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# EVOLUTION OF FLOOD RISK OVER LARGE AREAS: QUANTITATIVE ASSESSMENT FOR THE PO RIVER

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#### 8 ABSTRACT

The worldwide increase of damages produced by floods during the last decades strengthens the 9 common perception that flood risk is dramatically increasing due to a combination of different causes, 10 among which climate change is often described as the major driver. Nevertheless, the scientific 11 community is increasingly aware of the role of the anthropogenic pressures (e.g. steady expansion of 12 urban and industrial areas in dyke-protected floodplains) that may strongly impact the flood risk in a 13 given area by increasing potential flood damages and losses (i.e. so called "levee effect"). The scientific 14 15 literature on quantitative assessments of the "levee-effect" or robust methodological tools for 16 performing such assessments is still sparse. We refer to the dyke-protected floodplains of the middle 17 and lower portion of River Po (Northern Italy), a broad geographical area ( $\sim 46~000$  km<sup>2</sup>) with two 18 specific research questions in mind: (i) has the flood risk increased over the last half century? And, if 19 so, (ii) what are the main drivers of this change? First, we assess the flood-hazard evolution by 20 analysing three long series of daily streamflow available at different gauging stations. Secondly, we 21 quantitatively assess the temporal variability of the flood exposure and risk by looking at the evolution 22 in time of anthropogenic pressures (i.e. land-use and demographic dynamics observed from 1950s). 23 To this aim, we propose graphical tools (i.e. Hypsometric Vulnerability Curves-HVCs) that are suitable 24 for assessing vulnerability to floods over large geographical areas. Our study highlights the absence of

statistically significant trends in annual statistics of the observed streamflow series and a stable population density within the dike-protected flood-prone area. Nevertheless, the proposed floodvulnerability indexes show a significant increase of the exposure to floods in residential settlements, which has doubled since the 1950s.

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30 Key Words: "Levee effect"; exposure to floods; flood hazard and risk assessment; Po river;
31 Hypsometric vulnerability curve.

32

#### 33 1 Introduction

## 34 1.1 Flood-risk change: evidences, main drivers and open problems

Freshwater flooding (such as river floods, flash floods, urban inundation due to drainage problems, etc.) is the most impacting natural disaster in terms of number of people affected and economic damages (see e.g. EM-DAT; http://www.emdat.be/). Referring to the EM-DAT data-set, Jonkman (2005) analyzed the disasters occurred over the time period 1975-2001 and showed that floods are the most frequently recorded natural hazards occurring world-wide and, even though droughts and earthquakes might be more significant in terms of loss of life, floods are the events that most directly hit the largest number of people (around 2.2 billion of people between 1975-2001).

The common perception of an increasing frequency of floods and inundation phenomena during 42 the last decades is often supported by a growing concern on climate change (e.g. European 43 44 Environmental Agency-EEA, 2005; Wilby et al., 2008). In fact, some studies in the literature (e.g. IPCC, 45 2013, and Stern Review, 2007) seem to indicate that flood damages are expected to increase in the 46 near future as a consequence of a global climate change (see e.g. Hall et al., 2005; de Moel et al., 47 2011a). Climate change has increased worldwide the interest on understanding the interaction between human activities and the hydrological cycle. The scientific literature provides numerous 48 49 studies that analyze long time series of hydrological variables (such as rainfall, river discharges, temperature, etc.) to investigate the presence of significant trends in different contexts and at different scales (Petrow and Merz, 2009; Hamed, 2008; Vorogushyn and Merz, 2013; Villarini et al., 2011). However, it is worth noting that flood damages are the result of a complex system of factors that influence the overall dynamics and impacts of flood events (see e.g. Merz et al., 2010; Elmer et al., 2012), and climate variability is only one component.

Many studies highlighted that the economic and social development in flood-prone areas are key 55 elements for a correct interpretation of the increase of flood losses observed during last decades (see 56 e.g. Ludy and Kondolf, 2012; Di Baldassarre et al., 2013, and references therein). For instance, 57 considering the flood-related costs recorded in Europe over the time period 1970-2006, Barredo 58 59 (2009) shows that there is no evidence of a positive trend on normalized damages; that is, a large portion of the growth of nominal losses associated with floods can be explained by the evolution of 60 61 exposure to floods and wealth in floodplains. Similar results have been found looking at the damages and costs associated with hurricanes in United States between 1900 and 2005 (see Pielke and 62 Landsea, 1998, and Pielke et al., 2008) and to globally observed disasters associated with water (see 63 Neumayer and Barthel, 2011; Barredo, 2009). All these studies show that there are no clear evidences 64 of an increasing trend in the normalized economic damages, even though the difficulties in considering 65 the overall mitigation measures enforced by authorities or individuals prevent one to infer that 66 67 historical data do not show a clear positive trend in the frequency and/or intensity of weather-related 68 natural disasters (Neumayer and Barthel; 2011). Thus, even though historical data do not provide incontestable proofs of the loss increase due to climate change, caution is needed in the evaluation of 69 the overall effects of climate change and the precautionary principle should, in any case, support the 70 reduction of possible human impacts (Neumayer and Barthel; 2011). 71

These considerations are supported by investigations performed on flood risk projections over the future decades in different areas and contexts of the world (see e.g. Elmer et al., 2012; De Moel et al., 2011a; Bouwer et al., 2010). These studies highlight how land-use changes and economic development of hazard-prone areas (i.e. flood-risk exposure) may have an effect on the increase of flood losses that is comparable to, if not higher than, what is commonly associated with the expected climate change. For instance, population growth and the increase of exposed wealth in flood-prone
areas may significantly increase potential damages during flood events, and may end up being the
main factors controlling the increase in recorded damages (Bouwer et al., 2010).

These considerations strengthen the interpretation of floodplains as complex human-water systems, in which the interactions between the two elements is so strong that the current floodplain configuration is actually the result of the interplay between human activities (such as flood controls, land-use changes and other measures that may affect the frequency and magnitude of flooding events) and hydrological dynamics (e.g. the frequency and severity of floods may constrain the development of human settlements) (Di Baldassarre et al., 2013; Schultz and Elliott, 2012).

A typical expression of this strong interaction is the so-called "levee effect" (Tobin, 1995), also 86 named "levee paradox" or "call-effect", according to which the flood-prone areas protected by a levee 87 system attract and encourage new human settlements. The increase of the overall vulnerability of the 88 89 areas may potentially result in higher damage in case of extreme flood events that cannot be restrained by the existing levee system, or in case of levee-system failures (i.e. what is usually 90 identified as "residual flood risk"; see e.g. Castellarin et al., 2011a; Di Baldassarre et al., 2009). 91 92 Investigating a specific case study in California, Ludy and Kondolf (2012) clearly point out that the 93 presence of a levee system changes the perception of the flood likelihood in people living in the dyke-94 protected areas, which are perceived as completely safe from inundations. This feeling ends up increasing the vulnerability of floodplains, even in areas that were already affected by inundations, 95 where the demographic and economic growth experienced after the inundation, due to the 96 enhancement of the levee system, led to a well-being condition that is higher than before the 97 inundation (Schultz and Elliott, 2012). 98

99 All these considerations underline the necessity to analyze flood risk and its evolution in time by 100 means of holistic approaches, which take into account the interaction between social and hydrological 101 factors characterizing a large geographical areas. A better understanding of the interplay between 102 these elements represents a fundamental piece of information for the identification of robust large scale flood-risk mitigation strategies and the definition of viable development plans for flood-prone areas. However, although the "levee effect" phenomenon (Tobin, 1995; also named "call-effect") is frequently mentioned, the literature on its objective quantification is still very sparse and many studies refer to estimates evaluated on each case study (see e.g. Merz et al., 2009).

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#### 108 **1.2 Study aims**

Our study focuses on the middle-lower portion of the Po river and aims at analyzing the evolution 109 110 during the last half century of residual flood risk in the dyke-protected floodplains. The hydrological behaviour of the Po river basin has been investigated in several previous studies (see e.g., Zanchettini 111 112 et al., 2008; Montanari, 2012 and references therein), nevertheless the scientific literature does not report any comprehensive analysis of the historical flood-risk dynamics for the entire middle-lower 113 portion of the Po river nor of the influence on this dynamics of the main controlling factors (e.g. human 114 115 activities that developed during last decades, climatic variability, etc.). In particular, we address the investigation of the evolution in time of flood hazard and exposure to floods, being the flood risk of a 116 given area the combination of the probability of inundation (e.g. flood hazard) and of the expected 117 adverse consequences (i.e. flood exposure and damage susceptibility of the flood-prone areas, see e.g. 118 119 EXCIMAP, 2007).

First, we analyse long streamflow series available at different gauging stations located along the 120 121 study reach, statistically falsifying the hypothesis of changes in flood-hazard during the last half 122 century similarly to what have been shown for other regions of the world (see e.g. Kundzewicz et al., 2005; Svensson et al., 2005). Second, we propose a simplified and robust approach for the 123 124 quantification of flood-risk dynamics associated with the evolution of exposure to floods. Third, we quantitatively assess the evolution of flood risk in the dyke-protected floodplain of the study reach, 125 126 assessing the anthropogenic pressure by referring to land-use (i.e. focussing on residential areas) and 127 demographic dynamics observed from 1950s.

128 In particular, since the study area is protected against 200-year flood events (Po River Basin 129 Authority-Adb-Po, 1999), we focus on the residual risk dynamics, thus referring to a specific lowfrequency flooding scenario for which the protection measures are insufficient (see Section 5.1 for 130 131 more details). We propose simplified flood-vulnerability indexes based on land-use and topographic 132 information that are particularly suitable for large spatial scales, which we use to (1) assess the 133 importance of the different elements contributing to the definition of flood risk and, (2) represent the evolution in time of flood exposure and residual flood risk in the flood-prone area of interest. Finally, 134 135 we quantitatively assess whether during the last half-century the study area experienced the so called 136 levee-effect, and to what degree it impacted the residual flood risk.

Our manuscript is structured as follows: Section 2 illustrates the study area and data used for the analysis; Section 3 investigates the flood-hazard evolution during the last half century; Section 4 describes the methodologies used for investigating the flood-exposure evolution; Section 5 presents the selected inundation scenario and methodologies used for the large-scale estimation of flood damages; Section 6 reports the results of the study. Finally, Section 7 reports a comprehensive discussion of the results.

# 143 2 Study area and available data

The study area consists of the alluvial plain of the Po river, the longest Italian river that flows eastward through the Northern part of Italy for about 650 km. With a total extent of about 71 000 km<sup>2</sup> the Po river basin is the wider Italian catchment and covers a large portion of the Emilia-Romagna, Lombardy, Piedmont, Aosta Valley and Veneto (see Figure 1). This area, in particular the Alpine foothills and flat portion of the basin, represents one of the most developed and populated area of Italy: more than 45% of employed Italians live here producing almost 40% of the total Italian Gross Domestic Product (GDP) (Po River Basin Authority, AdB-Po, 2006; www.adbpo.it).

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- 152

The middle-lower stretch of the Po river flows across a flat and fertile alluvial area, named Pianura Padana (overall extent of around 46 000 km<sup>2</sup>), where the flood-prone areas that are closer to the Po river, or its major tributaries, are protected from frequent inundations by means of a complex system of embankments and other hydraulic structures (e.g. pumping stations, sluice gates, etc.) that are monitored and maintained by the Interregional Agency of the Po River (AIPO; www.agenziainterregionalepo.it) and by the Po River Basin Authority (AdB-Po).

160 The current embankment system represents the result of the people struggle during the last 161 centuries to prevent the loss of their properties and assets due to floods. From 1705 to 1951 Pianura 162 Padana was hit by 18 major floods with 225 embankment failures along the main river or its major tributaries (Govi and Turitto, 2000). In the inundations aftermath the embankment system was 163 continuously strengthened and extended, increasing from a total length of about 1 500 km on 1878, to 164 165 more than 2 900 km after the flood event of the 1951, when the lower stretch of the Po river experienced a catastrophic flood event that caused a large inundation ( $\sim 1080 \text{ km}^2$ ; see Masoero et al., 166 2013) and severe damages (e.g., 100 victims, 900 houses seriously damaged and around 200 000 167 168 refugees; Amadio et al., 2013).

Castellarin et al. (2011a) and Di Baldassarre et al. (2009) clearly emphasized this aspect showing 169 the evolution in time of the overall length of the embankment system along the Po river and major 170 171 tributaries between 1800 and '50-'60s and the associated increasing trend in the sequence of annual maximum water level at the Pontelagoscuro streamgauge (see Figure 1), located at the catchment 172 outlet (see also Heine and Pinter, 2012). During the last decades (i.e. from 60's) the actions of 173 174 adjustment of the levee system along the lower portion of the river mainly focused on the 175 strengthening of the existing embankment, while further embankment widening and raising were 176 implemented after the flood event of October 2000 (see Coratza, 2005; Castellarin et al., 2011a). The 177 current river configuration is reported in Figure 1 (box), which shows the main river stretch, the main 178 embankment system, as well as the area that can potentially be flooded in case of catastrophic flood

179 events (blue polygons). This area, named "Fascia-C" (literally C-Buffer, which we consistently use in 180 the remainder), is characterized by an overall extent of  $\sim 6\ 100\ \text{km}^2$  and was identified by the Po River Basin Authority (AdB-Po, 1999) as the envelope of all areas associated with a non-negligible residual 181 182 risk of being flooded, that is areas that can be flooded in case of sudden and unpredictable failures of 183 the embankment system (i.e. breaches in the embankments along the main river or tributaries that are 184 triggered e.g. by piping during major floods) or in case of flood event with a recurrence period higher 185 than the one adopted for the design of the embankments (i.e. ~200 year, AdB-Po, 1999). The box on Figure 1 shows the C-Buffer area divided into different compartments defined referring to the layout 186 of natural and man-made structures (e.g. embankments for the Po river and its main tributaries, rivers, 187 188 roads, etc.; see also Castellarin et al., 2011b).

Despite the existence of a non-negligible residual risk in the C-Buffer (i.e. the levee failure occurred in 1951 is an evidence of the residual risk that still exists in the flood-prone area), the feeling of safety ensured by the embankment system attracted human settlements and the area itself went through a significant economic development during the 20th century. In the light of these considerations, together with the availability of historical land-use information (see Section 2.1 for details), we investigate the factors that driven the evolution of the residual flood risk in the floodprone areas during last decades, focusing in particular in the period that goes from 1950s up to now.

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#### 197 **2.1 Available data**

We refer to data of various type collected from different sources. The following list briefly summarizes the data set used for the analyses, while further information on the actual utilization of these data are provided in Sections 3, 4 and 5:

Streamflow data: Table 1 summarizes the characteristics of daily streamflow series recorded
 at streamgauges of Moncalieri, Piacenza and Pontelagoscuro (see Figure 1), with lengths of 42,
 85 and 89 years, respectively.

Land-use maps: land-use maps are available for the C-Buffer and different time periods from
 cartographic offices of Emilia-Romagna and Lombardy administrative districts (see Figure 1).
 In particular, land-use information is retrieved from aerial imagery available for 1954 (G.A.I Gruppo Aereo Italiano and WWS flights) and 2008 (AGEA-2008), with a resolution of about
 150 m and 75 m, respectively, and classified referring to the standardized classes aggregation
 adopted by the CORINE (COoRdinated INformation on the Environment) project (EEA, 2009).

- *Demographic dynamics*: number of inhabitants available throughout Italy since 1861. The
   Italian National Statistical Institute (ISTAT; <u>http://www.istat.it</u>) provides information on the
   population dynamics with ten-year frequency at each census sections.
- Assets economic values: economical values of residential buildings in the alluvial area. The
   Italian Revenue Agency (Agenzia delle Entrate (AE); <a href="http://www.agenziaentrate.gov.it">http://www.agenziaentrate.gov.it</a>)
   provides the open-market values for different assets, taking into account different classes for
   residential and industrial buildings and the overall economic well-being of the region (see
   Section 5.2 for more details).
- *Topographic information*: topography of the study area is retrieved from TINITALY/01
   (Tarquini et al., 2007). Created by using heterogeneous elevation datasets (i.e. contour lines,
   elevation points, etc.), TINITALY/01 represents the most accurate Digital Elevation Model
   (DEM) covering Italy. It is characterized by a horizontal resolution of 10 m and a vertical
   accuracy (i.e. root mean square errors ranging from 0.8 to 6 m) higher relative to other global
   DEMs (i.e. SRTM, ASTER; see Tarquini et al., 2012).
- 224

# 225 **3** Flood-hazard evolution – trend detection in streamflow series

#### 226 **3.1 Methods**

Many studies investigated the streamflow regime of the Po river (see e.g., Visentini, 1953; Piccoli,
1976; Marchi, 1994). Zanchettini et al. (2008) analyzed the long-term daily streamflow variability at

229 Pontelagoscuro (see Figure 1) by referring to a time series longer than 200 years, in which some daily 230 streamflow values were re-constructed from historical information on water surface. The analysis 231 highlighted an increase in the streamflow values observed at the streamgauge of Pontelagoscuro 232 during last decades, concluding that this increase could be mainly attributed to the massive 233 embankment works implemented along the river network during previous decades, rather than to 234 climate changes. The authors also pointed out the existence of perturbation periods (mainly associated with droughts) lasting for several years. More recently, Montanari (2012) reached similar conclusions 235 by investigating the variability of daily streamflows observed along the Po river and some its major 236 tributaries. The study highlighted the presence of local perturbations (i.e. periods characterized by 237 water scarcity, or water abundance), whose memory lasts for long periods of time (i.e. several years), 238 239 which can be associated with the size of the drainage area. Even though this evidence suggests the presence of long-term persistence that would be worth investigating, the research of trend interested 240 241 only the gauged section of Pontelagoscuro and was made by means of a linear regression application.

In this study, we further analyse the variability of the daily streamflow regime of the Po river by 242 testing for trends the daily streamflow series collected at three gauging sections along the main 243 stream: Moncalieri, Piacenza and Pontelagoscuro (see also Figure 1 and Table 1). The streamgauges 244 are located along the same river and therefore the observed daily streamflow series are necessarily 245 statistically correlated to each other, which is likely to result in similar outcomes of statistical testing 246 (see Douglas et al., 2000). Nevertheless, we considered all three series since they refer to rather 247 different drainage areas and periods of time (see Table 1 and Figure 1). In particular, we adopted the 248 non-parametric Mann-Kendall (MK) test (Mann, 1945; Kendall, 1975), that is one of the most robust 249 250 trend detection method applied in many studies to different hydrological variables (see for example 251 Yu and Wang, 2004, and references therein) and spatial scales (see e.g. Douglas et al., 2000; Hamed, 252 2008; Villarini et al., 2011). The MK test analyses the ranks of the observations rather than their actual 253 values, it is non-parametric (distribution-free) and less sensitive to outliers than other parametric 254 approaches, therefore the MK test appears to be particularly suitable for detecting statistically 255 significant trends in hydrological time series (see Yue et al., 2002, Petrow et al., 2009). However, the presence of serial correlation among the daily streamflow data may impact the power of MK test (von Storch and Cannon, 1995). To overcome this problem we applied the trend free pre-whitening (TFPW) procedure to the study series; TFPW removes serial correlation from time series, and hence it eliminates the effect of serial correlation on the MK test (see Yue et al., 2002, for details). In particular, we perform a two-sided trend test at 5% significance level through the MK-TFPW procedure on the sequences of annual maxima (AMS), mean (MEAN) and standard deviation (SD) of daily streamflows.

262

Table 1

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# 264 **3.2 Results and Discussion on flood-hazard evolution**

Figure 2 shows the annual sequences of maxima (AMS), mean (MEAN) and standard deviation (SD) of daily streamflows at Moncalieri, Piacenza and Pontelagoscuro, along with the related linear regression lines fitted over the observation period. Table 2 reports the results of the Mann-Kendall (MK) trend analysis test, listing Sen's slope value,  $\beta$ , test *p*-value, and increase/decrease of the statistics over the observation period, *A*.

Figure 2 clearly highlights the absence of significant and consistent long-term trends on the daily 270 271 streamflow statistics (i.e. AMS, MEAN, SD) computed for the three streamgauges over the 272 corresponding observation periods. Considering Moncalieri cross-section, Sen's slopes, β, appear to be limited for all considered statistics, pointing out a small increase in the annual maxima and mean 273 274 discharge values ( $\beta$  equal to 2.09 and 0.31 m<sup>3</sup>/s/year, respectively; see Table 2), while the river daily 275 streamflow variability (i.e. SD) is almost constant over the period ( $\beta$ =-0.02 m<sup>3</sup>/s/year). *p*-values 276 reported for Moncalieri indicate the absence of statistically significant long-term trends at 5% level. 277 Similar results are observed at Piacenza, where MEAN and SD do not show significant changes over 278 the observation period, even though AMS is associated with a limited increase ( $\beta$  equal to 2.02 279 m<sup>3</sup>/s/year), which is consistent with the one observed for Moncalieri. The slight increase of annual 280 maximum daily discharges in the upstream cross-sections of Moncalieri and Piacenza (see Figure 1) is 281 confirmed at Pontelagoscuro, where this feature appears to be emphasized (see Figure 2 and Table 2). AMS series at Pontelagoscuro is associated with a slope  $\beta$  of 13.2 m<sup>3</sup>/s/year, with an overall increase of about 1178 m<sup>3</sup>/s for 90-year observation period; although not negligible, this trend is not significant from a statistical viewpoint (p-value = 0.106).

Furthermore, concerning the non-significant positive trend associated with the last 90 years of observations, it is worth highlighting that the same analysis repeated for the data observed after 1950 results in a statistically non-significant negative trend of -2.73 m<sup>3</sup>/s/year. Finally, Pontelagoscuro MEAN sequence does not evidence any change during the observation period, while SD shows an overall increase of about 225 m<sup>3</sup>/s, which is significant at the 5% level (see Table 2).

The extended analysis of historical stream flow series carried out in our work confirms the 290 291 findings of previous studies (e.g. Montanari 2012; Zanchettini et al., 2008) and highlights the absence of statistically significant trends on streamflow series along the overall river reach (see Figure 2). The 292 impact of the flood-hazard variability in the assessment of the residual flood risk dynamics during the 293 294 last half century appears to be practically negligible and statistically not significant, making reasonable the hypothesis of stationarity of the streamflows data set. On the basis of these considerations the 295 likelihood of extreme flood events responsible for the residual flood risk in the area of interest (such 296 297 as flood events with return period higher than 200 years) can be considered not significantly changed 298 during the last half century.

299

Table 2 – Figure 2

300

# **4 Evolution of exposure to floods: simplified tools for large-scale applications**

302 4.1 Land-use dynamics

We investigate the land-use evolution in the Po river basin focusing in particular on Emilia-Romagna and Lombardy administrative districts (see Figure 1), which cover entirely the C-Buffer (i.e. the floodable area in case of the Tr-500 flood event; see box in Figure 1). Our analysis considers landuse maps available for 1954 and 2008 (see Section 2.1). The maps were constructed on the basis of historical aerial photographs with different spatial resolution (150 m and 75 m for the 1954 and 2008 maps, respectively), however the land-use classifications adopted in both cases are consistent and enable one to compare the two time periods. The land cover data in both maps use a hierarchical structure similar to the one adopted by the CORINE project (EEA, 2009), in which different soil-uses are organized by means of several levels of aggregation. In this study the evaluation of the flood exposure evolution is performed referring to urban and residential areas only. Table 3 reports the land cover categories used for the different maps adopting the CORINE classification as reference.

314

#### Table 3

We evaluate the expansion of urban and residential areas by referring to two different spatial 315 scales. First we consider a local scale by referring to C-Buffer compartments only (see Figure 1). 316 Second, we evaluate the land-use evolution at a larger scale (i.e. regional analysis), comparing the 317 overall extension of urban areas in 1954 and 2008 in Emilia-Romagna and Lombardy districts. Results 318 319 obtained for the local (C-Buffer) and regional (large-scale) analyses can then be compared to gain a deeper understanding of the evolution of exposure to floods, providing interesting insights to foster 320 the discussion on the effectiveness of the "levee-effect" (or "call effect") on the floodplains areas (see 321 322 Sections 6 and 7).

323 We use the land-use maps described above to derive a large-scale assessment of the exposure to floods in the C-Buffer. In particular, we combined the land-use class of interest (i.e. urban settlements) 324 325 of each compartment with the digital description of the topography (i.e. 10 m DEM; see Section 2.1) to retrieve a simplified altimetric description of urban and residential areas through a so-called 326 327 hypsometric curve, which we named Hypsometric Vulnerability Curve (HVC). The hypsometric curve 328 of a given area reports on the x-axis the percentage (or the portion) of area characterized by elevations 329 lower than the value reported on the y-axis. HVCs of each compartment of the C-Buffer combine land-330 use information with information on elevation retrieved form the 10 m DEM. Zhang et al. (2011) firstly 331 proposed the use of hypsometric curves in the Florida Keys for the evaluation of the impact of 332 different scenarios of sea level rise on human population and real estate property.

Figure 3

335

336 As an example, Figure 3 reports a schematic representation of the HVC defined for a specific compartment and land-use class. We construct the urban and residential areas HVCs for each 337 compartment for 1954 and 2008 in a GIS (Geographic Information System) environment. HVCs 338 339 represent a valuable tool for a preliminary assessment of the exposure to floods of each compartment, 340 and, when one can construct curves relative to different time periods as in our case, these curves can be particularly useful for characterizing the dynamics of urban areas over a given historical period 341 (e.g. in the dike-protected floodplain of the Po river over the last half century). The schematic 342 representation of Figure 3 illustrates HVC and the information that can be retrieved from such a curve. 343 344 For instance, the HVC graphically represents the altimetric characteristics of a specific land-use class 345 in a given compartment (e.g. residential settlements), and HVCs of different periods enable one to 346 assess how and where (i.e. closer or farther to the river) a specific land-use class developed over time (see Section 6.1 and Figure 7 for details). Furthermore, assuming the dashed line of Figure 3 as a 347 hypothetical inundation level, its intersection with the HVC identifies the extent of the affected area 348 349 and may be particularly useful for a prompt assessment of flood damages (see Section 5.2 for details).

350

# 351 4.2 Population dynamics

The number of people living in flood-prone areas represents a fundamental element for the evaluation of the exposure to floods and is a key factor of the "levee effect" phenomenon (see e.g. Di Baldassarre et al., 2010, 2013; Barredo, 2009). Accordingly, we analyze the population dynamics in the Po river basin, assessing if the strengthening of the levee system carried out during last century (see Section 2 and also Di Baldassarre et al., 2009, and Castellarin et al., 2011a) is associated with any population growth in the flood-prone areas in spite of the residual flood risk. In particular, we evaluate the population dynamics from 1861 to 2011 considering the number of inhabitants recorded by the

Italian National Statistical Institute (ISTAT) (census data are provided with a 10-year frequency) and provided for each Italian municipality. Once collected, the population data have been gathered together distinguishing between Emilia-Romagna and Lombardy regions and all of the compartments of the C-Buffer (see Figure 1).

Given the extent of urban areas and the overall number of inhabitants living in a specific 363 municipality within a C-Buffer compartment we estimate the population density under the hypothesis 364 of a uniform distribution over the urban extent. The population density of a specific compartment is 365 calculated as the weighted average among different municipalities, weighting that data proportionally 366 to extent of urban areas. Then, we derive the Hypsometric Inhabitant Curves (HICs) for 1954 and 367 368 2008 by combining the average population density with the altimetry of the urban area in a given compartment (see the procedure adopted for the HVC construction; Figure 3). HICs are curves that 369 report the overall number of inhabitants living in a compartment below a given elevation: they 370 371 integrate information on the number of people living in a specific compartment with the overall extent 372 of urban areas, obtained from land use maps, and elevation retrieved from a DEM of the area of interest. The curves may represent useful tools for a preliminary evaluation of the exposure to floods 373 of a specific area. For instance, HICs may enable one to estimate the number of people that could be 374 affected by a given inundation scenario over a floodplain area; alternatively, HICs constructed for a 375 376 given inundation scenario and floodplain compartment by considering census data and land-use maps 377 for different years may effectively summarize the impacts of demographic dynamics on flood risk.

378

# 379 **5 Damage calculation for urban areas**

Flood risk management recently shifted its main focus from flood hazard (i.e. hazard reduction) to a risk-based view (i.e. risk reduction) (see e.g. Vis et al., 2003; Merz et al., 2010; De Moel et al., 2012). This approach considers the interplay between hydrological and socio-economic factors and the calculation of the expected flood damage represents a fundamental piece of information for the overall flood-risk mitigation process. The evaluation of the overall costs of natural hazards, such as flood 385 events, is a challenging task due to the variety of damage types that may be directly or indirectly 386 related to the hazard. Meyer et al. (2013) recently summarize these costs distinguishing four different 387 categories identified in relation to their nature and to the methodologies adopted for their assessment: 388 direct and indirect costs, business interruption costs, and intangible costs. Considering flood events, 389 direct costs represent the damages occurred to properties (e.g. buildings, stocks, cars, infrastructure, 390 etc.) physically hit by the flood. Business interruption costs result from the interruption of the economic activities in the flooded areas, for example because of inaccessibility or because of the 391 destruction of the working instruments (see Meyer et al., 2013). Indirect costs summarize all the 392 economic losses that can be related to direct and indirect (e.g. business interruption) damages, 393 394 occurred both inside or outside the affected area, even considering the effects on a broad timeframe 395 after the event (see Carrera et al., 2015 for more details). Finally, intangible costs consider the impact 396 on services, goods or human beings which have not a market value and for which the damage 397 estimation in monetary terms is not trivial, if not impossible (e.g. health and environmental impacts, damages to cultural heritage, etc.; Meyer et al., 2013; Markantonis et al., 2012). 398

399 Concerning the estimation of different types of flood losses the literature provides a series of 400 methodologies of various complexity based on different type of data and assumptions, and suitable for different scales of application (see Meyer et al., 2013, for a comprehensive review of these 401 402 approaches). Traditionally, the flood damage assessments mainly refer to direct losses in view of the greater ease with which they can be estimated. In particular, the scientific community proposes 403 simplified damage models that estimate the expected direct flood damages by means of depth-damage 404 functions (also named susceptibility functions), where the economic damage of a specific element (e.g. 405 406 a building) is a non-decreasing function of the water depth, which is sometimes integrated with some 407 other hazard factors (i.e. flow velocity, duration, pollution, etc.; see Jongman et al., 2012). More 408 recently, sophisticated multi-parameter models have been proposed for a local estimation of losses in 409 private households and companies (e.g. FLEMO; see Kreibich et al., 2010; Elmer et al., 2010). Even 410 though the former approach is less accurate and associated with a larger degree of uncertainty (see 411 e.g. Apel et al., 2008; De Moel et al., 2011b), in the light of the large spatial scale of interest (i.e. overall

412 C-Buffer area) we estimate the expected flood damage referring to a simplified approach based on the413 joint use of a depth-damage curve and the previously defined HVCs.

Differently from previous applications, where hypsometric curves were used only for identifying the extent and amount of affected properties (see Zhang et al., 2011 for sea level rise scenarios), we propose an original application of HVCs in combination with a given inundation scenario and specific depth-damage curves (e.g. accurately identified for a specific land-use or buildings type, see Section 5.2 for a detailed description about flood damage estimation) that enables the user to calculate the flood losses. We focus on direct damages (i.e. direct tangible damage) for residential building, while we neglect all other costs in this preliminary application.

421

#### 422 **5.1 Inundation scenario**

423 For the evaluation of the flood hazard we refer to the inundation scenario generated by the numerical model developed by Castellarin et al. (2011b) whom implemented a quasi-two-dimensional 424 (quasi-2D) model (Willems et al., 2002) for the Po river stretch considered herein (from Isola S. 425 Antonio to Pontelagoscuro, ~350 km; see Figure 1). The model describes the main river reach by 426 means of cross-sections retrieved from a detailed digital elevation model (LiDAR, with a spatial 427 resolution of 2 m), while all dike-protected floodplains are represented as storage areas connected to 428 429 each other and/or the main channel by means of weirs mimicking the system of minor levees. 430 Adopting a similar modeling strategy, all C-Buffer compartments are represented as storage areas and 431 connected to the main river, or dike-protected floodplains, by means of lateral structures that reproduce the main embankment crests. Volume-level curves regulate the hydraulic behavior of all 432 433 storage areas, and, in case of inundation of a dyke-protected floodplain or C-Buffer compartment, the 434 simulated water level is computed as a function of the water volume exchanged with the main river 435 and/or adjacent storage areas. Volume-level curves were estimated referring to LiDAR imagery (2 m 436 resolution) for the dyke-protected floodplains and to a 10 m resolution DEM (Tarquini et al., 2007) for 437 C-Buffer compartments. The quasi-2D model was calibrated referring to the historical flood event 438 occurred in October 2000 and then used for simulating a major flood event, hereafter referred to as
439 Tr500, which represents a low frequency/high intensity event associated to a return period of ~500
440 years (see Castellarin et al., 2011b for details).

441 The main embankment system of the middle and lower portion of the Po River is designed to cope with flood events associated with return periods up to  $\sim$ 200 years, which are significantly less 442 intense than the Tr500 event identified in Castellarin et al. (2011a and 2011b). Considering the 443 homogenous protection level ensured by the major embankment system along the entire study reach 444 we referred to the Tr500 event as the reference flood scenario, thus limiting the estimation of the 445 residual flood risk to the likelihood of this extreme event, neglecting the hazard related to flood events 446 associated to return period lower than 500-year but not contained by the embankment system or to 447 possible levee failures. Considering these latter possibilities (e.g. breaches on the embankment due to 448 449 seepage, piping, etc.) in our study we do not explicitly consider the possibility of levee failures for more frequent events. Nevertheless, the proposed approach is perfectly suitable for applications that 450 for example adopt comprehensive multivariate Monte Carlo resampling techniques for a through 451 characterization of the flooding hazard in the region of interest (see e.g. Vorugushyn et al., 2010; 452 453 Domeneghetti et al., 2013).

454 The Tr500 inundation scenario is modelled by simulating failures along the embankment system 455 (i.e. formation of breaches in case of overtopping of main embankments, see configuration BREACHBL in Castellarin et al., 2011b). Dike overtopping may occur in BREACHBL if the water level exceeds the 456 crest elevation of the embankments, under this circumstance, as consequence of the flow erosion on 457 the out-board side of the levee, the quasi-2D model simulates the formation of a levee-breach 458 459 according to literature information on width, depth and time of full development recorded for the Po 460 river (see e.g. Govi and Turitto, 2000). The numerical model enables the simulation of multiple 461 breaching events as a result of concurrent overtopping phenomena along the main embankment 462 system, thus enabling the inundation of several C-Buffer compartments during a single major flood 463 event (see details in Castellarin et al., 2011b). In order to better highlight the role of the exposure to 464 floods on the evolution of the flood risk the numerical simulations are performed, for both the periods of interest (i.e. 1954 and 2008), referring to the actual levee system configuration, thus neglecting the strengthening of the levee system eventually performed during last 50 years. Furthermore, the absence of consistent and statistically significant long-term trends on the streamflow series recorded along the Po river (see also Section 3.2) enables the use of the same inundation scenario for the entire period of interest (i.e. from 1954 to 2008), thus facilitating the evaluation of the flood exposure evolution on the overall flood risk.

471

472 **5.2 Estimation of direct economic losses** 

473 It is well known that the estimation of direct damages associated with a flood event is a 474 challenging task which is affected by a large amount of uncertainty (Cammerer et al., 2013). Concerning Italy, Molinari et al. (2014) related this uncertainty with the lack of high quality post-flood 475 event damage data, which are necessary for a proper calibration and validation of damage models. In 476 our analysis, considering the scale of interest (i.e. large scale analysis: middle-lower portion of the Po 477 river) and the nature of the proposed approach (i.e. simplified numerical tools to evaluate the flood 478 risk), the quantification of the flood exposure is performed by referring exclusively to the economic 479 value of private buildings prone to inundation events, neglecting other direct (e.g. damages to public 480 481 or commercial buildings) and indirect costs.

482 The Italian Revenue Agency (Agenzia delle Entrate, AE) publishes the economic value (E  $[\notin/m^2]$ ) of different types of private buildings (e.g. civil houses, offices, stores, etc.) in each Italian 483 484 administrative district (spatial scale of municipality) every six months (economic values of public 485 buildings are not provided by AE and thus excluded from the present investigation). Table 4 reports an 486 example of monetary estimates available for buildings of each municipality conditioned upon the 487 definition of use (i.e. residential, commercial, services or productive) and typology (i.e. detached 488 house, box, stores, etc.). Focusing on residential buildings and assuming an unique building type (i.e. 489 civil houses on Table 4), we define the reference economic value (E  $[\notin/m^2]$ ) for urban settlements 490 within any given compartment of the C-Buffer as the average of the E values provided for all the 491 municipalities, weighted proportionally to their urban extent located within the C-Buffer (see Table 5).
492 Therefore, the overall value of urban properties can then be approximated by the product of the
493 average economic value and the overall urban area extent in the compartment, which we obtained
494 from the land-use maps available for 1954 and 2008 (see Section 4.1).

It is worth noting that the damage evaluation relies on the assumption of a constant economic value for urban buildings over the period of interest (i.e. 1954 and 2008). Without lack of generality, our analysis considers two different land use maps, yet, for the sake of comparison, we refer to 2014 economic value of buildings for both historical land-use scenarios.

The literature provides a wide set of depth-damage curves that offers the possibility to cover differ applications contexts, considering different types of buildings (i.e. residential, commercial, industrial, etc.; see e.g. Thieken et al., 2008) and the effect of factors which may influence the expected damages (i.e. contamination, levels of private precaution, etc.; see e.g. Kreibich et al., 2010). These curves generally express the percentage of damage of a specific asset as a function of the water depth and are constructed on empirical damage data (i.e. historical inundation) or using expert judgment and synthetic analysis.

Among the available curves, we refer to the damage-curve implemented in the Multi-Colored Manual (MCM; Penning-Roswell et al., 2010) that estimates the expected losses for residential buildings as a function of the local water depth (see Figure 4). The MCM is one of the most advanced models for flood-damage estimation within Europe (Jongman et al., 2012) and represents a viable tool for the estimation of the losses related to floods.

511

512

#### Figure 4

513

514 Combining the MCM susceptibility curve and the overall economic value of residential buildings, 515 we compute the expected damage in a given C-Buffer compartment for a given inundation scenario 516 through a procedure that is schematically illustrated in Figure 5. The horizontal blue line of Figure 5a 517 represents the maximum water level [m a.s.l.] resulting from the quasi-2D simulation of the 518 inundation scenario of interest (see also Section 5.1). As already pointed out, the extent of the 519 inundated urban area  $(A_{tot})$  can be easily retrieved from the intersection between the elevation of the 520 maximum water level (blue line in Figure 5a) and the HVC of the flooded compartment. The damage 521 (*D*) to urban settlements is associated with the local water depth (*h*) by means of the depth-damage 522 curve (see Figure 5b for a schematic example). This curve also identifies a water-depth value ( $h_{100}$ ) 523 associated with 100% of damage, meaning that for buildings hit by water depths equal or higher than  $h_{100}$  the flood-loss coincides with the value of the buildings. Based on this hypothesis, one can estimate 524 the extent of urban area where the damage is maximum ( $A_{100}$  [km<sup>2</sup>] in Figure 5a) by subtracting  $h_{100}$ 525 (i.e. water depth equal to 3 m for the MCM depth-damage curve; see Figure 4) to the maximum flood 526 elevation (blue line in Figure 5a). Everywhere in  $A_{100}$  the water depth is higher than  $h_{100}$  and therefore 527 528 the flood damage can be estimated as:

$$D_{100} = E \cdot A_{100} \tag{1}$$

where  $E \ [€/m^2]$  indicates the overall average economic value of residential buildings in the compartment (see Table 4). In the remaining portion of the inundated urban area ( $A_{tot} - A_{100}$  in Figure 531 5a) the flood damage,  $D_h$ , depends on the local water depth and can be expressed as:

$$D_h = \int_{A_{100}}^{A_{tot}} E \cdot d[h(A)] dA$$
<sup>(2)</sup>

where the percentage of losses  $d(\cdot)$  is a function of h(A) through the depth-damage curve (see Figure 4). According to eq. (1) and (2) we calculate the total direct damage in the compartment, *D*, as:

$$\mathbf{D} = \mathbf{D}_{100} + \mathbf{D}_{\mathbf{h}} \tag{3}$$

It is worth noting that the damage estimate provided by eq. (3) could be easily extended to other buildings typologies (see Table 4) or land-uses by considering a better knowledge of these assets within a given compartment and their economic values, that is resorting to a set of different
hypsometric and depth-damage curves, possibly differentiated within the same compartment.

538

Table 4, Table 5, Figure 5

539

# 540 6 Results of the flood-exposure analysis

#### 541 6.1 Urban areas dynamics

542 Table 6 summarizes the main features of the Tr500 inundation scenario, listing the C-Buffer 543 compartments that are flooded due to overtopping of the levee crests and consequent levee breaching 544 (see Section 5.1 and Castellarin et al., 2011b for details). For each flooded compartment, Table 6 reports the maximum water depth, the total overflow volume and the maximum water inundation 545 level simulated by the quasi-2D model (see also Figure 5a for a schematic representation of these 546 terms). Table 6 also reports an estimate of the overall extent of urban areas flooded in 1954 and 2008 547 under the inundation scenario Tr500, which are obtained by combining the maximum water 548 inundation levels computed in Castellarin et al. (2011b) with the Hypsometric Vulnerability Curves 549 550 (HVCs) proposed in this study (A<sub>tot</sub> in Figure 5).

551

#### Table 6

Inundation occurs in 8 compartments as a consequence of just as many levee breaches; estimates
of the overall urban extent affected by the inundation scenario are equal to 1064 ha in 2008 and 496
ha in 1954.

According to eq. (1-3) and the MCM depth-damage curve (see Figure 4 and Figure 5), Figure 6 illustrates the overall losses, *D* [Billions of Euro], estimated for the flooded compartments by referring to the average economic value of urban buildings  $E (€/m^2)$  reported in Table 5. In particular, considering the urban extent mapped for 1954 and the related HVCs, the overall damage associated with urban buildings is equal to ~3.6 B€ (present value), with around 65% of the total losses concentrated in the compartments number 8 and 20 (see Figures 1 and 6). As a consequence of the 561 urban expansion, the losses estimated for the 2008 urban extent rise to  $\sim 8.1 \text{ B} \in (\text{present value})$ , more 562 than twice the 1954 losses. Compartments 8 and 20 are responsible for  $\sim$ 74% of the total damage in 563 2008. The higher damage in these compartments can be justified by considering the high economic 564 value of urban settlements (compartments 20 and 8 have the highest and the fourth-highest E values 565 among those provided by AE for the residential buildings, respectively; see Table 5) and the amount of 566 urbanized areas exposed to flood. In fact, looking at Table 6, the flooded urban areas of these 567 compartments are larger than the others for both reference years (1954 and 2008), thus resulting in high damages. Furthermore, the striking flood-risk evolution observed in these compartments in the 568 period 1954-2008 (see Figure 6) can also be explained by considering the spatial evolution of the 569 urban areas, that is the location where this urban extension predominately occurred. As an example, 570 Figure 7 reports the HVCs for urban areas of compartments 8 and 10 in the period 1954 and 2008, 571 while the blue dashed lines in both panels represent the maximum inundation levels obtained from 572 the quasi-2D model (see also Figure 5a). The comparison of those HVCs highlights that the urban 573 574 expansion on the compartments 8 mainly occurred in the most depressed portion of the compartment, thus exacerbating the flood exposure of urban settlements (a similar land-use evolution characterized 575 the compartment 20). On the contrary, referring to compartment 10, the urban development occurred 576 in the highest portion of the compartment (i.e. mainly above 45 m a.s.l.; see Figure 7) with the 577 consequence that the flood exposure did not increase significantly during the reference period. 578

The analysis of these different dynamics clearly emphasizes the importance of a correct land-use planning for flood-risk mitigation and highlights the suitability of HVCs as a tool for the identification of alternative flood-risk attenuation strategies (see Section 7 for a more comprehensive discussion).

- 582
- 583

Table 6 - Figure 6, Figure 7

#### 585 6.2 Population dynamics

Panel a) of Figure 8 illustrates the temporal dynamics of the number of inhabitants of Emilia-Romagna and Lombardy administrative districts (grey line), where the C-Buffer is located (see Figure 1), showing a nearly constant grow rate from 1861 to 2011. Focusing on the C-Buffer, the black line on Figure 8a highlights a different evolution, with a negative population trend that started during '50s and lasted since 2001. A similar pattern can be seen looking at the panel b) of Figure 8, which compares the population density in the C-Buffer and in Emilia-Romagna and Lombardy.

Figure 9 reports the estimated number of people living in the C-Buffer that are potentially affected 592 by the Tr500 inundation scenario. These values are estimated by combining the maximum water level 593 simulated for one of the 8 flooded compartments with its corresponding HIC (Hypsometric Inhabitants 594 Curve; see Section 4.2). Black and grey bars in Figure 9 represent the simulated number of people 595 affected by the inundation scenario in 1954 and 2008, respectively. As showed in the figure, the 596 597 number of inhabitants exposed to flood in 2008 (grey bars) is lower than the one estimated for 1954 598 for all compartments but no. 20, where the increase in the number of inhabitants is mainly due to the 599 presence of Parma, which is a rather large city. The cumulated number of potentially affected people that can be computed moving downstream along the study reach (i.e. going from Compartment 1 to 600 20) is illustrated as a black line for 1954 and grey line for 2008, totalizing ~30 400 people in 1954 and 601 ~ 29 400 people in 2008. 602

603

#### Figure 8, 9

604

# 605 7 Flood-risk evolution during the last half-century: Discussion

# 606 7.1 Flood-hazard vs. flood-exposure dynamics

607 Consistently with previous investigations performed for the Po river (see e.g. Montanari et al., 608 2012; Zanchettini et al., 2008), the results of trend detection analyses performed along the study reach 609 point out the absence of statistically significant temporal trends, aside from a slight increase of the annual variability of daily streamflows recorded at the Pontelagoscuro. Therefore the flood-hazard evolution along the middle and lower portion of Po river in the last five decades does not seem to play any significant control on the flood-risk dynamics over the same time span. This supports our assessment of residual flood-risk changes on the basis of a 500-year inundation scenario identified referring to streamflow data collected since 1917-21 along the study reach (see Castellarin et al., 2011a), which we consider for representing the residual flood-hazard for the study area (i.e. the C-Buffer, or dyke-protected flood prone area along the middle lower portion of the Po river).

We show that coupling HVCs with inundation scenarios simulated by means of a simplified 617 hydraulic model (e.g. quasi-2D) may represent a suitable and effective tool for an approximated 618 619 quantitative assessment of direct damages to residential settlements over large geographical areas. In 620 particular, concerning our case study we show that flood risk associated with direct economic losses to private buildings doubled since 1954, mainly due to the expansion of urbanized areas in the dyke-621 protected floodplain (i.e. C-Buffer). Figure 6 shows a significant variation of economic losses 622 623 associated with compartments 8 and 20 (see also Figure 1 and Figure 7), which are the most urbanized compartments and are characterized by large towns. Generalized expansion of urban areas 624 notwithstanding, the number of exposed inhabitants decreased in all C-Buffer compartments but 8 and 625 20, where it remained the same (compartment 8) or increased (compartment 20) during the study 626 period (see Figure 9). This result might be a consequence of inaccuracies of land-use maps adopted in 627 628 this analysis, but it also might be representative of an inefficient land planning and utilization (see e.g. Bhatta et al., 2010). The consequences of this phenomenon, usually known as "urban sprawl", can be 629 seen through changes in land-use and land-cover of a specific region, increasing the built-up and paved 630 area (Sudhira and Ramachandra, 2007), without a corresponding increase of inhabitants (see also 631 Figure 8). In fact, the birth and growth of residential settlements in rural areas is a common 632 633 phenomenon in Northern Italy, even though expansion of metropolitan areas is definitely more 634 evident (ISTAT, 2008; Settis, 2012). ISTAT (2008) found that the urban areas mapped during the 2001 635 census covered nearly the 6.4% of the Italian territory with an increase of about 15% compared to 636 1991, whereas, in the same period, the population grew only 0.4%. Differently from metropolitans

area characterized by high population density, rural areas in the North-Eastern part of the country (i.e.
Lombardy, Veneto and Romagna) experienced an unbridled soils consumption due to a low density
urban development (urban sprawl; ISTAT, 2008). These new settlements represent, in some cases, the
outcomes of inefficient and speculative urban, and even industrial in some cases, expansion plans,
which did not result in economic (i.e. well-being) and social developments (see Settis, 2012). As a
consequence, the extent of residential areas reported in land-use maps are not always representative
of a higher number of inhabitants.

644

# 645 7.2 Main assumptions and limitation of the proposed simplified approach for flood 646 damages computation

Despite the potential of the methodology, there are some limitations that have to be considered given the assumptions adopted in our study. First, the spatial distribution of different building types (e.g. commercial, stores, offices, etc.) over the area of interest cannot be inferred from land use maps that are typically adopted for large scale analysis (e.g. Corine Land Cover). The lack of accurate information concerning the location of specific building categories constrains the possibility to evaluate their exposure to floods through specific HVCs (i.e. different HVCs defined for civil or detached houses, garages or other buildings category such as those reported in Table 4).

Second, the adoption of AE estimates (see Table 5) inevitably undervalues the overall losses for 654 655 urban areas, and in particular for residential buildings, since a series of other direct (e.g. chattel, 656 furniture, stocks, etc.) and indirect (e.g. economic losses indirectly related to the loss of private 657 houses) costs are not considered and economically quantified. The estimate provided by AE 658 represents the present real estate market value of a given building type, that is more an expression of 659 the overall economic well-being of a specific area rather than the actual economic loss in case of a 660 flood event. This bias is expected to be more significant for the productive infrastructures (i.e. 661 industries), where a number of different variables (such as for example the type of production, the

technology level of the industries, the amount of stocks, the day of work interruption, etc.) stronglyinfluence the overall damages associated to inundation events.

664 Finally, using an averaged economic value for all urban assets within a given compartment may 665 introduce biases in the economic assessment of the flood impacts. The expansion and development of urban areas at higher elevations in the compartment (and thus in "safer" locations) may increase the 666 overall economic value use of urban settlements within the compartment. Consequently, averaging the 667 economic value over all residential areas in the compartment would increase the economic value also 668 of rural residential areas situated in the lowland portion of the compartment, with the paradox that a 669 670 correct land-use development policy may increase the risk in the flood-prone areas. This limitation can 671 be easily overcome by constructing different HVCs for different municipalities (or economically 672 different residential areas) within each compartment and by using them in parallel. Furthermore, when using a single HVC for all urban settlements within a given compartment, as in this study, bias 673 674 can be effectively reduced by referring to a single economic value, as we did (i.e. 2014), for all considered historical land-use scenarios (i.e. 1954 and 2008 in this study). Under this hypothesis, the 675 analysis of the urban development over the period of interest is considered exclusively in terms of 676 elevation, that is considering in which part of the compartment the urban area expanded (i.e. in areas 677 that are more or less prone-to-floods), without considering its economic development during the last 678 679 half century.

Despite these limitations, the proposed methodology appears appropriate for the purpose of the analysis, that is not aimed at providing a comprehensive and exhaustive quantification of the flood risk or of the overall flood losses expected in case of an extreme flood event, but rather to propose a tool which enables the inferring of factors that mainly driven the evolution of the residual flood risk in a specific area, or for investigating alternative flood-risk mitigation strategies at basin scale (see Section 7 for more details).

#### 687 **7.3 The "levee paradox" along the Po river**

Following the concept of the "levee effect" (see e.g., Tobin, 1995), the feeling of safety ensured by 688 689 levee systems may encourage the economic and social growth on the floodplain areas, leading to the 690 potential condition for a faster development of human settlements. However, considering our study area, we already stated that while during the last fifty years we observe an increase of the total 691 692 economic losses associated with a given inundation scenario (see Figure 6), the "levee effect" paradigm is not supported by the associate population dynamics. Considering Figure 8, the population 693 growth on the area closer to the river appears comparable with the one measured in the remaining 694 part of the basin (i.e. Emilia-Romagna and Lombardy) until 1950. Starting from the 50's, people moved 695 from the floodplains toward the major cities and settled far away from the main river, causing a 696 significant decrease of number of people exposed to floods. The "shock" induced by the flood disaster 697 occurred in the 1951 to the floodplain socioeconomic system (see e.g., Amadio et al., 2013; Di 698 Baldassarre et al., 2013) is clearly visible in Figure 8. Together with an increased flood-risk awareness 699 700 resulted from the 1951 inundation event, the rapid industrial and economic growth that characterized 701 the aftermath of the II World War is undoubtedly another important driver that attracted people from 702 rural areas towards richer and more industrialized areas, such as large cities.

Figure 10 further investigates the levee paradox in the study area. Panel a), in particular, 703 704 compares the growth rate of the urban settlements in the C-Buffer with the one observed in the Emilia-Romagna and Lombardy districts during the last half-century. Urban extent in the C-Buffer doubled in 705 the last fifty years (increase of about 180%), while the growth rate observed in Emilia-Romagna and 706 707 Lombardy districts is higher than or equal to 230%. Even though the urban development in the flood-708 prone area is evident and representative of a levee-effect, it appears to be less pronounced than in 709 other parts of the basin. These findings seem to support the idea that the expansion of residential 710 areas is related mainly to social and economic drivers, than to the proximity to the water, that no 711 longer represents a peculiarity of favorable development conditions in developed society (Di 712 Baldassarre et al., 2013). A different behavior could otherwise be expected considering the industrial 713 sector, where the availability of a large amount of fresh water still represents a key element for 714 developing productive activities. Panel b) of Figure 10 confirms these considerations for the study 715 area. Referring to the results of a preliminary investigation, panel b) of Figure 10 compares the extent 716 and growth rate of industries in the C-Buffer and in the Emilia-Romagna and Lombardy districts, 717 showing an opposite trend relative to what can be observed for residential areas. Even though 718 industrial areas grew over 712% in Emilia-Romagna and Lombardy, the industrial activities 719 experienced a higher grow-rate (1350%) in the areas closer to the river (i.e. C-Buffer). The presence of 720 a levee system, together with the proximity to abundance of fresh water, is evidently an incentive to 721 the development of industries, which is also encouraged by the lower costs of formerly rural areas. The dynamic of the industrial asset strongly impacts the evolution of the residual flood risk and will be 722 723 the objective of specific future analyses.

724

#### Figure 9

### 725 8 Conclusions

Our study considers the middle-lower portion of the Po river and analyzes the evolution of the residual flood-risk during the last half century for residential areas in the Pianura Padana, a large and socio-economically very important dyke-protected flood-prone area located in Northern Italy, by investigating changes in flood frequency (i.e. flood hazard) and exposure to floods.

Consistently with previous analyses (see e.g. Montanari, 2013; Zanchettini et al., 2008) our trend detection analysis, which we carried out on long historical series observed for the Po river, does not detect any evidence of a statistically significant change in the flood hazard along the Po river and supports the stationarity of the hydrological series during the period of interest (i.e. last five decades).

Changes in the residual flood risk, if any, could be mainly ascribed to an evolution of the exposure for floods. Therefore, we analyzed the possible alteration of exposure to floods in the study area, looking in particular at number of inhabitants and extension of residential areas. We propose the use of simplified graphical tools (i.e. Hypsometric Vulnerability Curves-HVCs and Hypsometric Inhabitants Curve-HICs) for a quantitative, yet approximate, large-scale assessment of the direct tangible economic losses to private residential buildings and of the number of people affected by a given inundation scenario. HVCs and HICs can be constructed using a minimal set of information (i.e. a digital elevation model, land-use map, census data) for any given flood-prone compartment represented in a quasi two-dimensional numerical schematization as a storage area. Despite the usefulness and ease of the proposed methodology it is worth noting that its application in our study relies on a number of simplifying assumptions that need to be acknowledged in order not to misinterpret the results (see also Section 5.2):

a) the flood-hazard assessment is performed by means of a simplified quasi-2D model (see
Castellarin et al., 2001b) in which the flood-prone compartments are reproduced as storage areas
regulated by means of volume-water level defined on a DEM with a resolution of 10 m (see
Section 5.1);

b) aggregation classes adopted by land-use maps (see Table 3) do not enable the identification of
specific building typology, such as for example detached house, garages, office, stores, etc. (see
Table 4); as a result, the economic estimates consider a single (average) building typology for
each compartment.

c) the economic estimates provided by AE represent the market value of the urban buildings in a
given municipality and are not representative of the actual potential damages expected in case of
inundations (e.g. damages to furniture are not considered);

- d) the population density adopted for the HICs is assumed to be uniform within a given
  municipality neglecting differences between rural and central urban areas.
- These limitations notwithstanding, our preliminary application demonstrates the usefulness of HVCs and HICs and their potential for flood-vulnerability and flood-risk assessment. The accuracy of the proposed methodology can be easily increased by referring to more accurate data (e.g. finer landuse discretization, advanced economic estimate; etc.), different HVCs defined for each municipality or land use type, or to detailed simulation of the inundation characteristics (e.g. flood dynamics simulated by means of 2D hydraulic models).

765 The analysis points out a significant growth of the extension of residential areas over the study 766 region, with a consequent increase in the expected damage that is almost doubled relative to the 767 considered inundation scenario (recurrence interval  $\sim$ 500 years). On the contrary, the number of 768 exposed inhabitants showed only marginal modifications during the study period. These findings offer 769 important elements to further the discussion on the existence and importance of the "levee effect" (or 770 call-effect, Tobin, 1995) along the middle-lower portion of the Po river. The study outcome also foster some general considerations on the arguable applicability of the call-effect for developed and 771 772 technologically advanced countries, where the physically proximity to fresh water may not represent the predominant factor for the development of residential settlements (Di Baldassarre et al., 2013). 773 Despite our study focused on the development of urban settlements only, different evidences seem to 774 arise from preliminary analysis performed relative to the industrial asset, from which we have noticed 775 in the C-Buffer a greater growth rate than the one occurred in the rest of Emilia-Romagna and 776 Lombardy districts. However, further investigations are needed addressing this specific point for 777 getting a more definite answer concerning the existence and entity of a call-effect relative to industrial 778 activities in the study area during the last fifty years. Further analyses are also required to enable the 779 780 assessment of flood-losses that are potentially expected in commercial and industrial areas, for which the economic values provided by the Italian Revenue Agency (AE) appear far from being useful as 781 indicators of the expected losses (see also Section 5.2). 782

783 Over the past two decades the flood-risk management experienced a shift from a hazard-driven view to a risk-based perspective, in which the risk management policies are increasingly identified and 784 785 evaluated in the light of system susceptibility and resilience, thus focusing on the capacity of the system to coexist with, and recover from, inundations (see e.g. Merz et al., 2010). The European Flood 786 787 Directive 2007/60 further promotes this process requiring the Member States to identify flood-risk 788 mitigation plans in order to reduce the adverse consequences (e.g. number of people affected, 789 damages, etc.) of a given inundation event. In this context, keeping in mind all the assumptions that 790 were previously highlighted, the combination of HVCs (and HICs) with inundation scenarios computed 791 through simplified hydraulic models can be a viable strategy for quantitative large-scale assessments

of the residual flood risk. The proposed methodology may be useful for decision-makers in charge of the definition of large scale flood-risk mitigation strategies, as the resort to HVCs can provide stakeholders with a preliminary estimation of the impact of a given inundation event and enables them to easily compare the effectiveness of alternative flood risk mitigation strategies (e.g. controlled flooding vs. strengthening of the existing levee system, see e.g. Vis et al., 2003; Merz et al., 2010; Castellarin et al., 2011a).

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### **TABLE**

**Table 1.** Characteristics of the long daily streamflow series available along the main stretch of the Po river996(observation period, mean ( $\mu$ ), standard deviation ( $\sigma$ ) and range of variation of the daily discharge data series),997along with the catchment area (A) at the specific gauging location.

Gauging station	Period	μ [m³/s]	σ [m³/s]	min-max [m³/s]	A [km²]
Moncalieri	1942-1984	80	89	3 - 2 170	4 885
Piacenza	1924-2009	959	773	52 - 12 600	42 030
Pontelagoscuro	1920-2009	1 490	1 007	168 - 9 780	71 000

Table 2. Results of the Mann-Kendall statistical trend detection tests for AMS, MEAN and SD data series at the gauges section of Moncalieri, Piacenza and Pontelagoscuro (see also Table 1): test significance *p*-value, Sen's slope ( $\beta$ ) and variation ( $\Delta$ ) over the period of available data. 

	Moncalieri				Piacenza Pontelagosci			ntelagoscur	0
	p-value	β [m³/s/year]	∆ [m³/s]	p-value	β [m³/s/year]	∆ [m³/s]	p-value	β [m³/s/year]	∆ [m³/s]
AMS	0.753	2.09	87.8	0.822	2.02	172.5	0.106	13.2	1178
MEAN	0.397	0.31	13.41	0.770	-0.28	-24.17	0.450	1.27	113
SD	1	-0.02	-0.90	0.796	0.07	5.95	0.043	2.53	225

**Table 3.** Aggregated land-use classes adopted for the characterization of urban settlements in different time1007periods [x indicates all sub-categories considered by finer land-use classifications].

	<b>CORINE (2006)</b>		G.A.I - WWS (1954)		AGEA-2008
Cod.	Class description	Cod.	Class description.	Cod.	Class description
111	Continuous urban fabric	1a	Continuous and discontinuous urban fabric	111x	Continuous and sparse urban fabric
112	Discontinuous urban fabric	1g	Green urban and sport areas	112x	Discontinuous and isolated residential fabric
14x	Green urban and sport areas			142x	Farmstead, gardens, parks and campground

Table 4. Example of economic values (E[€/m<sup>2</sup>]) provided by AE in relation to buildings typology in a given municipality (values and buildings typologies may vary from different municipalities).

		Category	Building typology	Economic value E [€/m²]	-
			Civil houses	1 975	-
		Residential	Garage, cellar, etc.	850	
			Detached houses	2 400	_
		Commercial	Stores	1 750	
			Warehouses	925	
		Tertiary	Offices	1 550	
		Manufacturing	Productive plant	850	
1011					X
1012					
1013					
1014					
1015					
1015					
				<b>Y</b>	
			$ \mathbf{A} \mathbf{A} \mathbf{A} $		
	(				

Table 5. Average economic values of civil buildings provided by the Italian Revenue Agency (AE) in the C-Buffer compartments flooded in case of the Tr500 event.

Compartment	Average value E [€/m²]		
1	~ 840		
2	~ 970		
3	~ 865		
6	~ 870		
8	~ 935		
10	~ 850		
18	$\sim 1\ 105$		
20	~ 1 245		

**Table 6.** Flood inundation of C-Buffer area for the Tr500 event. Inundation characteristics simulated by thequasi-2D model in each flooded compartments (see also Figure 5).

Compartment	Max. water depth W <sub>d</sub> [m]	Max. water level F <sub>el</sub> [m a.s.l.]	Volume [10 <sup>6</sup> m <sup>3</sup> ]	Flooded urban area 1954 A <sub>tot</sub> [ha]	Flooded urban area 2008 A <sub>tot</sub> [ha]
1	5.3	58.9	4.58	2.62	3.89
2	10.5	60.7	1.89	15.49	21.74
3	8.8	62.1	135.84	53.12	90.80
6	6.9	55.7	61.19	22.19	31.61
8	8.4	51.3	143.68	112.84	227.04
10	7.1	44.6	81.08	101.88	143.78
18	6.0	29.2	27.29	43.56	92.11
20	5.6	31.5	207.14	144.25	453.23
8 Compartments	-	-	~ 663	~ 496	~ 1064



Fig. 1. Study area: Po river basin with gauging stations (red dots) and Regions of interests (Emilia-Romagna and Lombardy); the numbered compartments (blue polygons) represent the area outside the levee system that is exposed to a residual flood risk (i.e. C-Buffer zone; AdB-Po, 1999, Castellarin et al., 2011b).



1042<br/>1043Figure 2. Annual series of maxima (AMS), mean (MEAN) and standard deviation (SD) of daily streamflows for Po<br/>river at Moncalieri (left), Piacenza (center) and Pontelagoscuro (right).



- **Fig. 3**. Examples of Hypsometric Vulnerability Curves for a specific C-Buffer compartment for 1954 and 2008.





**Fig. 4**. Depth-Damage curve adopted for urban areas and provided by MCM (Penning-Roswell et al., 2010).











Figure 6. Bars indicate the expected economic losses in billions of Euros (left axis) for the C-Buffer zone
 compartments and the Tr500 event with urban extent of 1954 (black) or 2008 (grey); solid lines (right axis)
 report the cumulative economic losses from compartment 1 to 20 for 1954 (black) and 2008 (grey).





**Figure 7.** Hypsometric Vulnerability Curves (HVCs) expressed in terms of total urban area extent [km<sup>2</sup>] for Compartment 8 (left) and 10 (right) in 1954 (black line) and 2008 (grey line) with the maximum inundation

1073 level for the Tr500 event (blued dashed line).





Figure 8. Demographic dynamics in the main administrative districts of the Po basin (Emilia-Romagna and Lombardy, see Fig. 1, grey line right axis) and in the C-Buffer zone (black line, left axis) in terms of number of inhabitants and population density (panel b). 1077



Figure 9. Estimated number of inhabitants that are potentially affected by the Tr500 inundation scenario for
 each flooded C-Buffer compartment (bars) and cumulated moving downstream (lines) considering the
 population living in the flood-prone area in 1954 (black) and 2008 (grey).

![](_page_54_Figure_0.jpeg)

![](_page_54_Figure_1.jpeg)

![](_page_54_Figure_2.jpeg)