,090	13,000	14,300	15,870
Po a Boretto	55,183	9,380	12,060	13,700	14,720
Po a Borgoforte	62,450	9,600	12,260	13,100	14,890
Po a Pontelagoscuro	70,091	9,470	12,070	13,000	14,650

**Table 3.5:** Peak discharge rates for the Po main course from Isola Sant’Antonio to Delta, with estimates for different return times (from 20 years to 500 years) (AdBPo, 2001, allegato tabelle 2-31).

The profile of flooding for a return time equal to 200 years has been drawn and compared to morphologic aspects and historical records about previous events, obtaining a map of potentially flooded area. Tab. 3.5 summarizes the percentage for each class of risk in the basin regions. Some 49.8% of municipalities in the basin range from high to very high risk, while the moderate risk class includes only 10.8% of the territory (AdBPo, 2009).

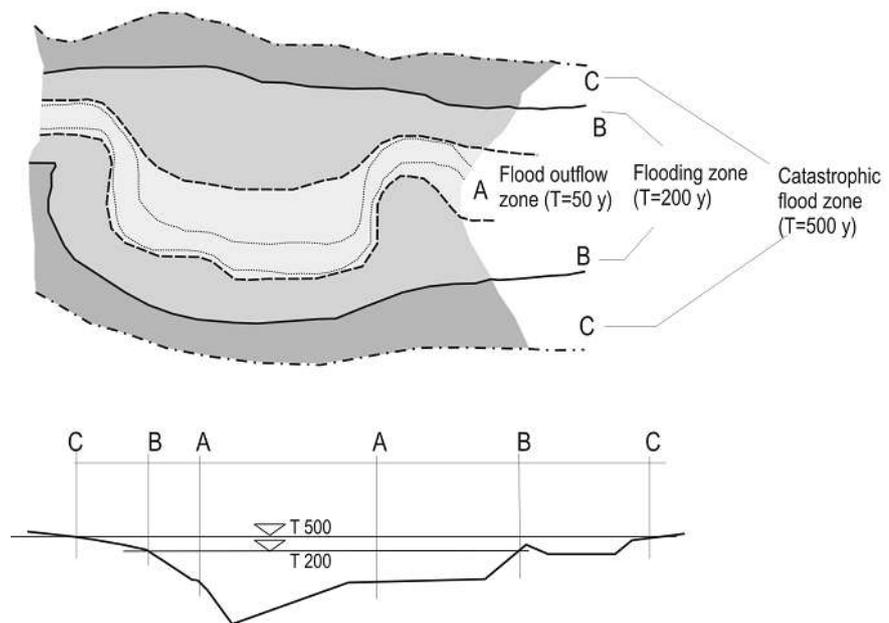
<b>Region</b>	<b>Risk classes (%)</b>			
	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>
Emilia Romagna	0.4	40.8	56.1	2.6
Piedmont	8.6	37.6	43.9	9.9
Lombardy	13.7	41.8	26.4	18.1
Valle d’Aosta	0	28.4	27	44.6

**Table 3.5:** Hydrogeological risk classes percentages compared in the basin Regions (adapted from AdBPo, 2009).

The interpretation of this data may lead to slightly different conclusions compared to tab. 3.1, seeing that Val d'Aosta shows a 44.6% of class 4 hydrogeological risk but just 1% of flood-prone areas, while the lower part of the basin in Emilia Romagna show a moderate risk while it has been the area where some of the most significant floods happened. This apparent contradiction is inherent in the definition of hydrogeological risk, which comprehends phenomena others than floods like erosion, landslides and avalanches that mainly affects mountain and foothill areas and happens more frequently than floods, so increasing the hazard value (AdBPo, 2009). A risk map of the flood risk alone is not available.

This analysis was instrumental to delimitate the C-zone, which corresponds (for the medium-lower part of the basin) to the area flooded during a catastrophic event with one or more breaks along the embankments.

The definition of three flood zones (“fasce”) is requested by the PAI (Hydrogeologic Arrangement Plan). They help defining the intensity of an event and the corresponding area that is expected to be flooded (figure 3.12). They are therefore defined:

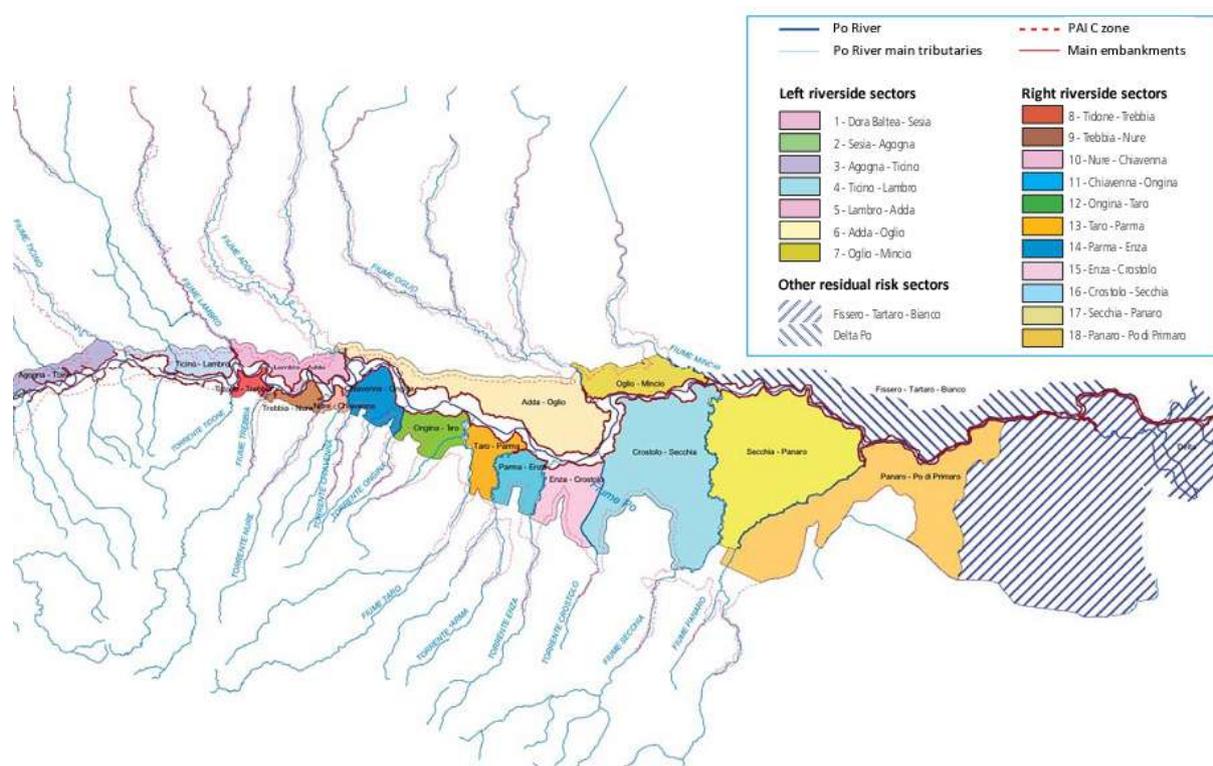


**Figure 3.12:** Schematic representation of a river flood zones (AdBPo, 2001).

- Zone A: ordinary floods area for a return time up to 50 years.
- Zone B: flood area for a return time up to 200 years. It corresponds to the area confined by the embankment system.
- Zone C: catastrophic flood area for a return time up to 500 years. It is the area outside the embankment system which is likely to be flooded during an exceptional event.

This classification must not be confused with the classification by FEMA (Federal Emergency Management Agency), where C and B are lower to medium risk zones and A is the high risk zone.

The primary objective of the risk management in the basin is to guarantee the homogeneity of conditions for the safety of human lives and territory, including the buildings and the properties. For this purpose, the residual risk connected to any event superior to the reference flood must be evaluated and managed through the controlled flooding of predisposed low vulnerability areas in the zone C (AdBPo, 2005).



**Figure 3.13:** Residual risk distribution (AdBPo, 2009).

To assess this residual risk, bi-dimensional hydraulic simulations have been produced, considering different rupture scenarios. Through this methodology has been possible to draw a map regarding the potential floodable areas, shown in figure 3.13.

With project SAFE (2002), AdBPo made a first inventory of buildings and infrastructures included inside zones A and B (tab. 3.6). 52 river streams are included in the zoned areas, for a total of 3,630 km<sup>2</sup>. Zones A+B cover a total area of 2,600 km<sup>2</sup>, in which are included 11,009 elements among 15 categories. 907 municipalities are involved.

<i>Category</i>	<i>Crossings</i>	<i>Zone A</i>	<i>Zone B</i>	<i>Total</i>	<i>%</i>
A – Farms and fields		17	77	94	0.85
B – Transport infrastructures		9	18	27	0.25
C – Caves		314	329	643	5.89
D – Landfills			7	7	0.06
E – Roads	404	250	457	1,111	10.85
F – Railways	139	17	37	193	1.77
I – Productive plants		491	722	1,213	11.42
M – Historical heritage			3	3	0.03
P – Bridges	217	15	17	249	2.26
Q – Water-use structures		73	88	161	1.48
R – Residential buildings		2,028	4,085	6,117	55.70
S – Service structures		19	37	56	0.51
T – Touristic activities		70	86	156	1.43
Z – Hydraulic infrastructures	623	114	41	778	7.07
X – Unidentified structures		3	2	5	0.05
TOTAL	1,383	3,420	6,006	10,809	100.00

**Table 3.5:** Inventory for categories of structures included inside Po River basin zones A and B (AdBPo, 2009).

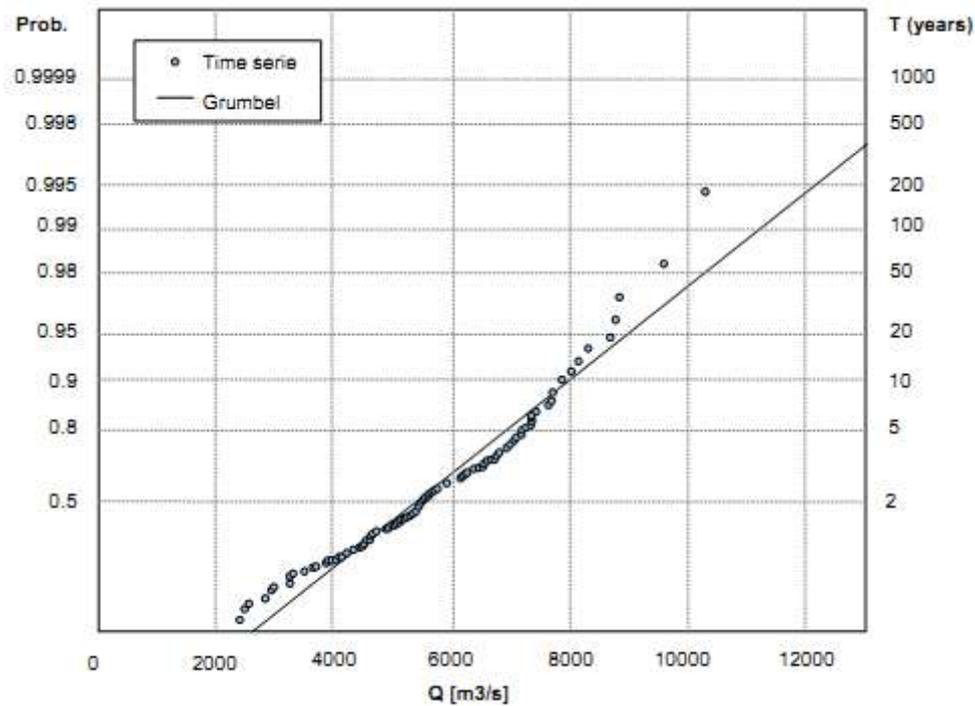
The lower course of the river is embanked with uninterrupted embankments for about 860 km before the delta, defending about 7,000 km<sup>2</sup> of plain included in the C zone (AdBPo, 2009).

### 3.6. Hydrometric trends and significant flood events

The knowledge about the historical flood events and the changes in the morphology of the river course is an element of primary importance for the floods risk evaluation, because the dynamic of flooding events tends to follow past events with strong similitude to their development.

The Po River Basin is characterized by interplay of two different discharge regimes: Alpine type, which is prone to floods in spring and summer and droughts in winter; and Apennine type, which is prone to floods in spring/autumn and droughts in summer. As a result, the river discharge has two peaks (spring and autumn) and two lows (winter and summer). The mean discharges measured at the basin closure (Pontelagoscuro station) are: 400 m<sup>3</sup>/sec during low flow periods, 1,540 m<sup>3</sup>/sec under average conditions, and some 9,750 m<sup>3</sup>/sec during high level (AdBPo, 2006). Figure 3.14 plots the discharge amounts registered at Pontelagoscuro against a probabilistic distribution (Gumbel model), showing the actual frequency for each discharge

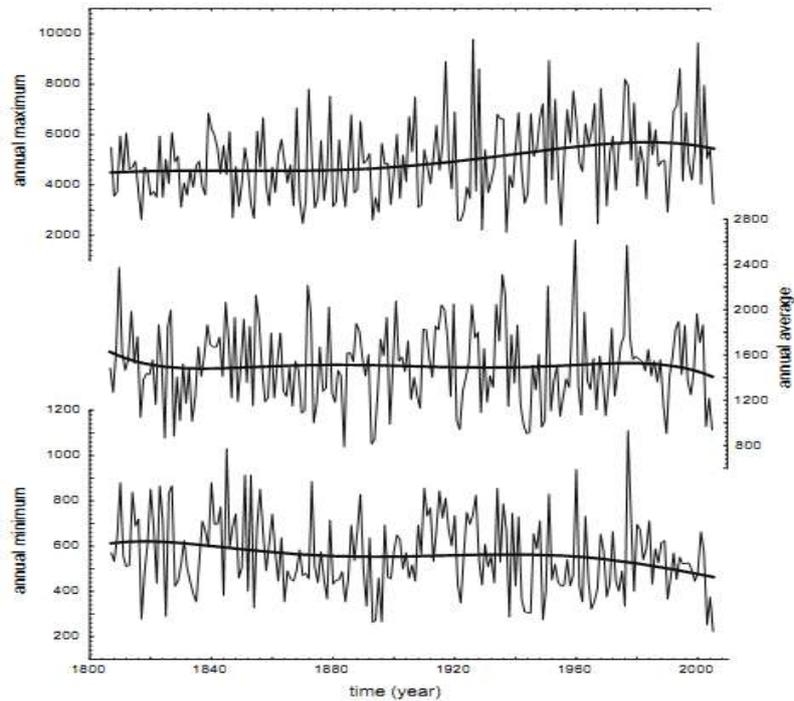
event. ARPA Emilia Romagna (Cacciamani, et al., 2008) quantifies as -20% the change in mean discharge at Pontelagoscuro station for 1975-2006, rising to -45% for summer season.



**Figure 3.14:** Gumbel distribution for discharge rates registered at the Po station Pontelagoscuro (ARPA, 2009).

Zanchettin et al. (2008) have reconstructed the Po River discharges for the period 1807–2005 (Figure 3.15), extending the available instrumental record from 1918 on. The records of water stages obtained from the historical archives of the “Hydrological Office of the Po River (Parma)” were converted into discharges based on proxy approximated catchment-average data of precipitation and evapotranspiration. The trend shows a slight decrease in the average and minimum discharge, which is especially noticeable in the last decades of the series, while the maximum time series start to slightly increase after the 1960. The author asserts that this change may be a consequence of the river embankments, completed in the ‘60s, rather than some change in the climatic context. Also Tibaldi, et al. (2007) agrees on this fact: as the containment measures proceeded, reducing the minor flood episodes, they caused a progressive and significant increase in flow levels and discharge.

Precipitations in the Po basin reach their peak (~500-700 mm) during spring (March-May) around Lake Maggiore, in the Dora Baltea Valley, and along the Apennines. In the summer (June-August) North of Lombardia receives some 400-500 mm of rainfall, whereas the precipitation downstream in the Po plain and in the Apennines does not exceed 200 and 300 mm respectively. In the autumn,



**Figure 3.15:** Annual maximum (top), average (middle) and minimum (bottom) of daily Po River discharges (1807-2005) (Zanchettin, et al., 2008).

the peaks range between 600-700 mm in the Pre-alpine and Apennines regions, whereas the downstream plain receives only some 200-250 mm. Finally, winter is characterized by very low rainfall in the Alps (100-150 mm in the Western and 150-200 mm in the Central Alps), whereas the precipitations in the higher areas of the Apennines top 500 mm. In the downstream plain, less than 150mm fall in Canavese, Monferrato, Langhe and along the Po course, whereas the Lombardia and Emilia plains receive some 200-350 mm rainfall (AdBPo, 2006).

In case of intense and persistent precipitations, the river floods can affect some 450 km from Valenza Po to the Adriatic Sea. These floods in the downstream section of the river can be very hazardous and cause a huge amount of damage, since the river levees are higher than the surrounding area, with a difference that might amount to 7-8 m. Important upstream tributaries such as Dora Baltea, Sesia and Tanaro in Piedmont, and Ticino in Lombardy are typically involved during this type of events. In November 1994, the river discharge amounted to over 11,000 m<sup>3</sup>/s just after the Tanaro confluence; this kind of discharge is more typical several hundreds kilometres down the river. Likewise, in October 2000, due to massive discharges from Dora Baltea and Sesia, the river reached 10,000 m<sup>3</sup>/s right after Valenza. In both cases, the high levels were caused by extreme weather conditions, with cumulative rainfall up to 700 mm over the period of five days (13-17 October). Notably, high river stages were recorded in June 1917 (discharge at Pontelagoscuro of 8,900 m<sup>3</sup>/sec), November 1951 (10,300 m<sup>3</sup>/sec), November

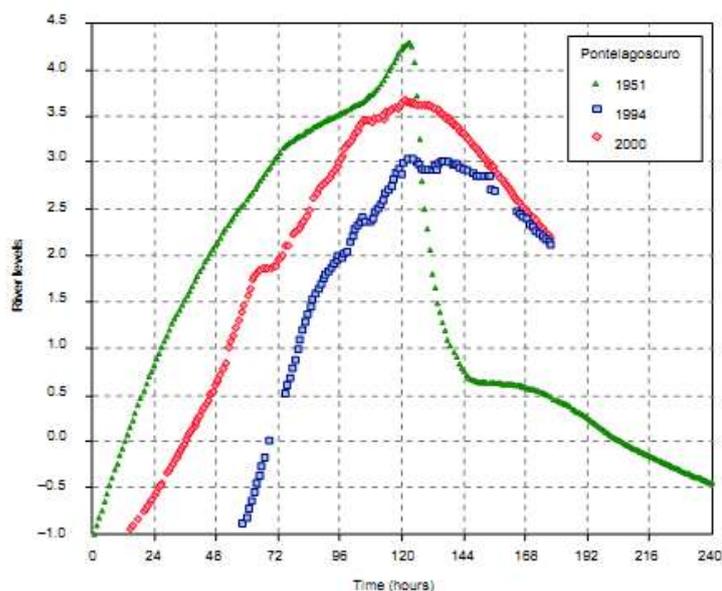
1968 (7,900 m<sup>3</sup>/sec), November 1994 (8,750 m<sup>3</sup>/sec), October 2000 (9,750 m<sup>3</sup>/sec), November 2002 (8,100 m<sup>3</sup>/sec), April 2009 (7,700 m<sup>3</sup>/sec) and December 2010 (5,000 m<sup>3</sup>/sec) (ARPA, 2009). It must be specified that 1994 and 2000 floods reached higher discharge levels in the middle section of the basin compared to 1951, flooding the midstream territories and thus unloading part of the flood peak. Table 3.7 shows discharge levels during four reference events, ordered per station from upstream.

Station	Maximal flow peak during flood (m <sup>3</sup> /sec)			
	1951	1968	1994	2000
Isola Sant'Antonio			10,500	10,500
Becca	11,250	9,060	11,500	11,200
Piacenza	12,800	9,500	11,055	12,240
Cremona		10,600	11,300	11,850
Boretto	12,100	8,700	10,400	11,900
Borgoforte	11,800	7,940	11,000	11,800
Pontelagoscuro	10,300	7,900	8,750	9,750

**Table 3.7:** Comparison between flood discharges during four flood events (AdBPo, 2005).

Figure 3.16 shows a comparison in the time trends for three of these major events (1951, 1994 and 2000). The event of October 2000 has been characterized by a record discharge peak but also by the duration of the peak flow.

The propagation speed of the peak between Ponte Becca and Boretto was significantly reduced from 22% to 47% compared to mean flood values. The 2000 flood had a less catastrophic impact on the downstream section, as already stated, also because of the lack of contributes from apenninic tributaries and thanks to the more fluent outflow to the sea.



**Figure 3.16:** Comparison between Po discharge levels and time (hours) for three major flood events (1951, 1994, 2000) (Colombo, 2004).

The flood event of October 2000 is the actual reference event set by the Basin Authority to define the objectives of future hydrological risk management (AdBPo, 2008). The previous reference is found in project SIMPO, which used the 1951 flood discharge numerically augmented by 10% within a model to take in account other potential breaks in the embankments (AdBPo, 2007). The adaption measures enforced by this project and its related Directive 25/7/1952 (elimination of any bottlenecks, adjustment of the embankments and improvement of flowing capacity) have been successfully concluded and tested during the extreme events of November 1994 and October 2000, which reached the highest levels of discharge and thus set the new standard for the maximal. In both of these events the discharge topped the historical record of 1951 already in the middle section of the basin (Piacenza, Cremona, Casalmaggiore). The recurring elevation of the maximal height of the embankments reached a structural limit in most of the downstream section, which means that the management to reduce the risk will need to find new solutions. The actual embankment system, though constantly monitored and maintained, cannot guarantee an absolute level of safety for the surrounding territory. There will be always a percentage of residual risk to take in account, and even if it can be reduced and mitigated, it cannot be eliminated by any hydraulic work.



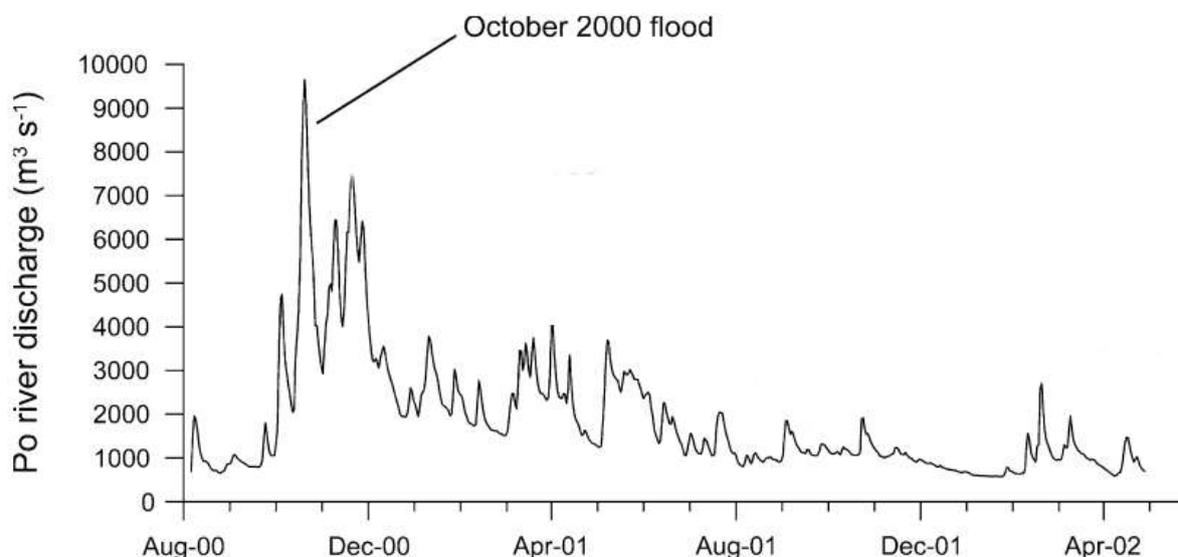
**Figure 3.17:** Sections of the Po River that are interested by major flooding. Yellow: upstream meandering section; Red: midstream section, multi-channel flow with interposed islets; Purple: downstream sinuous-straight section before the delta (AdBPo, 2005).

While the number of the ruptures in the embankments caused by each flood is clearly decreasing, the extent of flooded areas increased specially in the downstream sections (Mantova, Ferrara and Rovigo provinces, see fig. 3.17). This is clear comparing 1951 and 2000 floods: as in 1951 the river did not overtop any section upstream or midstream, it reached the highest peak in the last section of the basin; on the other hand, the 2000 event had a greater amount of discharge but it decreased while flooding the mid section, so saving the downstream part of the basin (AdBPo, 2005).

We will focus on the flood events 2000 on the main Po river stream as an up-to-date reference for climatic impact and socio-economical potential losses in the river basin. This event is particularly significant as it shows the highest discharge peak in the last few decades, and it is enough recent to be comparable with a near-future situation. As a historical background of flood impact in the lower part of the basin, the 1951 Polesine flood will be also taken into account.

### 3.7. Reference event: the 2000 flood

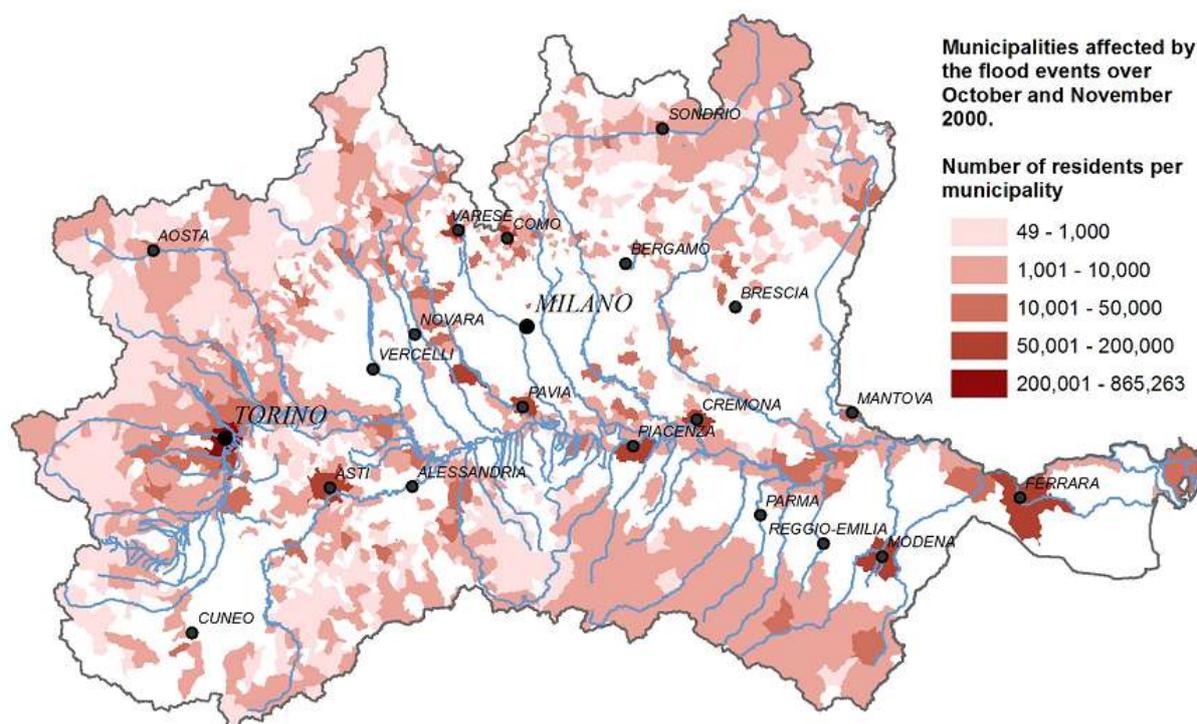
On October 2000, from 13th to 16th, a series of extreme precipitation events hit the Northwest of Italy, causing numerous floods and landslides. Triggered by a persistent torrential rain exceeding in some places 700 mm in 60 hours, the flow discharge of the Po river and some of its tributaries registered record levels (almost 10,000 m<sup>3</sup>/s high upstream) with return period of 200 years and higher (Fig. 3.18). The communities of Piedmont, Valle d'Aosta and Liguria regions were affected particularly hard, but floods were registered also in Lombardy, Emilia Romagna and Veneto. The sub-basins where most severe floods were registered include Toce (Piedmont), Sesia (Piedmont), Dora Baltea (Piedmont and Valle d'Aosta), Orco (Piedmont), Stura di Lanzo (Piedmont), Dora Riparia (Piedmont), Pellice (Piedmont) and the Western part of the Po river (Piedmont) (ARPA Piemonte 2003a). At some places precipitation of up to 740 mm in just four days were recorded.



**Figure 3.18:** Discharge graph from August 2000 to April 2002, showing the peak discharge during the extreme event in October.

The EM-DAT International Disasters Database indicates 25 casualties, a population of 43,000 affected by the floods and overall damage amounting to 8 billion US\$ in 2000 dollar value (EM-DAT, 2009). Barredo (2006) comes to similar results, including into the analysis also collateral events in France and Switzerland.

Furthermore, it caused significant structural damage, lifelines interruption, environmental damage and social hardship. During the flood, 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% of the territory causing damage to infrastructure and property topping 1 billion € (Regione Piemonte, 2000). The flood affected more than 700 municipalities and almost all main 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). The full map of the event can be found in the annexes A and B. The area hosts several chemical plants and industrial waste treatment plants. Moreover, at Saluggia (in Vercelli Province, close to the Dora Baltea river) is located one of the largest nuclear waste deposits in Italy. The dismantled nuclear power plant at Trino Vercellese (Vercelli Province) was also flooded with no relevant consequence. The nuclear laboratory at Bosco Marengo (Alessandria Province) was not impacted (ARPA Piemonte, 2003).



**Figure 3.19:** Municipalities that suffered major damages from the October-November 2000 floods classified by municipality resident population. FEEM elaboration on data by ISTAT.

The region was besieged by another significant flood only one month later, in November 2000, and then again in 2001 and 2002. Figure 3.19 summarizes the municipalities impacted during these floods. The financial resources allocated for aftermath recovery and flood risk mitigation were progressively designated to address the cumulative damage from all these events, making it difficult to estimate the economic costs of the October 2000 flood event alone. The information available about the revisited events is ill-suited for a full comprehension of the risk. Despite the obligation imposed by the Directive 2007/60/EC on the assessment and management of flood risks (Floods Directive, transposed into Italian legislative framework by the Decree-law 47/2010) to collect and assess information about the past flood events, in practice the knowledge base is patchy. In general, while the meteorological conditions leading to high river stages and floods, as well as the evolution of the flood events, are well documented and analyzed, the assessment of the impacts of floods are limited to single, localized episodes.

### **Meteorological and hydrometric conditions leading to the extreme event**

The meteorological and hydrological evolution of the flood event had been extensively analyzed in several reports (Ratto, et al., 2003; ARPA Piemonte, 2003; Regione Piemonte, 2000). Here we provide the key insights.

A large cyclonic circulation centered above the British islands reached the North-Western part of Italian peninsula, pushing warm and humid currents from the South-West. First precipitations were registered in the alpine area in the afternoon of Wednesday, October 11th. On Thursday, October 12th, the cyclonic movement, “Jasmine”, pushed cold currents from the north part of the Atlantic Ocean, causing a depression above the Iberian Peninsula that pushed further humid warm currents from the Mediterranean area to the northern part of Italy. On Friday the 13th the cyclonic current shifted at north and extended at the southern part of the Mediterranean Sea, bringing warm and humid air and continuous precipitations to alpine area of Piedmont and Valle d’Aosta. The freezing level rose from 2,900 to 3,400 meters a.s.l. contributing to snow melting. On Saturday the 14<sup>th</sup>, precipitations extended over the entire region, with particular intensity in the areas of Ossola valley, Sesia valley, Orco and Stura di Lanzo. In the evening the cumulative precipitation reached on average 250 mm, with peaks at Paione lake (580 mm), Pizzanco (530 mm), Varzo (420mm) and Ala di Stura (400mm). On Sunday, October 15th, the cyclonic circulation shifted to the north, pushing cold currents to the North-West of Italy. This sudden fall of temperature of 3 or 4°C caused a super-saturation of the abundant humidity in the air, with the consequent increase of the precipitation intensity. The 6 hours average precipitation over the entire region amounted to 100 mm. On Monday, October 16th, precipitation continued over the entire region. During the night, the rainfall continued to lose intensity and stopped in the early hours on October 17th (Ratto, et al., 2003; ARPA Piemonte, 2003; Regione Piemonte, 2000; Nimbus, 2000)

The highest precipitations were recorded in the alpine and pre-alpine area of Piedmont (Ratto, et al., 2003; ARPA Piemonte, 2003; Regione Piemonte, 2000; Nimbus, 2000):

- Western Ossola area, between 610 and 740 mm (estimated return period of 50 years);
- Sesia valley, between 610 and 632 mm (return period of 20 years);
- Canavese and Lanzo valley, between 407 and 712 mm (return period between 20 and 50 years);
- Sangone and Po valley, around 596 mm.

The high intensity and persistence of the precipitation led to high stages on the Po River and on almost all its important tributaries. Po River inside the city of Turin reached its maximum flow at 2,350 m<sup>3</sup> per second, exceeding so the previous maximum registered in 1949 (2,230 m<sup>3</sup> per

second). This is more than twenty-three times the registered average flow of 100 m<sup>3</sup> per second. Downstream the confluence with the Orco torrent and the Dora Baltea River, the Po River reached 8,000 m<sup>3</sup> per second and further downstream after the confluence with the Sesia River the discharge rose to 10,000 m<sup>3</sup> per second. The Po River reached its maximum historical discharge (around 13,000 m<sup>3</sup> per second) at Pontelagoscuro (FE) during the extreme events of 1951 and 2000 (Ratto, et al., 2003; ARPA Piemonte, 2003; Regione Piemonte, 2000; Nimbus, 2000).

### **Reported losses**

The most detailed studies about the economic impacts of the natural disaster under consideration have been conducted by the regional and local institutions in Piedmont and Valle d'Aosta (Regione Piemonte, 2000; Regione Autonoma della Valle d'Aosta, 2001-2002). Neither of these studies contains a comprehensive analysis of welfare losses triggered by the flood. 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 flood event led to lifelines interruptions in the affected regions. The damage on the highways A4 between Milan and Turin, and A5 between Turin and Aosta amounted to 12 and 13 million € respectively. Regional and provincial road network suffered damage exceeding 250 million €. Several bridges were destroyed including the bridges in Noasca, Robassomero, Salassa, Feletto and others, leading to a temporal isolation of a number of small and medium sized towns (Nimbus, 2000). The restoration of the railway between Turin and Aosta lasted for more than 2 years. Electricity network was interrupted in several places. Problems were also registered at some power plants. The hydropower plant at Funghera, for instance, necessitated a technical intervention that lasted for six months. Telecommunications and drinking water supply was interrupted too (Nimbus, 2000). For almost a week, Turin, Moncalieri and some 30 small villages experienced interruptions of water supply. The large industrial plants such as FIAT at Mirafiori and Rivalta were also affected by the flood (Regione Piemonte, 2000; Regione Autonoma della Valle d'Aosta, 2001-2002).

Reparation of main lifelines had been given the uttermost priority in the chronology of the interventions, so as to restore basic life conditions (Regione Piemonte, 2000; Regione Autonoma della Valle d'Aosta, 2001-2002). As second, the debris left behind the flood in urban areas was removed. In the meanwhile, there was the need to remove the landslips material from

the main roads and railways and to consolidate the hydrological structure of the main water streams. In the Valle d'Aosta Region, attending to the official documents of the local institutions, the cost of the first interventions borne by the local administrations is quantified to € 40 million. The costs suffered by the regional institutions amount to € 20 million, split up in the following way: 35.7% for the water system, 25.5% for the restoration of the road system and 38.8% for the restoration of the sites subject to landslips (Regione Piemonte, 2000; Regione Autonoma della Valle d'Aosta, 2001-2002). 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 (Regione Autonoma della Valle d'Aosta, 2001-2002).

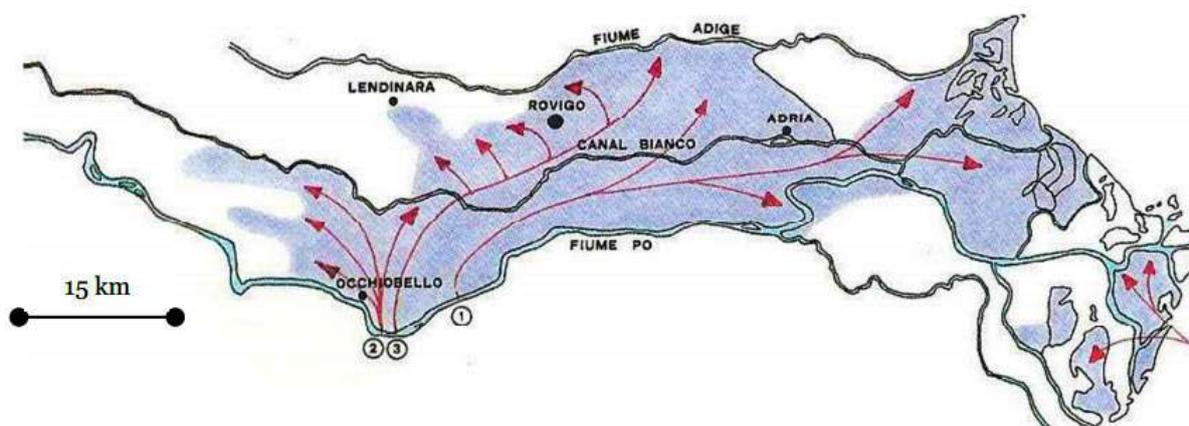
In the Piedmont Region, the estimated recovery costs amounted to € 2,881 million, split up as follow: 26% for local infrastructures; 10% for provincial infrastructures; 64% for intervention of hydraulic restoration and hydro-geological intervention. Total expenses borne by the regional administration amounted to € 786.5 million (Regione Piemonte, 2000). In conclusion, serious losses affected all sectors: infrastructures, roads and railroads and related viability, private goods, productive activities and agricultural businesses. Overall, the economic damage attained some € 3 billion. The amount of these costs could give an idea of the gravity of the event affecting the area.

### **3.8. Reference event: the 1951 flood**

The disastrous event which affected the lower fraction of the Po River in November 1951 exceeded all the previous registered events in the basin from Ticino confluence to the sea, inundating about 1,000 km<sup>2</sup> of land. The discharge levels reached a peak of 12,000 m<sup>3</sup>/s (4.28 m hydrometric height). The most affected regions were Veneto, Emilia Romagna and Piedmont, but also Lombardy and Liguria were somehow involved (Marchi, et al., 1995; AdBPo, 2009).

The causes of this catastrophic event have been investigated. The structure and morphology of the Po riverbed and embankments was 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 8<sup>th</sup>, 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 12<sup>th</sup>, 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 14<sup>th</sup> 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 14<sup>th</sup> and 15<sup>th</sup>, for a total length of the rupture of 736 m causing a flood lasting for about 20 hours (fig 3.20). Though this breaches, over 8,000 m<sup>3</sup> of water flowed out of the river and crashed on the plain which is 5-6 meters below the embankments, inundating in 11 days about 1,000 km<sup>2</sup> in Polesine lowland (Rovigo province) with 2-3 m depth water. Rovigo, Adria, Cavarzere and Loreo were evacuated and completely flooded on November 19<sup>th</sup>. Also part of Mantova and Venice provinces were reached by the water. Finally, on November 20<sup>th</sup>, the flood wave discharged in the Adriatic Sea (Turitto, 2004; Marchi, et al., 1995; Lastoria, et al., 2006; AdBPo, 2009).



**Figure 3.20:** Flood expansion during the 1951 event in Polesine (Rovigo Province). The numbers show the three breaks in the embankments system.

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. Some 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; consequently, the present exposure potential needs to be fully evaluated.

### **3.9. Pilot case study for damage assessment: the Polesine area**

A separate discussion must be reserved for an area which is formally not a part of the Po river basin, but it is strictly related to it, especially when it comes to flooding and impacts. This area is called Polesine and, as already stated in previous paragraph, it has been the scenery of the disastrous 1951 Po flooding.

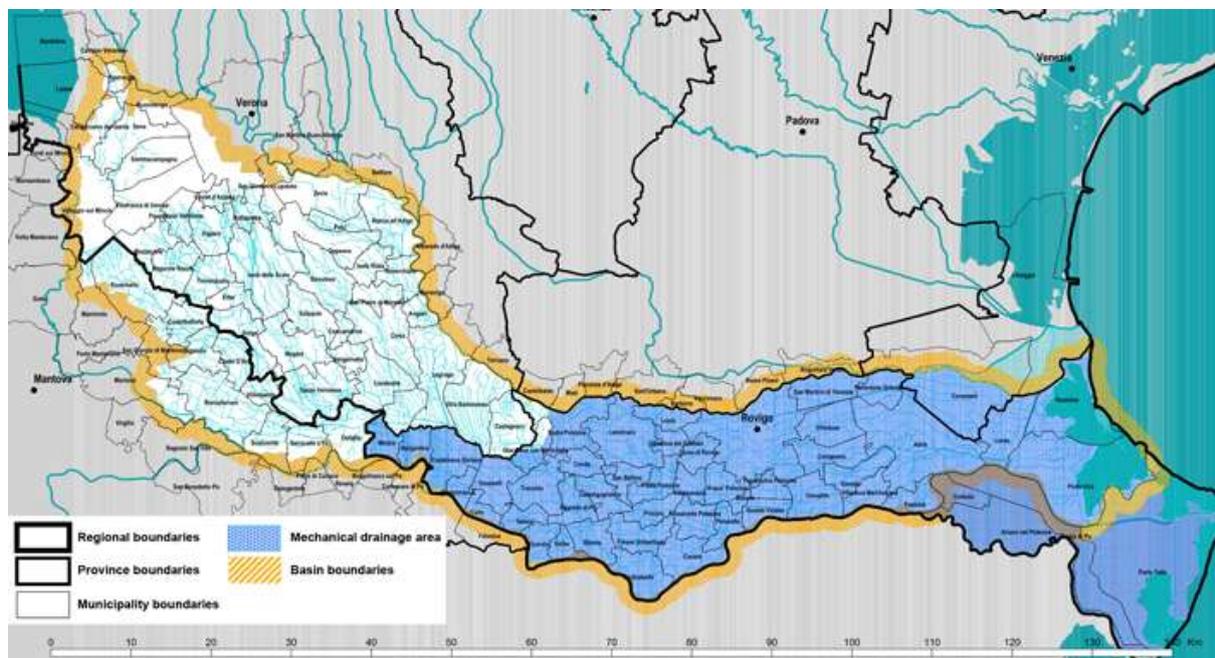
The term “Polesine” identifies the area located between the final section of the two major Italian rivers Po and Adige, before the Adriatic Sea. It is an hybrid river basin, since both river Po and river Adige are involved. It is officially defined as the “Fissero-Tartaro-Canalbianco river basin”. Nowadays, this area coincides with the Rovigo province, the southern of the seven provinces of Veneto, plus the portion of Venetian municipality of Cavarzere below the river Adige. Historically, its name means “swamp land”, as the territory was prone to constant modification and submerging caused by the rivers flooding, before the huge drainage work carried out by the population through the centuries.

The canal Tartaro-Canalbianco is one of the few Italian rivers originated from spring water. For the first 52 km of its course it is called Tartaro, and it is connected with the lake network of Mantova. The mid section of the stream is an artificial canal called Canalbianco, which cross longitudinally the entire Rovigo province for 78 km until Volta Grimana. The final section flow into a former Po delta branch named “Po di Levante” which runs for 17 km into the canal Brondolo and the delta. The total length of the river is 147 km and it is part of the waterway system connecting Mantova with the Adriatic Sea.

The present morphology of the Po river delta is the results of centuries of hand-made transformation carried out by authorities through history. Between 1600 and 1604 the Venetian

Republic diverted the stream of river Po to the south, preserving the Venetian lagoon from further transformations caused by sediments transport from the river, and deeply changing the hydrographic profile of this land. Other human actions influenced the basin during the 20<sup>th</sup> century, such as methane extractions and sediment excavation, causing subsidence and lowering the floodplain till 3.5 meters below sea level.

Today, the Polesine territory is a strip of land with a length of approximately 100 km and 20 km width. Its area measures 1930 km<sup>2</sup> and it includes 50 municipalities. It is delimited for almost all its perimeter by embankments and barriers, similarly to a polder, and it is characterized by a strong agricultural connotation, lack of forestry, consistent water projects to defend the province and provide irrigation, and sparse, scattered urbanization through the monotonous landscape. The inner hydrographic network includes more than 2,000 km of canals and 80 dewatering pumps, constantly working to drain the excess of meteoric water. This system is strongly stressed during intense precipitation event, 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, as can be seen in the map (fig. 3.21).



**Figure 3.21:** Fissero-Tartaro-Canalbianco river basin. Area regulated by mechanical drainage system (waterpumps) are highlighted in blue (source: Regione Veneto, 2009).

There are three different land-reclamation authorities operating in the Polesine.

- The Polesine-Adige-Canalbianco authority includes the 532 km<sup>2</sup> area between Adige and Canalbianco, which is 94% of agricultural use. The altitude of the territory ranges from -4 to 7 m a.s.l., with 56% of the territory at the 0 level.
- The Padana Polesana authority manages the western area between Po and Canalbianco before Volta Grimana. The area measures 579 km<sup>2</sup>, 93% agricultural. It is the higher part of the territory, with only 12% of the surface at the sea level.
- The Po-Adige Delta authority involves the eastern area of the basin, 512 km<sup>2</sup>, between Canal Brondolo, the Adriatic Sea, the river Adige and the Po di Venezia. Some 74% of the land-use is agricultural, 2.3% is urbanized, and 24% is employed for fish-farming. 97% of the territory is around the 0 altimetric level, overall ranging from -3.7 to 1.5 meters.

In some periods of the year (mostly spring and autumn) the rivers reach a higher altimetric level, meaning they flow pensile compared with the surrounding territory (fig. 3.22). This is the result of both subsidence of the floodplain (5 mm/year) and the constant deposit of sediments in the riverbed. The Po levees reach an average of 10 meters of height above the floodplain even along the river delta.



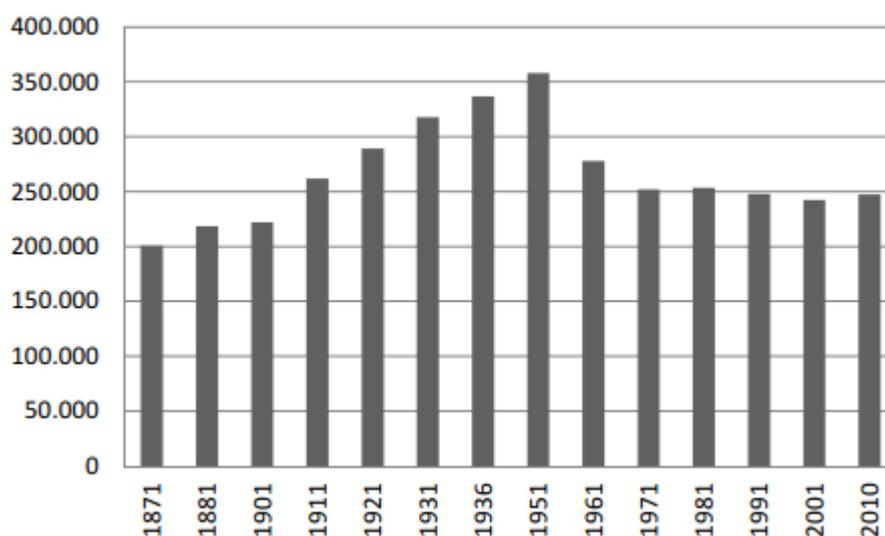
**Figure 3.22:** Schematic representation (not in scale) of altimetric difference between water streams and Polesine floodplain (Santato, 2010).

Despite the massive amount of water defenses, numerous flood events involved this territory, with the 1951 event (see cap. 3.8) being the more disastrous of last centuries. From 1952 to 1966, some 20 flood events from the rivers and from the sea engaged this province; after that, methane extraction wells were closed to avoid further subsidence, and massive defense

measures were built to avoid any disastrous events in the future. The map of hydraulic risk in the Polesine can be found in Annex C.

### Value at stakes: socio-economic profile of Polesine

Around 250,000 people live in Polesine, of which 50,000 are located in the chief town of Rovigo. The Population density (138 people/km<sup>2</sup>) is low compared with both the regional mean (268 people/km<sup>2</sup>) and the national mean (201 people/km<sup>2</sup>). The growth trend is almost flat since the disaster of 1951 (fig. 3.23) and projections suggest it will remain stable for the next 40 years, while the average age will increase (Regione Veneto, 2009). This means that the local population will get older while youth tends to emigrate outside the province. In fact, after the 1951 flooding, 150,000 people left the province and entrepreneurs start preferring other territories to invest and create business. This consequence obviously affected the job market, arresting the economical development of the area and forcing new jobseekers to move outside.



**Figure 3.23:** numbers of people living in Polesine since 1871. The trend shows no significant changes in the last 40 years. The massive emigration happened after 1951 is clearly visible (Santato, 2010).

The primary sector has a major role in this province, even if the number of farms is at sixth place in the region (10,787, corresponding to 5.6% of the total regional amount). This territory maintained a marked agricultural vocation and it was just marginally affected by the fast industrializing process happening in the Italian north-east area from the '70-'80s. The mechanized arable land monocultures (maize, cereals and soy) cover the most of the agricultural surface (95% c.a.), with little forage and meadow areas supplying the few remaining zootechnical enterprises. Permanent arboreal cultures are not really diffused (4,15%)

since neighbor provinces are more specialized in vineyards and fruit trees cultivation, thus providing a strong market competition. On the contrary, fishing and fish farming is a diffused activity on the coastal side of the province, even though the number of fish-farms valleys has significantly reduced since the last century. Tourism is an increasing business in the province, with almost 2 million visitors every year (mainly during summer), allowing the presence of little to medium size tourism-related enterprises. In conclusion, nowadays the Polesine is a monoculture lowland with few urban areas and reduced natural environments, the latter being mainly located in the eastern part of the delta.

## 4. Climatic Scenario

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### 4.1. Effect of climate change on flood scenario in Europe

#### Global meteorological forcing

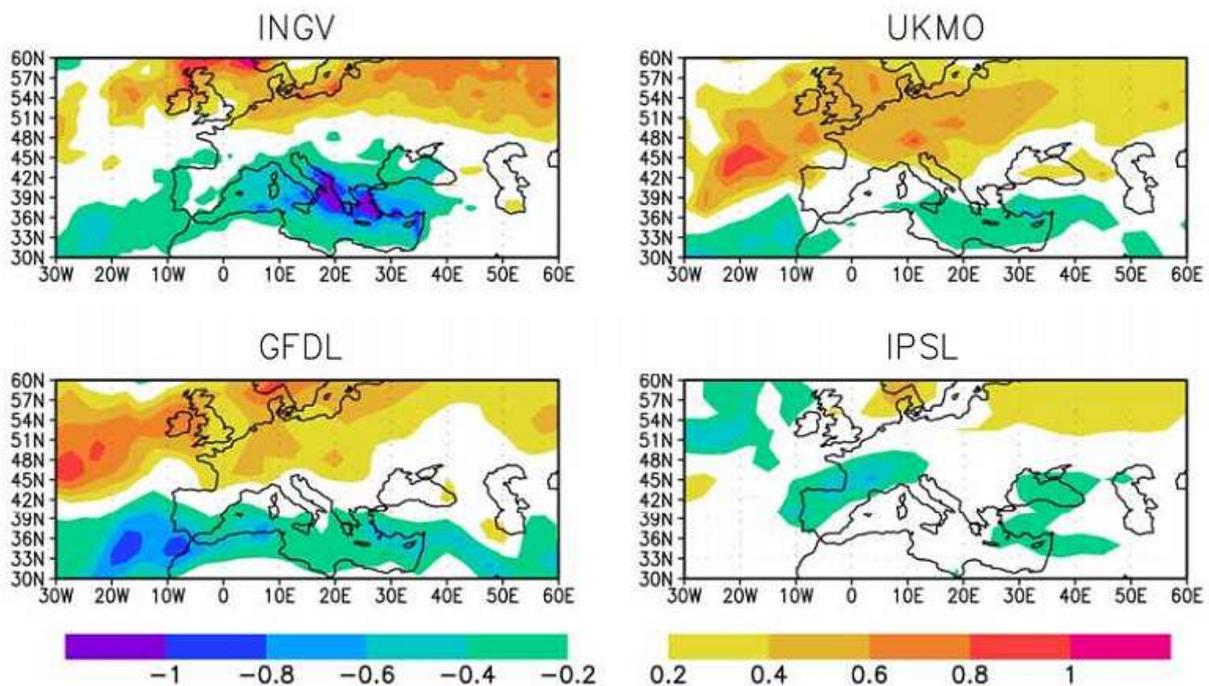
Over the past decades, the European Union witnessed a striking increase in the losses caused by natural disasters, in particular by hydro-meteorological disasters. Every year large areas of Europe are hit by droughts and/or floods, directly or indirectly affecting many communities and economic sectors. Floods are cause of enormous damage in Europe both on economical and social aspects: the present expected damage is 6.5 billion € per year, and chances of human casualties are always accounted. Considering the A2 climate change scenario from the Special Report on Emission Scenarios (SRES A2) produced by IPCC (Fourth Assessment Report), projections suggest that economical losses may rise to 18 billion € per year for the period 2071-2100 (Kundzewicz, et al., 2010).

In fact, as the increase in greenhouse gasses (GHG) concentrations in the atmosphere will cause the so-called “global warming”, the hydrological cycle of earth will also be affected. Projections from IPCC 2007 report (IPCC, 2007) quantify the future warming by an increase of 0.2°C every ten years for a wide range of predictive models about atmospheric circulation (AOGCM), employed to define global scenarios of climate change. IPCC also notes that, for concentration of GHG and aerosol settled to levels of year 2000, there will be still an increment in temperature quantified in 0.1°C every ten years. The forecasted increments in the average temperature values will augment the moisture content of the atmosphere and so the global mean precipitation, which will consistently affect the discharge volumes of watersheds. Apart from the average trends, the most significant consequence expected from climate change is the increase in the magnitude of extreme events, both floods and droughts. In particular, the raise in magnitude and frequency of extreme precipitations will have consequences on river discharges leading to a more intense and frequent river flooding (Dankers, et al., 2008; Lehner, et al., 2006). A direct correlation links the rise of temperature with extreme precipitation through the Clausius-Clapeyron relation, as found by Lenderink, et al. (2010) for Western Europe.

Global warming will also change the seasonality of river discharges, since winter precipitations will fall more as rain than snow in most area of Europe, causing a reduction in the snow

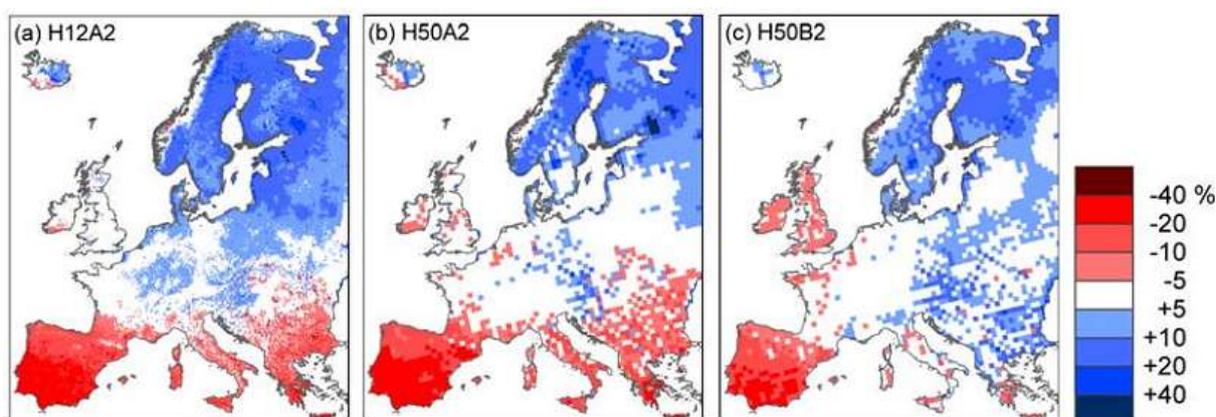
coverage. This, together with the anticipation of snowmelt, will reduce spring river flows in favor of a more consistent runoff during winter months. However, in regions that currently have low amounts of snow precipitation during the year (central and southern Europe), the water runoff is more dependent on alteration of rainfall and will be less affected by the raise of temperature, so that extreme rainfalls will cause immediate effects on the flow peaks (Kundzewicz, et al., 2010).

It is important to notice that not all climate projections agree on the change in precipitation regime; while an ubiquitous increase in temperature means is a projection shared by various models (+0.1/+0.2 °C per decade, the magnitude depending on the GHG scenario), some of them disagree even on the sign of the change for precipitation values (Kundzewicz, et al., 2010). For example, as reported in Navarra (2007), four different models for the IPCC A2 scenario (2061-2090) give noticeably different output for winter precipitation in Europe (figure 4.1). Generally speaking, northern Europe will probably become wetter and southern Europe will be drier, but it is hard to assess this change to a local scale due to inadequate resolution of global models.



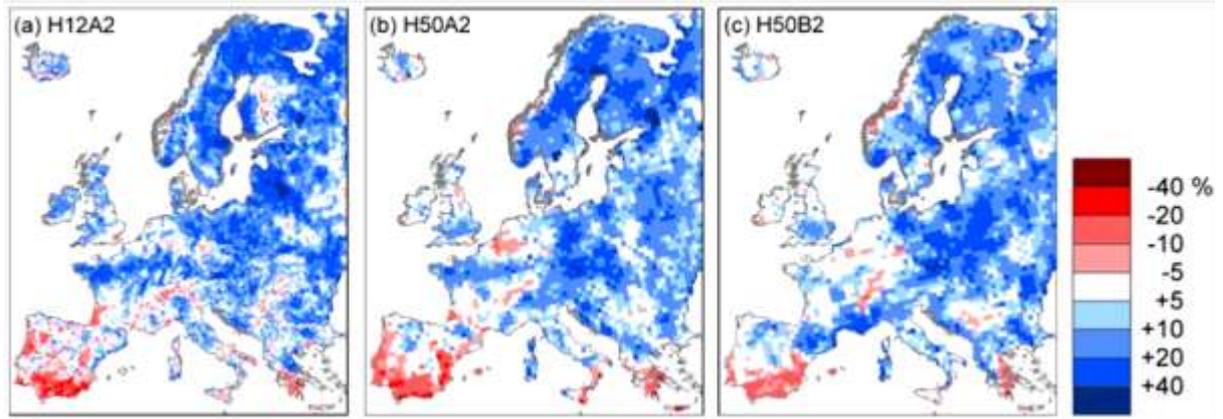
**Figure 4.1:** Four different projections for winter-spring precipitation (JFM) for the A2 scenario (2061-2090) compared to a 30-year average control run (1961-1990) (adapted from Navarra, 2007).

Considering the RCM HIRHAM simulative model (Regional Climate Model developed by DMI and Max Planck Institute), we can see how rainfalls are forecasted to change according to the IPCC scenario A2 (medium-high emissions scenario, with atmospheric  $[\text{CO}_2]$  reaching 715 ppm at 2100) and scenario B2 (medium-low scenario, with  $[\text{CO}_2]$  reaching 562 ppm.), as shown in figure 4.2. “H50A2” and “H50B2” are referred to the two runs of the model with a resolution of 50km and a GHG forcing reflecting the IPCC A2 and B2 scenarios, respectively. “H12A2” refers to a model run with a finer resolution of 12Km for the IPCC A2 scenario. The time frame used for the simulation run is period 2071-2100, which is compared to a control run on 1961-1990. While some discrepancy between H50A2 and H50B2 show uncertainty regarding UK and eastern Europe, they eventually agree about central Europe and Spain. Regarding Italy, a slight decrease in annual rainfall seems to be more probable, but the intensity of the change is difficult to assess. The Po River basin is part of the area where the two runs of the model do not agree, with the magnitude of the change shifting from +5% to -5%.



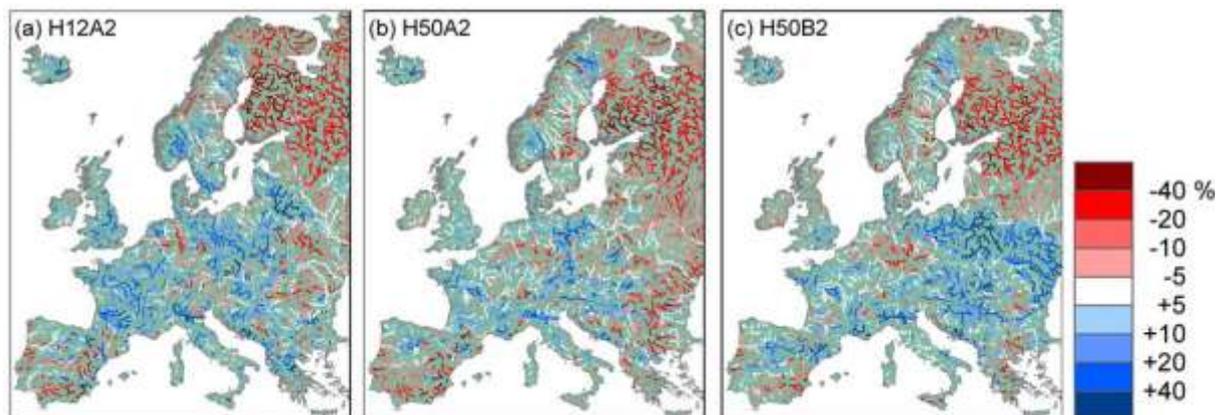
**Figure 4.2:** Variation in the annual average precipitation for scenario A2 and B2 (2071-20100). Values are compared to a 30-year average control run (1961-1990) (adapted from Dankers, et al., 2008).

However, the behaviour of extreme events is projected to diverge from the means over many areas of Europe: the intensity and the annual maximum of daily precipitation is forecasted to rise even in areas where the mean amount of rainfall will lower: in particular at middle and high latitudes, rainfalls are projected to concentrate into more intense events, with longer dry periods in between (Kundzewicz, et al., 2010; Dankers, et al., 2008). Figure 4.3 shows the change in the annual maximum for 5-day accumulated rainfall obtained through the RCM HIRHAM simulative model.



**Figure 4.3:** Variation in the annual maximum for 5-day accumulated rainfall 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).

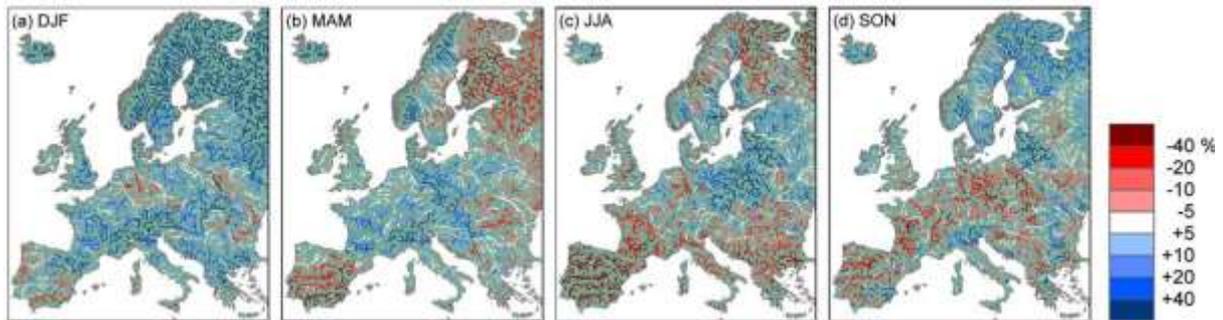
Accumulated rainfalls are reflected in terms of flow discharge, shown in figure 4.4. The results of HIRHAM simulations for temperature, precipitation, solar radiation, humidity and wind have been applied as input to run the hydrological model LISFLOOD, a spatially distributed model used for operational flood forecasting. It uses a 5-km grid on the whole European area, and includes parameters about soil morphology and land-use from EU databases as well as data on infiltration, snowmelt, river flow, reservoirs dynamic. Further statistical corrections have been applied to the output of LISFLOOD.



**Figure 4.4:** Variation in the 100-years discharge levels for scenario A2 and B2 (2071-20100) on the basis of a Gumbel distribution. Values are compared to a 30-year average control run (1961-1990) (adapted from Dankers, et al., 2008).

The Po River basin is included in the area that will face a lowering of precipitation means, but projections about river discharge show in that area a noticeable increase in flood hazard for all seasons except summer, as in figure 4.5. We can notice that the Po River basin shows an annual increment of 100-year river discharge between 20% and 40%. As in the 12-km grid model run

(H12A2) in fig. 4.4, especially upstream tributaries will see a remarkable increment in the frequency of 100-year return floods, even if the partial discordance (15% of grid cells) on the sign and intensity of change with the B2 scenario (H50B2) suggests a substantial uncertainty (Dankers, et al., 2008).

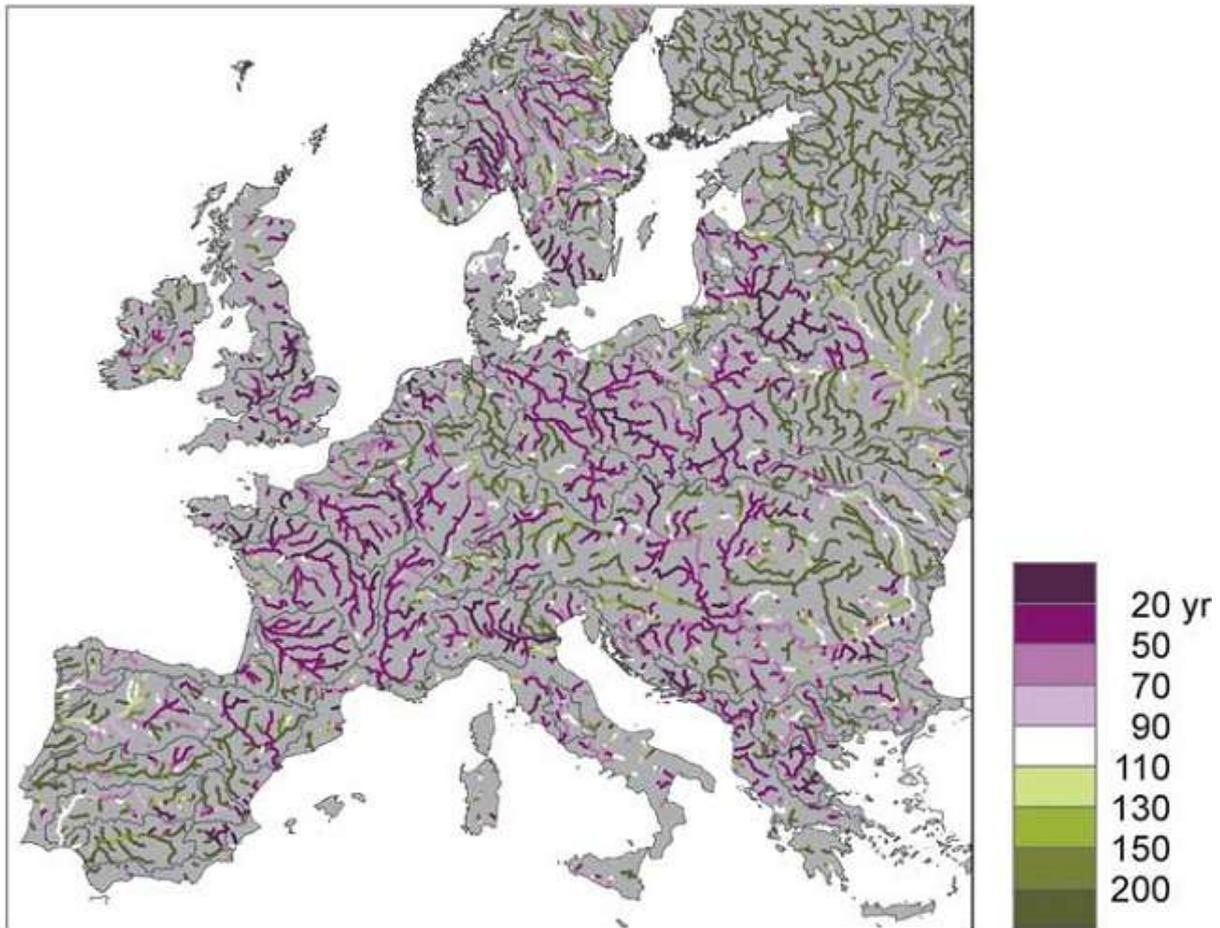


**Figure 4.5:** Seasonal variation in the 100-years discharge levels for the H12A2 model run, on the basis of a Gumbel distribution. 20-40% increase in river discharge are shown in Winter (a), Spring (b) and Autumn (c), while Summer (c) presents a decrement between 10-20% (adapted from Dankers, et al., 2008).

Yet, small-scale and meso-scale processes have critical influence on the river peak flows, so that the percentage values cannot be considered much significative. This is the reason why single watersheds are typically analyzed with customized hydrological models, which are tuned taking in account the detailed conformation of the basin and the local processes; though this may cause single case-studies to be incomparable due to the employment of different models or different statistical methods (Lehner, et al., 2006).

### Flood frequency

The increase in the magnitude of exceptional river discharge will significantly affect the recurrence of the present-time 100-years flood events. Figure 4.6 shows how the frequency of actual 100-years flood will change in Europe.



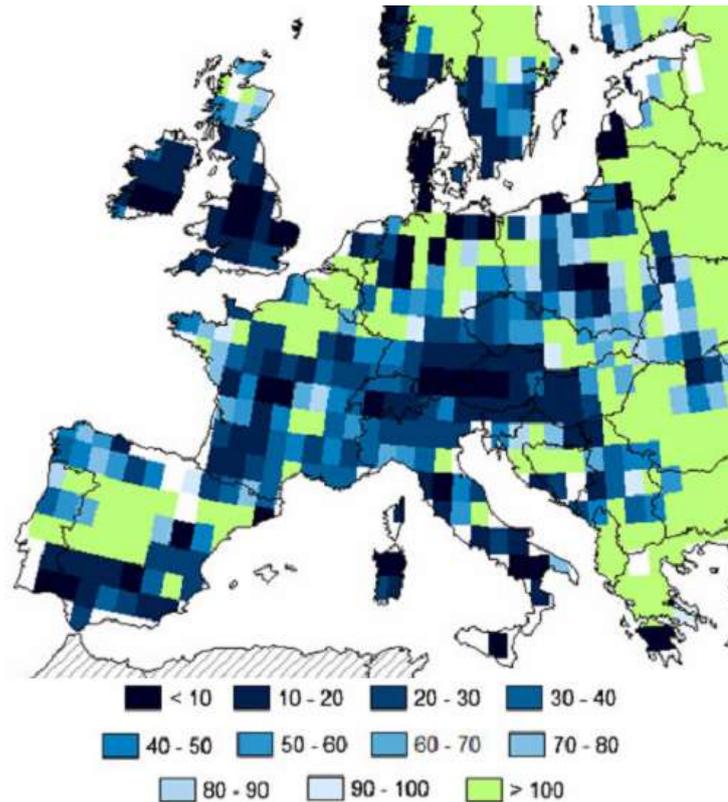
**Figure 4.6:** Variation in frequency of actual 100-years discharge levels for the H12A2 model run, on the basis of a Gumbel distribution (adapted from Dankers, et al., 2008).

In river Po as much as in several other major rivers (Loire, Elbe, Oder, Danube) the return period for the actual 100-years events is estimated to decrease to 50 years or even 20 years: more than twice than the present (Dankers, et al., 2008).

Comparing the map of projections to a similar analysis run by Hirabayashi et al. (2008, as reported in Kundzewicz, et al., 2010), reported in figure 4.7, we can see broad areas of agreement in the results, with more frequent exceptional floods in northern Italy as in Poland, France, UK and southern Sweden.

Even though these shared results may give some knowledge about mid-term future scenario, we have to take in account the amount of uncertainty connected with this kind of analysis. First, the data about discharge trends used to

compare future projections are referred to the past 30 years: this period of time is relatively short to assess a flood return period of 100 years. Secondly, an important extent of uncertainty comes from the impossibility to foresee all the futur socio-economical changes in the area, such as development, use of soil, or mitigation and adaptation policies. All these variables also inherently carry complex feedback effects which are hard to include as functions in a climate impact model. For these reasons, Kundzewicz, et al. (2010) concludes that “observations to-date provide no conclusive and general proof on how climate change affects flood risk” (Kundzewicz, et al., 2010).



**Figure 4.7:** Frequency of actual 100-years discharge levels for the A1B SRES scenario (2071-2100) (adapted from Kundzewicz, et al., 2010).

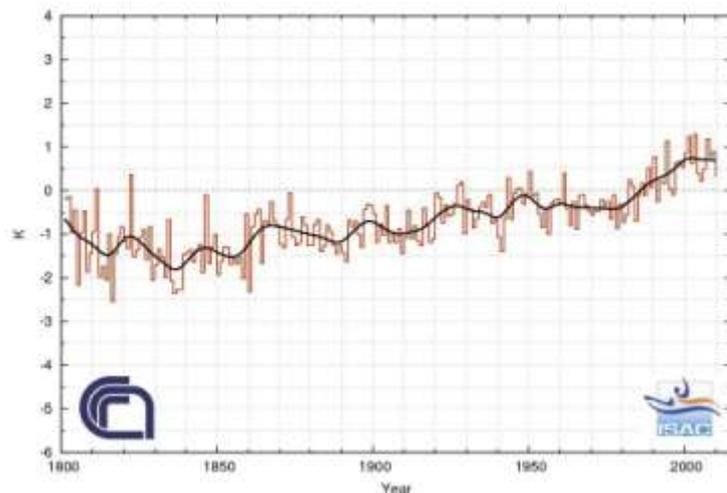
## 4.2. The local scenario: trends and forecasting

We had explained the reasons why macro-scale projections are not fully adequate to provide reliable conclusions about the meso-scale and the small-scale of a single watershed, though they can give some indication about the general trend. So we are going to introduce local observations and measurement to help defining with finer detail the processes occurring in the case study area.

### Past trends in Temperature and Precipitation

Through the analysis of thermometric and pluviometric time series carried out in about 100 Italian meteorological stations, Brunetti et al. (2007) draw the trend of temperature and rainfall. This analysis takes in exam the regional mean series instead of the single stations, to make the statistical signal more solid and less prone to casual errors. The results show an increment of 1°C every 100 years, uniformly distributed through all Italian regions, even though it is not evenly distributed over the year.

Temperature time series shown in figure 4.8 reveal a stationary trend until 1970, followed by a rapid increase leading to 2003, the warmest year of the whole series. Observing seasonal series, significant differences can be highlighted; in particular, the strong warming increase in the last part of the series is noticeable during spring and summer, but not

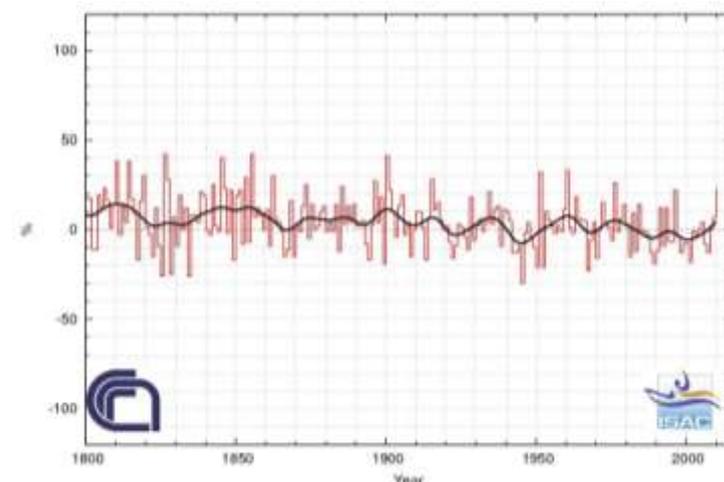


**Figure 4.8:** Temperature time series for the past 200 years (Brunetti, et al., 2007).

during autumn and winter, seasons in which this trend is less marked.

For the precipitation time series, the decrease in precipitation is still visible, but it is defined as

“minor and statistically little significant”.



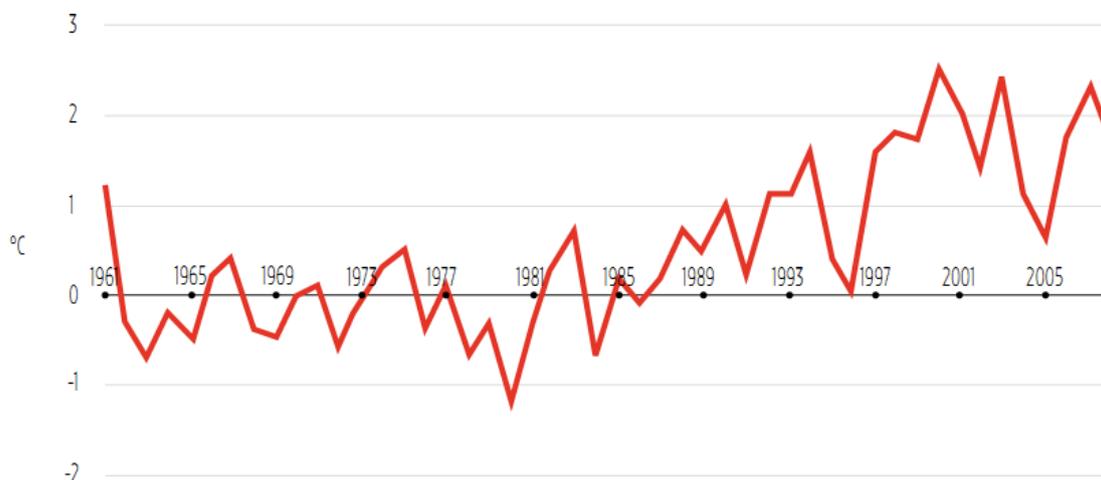
**Figure 4.9:** Precipitation time series for the past 200 years (Brunetti, et al., 2007).

As shown in figure 4.9, the sequence of relative maximum and minimum in annual precipitation does not highlight any significant tendency towards an increase or decrease. As for the thermometric series, also in this case there is a good

correspondence between different regional series (Brunetti, et al., 2007).

The trends values are slightly negative, but Brunetti states this can be caused by a particularly high value of rainfalls in the first decades of the series; while if we consider the series from 1900, this trend tends to be not important. However, the trend tends to become slightly more negative in the last 50 years.

To compare another source, data proposed by ARPA Emilia Romagna (Cacciamani, et al., 2010), graphed in figure 4.10, show an increase in temperature trends from the '80s to 2010 in the Po River basin. The estimate is  $+2^{\circ}\text{C}$  in the last 40 years, which means an average of  $+0.5^{\circ}\text{C}$  every ten years: this result is five times higher compared to Brunetti et al. (2007). In details, the last 20 years result to be the warmest of the whole series. This trend is common to every period of the year, but appears to be more marked during summer.

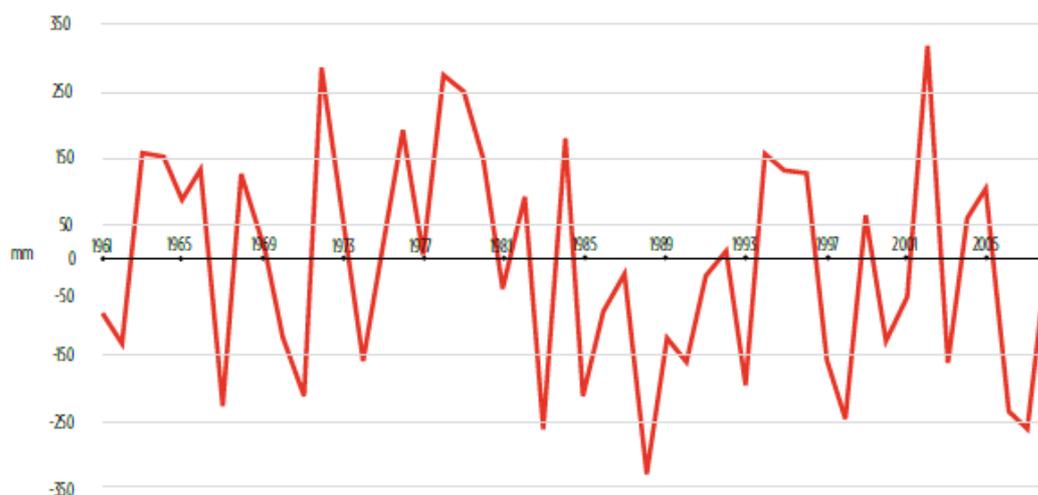


**Figure 4.10:** Trend in daily max temperature for 1961-2008 compared to 1961-1990 average (Cacciamani, et al., 2010).

The reduction of annual mean precipitation in the last 30 years is quantified by 20%. This analysis detects an overall decrease of rainfall and, in parallel, an increase in important rain episodes by some degrees. The decline is estimated to 50% during spring and summer, while it is much less marked during autumn. Snow precipitation in winter result to be equally decreasing, so as the volume of glaciers and snow cover; this is mainly a consequence of the shorter duration of the snow accumulation season, which starts later and ends earlier. A prosecution of the actual negative trend is expected for the future, with an increase of inter-annual and inter-regional variability.

This trend, joint with the progressive increase in water consumption, provoke a significant reduction in the mean water flow of Po river, especially in the final section of the basin

(Pontelagoscuro station), by 20% on annual basis and by 45% during summer season (1975-2006). It is highlighted how the general reduction of precipitation happens with a sudden negative shift of the values from the beginning of the '80s compared to the mean 1960-1990 (figure 4.11).



**Figure 4.11:** Trend in mean annual precipitation for 1961-2008 compared to 1961-1990 average (Cacciamani, et al., 2010).

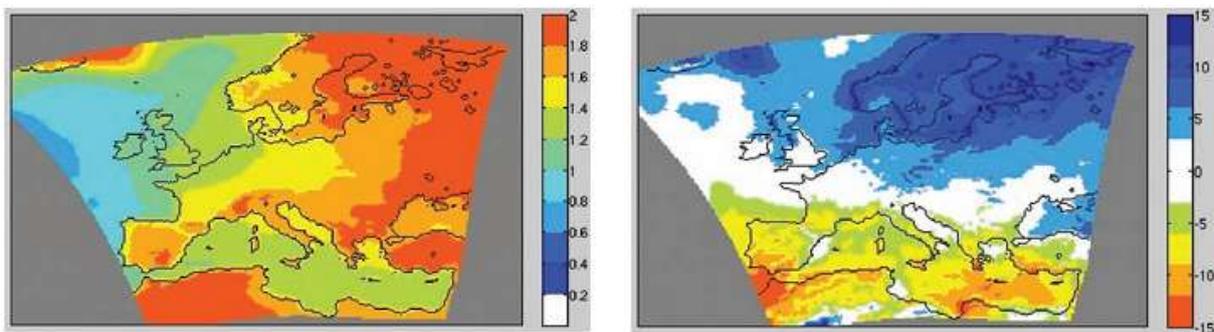
The difference in mean rainfall quantities in the last 25 years is estimated to be about 100 mm. It is a noticeable measure, corresponding to 10% of the mean annual rain in Emilia Romagna (Cacciamani, et al., 2010). These conclusions, compared against Brunetti et al. (2007), appear to be slightly biased by the reduction of the observations timeframe; nevertheless the slow decreasing trend noticeable in the last years of the series is concordant with the forecasting provided by the macro-scale models already examined.

### Future local scenario

To reduce the uncertainty on 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, et al., 2009) aimed at this goal. ARPA Emilia Romagna gave its contribution to these projects producing a downscaled model for its region. 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, et al., 2007). These two techniques are

comparable in their efficiency for simulating climate change (STARDEX, 2005). Some of the more reliable results of these researches regard the climate change scenarios of temperature and precipitation for 2021-2050, compared to 1961-1990 trends. The GHG emission scenarios used to run the simulations are, again, SRES A2 (medium-high scenario,  $[\text{CO}_2]$  reaching 715 ppm) and B2 (medium-low scenario,  $[\text{CO}_2]$  reaching 562 ppm) (Van der Linden, et al., 2009; STARDEX, 2005).

Coherently with the RCM HIRHAM models (Dankers, et al., 2008), the temperature signal 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 4.12). Results from different models used in the ensemble are comparable with modest variability throughout Europe, which imply a strong credibility (Cacciamani, et al., 2010).



**Figure 4.12:** Climate change signal for annual temperature (right) and precipitation (left) for 2021-2050. The total change is expressed as percentage compared to 1961-1990 means. Data are obtained as a mean of the multi-model ENSEMBLES RCMs (Van der Linden, et al., 2009).

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, et al., 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, et al., 2010; STARDEX, 2005; Tomei, et al., 2010).

## 5. Materials and Methods

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### 5.1. Methodological approach to flood damage evaluation

On the basis of the theoretical framework drawn in chapter 2 and the review of literature of chapters 3 and 4, four basic operational steps are drawn to define the fittest methodology for assessing flood damage in our case study. Guidelines on flood damage evaluation from Messner, et al. (2007) are also taken in account as a reference, as they are based on the comparison between several valuable studies on flood damage evaluation.

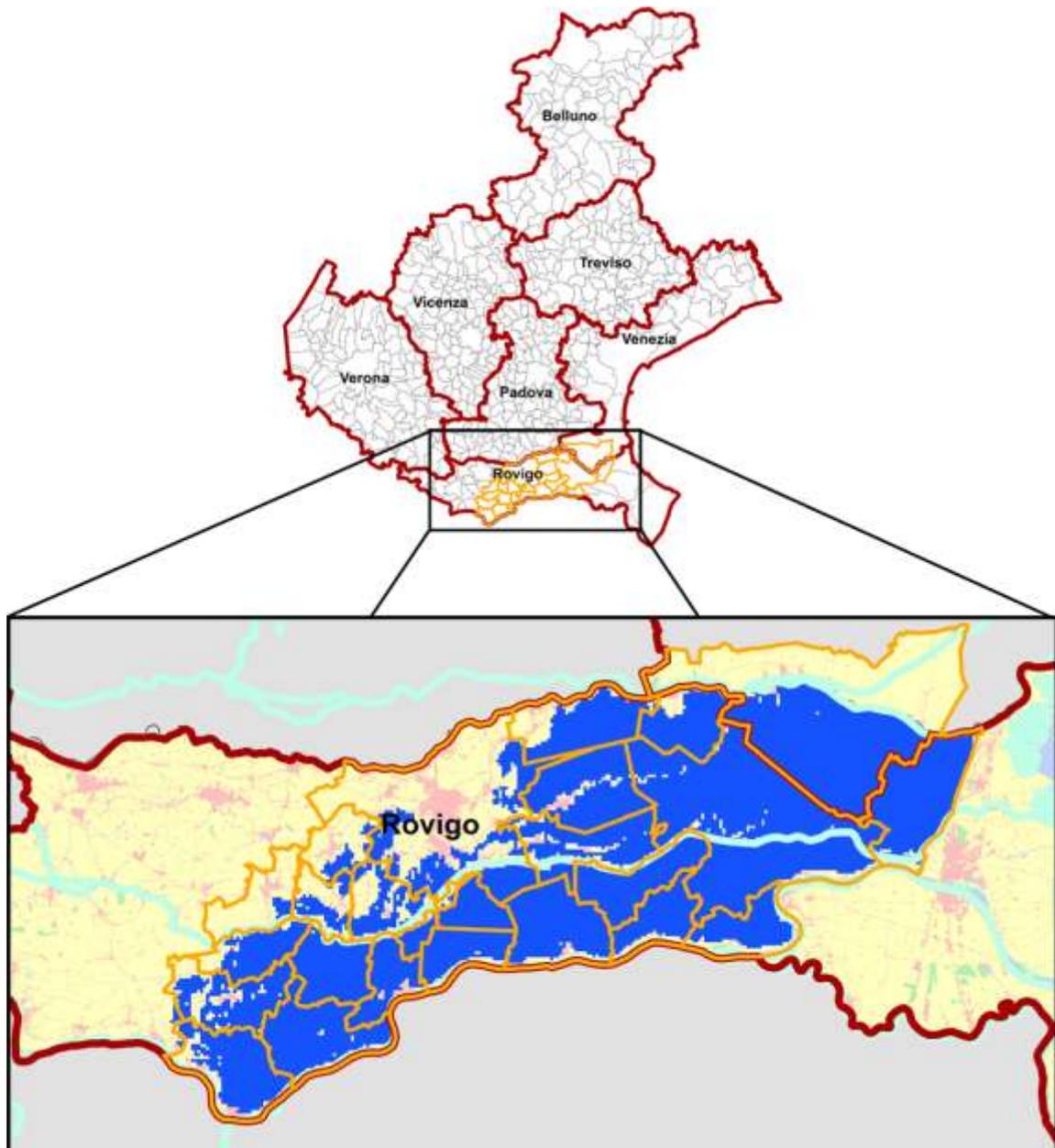
Our methodology is based on the risk paradigm described in chapter 2.1. The final output of this evaluation is the quantification of the Risk value and its visualization in a GIS environment. The Risk value represents the potential damage suffered in the involved area and it is defined as the product of Hazard, Exposure and Vulnerability. These parameters are operationalized in Step 2 and 3.

For what concerns operational instruments, ArcGIS has been the main tool employed to manage, visualize and elaborate the data. Datasets from different sources have been added and transformed to share the same geo-referencing system.

### 5.2. Step One: selection of an appropriate approach

The approach is chosen on the basis of four variables.

1. **Spatial level:** a preliminary analysis of the maximal hazard extension allow to limit the area of the analysis, identifying a total of 25 municipalities (24 included in Rovigo Province and 1 included in Venice Province, highlighted in fig. 5.1 and listed in tab. 5.1) which are involved in the simulated flood scenario. The size of the area suggests a meso-scale approach, which drives the choice of the dataset and the level of aggregation for land-use units; though, data from different sources may have different resolution, needing a further elaboration.



**Figure 5.1:** Veneto Region, spatial identification of the area involved in the maximal flood scenario. Red lines define Provinces boundaries, yellow lines define involved municipalities. The blue area represents the maximal flood extension.

#	Area (km <sup>2</sup> )	Municipality	Province	Population
1	140.6	Cavarzere	VE	15,005
2	31.1	San Martino di Venezze	RO	4,030
3	21.5	Pettorazza Grimani	RO	1,699
4	108.5	Rovigo	RO	51,872
5	113.6	Adria	RO	20,549
6	32.5	Villadose	RO	5,309
7	16.1	Costa di Rovigo	RO	2,791
8	30.1	Ceregnano	RO	3,846
9	20.9	Fratta Polesine	RO	2,771
10	20.0	Arquà Polesine	RO	2,911
11	14.0	Villamarzana	RO	6,146
12	18.2	Villanova Marchesana	RO	5,719
13	11.5	Pontecchio Polesine	RO	1,913
14	6.0	Bosaro	RO	1,400
15	22.1	Papozze	RO	1,705
16	21.9	Frassinelle Polesine	RO	1,538
17	16.5	Polesella	RO	4,184
18	27.4	Fiesso Umbertiano	RO	4,311
19	32.7	Canaro	RO	2,877
20	32.5	Occhiobello	RO	11,315
21	17.7	Pincara	RO	1,274
22	39.5	Loreo	RO	3,754
23	31.8	Crespino	RO	2,082
24	24.3	Gavello	RO	1,648
25	17.2	Guarda Veneta	RO	1,215
TOTALE	868.5			161,864

**Table 5.1:** List of municipalities involved in the maximal flood scenario (source: Regione Veneto, 2008).

2. **Objective of the study:** this research follows the dominant approach focusing on direct tangible damage, which usually contributes for a significant portion of the total (Messner, et al., 2007). Our analysis do not aim to assess the precise amount of damages (e.g. for investment purpose), but rather to give a general overview on potential future damage scenarios; moreover, the time available for this research is limited, so less costly and time-consuming methods are preferred. This choice, together with the scale of the study, will define the number of land-use classes and their level of aggregation.
  
3. **Availability of resources:** again, due to limited amount of time and financial resources, the highest level of precision is not affordable to be reached. Quicker, easier and approximated methods have to be chosen in order to comply with these restrictions. The computation of potential damage is carried through the employment of functions correlating the water depth (hazard value) with land-use data (exposure value). Each land-use class employs a proper function including a corresponding parameter for vulnerability. The creation of

appropriate and specific functions for the case study area would require a huge amount of time and on-site work, so they are obtained from third parts studies.

- 4. Availability of pre-existing data:** the existence of adequate land-use data and damage functions is essential. Free regional datasets on land-use and ISTAT national statistic database supply for the details about the assets at risk, while data about flood characteristics are provided by ARPA ER. Depth-damage functions for each land-use classes are supplied by the EC Joint Research center, which developed them in a dedicated study (HKV Consultants, 2007).

### **5.3. Step Two: determination of the damage categories**

Direct tangible damage categories are varied, and include buildings, infrastructures, cars, inventories, etc. However, some of them usually occupy a bigger share of the total damage, while others can be neglected due to case-depending reasons. It is then reasonable to reduce the effort of the study, using only the most important damage categories.

In our study, damage on streets and railways may be neglected because this type of infrastructures is not very susceptible to flood depth and duration, but only to high flood speed. This kind of damage in plain flood areas rarely accounts for more than 1%, mostly because of bridges (Messner, et al., 2007). However, roads and railroads are always taken in account in this kind of studies. Given the easy availability of data about this category, it will be eventually included in the impact assessment.

Another exposed category which may account for a significant rate of the total damage is the damage to cars and other vehicles, though this share of damage can be easily avoided if emergency alerts are made in time. Differently, commercial vehicles are accounted as part of the fixed asset of commercial activities. To assess the flood impact on private vehicles, the average market price of used car (replacement cost) is applied. However, this approach gives approximate results which must be considered as merely indicative of the real value.

Compared to the total amount of damage, agrarian products (crops and livestock) are generally not a significant part. In addition to this, their share of damage is not easily evaluable: crop damage is strongly season-dependent, while harm to livestock depends on the readiness of the alert and evacuation. Therefore, their detailed evaluation makes sense only in very rural

contexts. In other cases, simple methods such as application of typical damage share can be employed. A further discussion on the seasonality of crops will be made.

#### **5.4. Step Three: gathering information about hazard characteristics and values at risk**

Four main parameters are defined for this step:

*1. Flood characteristics (Hazard value):* 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 on 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 by ARPA-SIM Emilia-Romagna 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

The first two models have already been mentioned as they are normally applied in the early flood warning system (see paragraph 2.7). 1D models are relatively simple, fast and not much data-intensive; they calculate the behavior of a mono-dimensional flow between the cross sections of the river basin through the St. Venant equation. 2D models are more complicated, but they allow a more detailed description of the flow processes. They need more input data about the flow and the surface area (Digital Terrain Model) and a longer time to run. Each scenario elaboration required approximately one day of calculation by ARPA-SIM computer network.

Different scenarios have been generated from these models, with different starting hypothesis drawn on the basis of the climatic forecasting background discussed in chapter 4. At first, 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 in 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 Canalbiano, Adigetto and Ceresolo) are not considered as streams contributing 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.

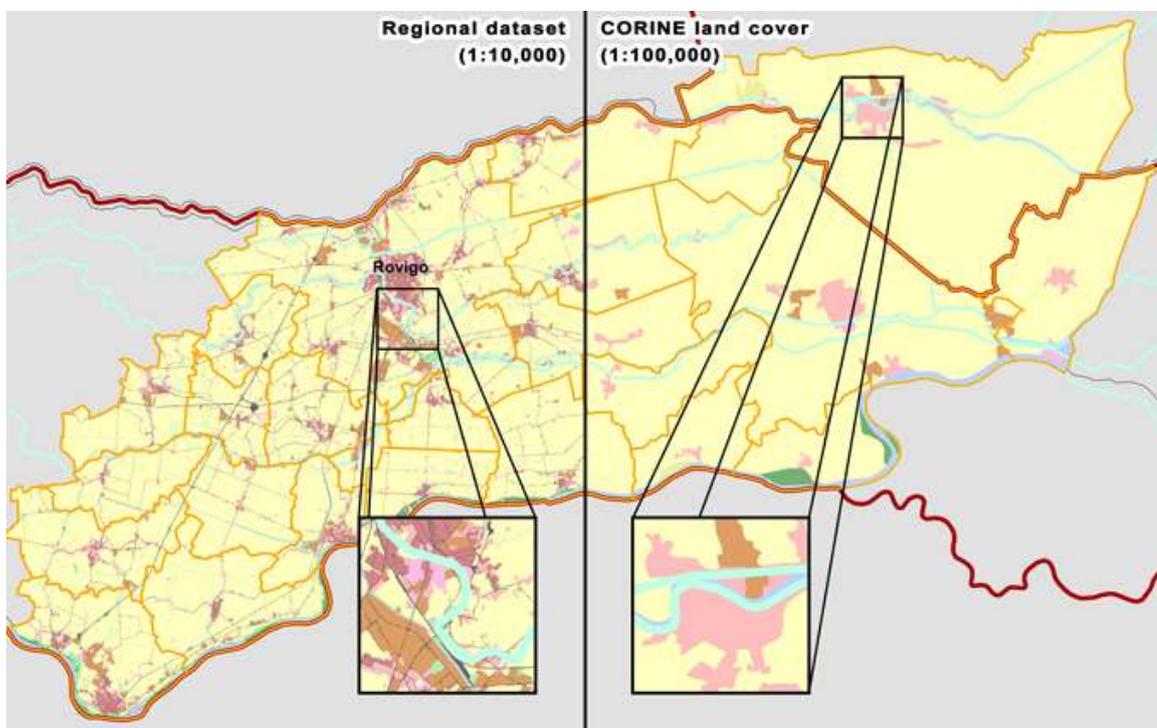
To obtain realistic discharge scenarios, observation data of the October 2000 event (see paragraph 3.7) have been used to define the base scenario in the period 10-18 October. Climate Change conditions reviewed in chapter 4 have been discussed with the experts from the ARPA-SIM (“hydro-meteorological 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 (see paragraph 3.8). 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.

<i>Scenarios</i>	<i>Definition</i>	<i>Rainfall rates (compared to 2000 event)</i>	<i>Rupture</i>
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 5.2:** 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.

- 2. Assets at risk (*Exposure value*):** land-use data about the number and typology of affected properties can be obtained from pre-existing data sources, as defined in Step One. The CORINE Land Cover (CLC) project provides data about aggregated land-use for all European countries with a working scale of 1:100,000, while the surface area of the smallest unit mapped in the project is 0.25 km<sup>2</sup>. In this scale, the smallest area corresponds to a 5x5 mm square (European Environmental Agency, 1994). While often successfully used for national-scale studies, this coarse resolution does not provide useful insight for our case study. Regional web-database (Regione Veneto, 2009) provides with more 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 km<sup>2</sup>. There are 62 land-use categories, divided in 5 hierarchic levels. The detail comparison between the two datasets is shown in fig. 5.2.



**Figure 5.2:** detail comparison between Regional land-use dataset (1:10,000) and CORINE land cover dataset (1:100,000) at the same level of aggregation.

For the sake 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 5.3. Forest and semi-natural areas, wetlands and water bodies are other main categories not taken in account in the impact assessment.

<i>Urban surface</i>	<i>Agricultural surface</i>
<ul style="list-style-type: none"> <li>• Continuous urban fabric (density &gt;50%)</li> <li>• Discontinuous urban fabric (density &lt;50%)</li> <li>• Industrial and commercial</li> <li>• Mine, dump and construction sites</li> <li>• Other artificial areas</li> </ul>	<ul style="list-style-type: none"> <li>• Arable land (maize, cereals, soya, beet, sunflower)</li> <li>• Permanent crops (fruit trees, vineyards)</li> <li>• Pastures</li> </ul>

**Table 5.3:** 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 km<sup>2</sup> 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.

3. **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 €/m<sup>2</sup>. 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 discretionary 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.

4. ***Susceptibility of assets at risk (Vulnerability value)***: damage functions can be “relative”, showing the damage as a share of the total value, or “absolute” showing just the total amount of damage related to flood characteristics. Both of them operate at any scale, but absolute damage functions should be preferred if they are already available for the case study area, as they reduce the effort of the study (Messner, et al., 2007). 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:
- $$Damage = a \times \sqrt{depth}$$

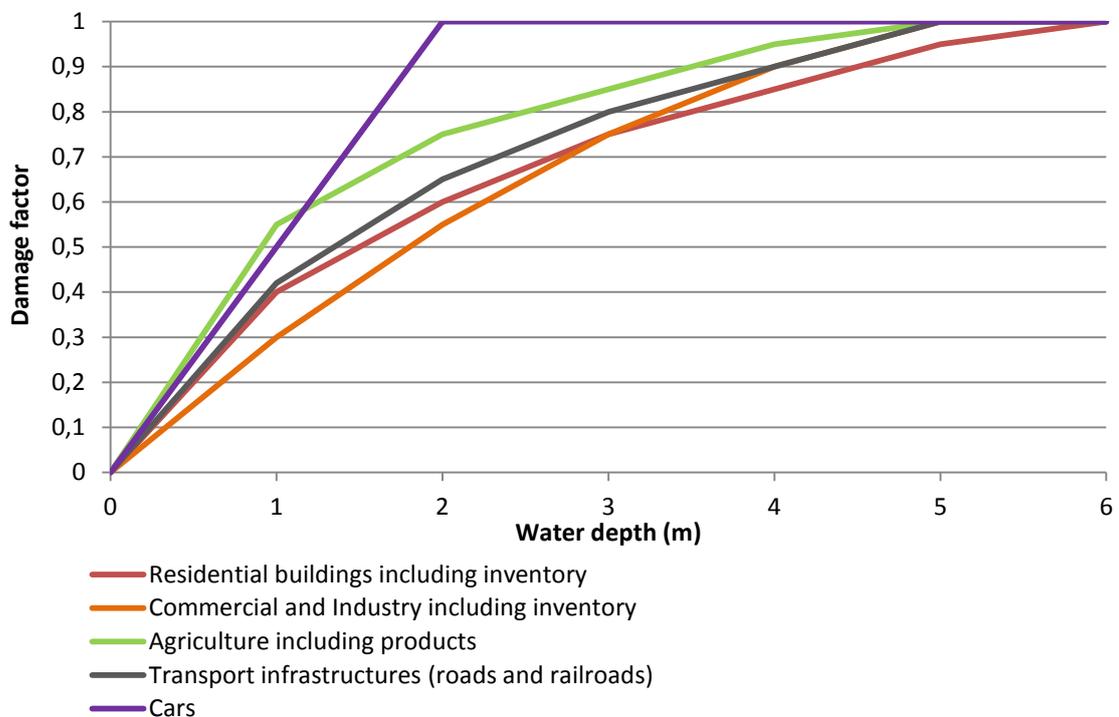
with “a” being the parameter dependent on the category.

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 economical 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).

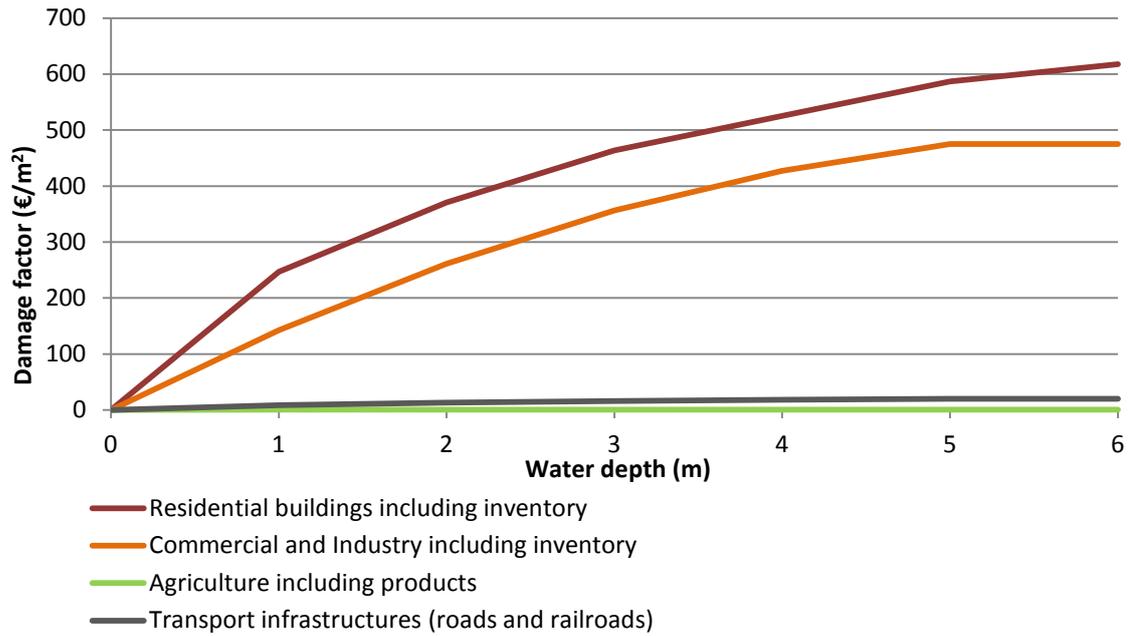
The following table (5.4) summarizes the average functions for each land-use category. Figure 5.3 and 5.4 show the line graphs relative to the damage functions.

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
	<b>Maximum damage value (€/m<sup>2</sup>)</b>				<b>(€/n)</b>
	618	475	0.63	20	14,450

**Table 5.4:** Depth-damage factors and maximal damage for each category (adapted from HKV Consultants, 2007).



**Figure 5.3:** Average depth-damage functions for each damage category.



**Figure 5.4:** Depth-damage costs in €/m<sup>2</sup> each land-use category (Italy).

Damage amounts can be further translated into Purchasing Power Parities (PPP), which is an international indicator to express an amount of money in term of national GDP purchasing power. Its currency is the International Dollar. The conversion factor for Italy is equal to 0.87 (1 PPP \$ = 0.87€) (rates from data.un.org).

### 5.5. Step Four: calculate the expected damage for a certain event

After collecting all the data, the total amount of damage for each category is thereby calculated. Figure 5.5 summarizes the evaluation process discussed until now.



**Figure 5.5:** schematic representation of the flood damage evaluation process.

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 total uncertainty in the results includes contributes of uncertainty from flood simulation, from land-use data, from value assessment, and from depth-damage functions. The quantitative dimension of these uncertainties is not measurable, but a qualitative appraisal can be made. Flood risk management needs a more detailed evaluation of uncertainty to support decision making, but for high-level strategic decision making an approximated damage evaluation can be sufficient (Messner, et al., 2007).

The methodological approach described in this chapter is summarized in table 5.5.

<b>Step 1</b>	<b>Approach and data requirements</b>	<ul style="list-style-type: none"> <li>• Meso-scale (province, municipalities)</li> <li>• Flood scenarios and characteristics</li> <li>• Aggregated land-use data</li> <li>• Approximate values for land-use categories</li> <li>• Damage functions</li> </ul>
<b>Step 2</b>	<b>Damage categories considered</b>	<ul style="list-style-type: none"> <li>• Land-use categories</li> <li>• Furniture</li> <li>• Cars</li> <li>• Agricultural products</li> </ul>
<b>Step 3</b>	<b>Flood characteristics</b>	<ul style="list-style-type: none"> <li>• 4 different flood scenarios</li> <li>• Area</li> <li>• Depth</li> </ul>
	<b>Land-use data</b>	<ul style="list-style-type: none"> <li>• Regional GIS dataset: 4 aggregated categories</li> <li>• ISTAT: population and vehicles numbers</li> </ul>
	<b>Determination of values of assets</b>	<ul style="list-style-type: none"> <li>• Transfer from previous studies</li> </ul>
	<b>Damage functions</b>	<ul style="list-style-type: none"> <li>• 5 depth-damage functions (matched with damage categories) transferred from previous studies</li> </ul>
<b>Step 4</b>	<b>Damage calculation and presentation</b>	<ul style="list-style-type: none"> <li>• ArcGIS overlay and spatial analyst</li> <li>• Shapefile data and maps</li> </ul>

**Table 5.5:** Summary for damage evaluation approach.

## 6. Findings and Discussion

### 6.1. Hazard

#### Discharge scenarios

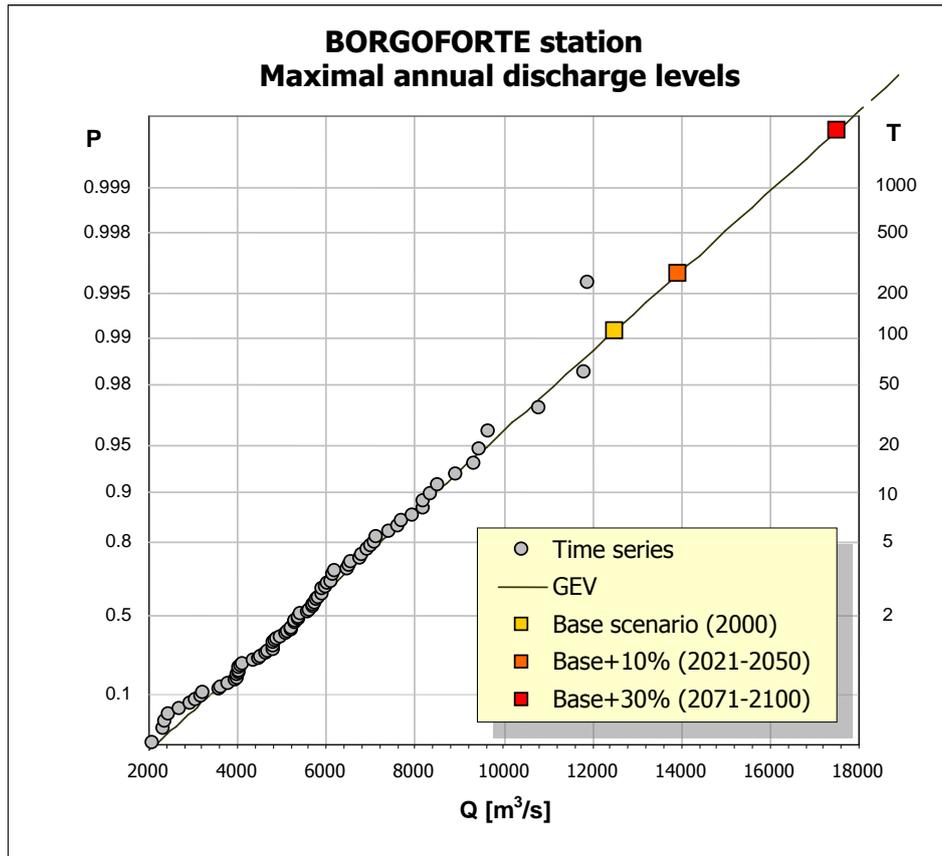
The output of the model previously described provides the characteristic of the hazard for each scenario. The rupture in the embankment system is located in Occhiobello, like in the 1951 event. An aerial picture of the simulated breach in the embankment can be found in Annex K. The choice of the same 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 in account in the discussion. Also, the influence of the mechanical drainage system (waterpumps) is not accounted to assess the flood outflow. In any case, 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 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 by ARPA-SIM through the L-moments method (Hosking, 1990).

Figure 6.1 presents the adapted probabilistic Gumbel distribution of the time series, which is employed to calculate the frequency of the events in our scenarios. The X coordinate represents the discharge value, while on the Y coordinate are shown the parameters P (probability) and T (return time). The three colored squares indicate the values corresponding to each discharge scenario. In table 6.1 are presented the return times relative to each flood scenario.

<i>Scenarios</i>	<i>Max discharge (m<sup>3</sup>/s)</i>	<i>Return time (years)</i>
2000 (Base scenario)	12500	110
2021-2050 (Base +10%)	14000	270
2071-2100 (Base +30%)	17500	>1000

**Table 6.1:** Flood scenarios and their related discharge rates (Borgoforte station) and return times.



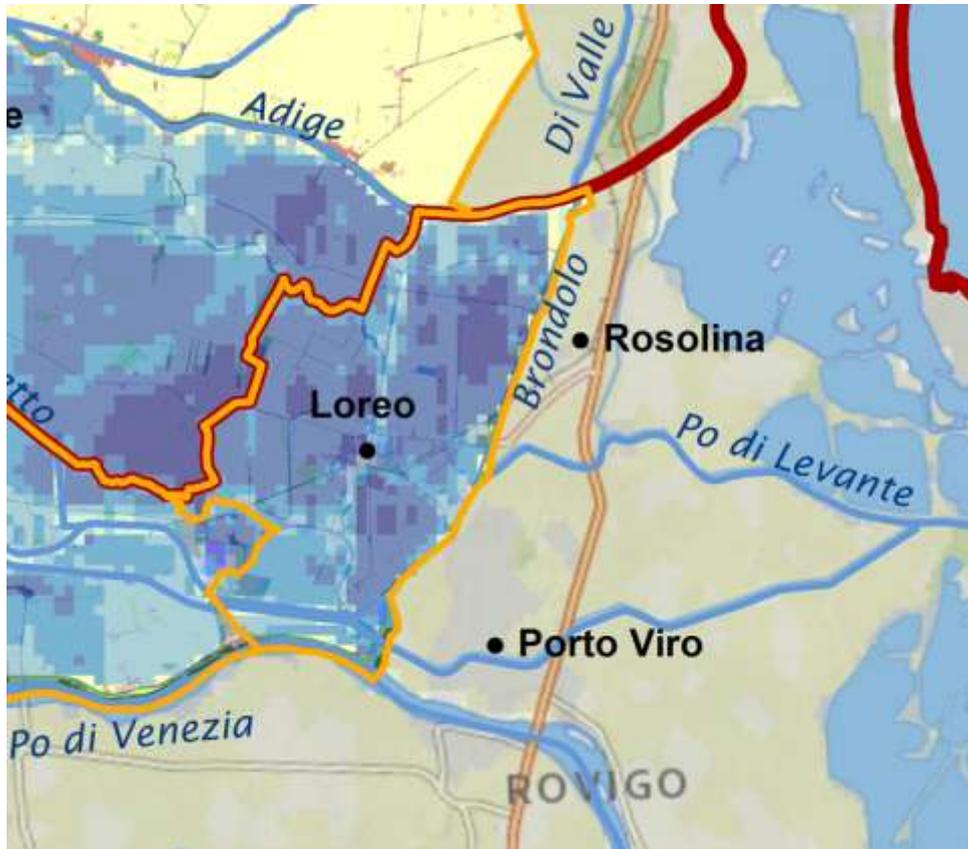
**Figure 6.1:** probabilistic Gumbel distribution of discharge flow for the three discharge scenarios at Borgoforte station.

### Rupture scenarios

Full maps for each levee breach scenarios can be found in the Annexes E, F, G and H, while the aerial photo of the simulated breach can be found in Annex K. We can see how the Canalbianco embankments represents an obstacle for the further extension of the flood in the base scenario and in the 2021-2051 scenario, while in the 2071-2100 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 (fig. 6.2), whereof 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.

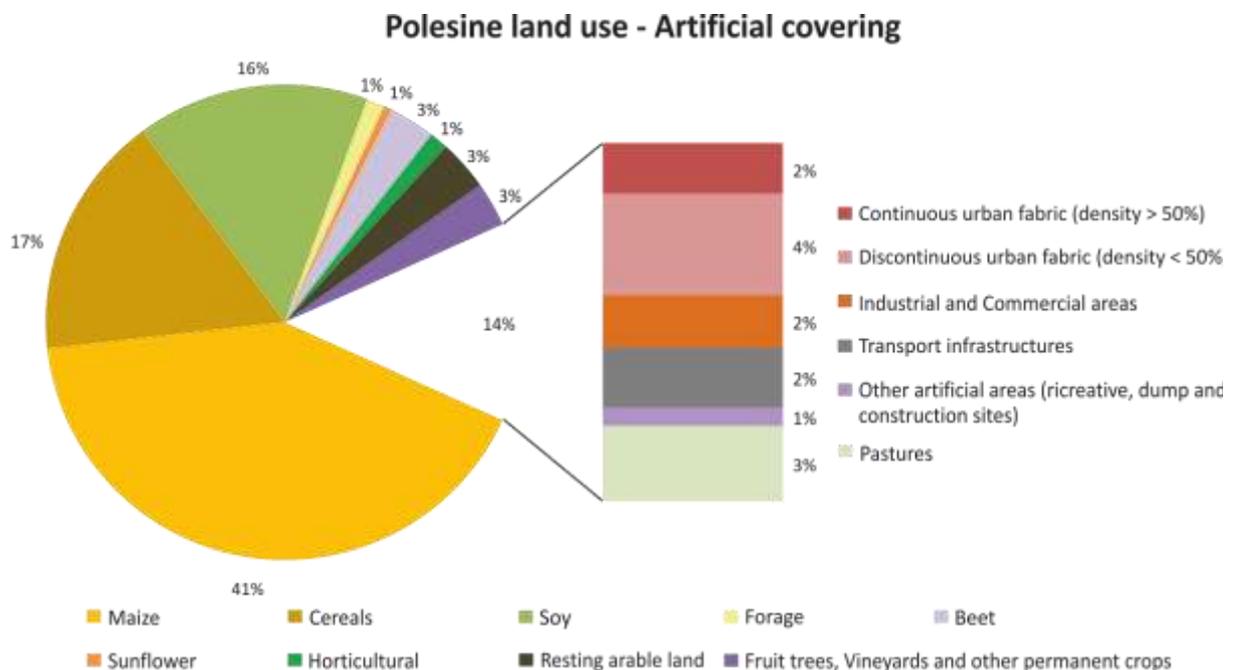


**Figure 6.2:** the canal Brondolo represents the eastern limit for the flood propagation.

## 6.2. Exposure

The total area of involved municipalities measures 868.5 km<sup>2</sup>. The base scenario involves some 277.36 km<sup>2</sup> (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<sup>2</sup> (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<sup>2</sup> (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<sup>2</sup> (68%), engaging several minor towns in addition to the area covered by the previous scenarios, and increasing the maximal water depth in many areas.

Land-use map and categories can be found in Annex D. 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, as in fig. 6.3. 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.



**Figure 6.3:** Percentage of different artificial land use in the impact area (25 municipalities).

Discretionary values such as agricultural products and private vehicles need to be discussed separately.

### **Agricultural products**

When considering impact on the cultures, seasonality is an important factor to be taken in account. The land-use class indicated the primary product for that area, which are usually alternated with renewal cultures. The sowing and harvesting time have been identified for each crop, specifically for the Polesine region. Also, the corresponding renewal crops have been searched (Edagricole):

- *Maize*: sowed from April to June, harvested from September to November depending from weather conditions. Usually has been already harvested by the end of September in Polesine. Renewal crops are soy, meadow, or maize itself.
- *Cereals (wheat, oat, barley)*: sowed in October-November, harvested in June. Renewal crops are maize, beet, or meadow.
- *Soy*: sowed from April to June, harvested in September-October. Alternated with maize or again soy.
- *Beet*: sowed from February to April in northern Italy, harvested from July to September. Often alternated with wheat.
- *Sunflower*: sowed in May-June, harvested in August-September. Often used as renewal crop.

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.

### **Population and Vehicles**

Maps about the number and distribution of population and vehicles in the involved area can be found in Annex I and J.

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.

### 6.3. Risk assessment: quantification of potential damage

Full maps representing the damage classes for each flood scenario can be found in the Annexes L, M, N, and O. 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.

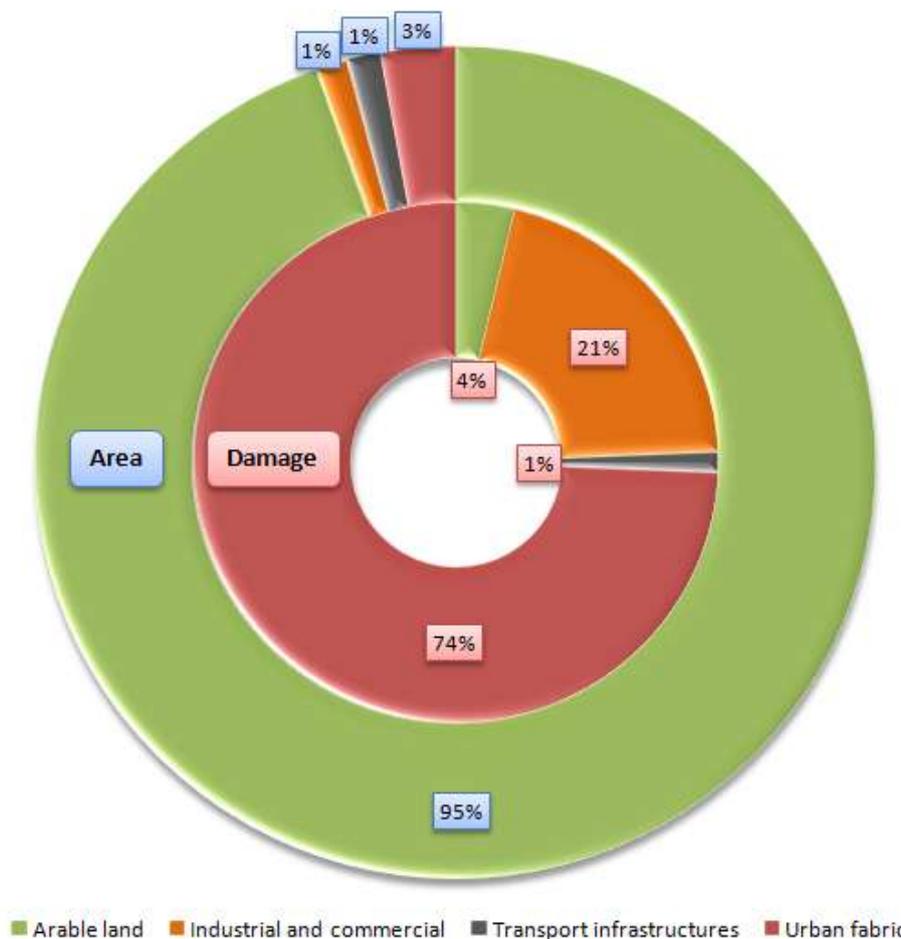
The calculation of the damage related to each land-use categories have been carried out in ArcGIS environment, employing the damage functions already presented in chapter 5.4. For the urban fabric, which is not purely residential, a mixed function is used: the fabric is considered as composed of 25% 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. See table 6.2. Damage is expressed in million € at the 2000 value for each scenario. Potential inflation taking place in future scenarios is impossible to calculate, so it has not been taken in account for normalization.

<i>Scenarios</i>	<i>Involved area (km<sup>2</sup>)</i>	<i>Total damage (million €)</i>
2000 (Base scenario)	277.36	3,005
2021-2050 (Base +10%)	355.36	4,740
2071-2100 (Base +30%)	507.56	7,720
2071-2100 (Base +30%) 400 m	590.08	10,571

**Table 6.2:** total flooded area for land-use categories and corresponding damage for each flood scenario.

The percentage of damage among the land-use categories is compared to their corresponding coverage area in fig. 6.4.



**Figure 6.4:** Comparison between covered area and related damage for land-use categories in the Base Scenario.

### Population and Vehicles

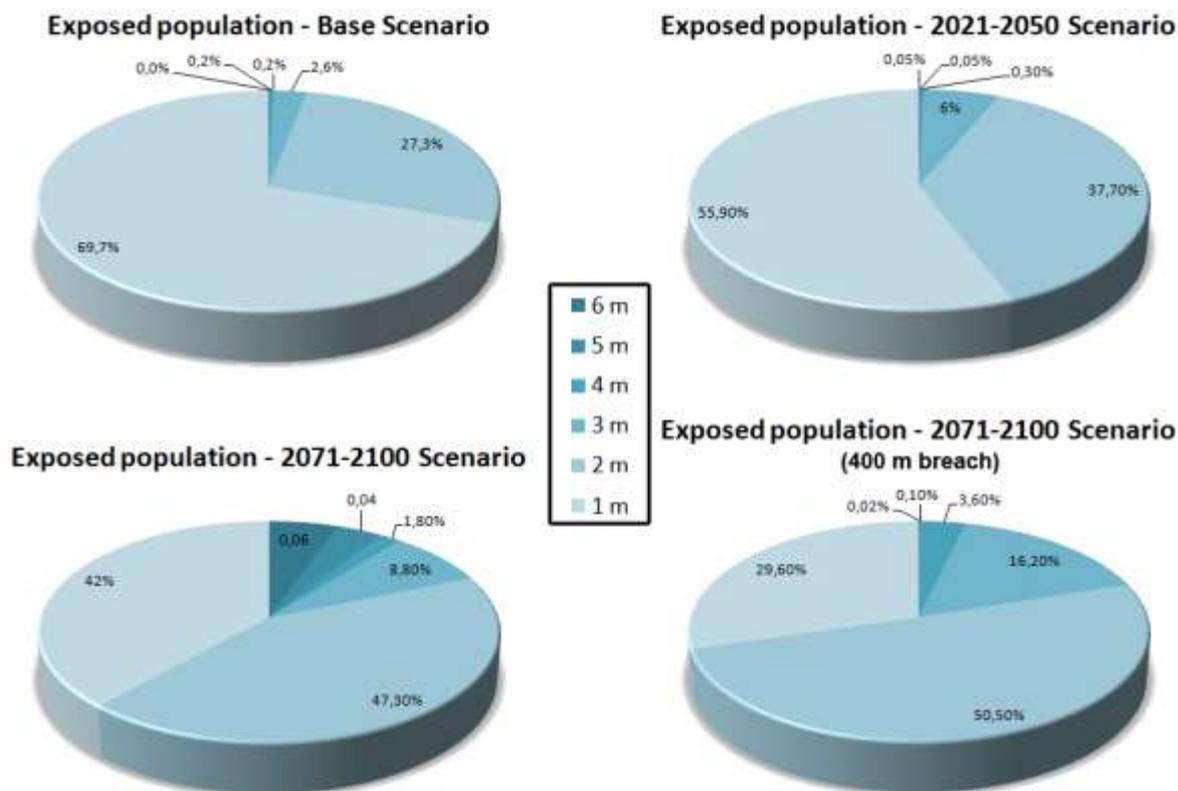
The maps about population exposure can be found in Annexes P, Q, R and S.

The total population of 161,864 is distributed for the most over a total urban area of 47.61 km<sup>2</sup>, corresponding to a density of 3,400 people over urban km<sup>2</sup>. 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 (see tab. 6.3).

<i>Scenarios</i>	<i>Involved urban area (km<sup>2</sup>)</i>	<i>Total exposed population</i>
2000 (Base scenario)	7.77	23,255
2021-2050 (Base +10%)	11.52	35,733
2071-2100 (Base +30%)	17.29	54,067
2071-2100 (Base +30%) 400 m	22.21	70,132

**Table 6.3:** total amount of population exposed to the hazard for each flood scenario.

The percentage distribution to each flood depth class is represented in fig. 6.5.



**Figure 6.5:** Percentage of exposed population to each flood depth class for each scenario.

The maps representing damage on vehicles can be found in Annexes T, U, V and W.

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 (tab. 6.4).

<i>Scenarios</i>	<i>Flooded vehicles</i>	<i>Damage amount (million €)</i>
2000 (Base scenario)	13,804	128.106
2021-2050 (Base +10%)	21,120	216.128
2071-2100 (Base +30%)	32,209	362.861
2071-2100 (Base +30%) 400 m	41,744	507.896

**Table 6.4:** total amount of flooded vehicles and corresponding damage cost.

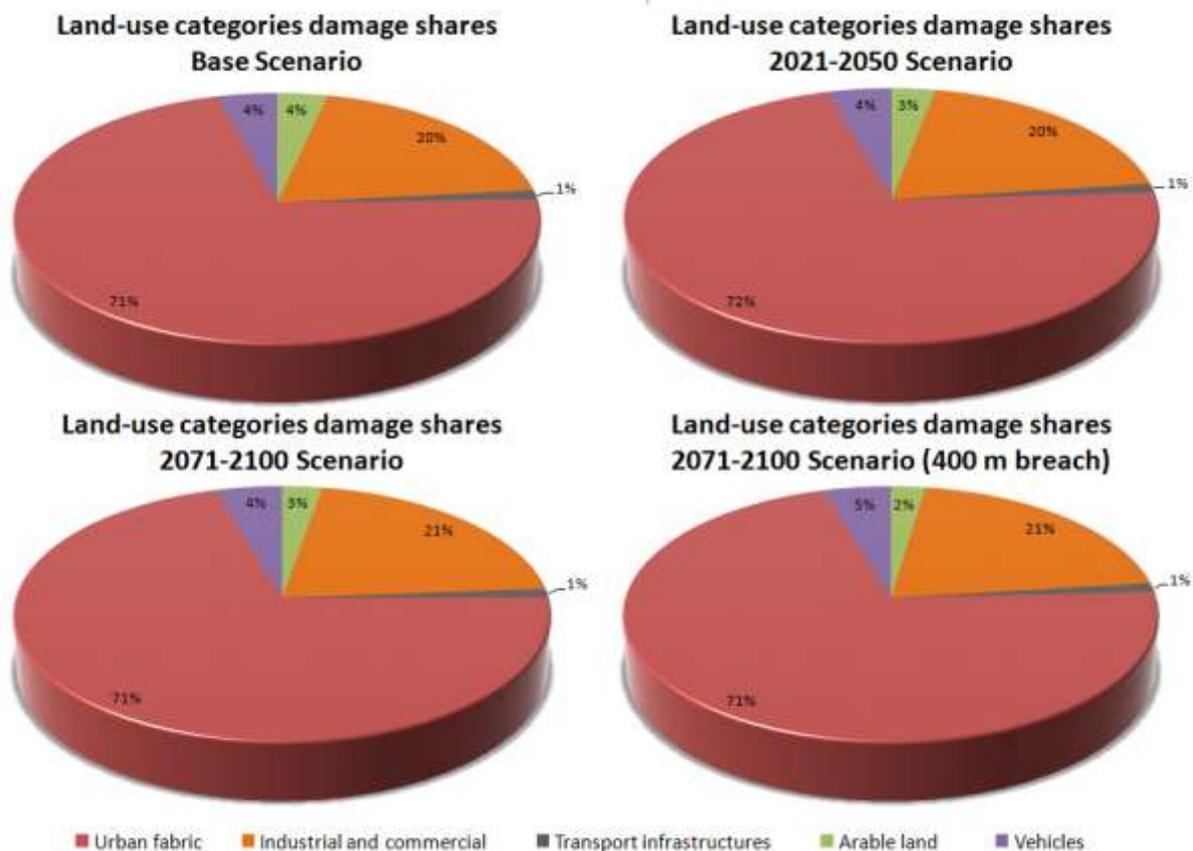
## Total Damage

Finally, table 6.5 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).

Scenarios	Total damage (million €)	Total damage (million \$ in PPPs)
2000 (Base scenario)	3,133	3,601
2021-2050 (Base +10%)	4,956	5,696
2071-2100 (Base +30%)	8,083	9,291
2071-2100 (Base +30%) 400 m	11,079	12,734

**Table 6.5:** total direct damage for each flood scenario considering both land-use categories and vehicles.

The percentage of damage spread among the damage categories is represented in fig. 6.6.



**Figure 6.6:** Percentage of damage related to each land-use category and vehicles for each rupture scenario.

The relative shares of damage do not differ much 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%, as anticipated in chapter 5.3. 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%).

## 6.4. Discussion

The damage assessment of the four potential scenarios can be compared with the reference events of 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 6.6 summarizes the characteristics of each event, while figure 6.7 gives a visual representation of the compared scenarios.

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

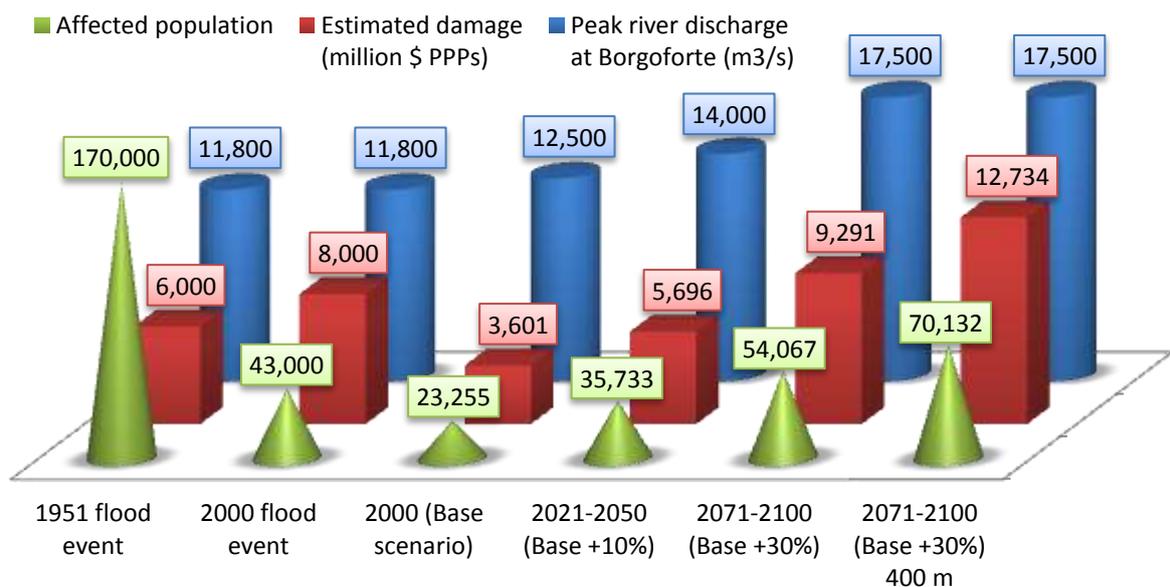
**Table 6.6:** comparison between reference events and simulated flood scenarios, considering flood discharge rates, total economic damage and affected population.

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<sup>3</sup>/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 (see fig.3.23), 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 out in chapter 3, 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. The following phases of the PREEMPT project will hopefully help to disclose this uncertainty by making a more thorough analysis of past events.



**Figure 6.7:** Graphic comparison of discharge, economic cost and affected population for each flood scenario.

Another important distinction must be made taking in account the Early Flood Warning System described in chapter 2.7: given the reliable forecasting supplied by the ARPAs system, a timely warning should 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-economical 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.

## **6.5. Conclusion and Future directions**

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-economical 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 in further research, also a macro-economic probabilistic model can be coupled 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.

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 in account by river authorities.

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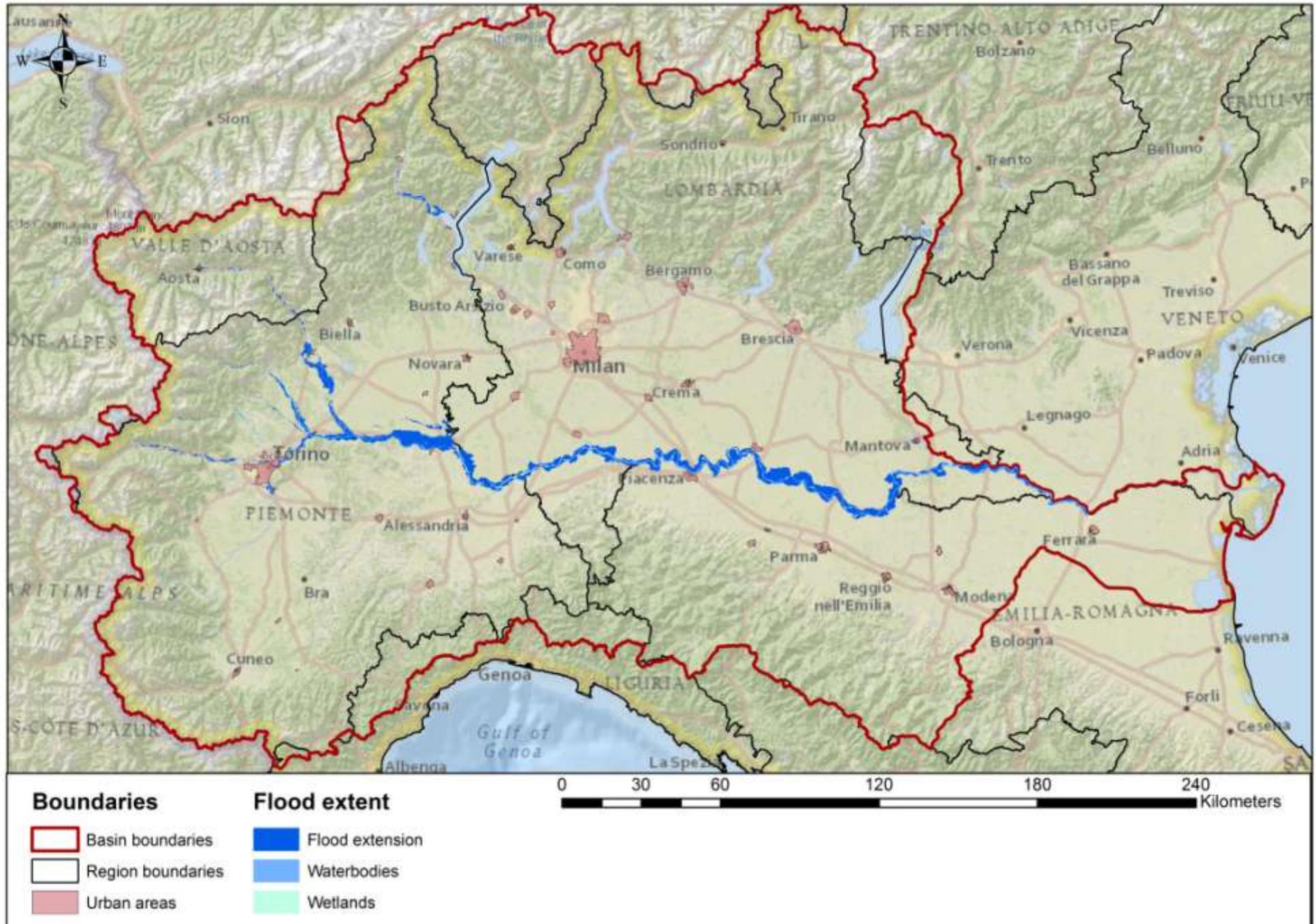
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## **8. Annexes**

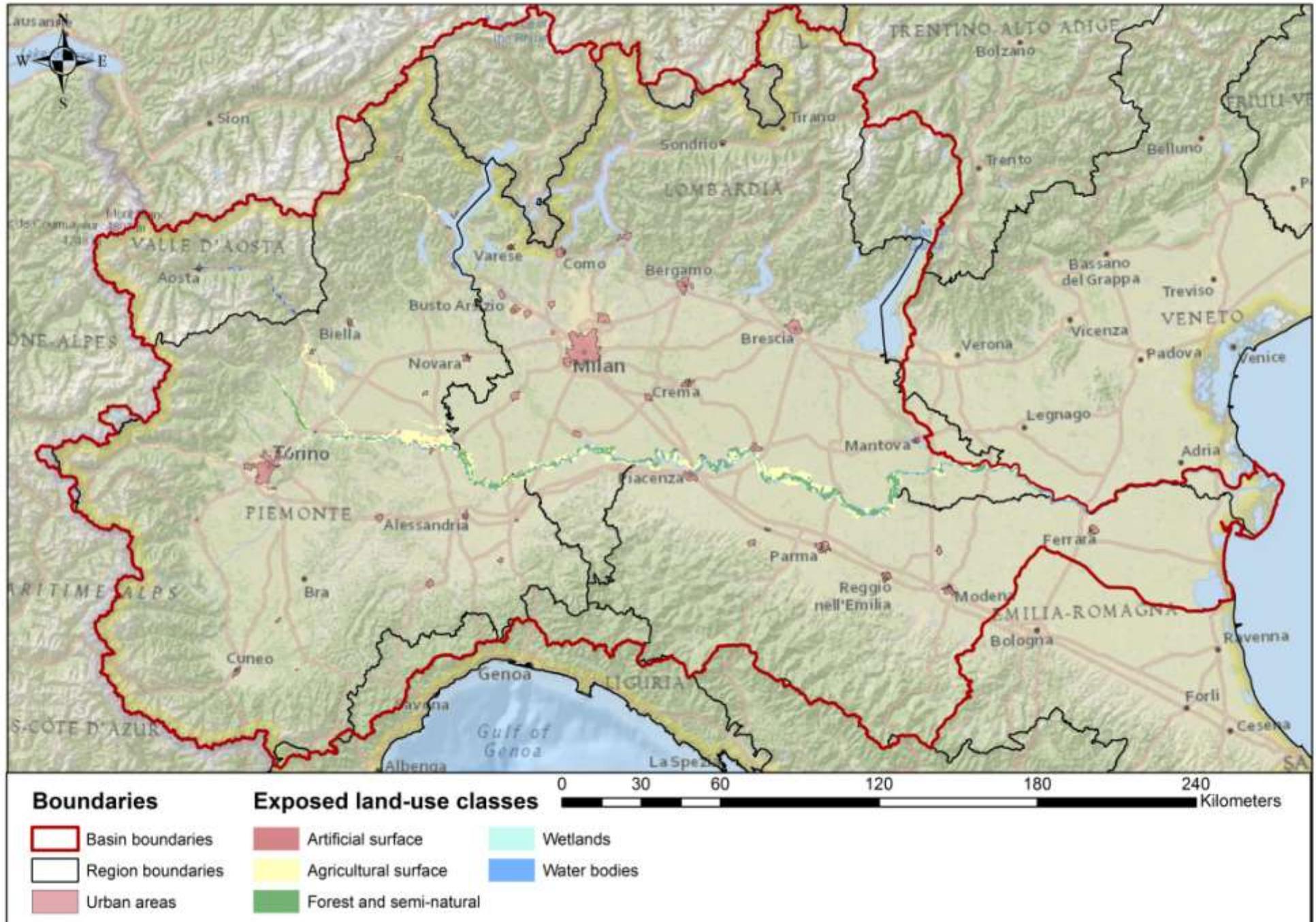
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Full maps relative to the flood events and additional photographic information can be found in the following pages.

# Flood event of October 2000 – Flood extension

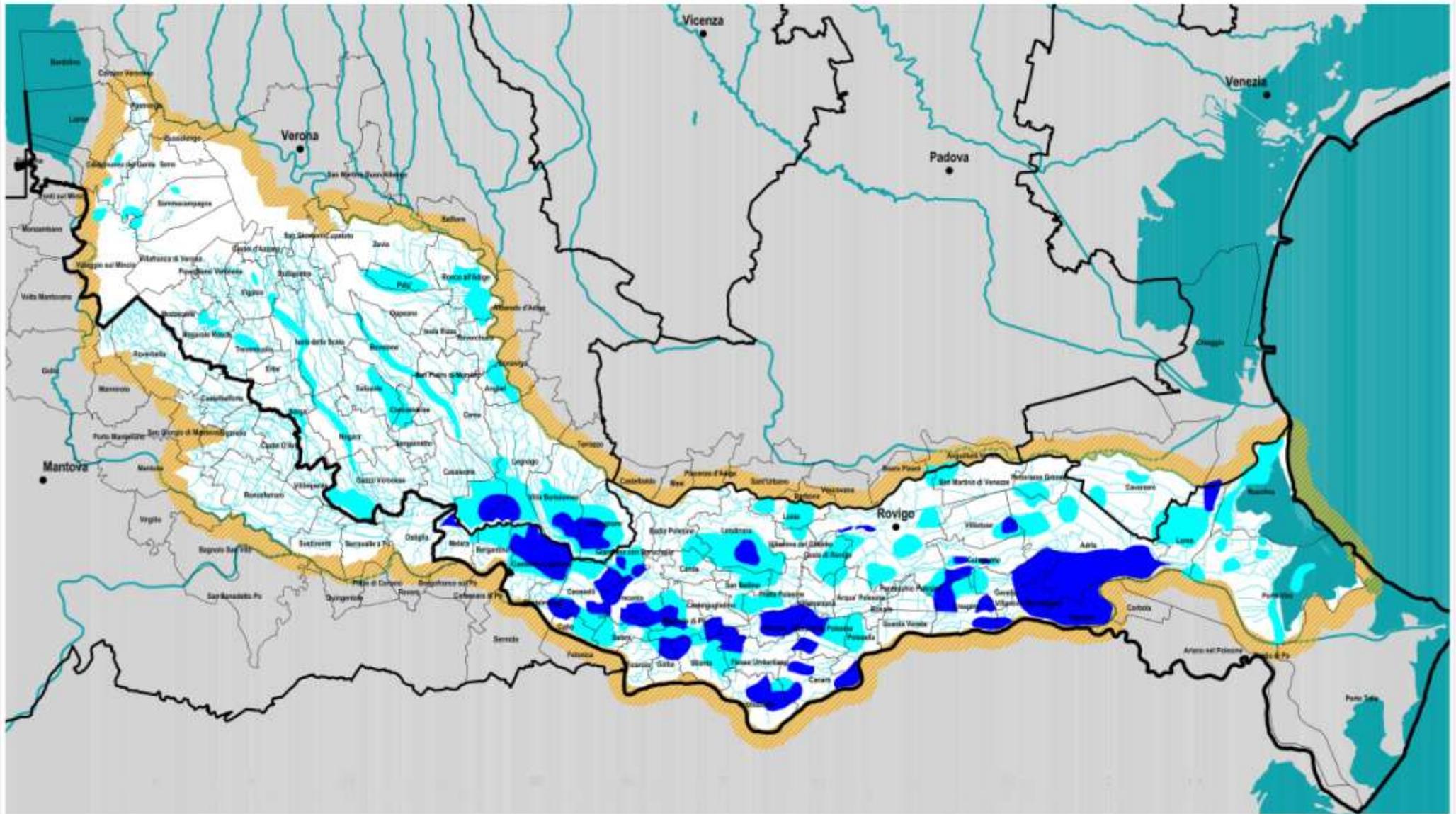


## Flood event of October 2000 – Land-use categories involved in flooding



# Map of hydraulic risk for the Polesine territory (Fissero-Tartaro-Canalbianco basin)

Autorità di Bacino del Fiume Fissero-Tartaro-Canalbianco - Progetto di Piano Stralcio di Assetto Idrogeologico

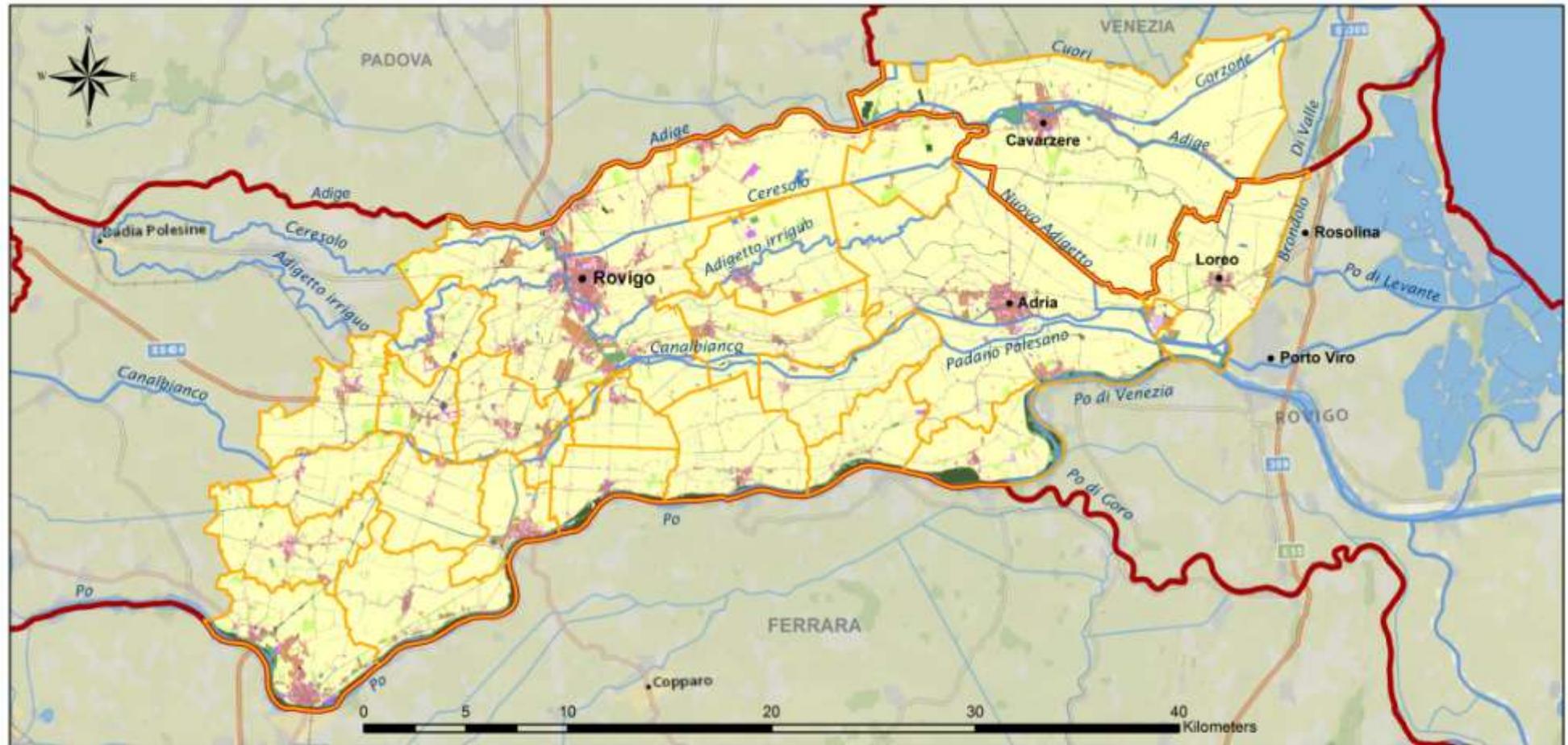


Cartografia di riferimento Veneto CTR 10.000 (1983)  
 Limite comunali Veneto CTR 10.000 (aggiornati al 1999)  
 Limite di bacino definiti su DPR 14/98 (DL n.247, 22/10/98)  
 Area soggette a scoto meccanico derivate da informazioni dei  
 consorzi di bonifica  
 Area allagate individuate con modellazione idraulica (2000)

**CARTA DEL RISCHIO IDRAULICO  
 UNIONE REGIONALE VENETA BONIFICHE**  
**RISURB** SCALA 1:400.000  
marzo 2002

Elaboratori:  
 Regione Veneto  
 Segreteria Regionale all'Ambiente e Lavori Pubblici  
 Direzione D'Area del Sudio e Protezione Civile

## Polesine land-use categories

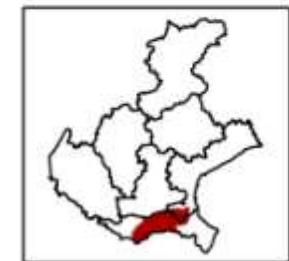


### Boundaries

-  Municipality
-  Province

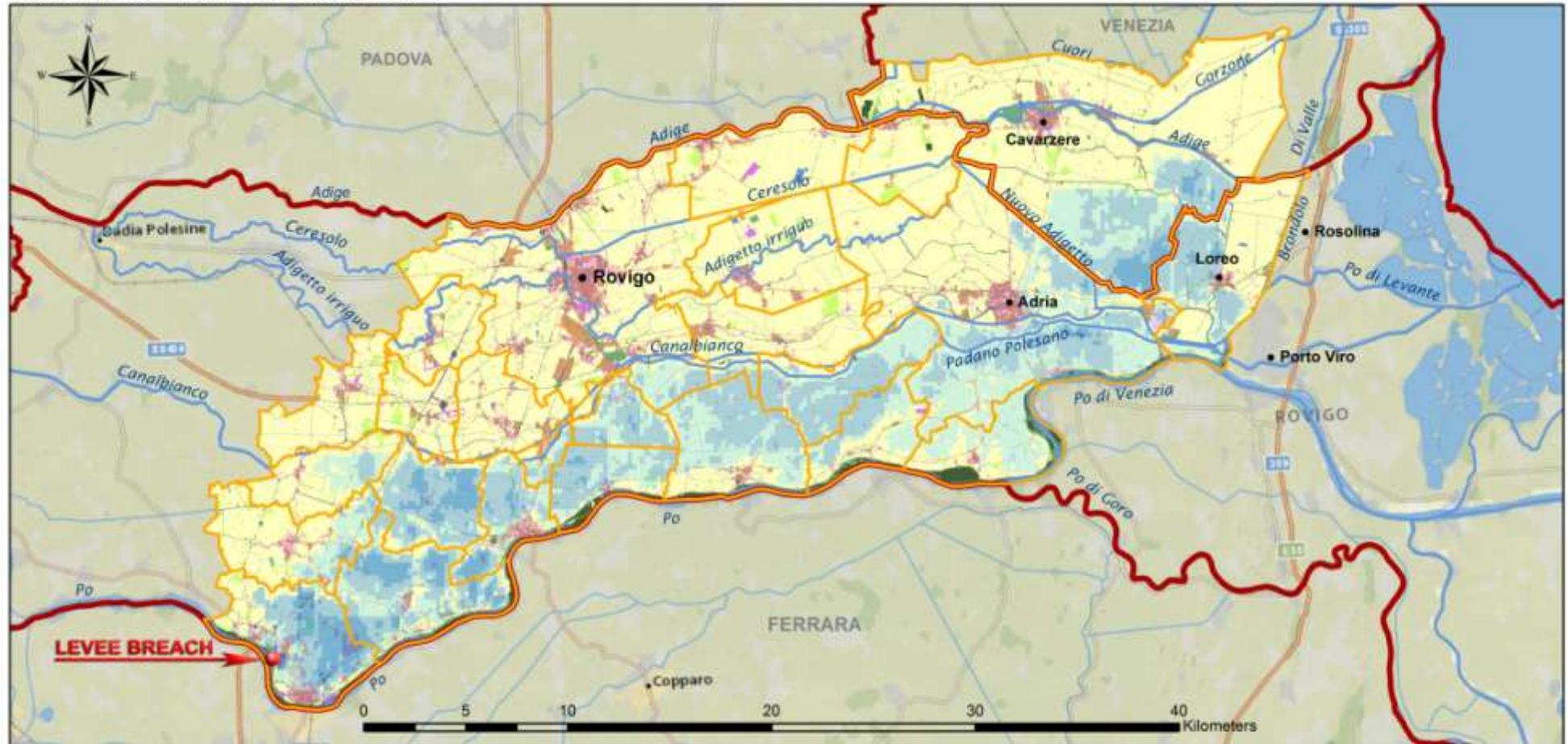
### Land use Classes

- |   |  |
|---|--|
|  1.1.1 Continuous urban fabric         |  2.1 Arable land                      |
|  1.1.2 Discontinuous urban fabric      |  2.2 Permanent crops                  |
|  1.2.1 Industrial and Commercial areas |  2.4 Heterogeneous agricultural areas |
|  1.2.2 Transport infrastructures       |  2.3 Pastures                         |
|  1.3 Mine, dump and construction sites |  3 Forest and semi-natural areas      |
|  1.4 Other artificial areas            |  4 Wetlands                           |
|   |  5 Water bodies                       |



# Flood simulation – Base scenario (2000) – 200 meters breach

Base scenario - 2000 - 200 meters breach



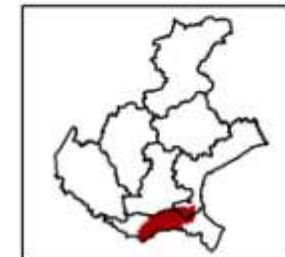
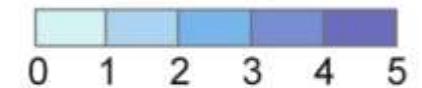
## Boundaries

-  Municipality
-  Province

## Land use Classes

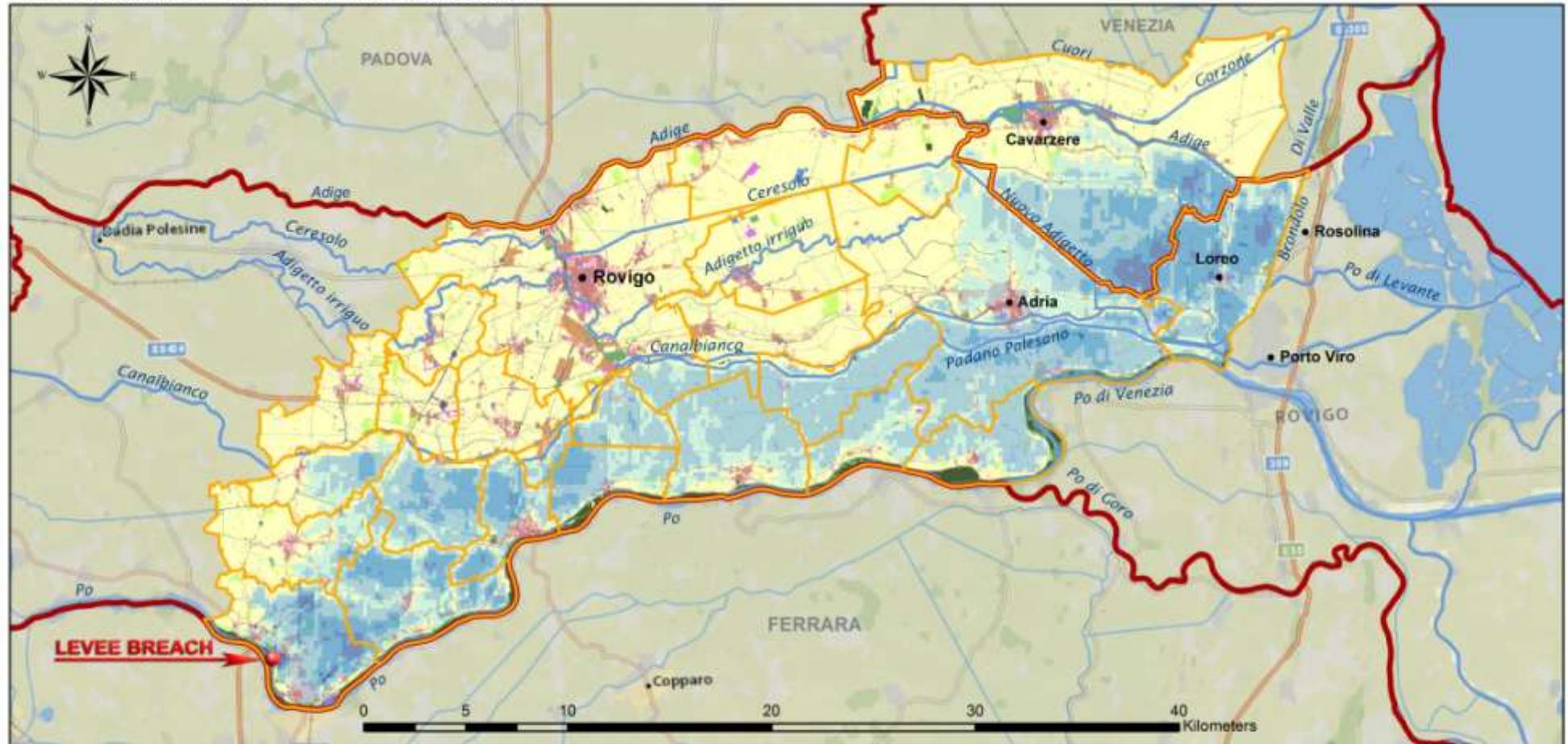
- |   |  |
|---|--|
|  1.1.1 Continuous urban fabric         |  2.1 Arable land                      |
|  1.1.2 Discontinuous urban fabric      |  2.2 Permanent crops                  |
|  1.2.1 Industrial and Commercial areas |  2.4 Heterogeneous agricultural areas |
|  1.2.2 Transport infrastructures       |  2.3 Pastures                         |
|  1.3 Mine, dump and construction sites |  3 Forest and semi-natural areas      |
|  1.4 Other artificial areas            |  4 Wetlands                           |
|   |  5 Water bodies                       |

## Water depth



# Flood simulation – 2021-2050 scenario (2000 +10%) – 200 meters breach

2021-2050 scenario - 2000 +10% - 200 meters breach



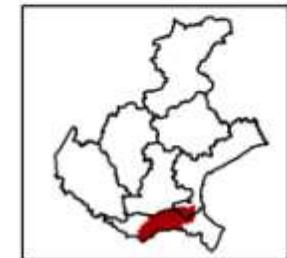
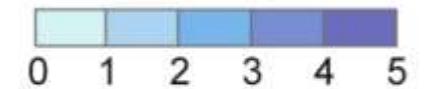
## Boundaries

-  Municipality
-  Province

## Land use Classes

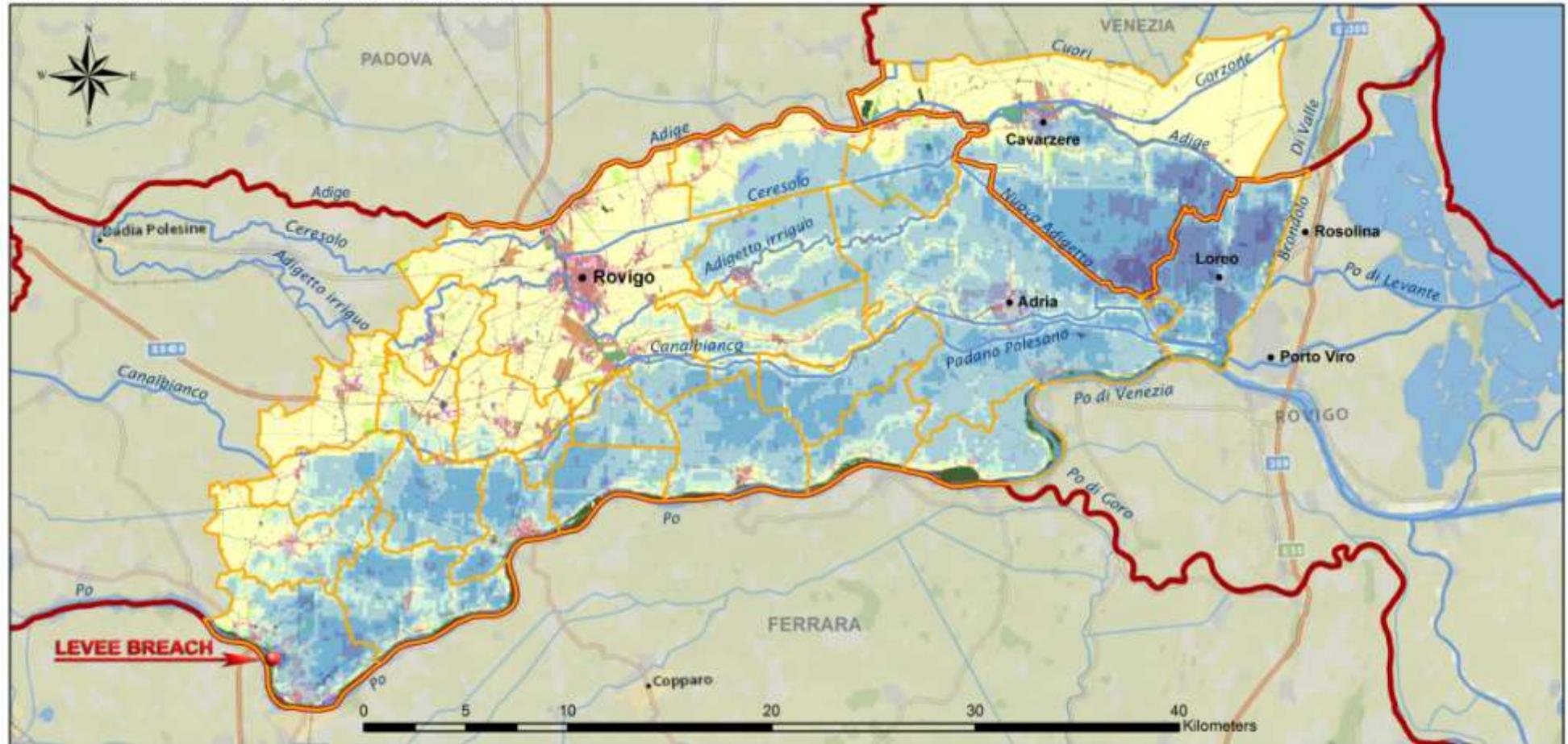
- |   |  |
|---|--|
|  1.1.1 Continuous urban fabric         |  2.1 Arable land                      |
|  1.1.2 Discontinuous urban fabric      |  2.2 Permanent crops                  |
|  1.2.1 Industrial and Commercial areas |  2.4 Heterogeneous agricultural areas |
|  1.2.2 Transport infrastructures       |  2.3 Pastures                         |
|  1.3 Mine, dump and construction sites |  3 Forest and semi-natural areas      |
|  1.4 Other artificial areas            |  4 Wetlands                           |
|   |  5 Water bodies                       |

## Water depth



# Flood simulation – 2071-2100 scenario (2000 +30%) – 200 meters breach

2071-2100 scenario - 2000 +30% - 200 meters breach



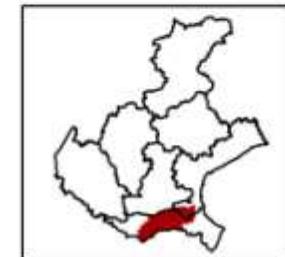
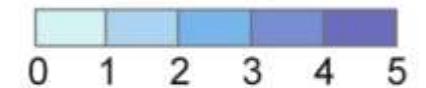
## Boundaries

-  Municipality
-  Province

## Land use Classes

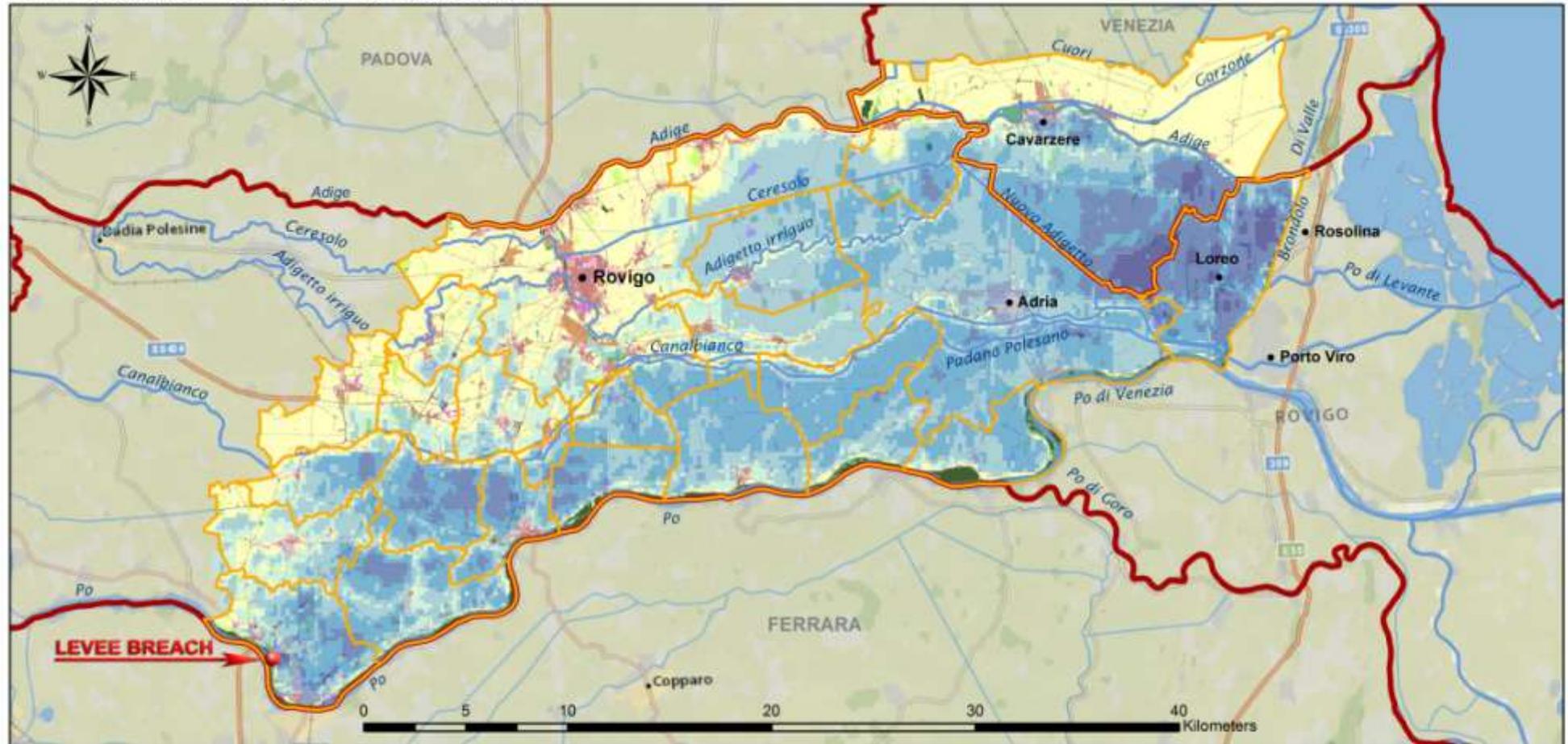
- |   |  |
|---|--|
|  1.1.1 Continuous urban fabric         |  2.1 Arable land                      |
|  1.1.2 Discontinuous urban fabric      |  2.2 Permanent crops                  |
|  1.2.1 Industrial and Commercial areas |  2.4 Heterogeneous agricultural areas |
|  1.2.2 Transport infrastructures       |  2.3 Pastures                         |
|  1.3 Mine, dump and construction sites |  3 Forest and semi-natural areas      |
|  1.4 Other artificial areas            |  4 Wetlands                           |
|   |  5 Water bodies                       |

## Water depth



# Flood simulation – 2071-2100 scenario (2000 +30%) – 400 meters breach

2071-2100 scenario - 2000 +30% - 400 meters breach



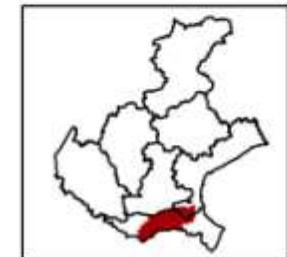
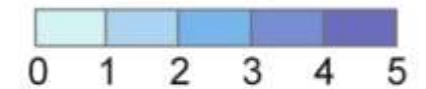
## Boundaries

-  Municipality
-  Province

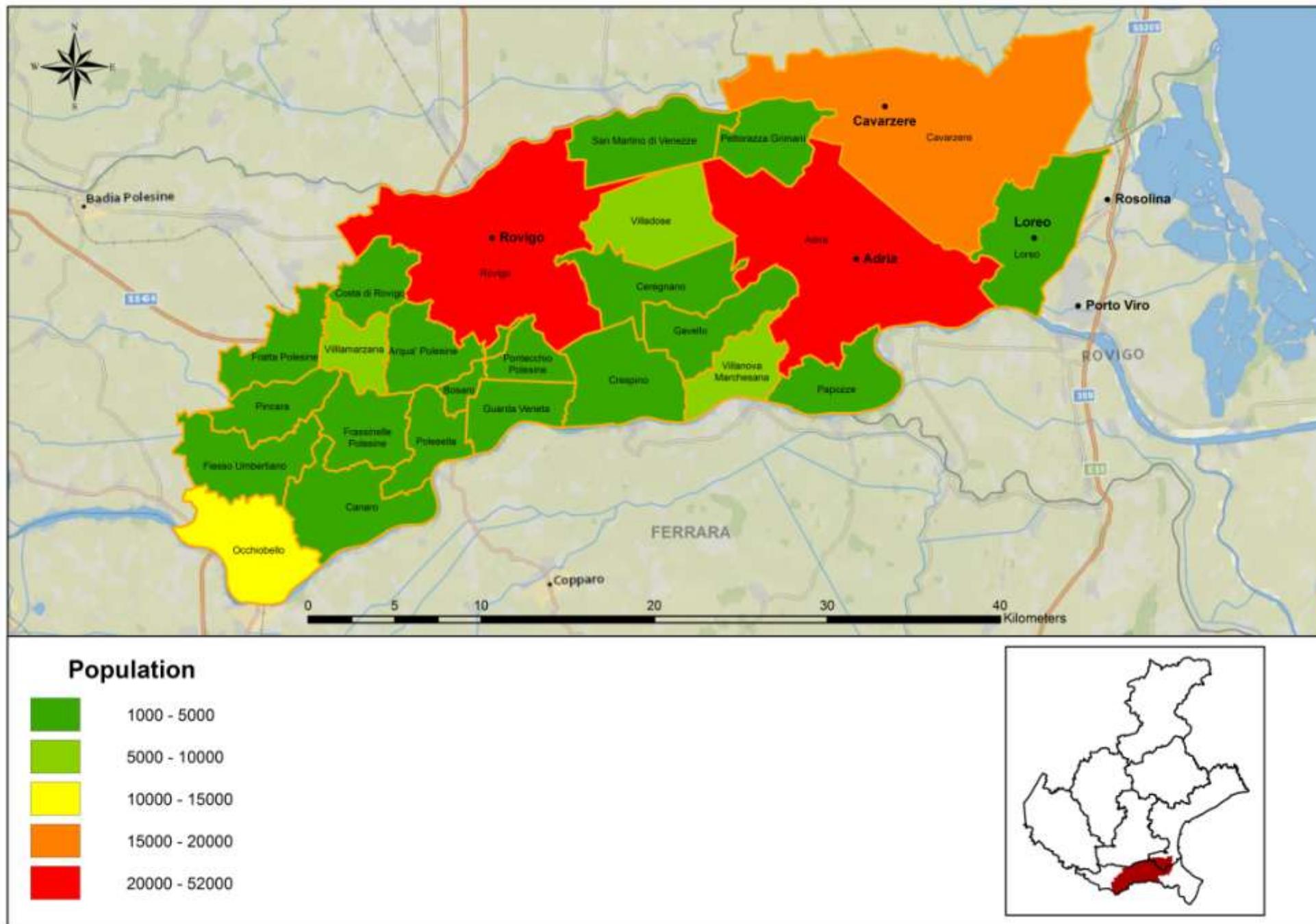
## Land use Classes

- |   |  |
|---|--|
|  1.1.1 Continuous urban fabric         |  2.1 Arable land                      |
|  1.1.2 Discontinuous urban fabric      |  2.2 Permanent crops                  |
|  1.2.1 Industrial and Commercial areas |  2.4 Heterogeneous agricultural areas |
|  1.2.2 Transport infrastructures       |  2.3 Pastures                         |
|  1.3 Mine, dump and construction sites |  3 Forest and semi-natural areas      |
|  1.4 Other artificial areas            |  4 Wetlands                           |
|   |  5 Water bodies                       |

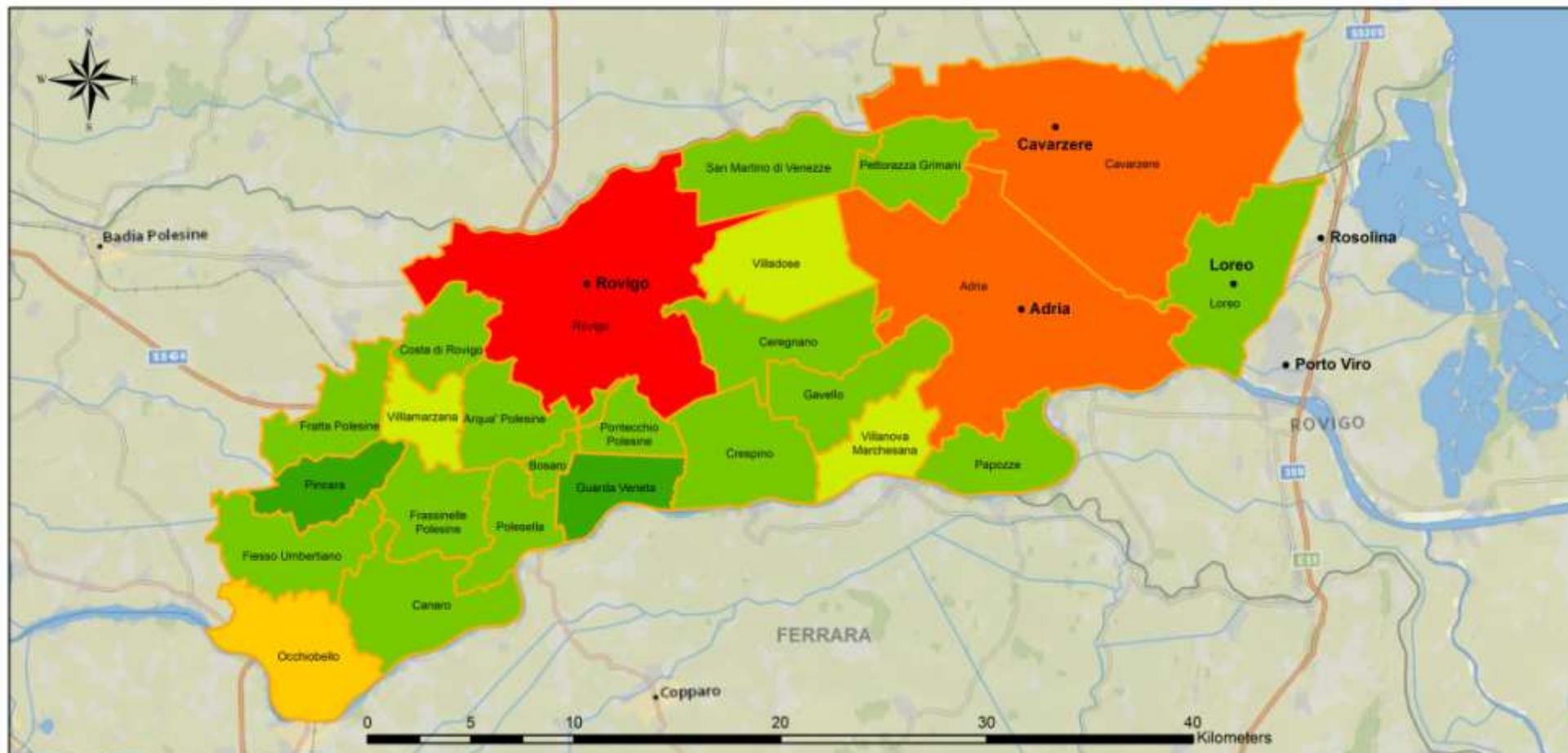
## Water depth



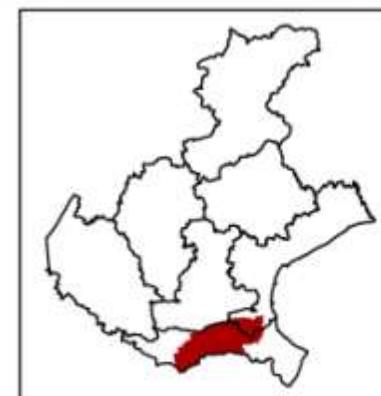
## Distribution of Polesine population per Municipality (2008)



## Distribution of Polesine vehicles per Municipality (2008)



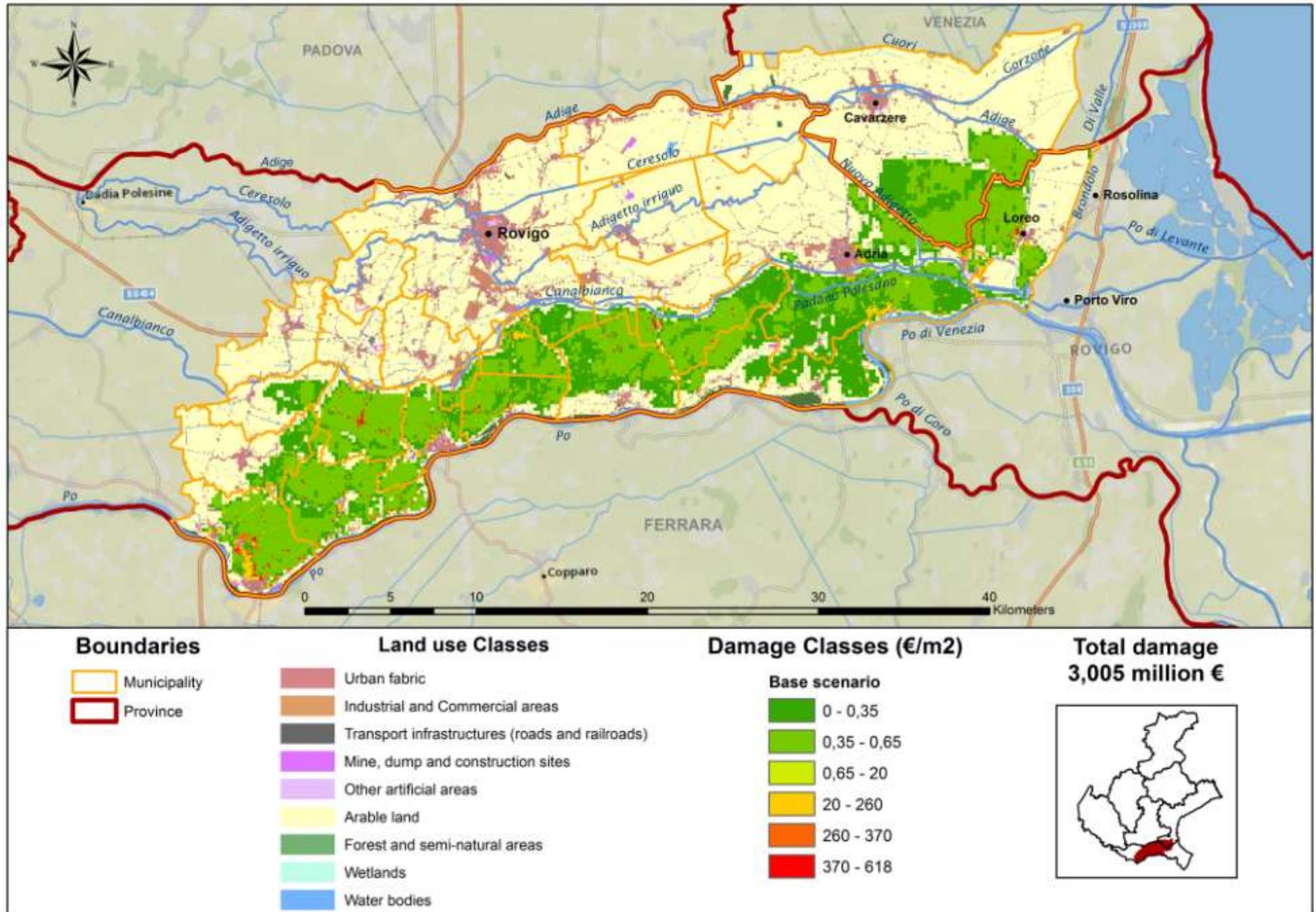
### Vehicles



Simulated levee breach on aerial photo

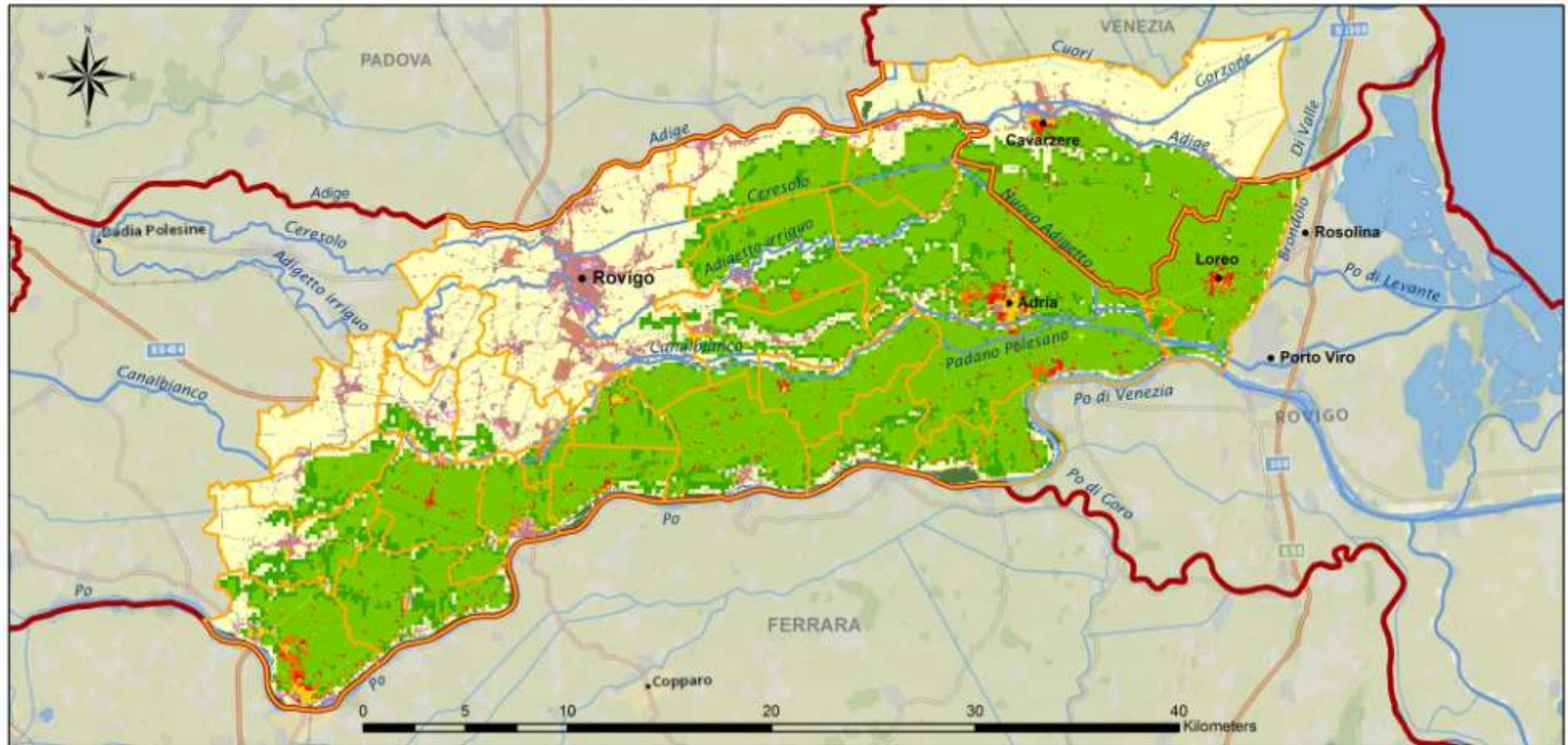


Damage assessment – Base scenario (2000) – 200 meters breach





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

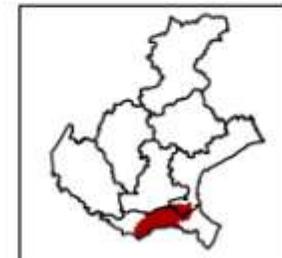
**Damage Classes (€/m<sup>2</sup>)**

**2071-2100 scenario**

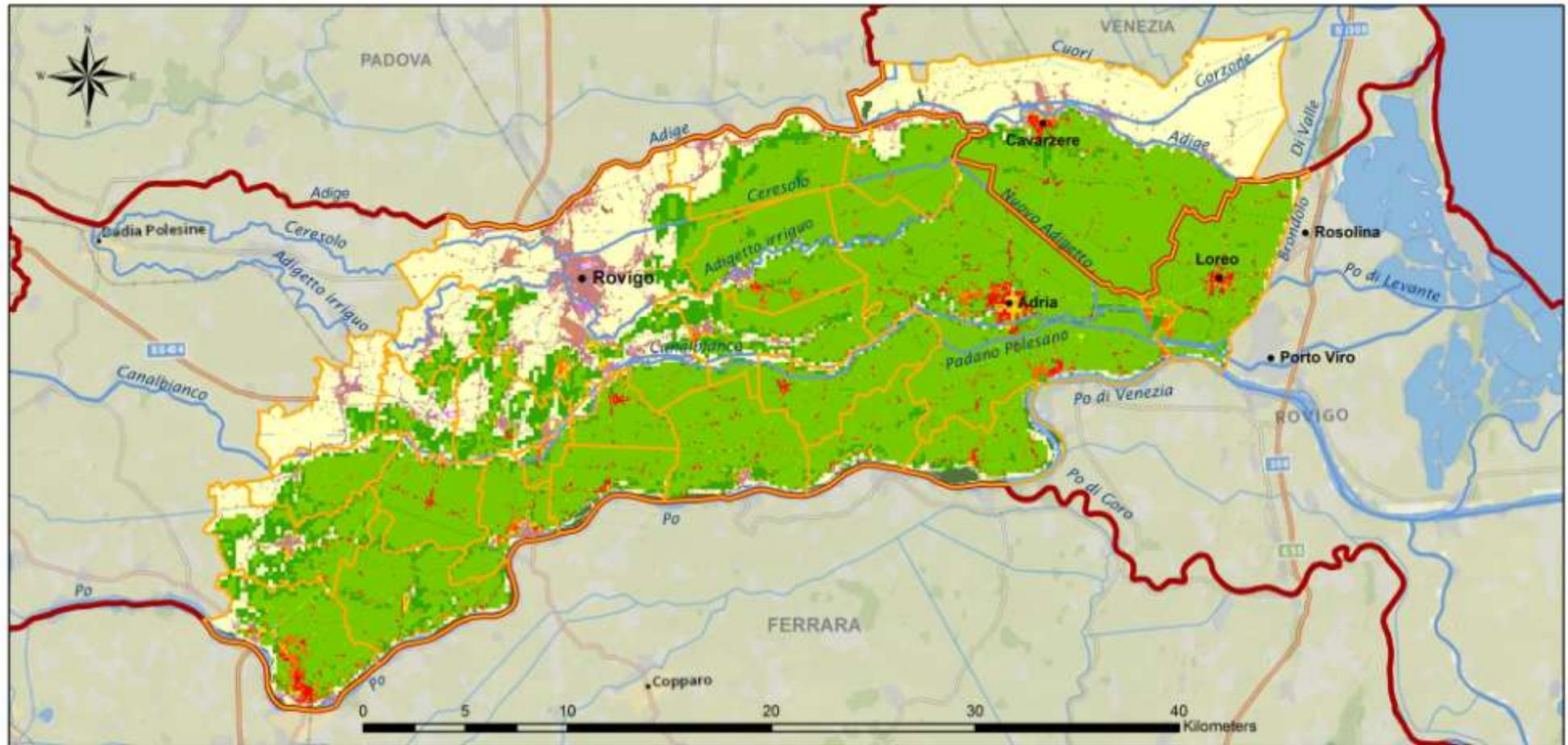
-  0 - 0,35
-  0,35 - 0,65
-  0,65 - 20
-  20 - 260
-  260 - 370
-  370 - 618

**Total damage**

**7,720 million €**



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



**Boundaries**

-  Municipality
-  Province

**Land use Classes**

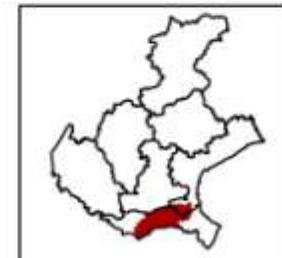
-  Urban fabric
-  Industrial and Commercial areas
-  Transport infrastructures (roads and railroads)
-  Mine, dump and construction sites
-  Other artificial areas
-  Arable land
-  Forest and semi-natural areas
-  Wetlands
-  Water bodies

**Damage Classes (€/m²)**

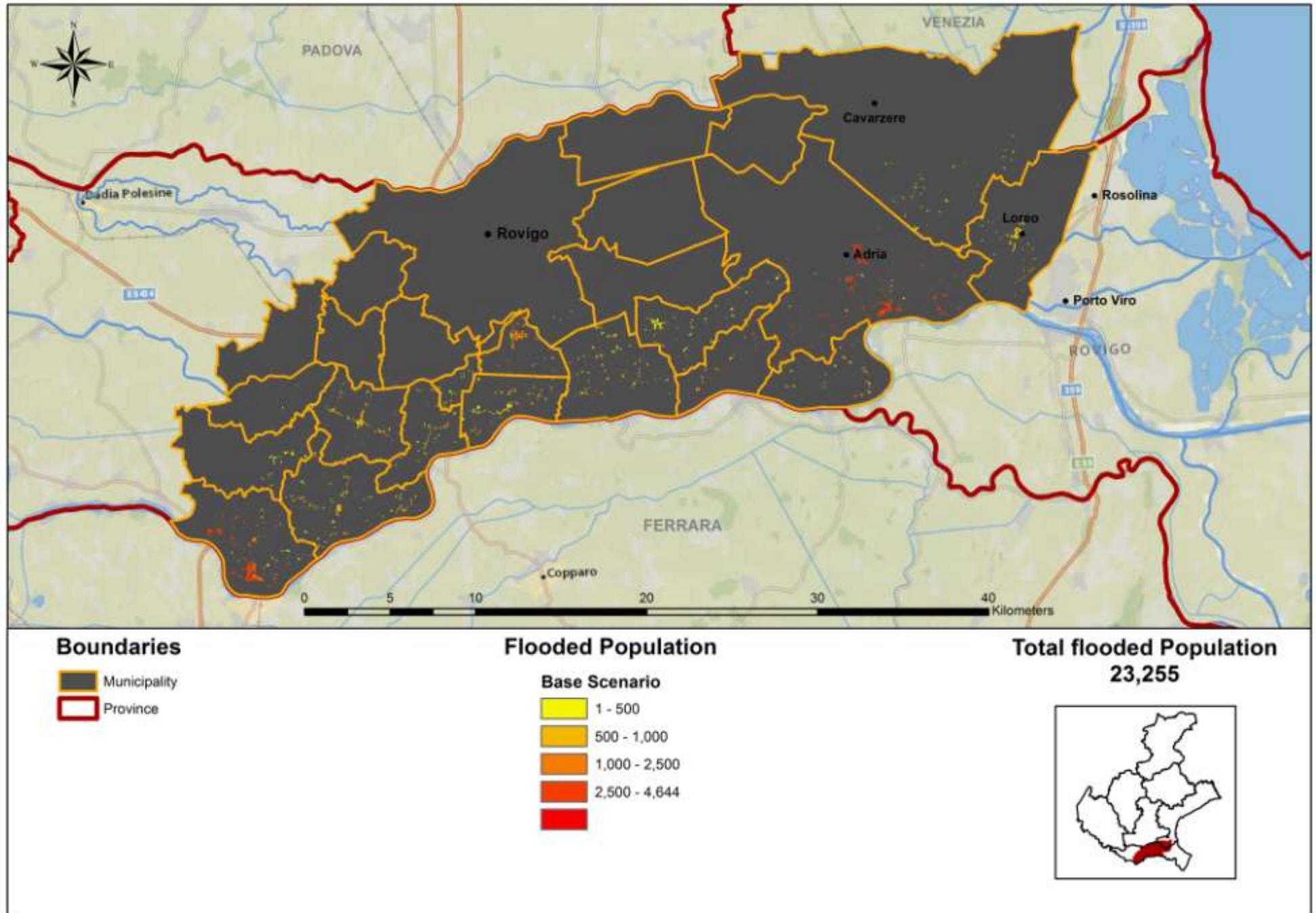
**2071-2100 400m scenario**

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

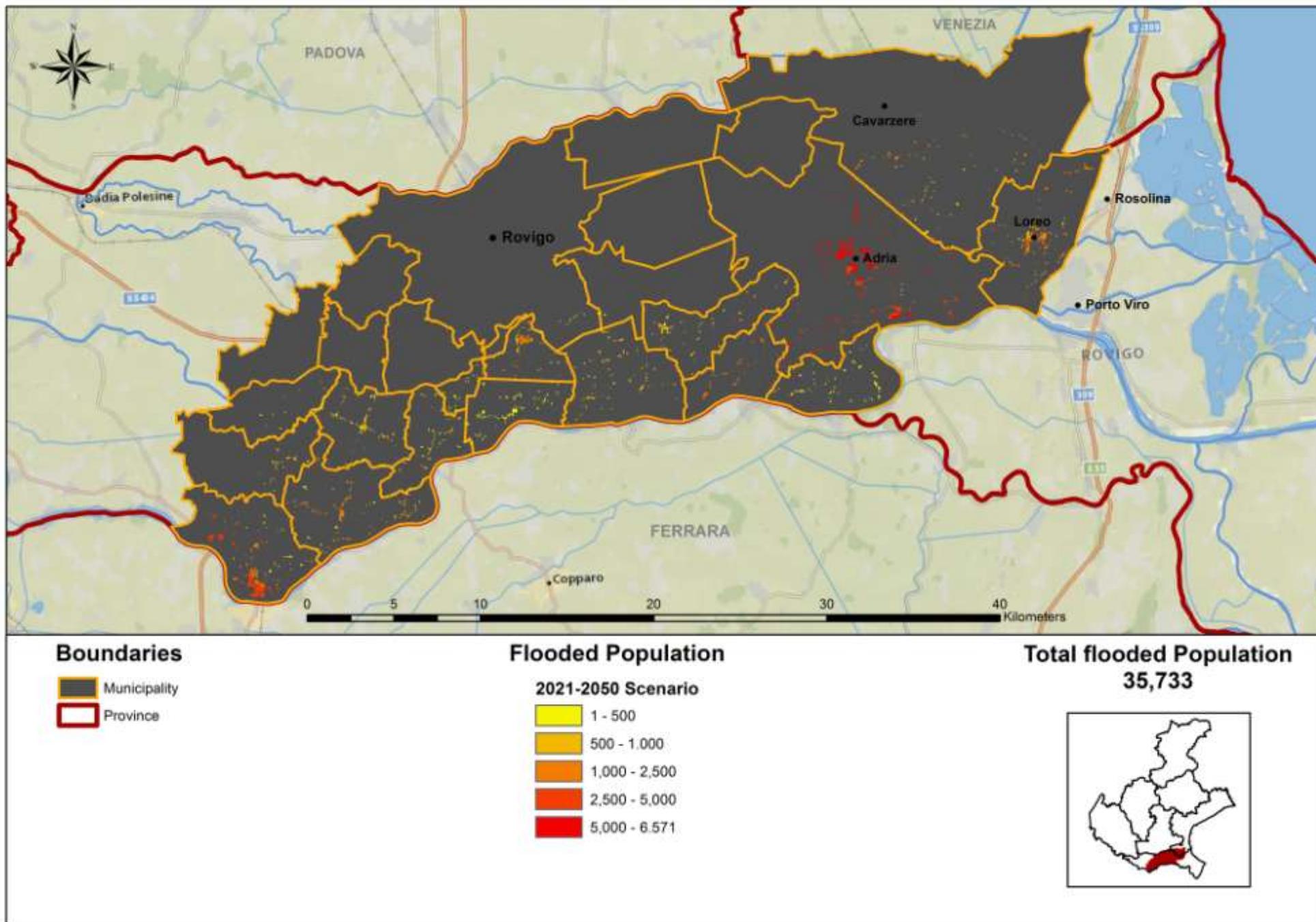
**Total damage**  
**10,571 million €**



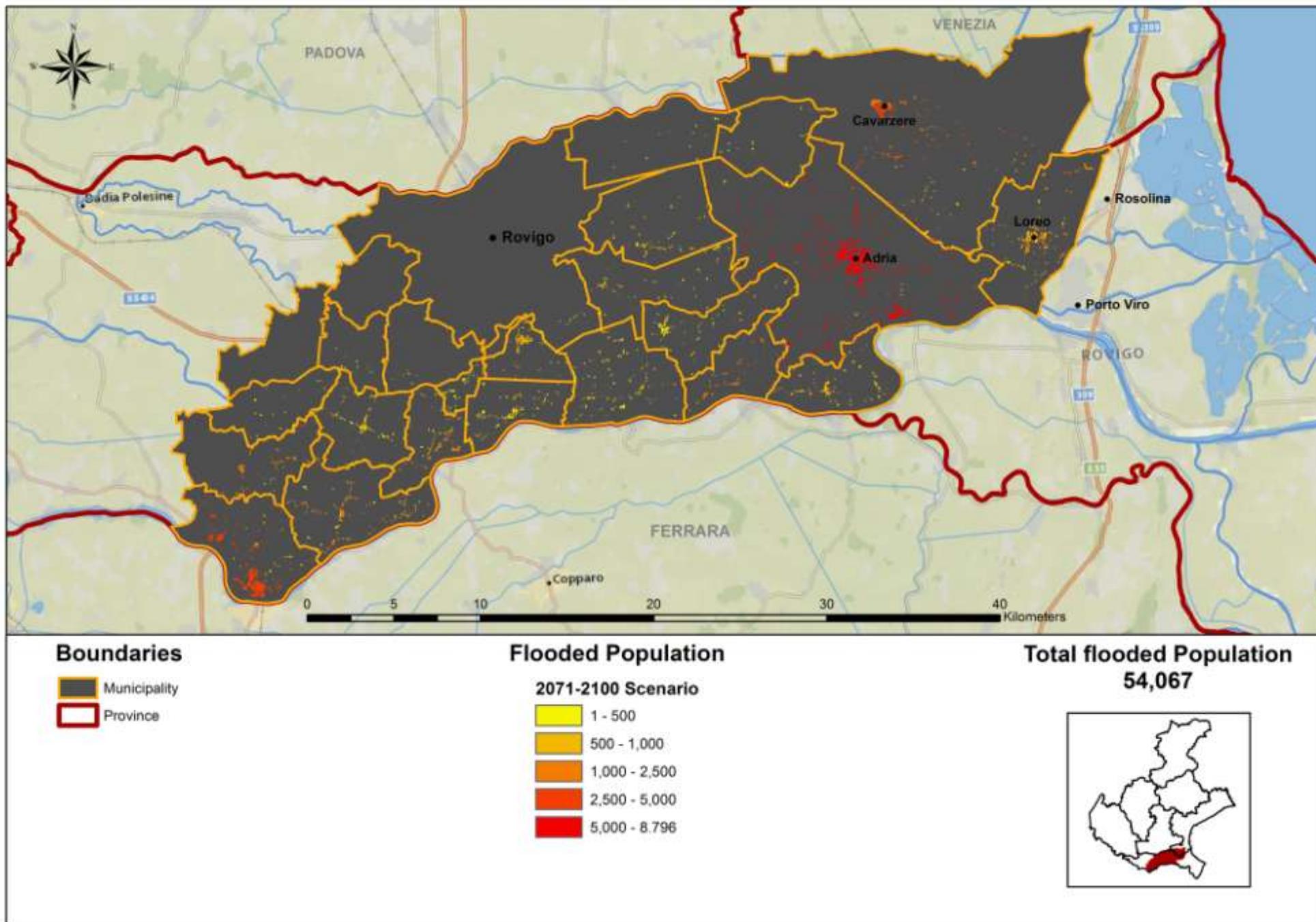
Exposed Population – Base scenario (2000) – 200 meters breach



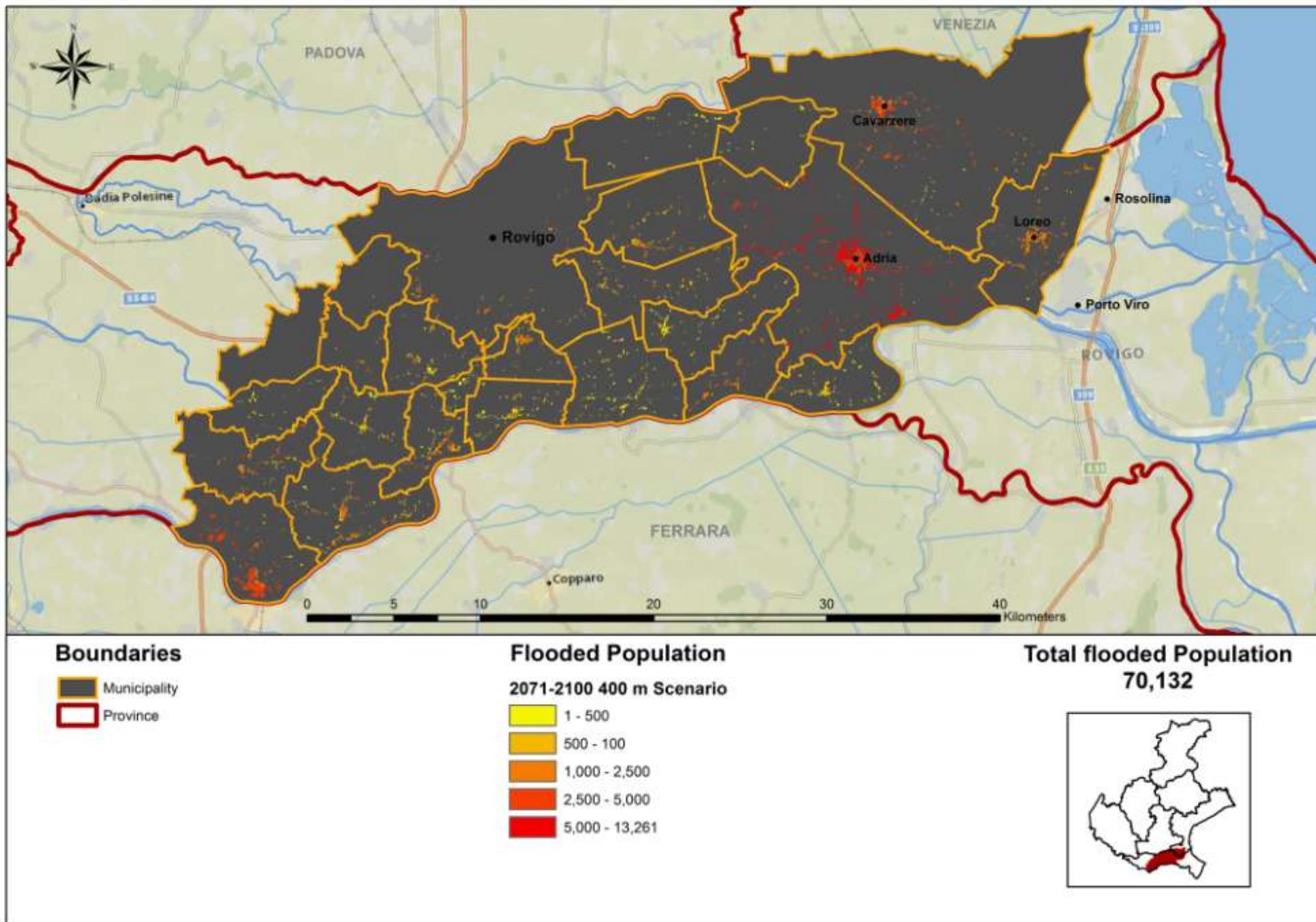
Exposed Population – 2021-2050 scenario (2000 +10%) – 200 meters breach



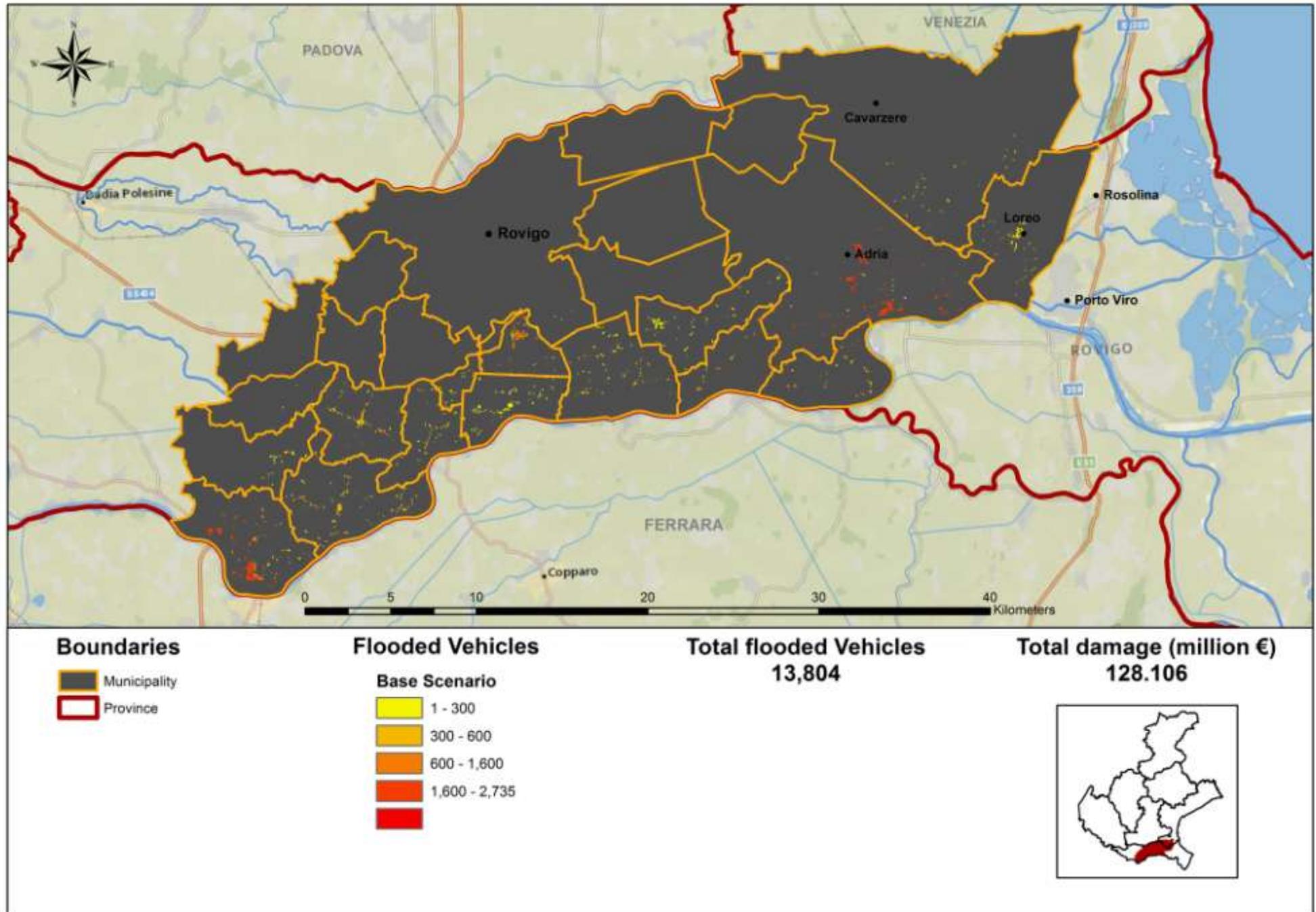
Exposed Population – 2071-2100 scenario (2000 +30%) – 200 meters breach



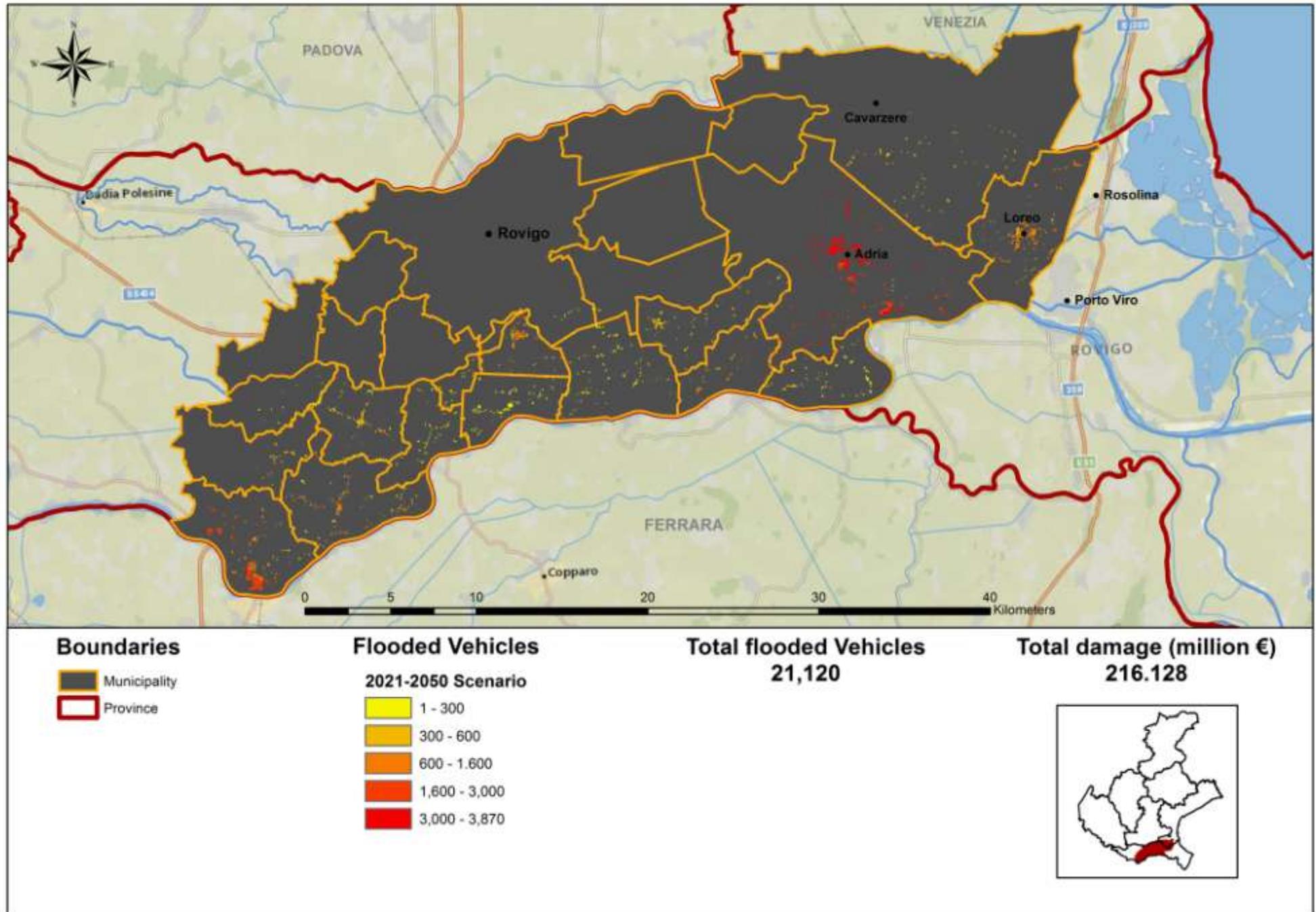
Exposed Population – 2071-2100 scenario (2000 +30%) – 400 meters breach



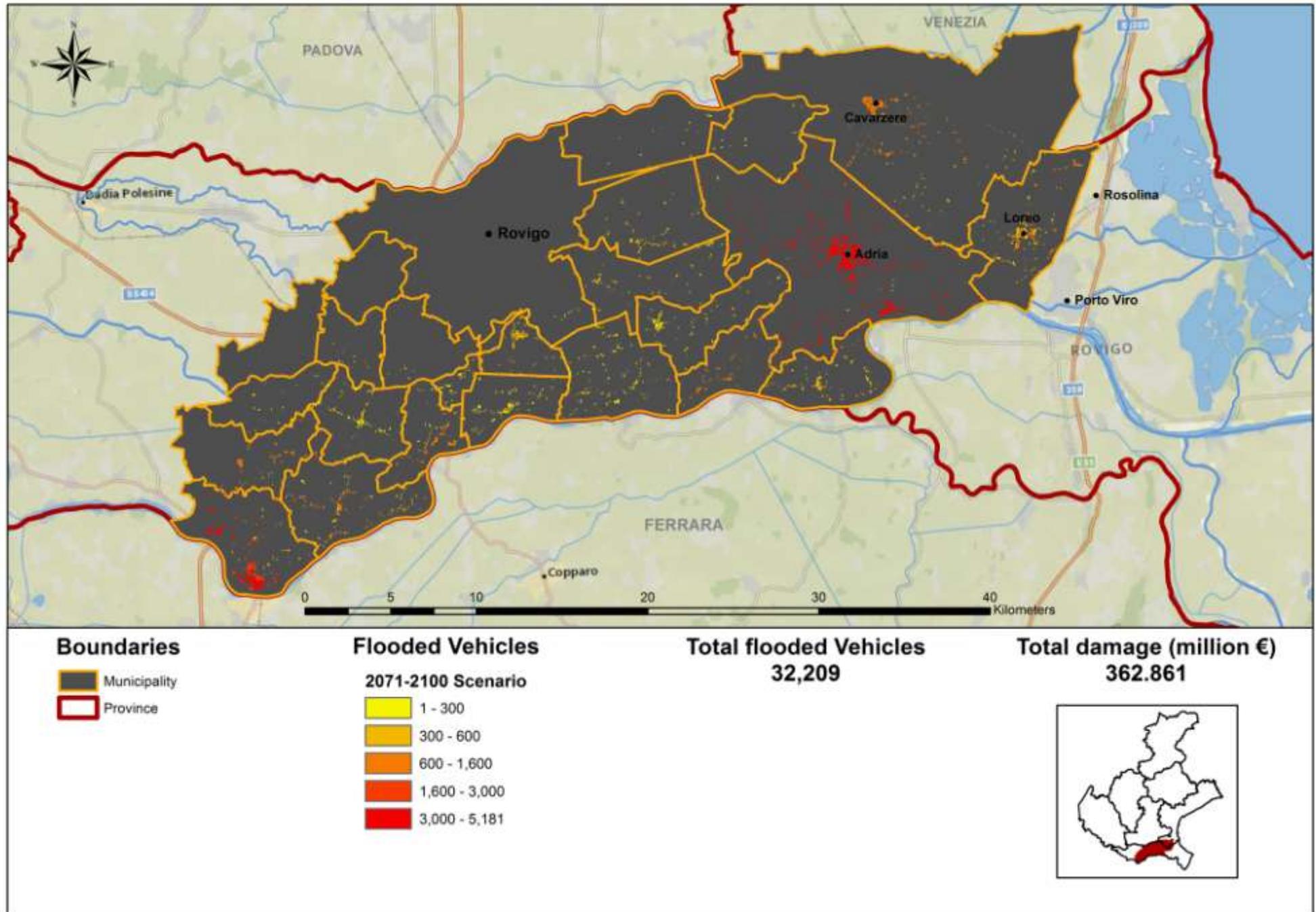
Vehicles damage assessment – Base scenario (2000) – 200 meters breach



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



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



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

