Journal of Hydrology 527 (2015) 809–823

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Evolution of flood risk over large areas: Quantitative assessment for the Po river

Alessio Domeneghetti *, Francesca Carisi, Attilio Castellarin, Armando Brath

DICAM, University of Bologna, School of Engineering, Viale del Risorgimento, 2, Bologna, Italy

ARTICLE INFO

Article history:
Received 22 September 2014
Received in revised form 16 March 2015
Accepted 23 May 2015
Available online 27 May 2015
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Emmanouil N. Anagnostou, Associate Editor

Keywords:
"Levee effect"
Exposure to floods
Flood hazard and risk assessment
Po river
Hypsometric vulnerability curve

SUMMARY

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

1. Introduction

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

Freshwater flooding (such as river floods, flash floods, and urban inundation due to drainage problems) 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 and 2001).

The common perception of an increasing frequency of floods and inundation phenomena during the last decades is often supported by a growing concern on climate change (e.g. European Environmental Agency – EEA, 2005; Wilby et al., 2008). In fact, some studies in the literature (e.g. IPCC, 2013; Stern Review, 2007) seem to indicate that flood damages are expected to increase in the near future as a consequence of a global climate change (see e.g. Hall et al., 2005; de Moel et al., 2011a). Climate change has increased worldwide the interest on understanding the interaction between human activities and the hydrological cycle. The scientific literature provides numerous studies that analyze long time series of hydrological variables (such as rainfall, river discharges, and temperature) 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.

* Corresponding author. Tel.: +39 051 2093355.
E-mail address: alessio.domeneghetti@unibo.it (A. Domeneghetti).

http://dx.doi.org/10.1016/j.jhydrol.2015.05.043
0022-1694/

Many studies highlighted that the economic and social development in flood-prone areas are key elements for a correct interpretation of the increase of flood losses observed during last decades (see e.g. Ludy and Kondolf, 2012; Di Baldassarre et al., 2013, and references therein). For instance, considering the flood-related costs recorded in Europe over the time period 1970–2006, Barredo (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 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 Landsea, 1998; Pielke et al., 2008) and to globally observed disasters associated with water (see Neumayer and Barthel, 2011; Barredo, 2009). All these studies show that there are no clear evidences of an increasing trend in the normalized economic damages, even though the difficulties in considering the overall mitigation measures enforced by authorities or individuals prevent one to infer that historical data do not show a clear positive trend in the frequency and/or intensity of weather-related 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 the overall effects of climate change and the precautionary principle should, in any case, support the reduction of possible human impacts (Neumayer and Barthel, 2011).

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 named "levee paradox" or "call-effect", according to which the flood-prone areas protected by a levee system attract and encourage new human settlements. The increase of the overall vulnerability of the 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 identified as "residual flood risk"; see e.g. Castellarin et al., 2011a; Di Baldassarre et al., 2009). Investigating a specific case study in California, Ludy and Kondolf (2012) clearly point out that the presence of a levee system changes the perception of the flood likelihood in people living in the dyke-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, where the demographic and economic growth experienced after the inundation, due to the enhancement of the levee system, led to a well-being condition that is higher than before the inundation (Schultz and Elliott, 2012).

All these considerations underline the necessity to analyze flood risk and its evolution in time by means of holistic approaches, which take into account the interaction between social and hydrological factors characterizing a large geographical areas. A better understanding of the interplay between 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).

1.2. Study aims

Our study focuses on the middle-lower portion of the Po river and aims at analyzing the evolution during the last half century of residual flood risk in the dyke-protected floodplains. The hydrological behavior of the Po river basin has been investigated in several previous studies (see e.g., Zanchettini 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 portion of the Po river nor of the influence on this dynamics of the main controlling factors (e.g. human 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 given area the combination of the probability of inundation (e.g. flood hazard) and of the expected adverse consequences (i.e. flood exposure and damage susceptibility of the flood-prone areas, see e.g. EXCIMAP, 2007).

First, we analyze long streamflow series available at different gauging stations located along the study reach, statistically falsifying the hypothesis of changes in flood-hazard during the last half 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 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, assessing the anthropogenic pressure by referring to land-use (i.e. focussing on residential areas) and demographic dynamics observed from 1950s.

In particular, since the study area is protected against 200-year flood events (Po River Basin Authority – Adb-Po, 1999), we focus on the residual risk dynamics, thus referring to a specific low-frequency flooding scenario for which the protection measures are insufficient (see Section 5.1 for more details). We propose simplified flood-vulnerability indexes based on land-use and topographic information that are particularly suitable for large spatial scales, which we use to (1) assess the 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, we quantitatively assess whether during the last half-century the study area experienced the so called 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.

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^2 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 Fig. 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).

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^2), 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).

The current embankment system represents the result of the people struggle during the last centuries to prevent the loss of their properties and assets due to floods. From 1705 to 1951 Pianura 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 continuously strengthened and extended, increasing from a total length of about 1500 km on 1878, to more than 2900 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 km^2; see Masoero et al., 2013) and severe damages (e.g., 100 victims, 900 houses seriously damaged and around 200,000 refugees; Amadio et al., 2013).

Castellarin et al. (2011a) and Di Baldassarre et al. (2009) clearly emphasized this aspect showing the evolution in time of the overall length of the embankment system along the Po river and major tributaries between 1800 and 50–60s and the associated increasing trend in the sequence of annual maximum water level at the Pontelagoscuro streamgauge (see Fig. 1), located at the catchment outlet (see also Heine and Pinter, 2012). During the last decades (i.e. from 60s) the actions of adjustment of the levee system along the lower portion of the river mainly focused on the strengthening of the existing embankment, while further embankment widening and raising were implemented after the flood event of October 2000 (see Coratza, 2005; Castellarin et al., 2011a). The current river configuration is reported in Fig. 1 (box), which shows the main river stretch, the main embankment system, as well as the area that can potentially be flooded in case of catastrophic flood events (blue polygons). This area, named "Fascia-C" (literally C-Buffer, which we consistently use in the remainder), is characterized by an overall extent of $\sim$6100 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 risk of being flooded, that is areas that can be flooded in case of sudden and unpredictable failures of the embankment system (i.e. breaches in the embankments along the main river or tributaries that are triggered e.g. by piping during major floods) or in case of flood event with a recurrence period higher than the one adopted for the design of the embankments (i.e. $\sim$200 year, AdB-Po, 1999). The box in Fig. 1 shows the C-Buffer area divided into different compartments defined referring to the layout of natural and man-made structures (e.g. embankments for the Po river and its main tributaries, rivers, 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 flood-prone areas during last decades, focusing in particular in the period that goes from 1950s up to now.

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 3–5:

– *Streamflow data:* Table 1 summarizes the characteristics of daily streamflow series recorded at streamgauges of Moncalieri, Piacenza and Pontelagoscuro (see Fig. 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 Fig. 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; http://www.istat.it) 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); http://www.agenziaentrate.gov.it) 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).

3. Flood-hazard evolution – trend detection in streamflow series

3.1. Methods

Many studies investigated the streamflow regime of the Po river (see e.g., Visentini, 1953; Marchi, 1991). Zanchettini et al. (2008) analyzed the long-term daily streamflow variability at Pontelagoscuro (see Fig. 1) by referring to a time series longer than 200 years, in which some daily streamflow values were

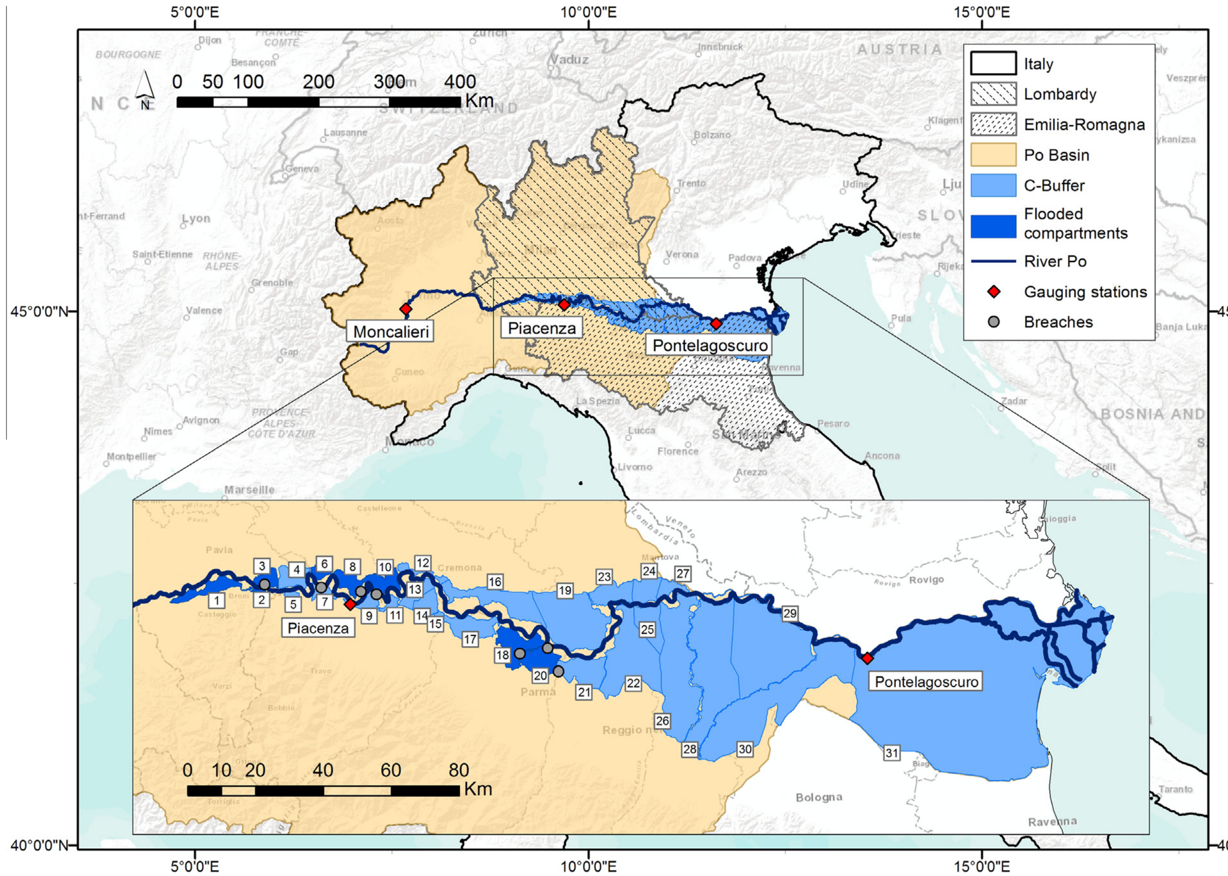

Fig. 1. Study area: Po river basin with gauging stations (red dots) and regions of interests (Emilia-Romagna and Lombardy); the numbered compartments (blue polygons) represent the area outside the levee system that is exposed to a residual flood risk (i.e. C-Buffer zone; AdB-Po, 1999; Castellarin et al., 2011b). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Characteristics of the long daily streamflow series available along the main stretch of the Po river (observation period, mean (μ), standard deviation (σ) and range of variation of the daily discharge data series), along with the catchment area (A) at the specific gauging location.

Gauging station	Period	μ (m^3/s)	σ (m^3/s)	Min–max (m^3/s)	A (km^2)
Moncalieri	1942–1984	80	89	3–2170	4885
Piacenza	1924–2009	959	773	52–12,600	42,030
Pontelagoscuro	1920–2009	1490	1007	168–9780	71,000

re-constructed from historical information on water surface. The analysis highlighted an increase in the streamflow values observed at the streamgauge of Pontelagoscuro during last decades, concluding that this increase could be mainly attributed to the massive embankment works implemented along the river network during previous decades, rather than to 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 by investigating the variability of daily streamflows observed along the Po river and some its major tributaries. The study highlighted the presence of local perturbations (i.e. periods characterized by water scarcity, or water abundance), whose memory lasts for long periods of time (i.e. several years), 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 only the gauged section of Pontelagoscuro and was made by means of a linear regression application.

In this study, we further analyze the variability of the daily streamflow regime of the Po river by testing for trends the daily streamflow series collected at three gauging sections along the main stream: Moncalieri, Piacenza and Pontelagoscuro (see also Fig. 1 and Table 1). The streamgauges are located along the same river and therefore the observed daily streamflow series are necessarily statistically correlated to each other, which is likely to result in similar outcomes of statistical testing (see Douglas et al., 2000). Nevertheless, we considered all three series since they refer to rather different drainage areas and periods of time (see Table 1 and Fig. 1). In particular, we adopted the non-parametric Mann–Kendall (MK) test (Mann, 1945; Kendall, 1975), that is one of the most robust trend detection method applied in many studies to different hydrological variables (see for example Yue and Wang, 2004, and references therein) and spatial scales (see e.g. Douglas et al., 2000; Hamed, 2008; Villarini et al., 2011). The MK test analyses the ranks of the observations rather than their actual values, it is non-parametric (distribution-free) and less sensitive to outliers than other parametric approaches, therefore the MK test appears to be particularly suitable for detecting statistically significant trends in hydrological time series (see Yue et al., 2002; Petrow and Merz, 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.

3.2. Results and discussion on flood-hazard evolution

Fig. 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, β, test p-value, and increase/decrease of the statistics over the observation period, Δ.

Fig. 2 clearly highlights the absence of significant and consistent long-term trends on the daily streamflow statistics (i.e. AMS, MEAN, SD) computed for the three streamgauges over the 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 discharge values (β equal to 2.09 and 0.31 m^3/s/year, respectively; see Table 2), while the river daily streamflow variability (i.e. SD) is almost constant over the period ($\beta = -0.02$ m^3/s/year). p-Values reported for Moncalieri indicate the absence of statistically significant long-term trends at 5% level. Similar results are observed at Piacenza, where MEAN and SD do not show significant changes over the observation period, even though AMS is associated with a limited increase (β equal to 2.02 m^3/s/year), which is consistent with the one observed for Moncalieri. The slight increase of annual maximum daily discharges in the upstream cross-sections of Moncalieri and Piacenza (see Fig. 1) is confirmed at Pontelagoscuro, where this feature appears to be emphasized (see Fig. 2 and Table 2). AMS series at Pontelagoscuro is associated with a slope β of 13.2 m^3/s/year, with an overall increase of about 1178 m^3/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^3/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^3/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 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 Fig. 2). The impact of the flood-hazard variability in the assessment of the residual flood risk dynamics during the 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 likelihood of extreme flood events responsible for the residual flood risk in the area of interest (such as flood events with return period higher than 200 years) can be considered not significantly changed during the last half century.

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

4.1. Land-use dynamics

We investigate the land-use evolution in the Po river basin focusing in particular on Emilia-Romagna and Lombardy

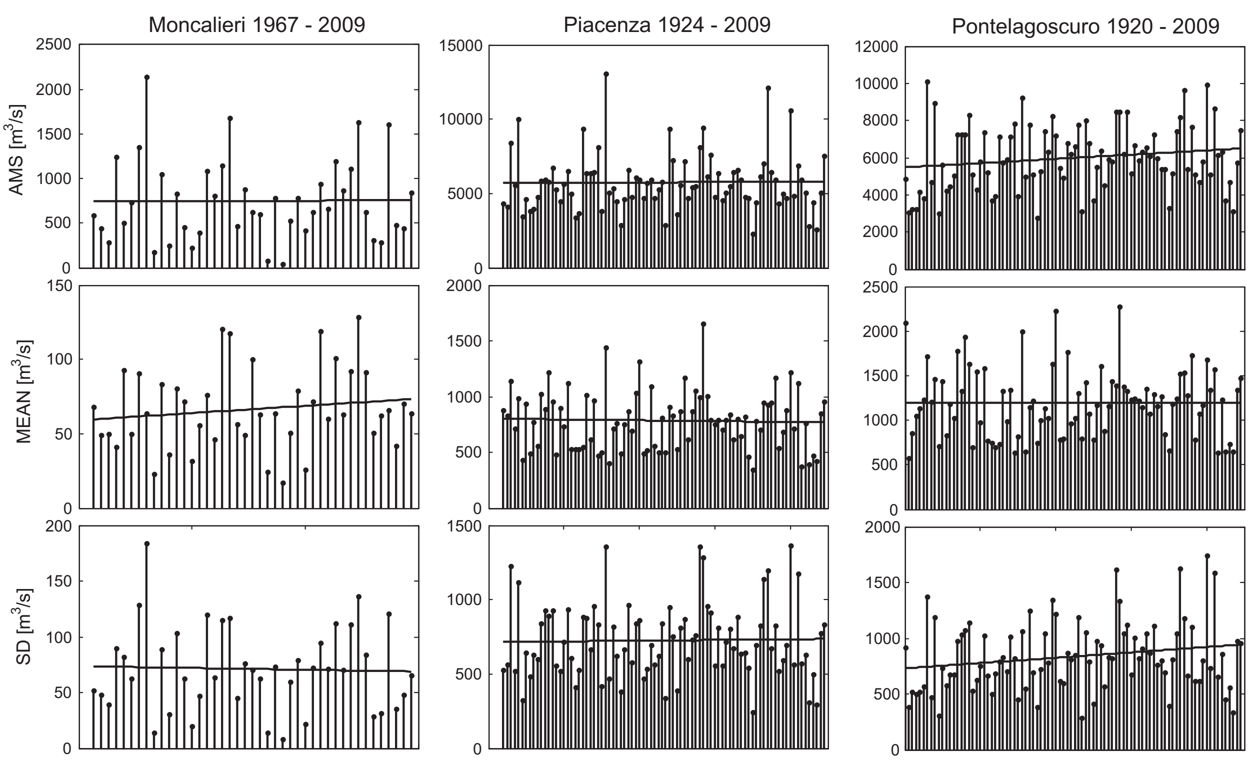

Fig. 2. Annual series of maxima (AMS), mean (MEAN) and standard deviation (SD) of daily streamflows for Po river at Moncalieri (left), Piacenza (center) and Pontelagoscuro (right).

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 (β) and variation (Δ) over the period of available data.

	Moncalieri			Piacenza			Pontelagoscuro		
	p-Value	β (m^3/s/year)	Δ (m^3/s)	*p*-Value	β (m^3/s/year)	Δ (m^3/s)	*p*-Value	β (m^3/s/year)	Δ (m^3/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

administrative districts (see Fig. 1), which cover entirely the C-Buffer (i.e. the floodable area in case of the Tr-500 flood event; see box in Fig. 1). Our analysis considers land-use 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.

We evaluate the expansion of urban and residential areas by referring to two different spatial scales. First we consider a local scale by referring to C-Buffer compartments only (see Fig. 1). Second, we evaluate the land-use evolution at a larger scale (i.e. regional analysis), comparing the overall extension of urban areas in 1954 and 2008 in Emilia-Romagna and Lombardy districts. Results 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 the discussion on the effectiveness of the "levee-effect" (or "call effect") on the floodplains areas (see Sections 6 and 7).

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) 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 hypsometric curve, which we named Hypsometric Vulnerability Curve (HVC). The hypsometric curve of a given area reports on the *x*-axis the percentage (or the portion) of area characterized by elevations lower than the value reported on the *y*-axis. HVCs of each compartment of the C-Buffer combine land-use information with information on elevation retrieved form the 10 m DEM. Zhang et al. (2011) firstly proposed the use of hypsometric curves in the Florida Keys for the evaluation of the impact of different scenarios of sea level rise on human population and real estate property.

As an example, Fig. 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 compartment for 1954 and 2008 in a GIS (Geographic Information System) environment. HVCs represent a valuable tool for a preliminary assessment of the exposure to floods of each compartment, 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 (e.g. in the dike-protected floodplain of the Po river over the last half century). The schematic representation of Fig. 3 illustrates HVC and the information that can be retrieved from such a curve. For instance, the HVC graphically represents the altimetric characteristics of a specific land-use class in a given compartment (e.g. residential settlements), and HVCs of different periods enable one to 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 Fig. 7 for details). Furthermore, assuming the dashed line of Fig. 3 as a hypothetical inundation level, its intersection with the HVC identifies the extent of the affected area and may be particularly useful for a prompt assessment of flood damages (see Section 5.2 for details).

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; 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 Fig. 1).

Given the extent of urban areas and the overall number of inhabitants living in a specific municipality within a C-Buffer compartment we estimate the population density under the hypothesis of a uniform distribution over the urban extent. The population density of a specific compartment is calculated as the weighted average among different municipalities, weighting that data proportionally

Table 3
Aggregated land-use classes adopted for the characterization of urban settlements in different time periods (*x* indicates all sub-categories considered by finer land-use classifications).

CORINE (2006)		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	111×	Continuous and sparse urban fabric
112	Discontinuous urban fabric	1g	Green urban and sport areas	112×	Discontinuous and isolated residential fabric
14×	Green urban and sport areas			142×	Farmstead, gardens, parks and campground

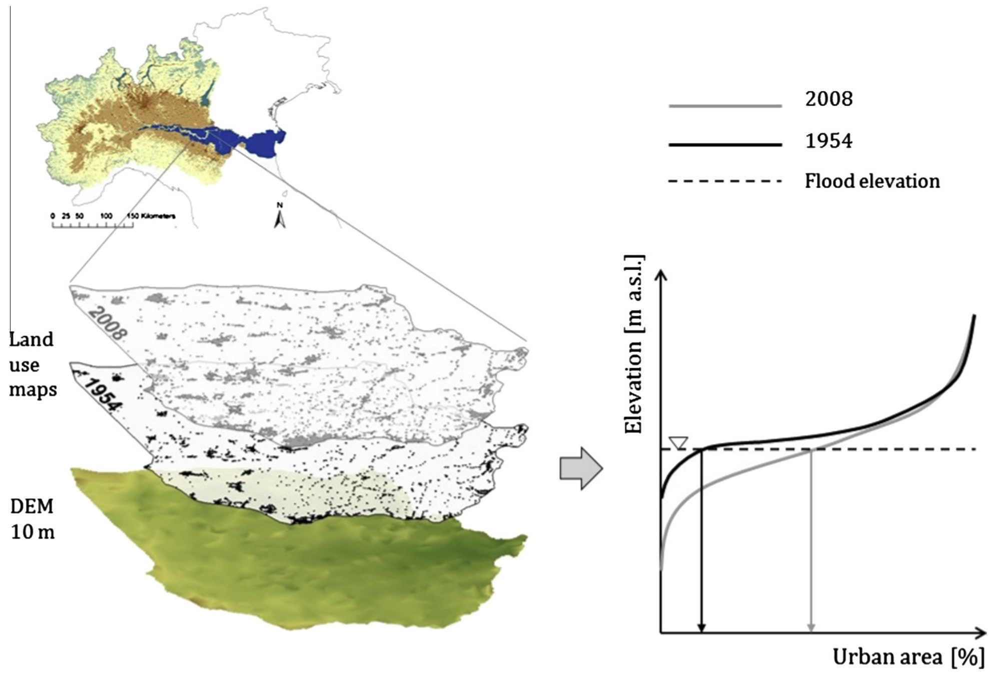

Fig. 3. Examples of Hypsometric Vulnerability Curves for a specific C-Buffer compartment for 1954 and 2008. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

to extent of urban areas. Then, we derive the Hypsometric Inhabitant Curves (HICs) for 1954 and 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; Fig. 3). HICs are curves that report the overall number of inhabitants living in a compartment below a given elevation: they integrate information on the number of people living in a specific compartment with the overall extent 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 of a specific area. For instance, HICs may enable one to estimate the number of people that could be affected by a given inundation scenario over a floodplain area; alternatively, HICs constructed for a given inundation scenario and floodplain compartment by considering census data and land-use maps for different years may effectively summarize the impacts of demographic dynamics on flood risk.

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 events, is a challenging task due to the variety of damage types that may be directly or indirectly related to the hazard. Meyer et al. (2013) recently summarize these costs distinguishing four different categories identified in relation to their nature and to the methodologies adopted for their assessment: direct and indirect costs, business interruption costs, and intangible costs. Considering flood events, direct costs represent the damages occurred to properties (e.g. buildings, stocks, cars, infrastructure, 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 destruction of the working instruments (see Meyer et al., 2013). Indirect costs summarize all the economic losses that can be related to direct and indirect (e.g. business interruption) damages, occurred both inside or outside the affected area, even considering the effects on a broad timeframe after the event (see Carrera et al., 2013 for more details). Finally, intangible costs consider the impact on services, goods or human beings which have not a market value and for which the damage 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).

Concerning the estimation of different types of flood losses the literature provides a series of 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 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 simplified damage models that estimate the expected direct flood damages by means of depth–damage functions (also named susceptibility functions), where the economic damage of a specific element (e.g. a building) is a non-decreasing function of the water depth, which is sometimes integrated with some other hazard factors (i.e. flow velocity, duration, pollution, etc.; see Jongman et al., 2012). More recently, sophisticated multi-parameter models have been proposed for a local estimation of losses in private households and companies (e.g. FLEMO; see Kreibich et al., 2010; Elmer et al., 2010; Messner et al., 2007). Even though the former approach is less accurate and associated with a larger degree of uncertainty (see e.g. Apel et al., 2008; De Moel et al., 2011b), in the light of the large spatial scale of interest (i.e. overall C-Buffer area) we estimate the expected flood damage referring to a simplified approach based on the 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.

5.1. Inundation scenario

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 (quasi-2D) model (Willems et al., 2002) for the Po river stretch considered herein (from Isola S. Antonio to Pontelagoscuro, ~350 km; see Fig. 1). The model describes the main river reach by means of cross-sections retrieved from a detailed digital elevation model (LiDAR, with a spatial resolution of 2 m), while all dike-protected floodplains are represented as storage areas connected to each other and/or the main channel by means of weirs mimicking the system of minor levees. Adopting a similar modeling strategy, all C-Buffer compartments are represented as storage areas and 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 storage areas, and, in case of inundation of a dyke-protected floodplain or C-Buffer compartment, the simulated water level is computed as a function of the water volume exchanged with the main river and/or adjacent storage areas. Volume-level curves were estimated referring to LiDAR imagery (2 m resolution) for the dyke-protected floodplains and to a 10 m resolution DEM (Tarquini et al., 2007) for C-Buffer compartments. The quasi-2D model was calibrated referring to the historical flood event occurred in October 2000 and then used for simulating a major flood event, hereafter referred to as Tr500, which represents a low frequency/high intensity event associated to a return period of ~500 years (see Castellarin et al., 2011b for details).

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 ~200 years, which are significantly less intense than the Tr500 event identified in Castellarin et al. (2011a,b). Considering the homogenous protection level ensured by the major embankment system along the entire study reach we referred to the Tr500 event as the reference flood scenario, thus limiting the estimation of the residual flood risk to the likelihood of this extreme event, neglecting the hazard related to flood events associated to return period lower than 500-year but not contained by the embankment system or to possible levee failures. Considering these latter possibilities (e.g. breaches on the embankment due to 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 for example adopt comprehensive multivariate Monte Carlo resampling techniques for a through characterization of the flooding hazard in the region of interest (see e.g. Vorogushyn et al., 2010; Domeneghetti et al., 2013).

The Tr500 inundation scenario is modeled by simulating failures along the embankment system (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 crest elevation of the embankments, under this circumstance, as consequence of the flow erosion on the out-board side of the levee, the quasi-2D model simulates the formation of a levee-breach according to literature information on width, depth and time of full development recorded for the Po river (see e.g. Govi and Turitto, 2000). The numerical model enables the simulation of multiple breaching events as a result of concurrent overtopping phenomena along the main embankment system, thus enabling the inundation of several C-Buffer compartments during a single major flood event (see details in Castellarin et al., 2011b). In order to better highlight the role of the exposure to 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.

5.2. Estimation of direct economic losses

It is well known that the estimation of direct damages associated with a flood event is a 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 event damage data, which are necessary for a proper calibration and validation of damage models. In our analysis, considering the scale of interest (i.e. large scale analysis: middle-lower portion of the Po river) and the nature of the proposed approach (i.e. simplified numerical tools to evaluate the flood risk), the quantification of the flood exposure is performed by referring exclusively to the economic value of private buildings prone to inundation events, neglecting other direct (e.g. damages to public or commercial buildings) and indirect costs.

The Italian Revenue Agency (*Agenzia delle Entrate*, AE) publishes the economic value (E (€/m^2)) of different types of private buildings (e.g. civil houses, offices, stores, etc.) in each Italian administrative district (spatial scale of municipality) every six months (economic values of public buildings are not provided by AE and thus excluded from the present investigation). Table 4 reports an example of monetary estimates available for buildings of each municipality conditioned upon the definition of use (i.e. residential, commercial, services or productive) and typology (i.e. detached house, box, stores, etc.). Focusing on residential buildings and assuming an unique building type (i.e. civil houses in Table 4), we define the reference economic value (E (€/m^2)) for urban settlements within any given compartment of the C-Buffer as the average of the E values provided for all the municipalities, weighted proportionally to their urban extent located within the C-Buffer (see Table 5). Therefore, the overall value of urban properties can

Table 4
Example of economic values (E (€/m^2)) 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 (€/m^2)
Residential	Civil houses	1975
	Garage, cellar, etc.	850
	Detached houses	2400
Commercial	Stores	1750
	Warehouses	925
Tertiary	Offices	1550
Manufacturing	Productive plant	850

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 (€/m^2)
1	~840
2	~970
3	~865
6	~870
8	~935
10	~850
18	~1105
20	~1245

then be approximated by the product of the average economic value and the overall urban area extent in the compartment, which we obtained 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-Rowsell et al., 2010) that estimates the expected losses for residential buildings as a function of the local water depth (see Fig. 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.

Combining the MCM susceptibility curve and the overall economic value of residential buildings, we compute the expected damage in a given C-Buffer compartment for a given inundation scenario through a procedure that is schematically illustrated in Fig. 5. The horizontal blue[1] line of Fig. 5a represents the maximum water level (m a.s.l.) resulting from the quasi-2D simulation of the inundation scenario of interest (see also Section 5.1). As already pointed out, the extent of the inundated urban area (A_{tot}) can be easily retrieved from the intersection between the elevation of the maximum water level (blue line in Fig. 5a) and the HVC of the flooded compartment. The damage (D) to urban settlements is associated with the local water depth (h) by means of the depth–damage curve (see Fig. 5b for a schematic example). This curve also identifies a water-depth value (h_{100}) 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 the extent of urban area where the damage is maximum (A_{100} (km^2) in Fig. 5a) by subtracting h_{100} (i.e. water depth equal to 3 m for the MCM depth–damage curve; see Fig. 4) to the maximum flood elevation (blue line in Fig. 5a). Everywhere in A_{100} the water depth is higher than h_{100} and therefore the flood damage can be estimated as:

[1] For interpretation of color in Fig. 5, the reader is referred to the web version of this article.

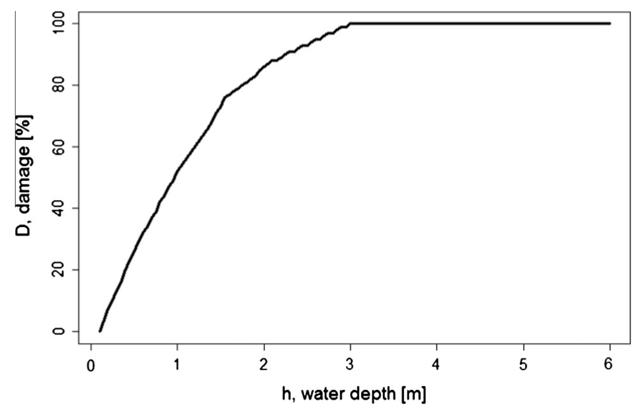

Fig. 4. Depth–damage curves adopted for urban areas and provided by MCM (Penning-Roswell et al., 2010).

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

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 Fig. 5a) the flood damage, D_h, depends on the local water depth and can be expressed as:

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

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

$$D = D_{100} + D_h \tag{3}$$

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.

6. Results of the flood-exposure analysis

6.1. Urban areas dynamics

Table 6 summarizes the main features of the Tr500 inundation scenario, listing the C-Buffer compartments that are flooded due to overtopping of the levee crests and consequent levee breaching (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 level simulated by the quasi-2D model (see also Fig. 5a for a schematic representation of these terms). Table 6 also reports an estimate of the overall extent of urban areas flooded in 1954 and 2008 under the inundation scenario Tr500, which are obtained by combining the maximum water inundation levels computed in Castellarin et al. (2011b) with the Hypsometric Vulnerability Curves (HVCs) proposed in this study (A_{tot} in Fig. 5).

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 Eqs. 1–3 and the MCM depth–damage curve (see Figs. 4 and 5), Fig. 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

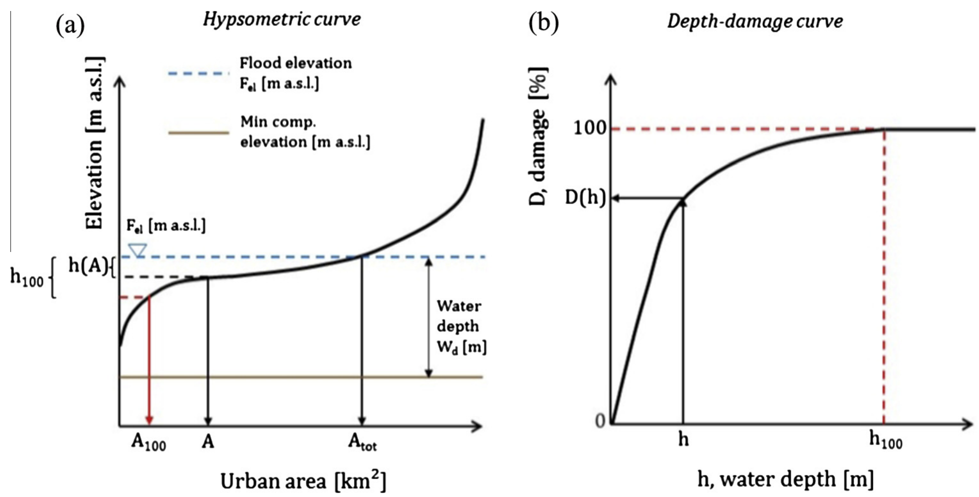

Fig. 5. Schematic representation of the combination of a hypsometric (left) and depth–damage (right) curves for estimating flood damages in urban areas.

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

Compartment	Max. water depth W_d (m)	Max. water level F_{el} (m a.s.l.)	Volume (10^6 m^3)	Flooded urban area 1954 A_{tot} (ha)	Flooded urban area 2008 A_{tot} (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

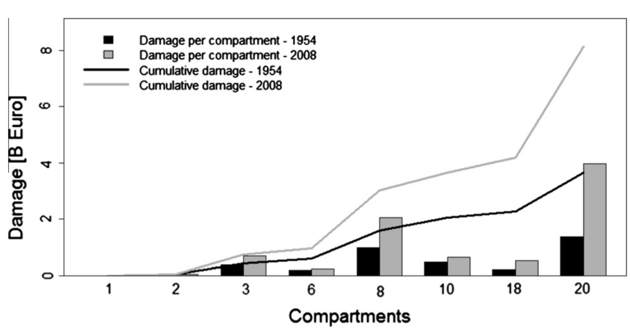

Fig. 6. Bars indicate the expected economic losses in billions of euros for the C-Buffer zone compartments and the Tr500 event with urban extent of 1954 (black) or 2008 (gray); solid lines report the cumulative economic losses from compartment 1 to 20 for 1954 (black) and 2008 (gray).

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 Figs. 1 and 6). As a consequence of the urban expansion, the losses estimated for the 2008 urban extent rise to ~8.1 B€ (present value), more than twice the 1954 losses. Compartments 8 and 20 are responsible for ~74% of the total damage in 2008. The higher damage in these compartments can be justified by considering the high economic value of urban settlements (compartments 20 and 8 have the highest and the fourth-highest E values among those provided by AE for the residential buildings, respectively; see Table 5) and the amount of urbanized areas exposed to flood. In fact, looking at Table 6, the flooded urban areas of these 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 period 1954–2008 (see Fig. 6) can also be explained by considering the spatial evolution of the urban areas, that is the location where this urban extension predominately occurred. As an example, Fig. 7 reports the HVCs for urban areas of compartments 8 and 10 in the period 1954 and 2008, while the blue dashed lines in both panels represent the maximum inundation levels obtained from the quasi-2D model (see also Fig. 5a). The comparison of those HVCs highlights that the urban 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 the compartment 20). On the contrary, referring to compartment 10, the urban development occurred in the highest portion of the compartment (i.e. mainly above 45 m a.s.l.; see Fig. 7) with the consequence that the flood exposure did not increase significantly during the reference period.

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).

6.2. Population dynamics

Panel (a) of Fig. 8 illustrates the temporal dynamics of the number of inhabitants of Emilia-Romagna and Lombardy administrative districts (gray line), where the C-Buffer is located (see Fig. 1),

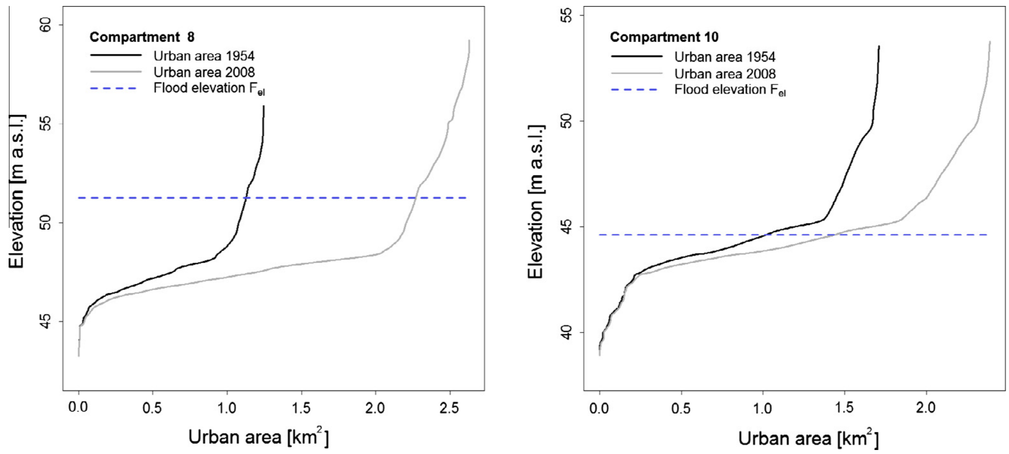

Fig. 7. Hypsometric Vulnerability Curves (HVCs) expressed in terms of total urban area extent (km^2) for compartment 8 (left) and 10 (right) in 1954 (black line) and 2008 (gray line) with the maximum inundation level for the Tr500 event (blued dashed line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

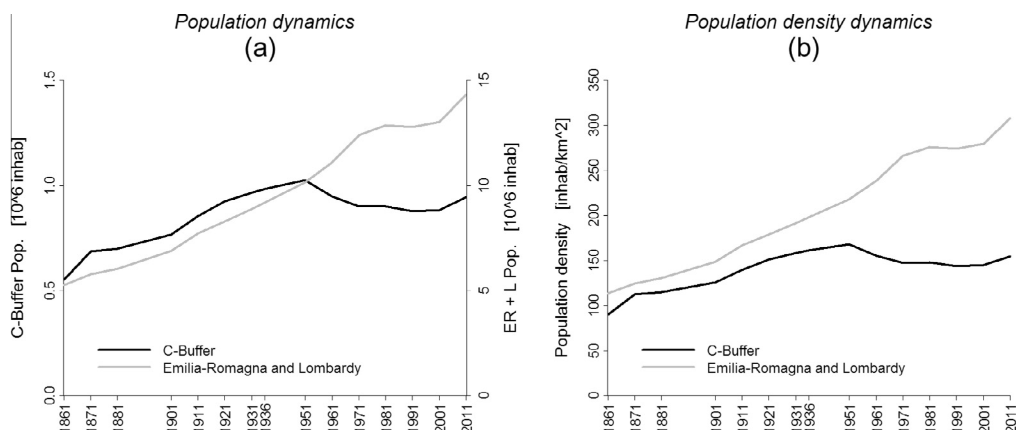

Fig. 8. Demographic dynamics in the main administrative districts of the Po basin (Emilia-Romagna and Lombardy, see Fig. 1, gray line right axis) and in the C-Buffer zone (black line, left axis) in terms of number of inhabitants (panel a) and population density (panel b).

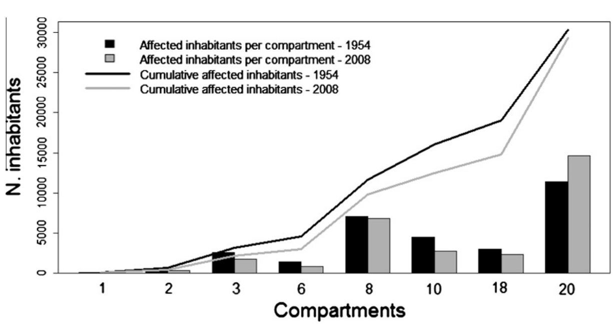

Fig. 9. Estimated number of inhabitants that are potentially affected by the Tr500 inundation scenario for each flooded C-Buffer compartment (bars) and cumulated moving downstream (lines) considering the population living in the flood-prone area in 1954 (black) and 2008 (gray).

showing a nearly constant grow rate from 1861 to 2011. Focusing on the C-Buffer, the black line in Fig. 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 Fig. 8, which compares the population density in the C-Buffer and in Emilia-Romagna and Lombardy.

Fig. 9 reports the estimated number of people living in the C-Buffer that are potentially affected by the Tr500 inundation scenario. These values are estimated by combining the maximum water level simulated for one of the 8 flooded compartments with its corresponding HIC (Hypsometric Inhabitants Curve; see Section 4.2). Black and gray bars in Fig. 9 represents the simulated number of people affected by the inundation scenario in 1954 and 2008, respectively. As showed in the figure, the number of inhabitants exposed to flood in 2008 (gray bars) is lower than the one estimated for 1954 for all compartments but no. 20, where the increase in the number of inhabitants is mainly due to the 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 20) is illustrated as a black line for 1954 and gray line for 2008, totalizing ~30,400 people in 1954 and ~29,400 people in 2008.

7. Flood-risk evolution during the last half-century: discussion

7.1. Flood-hazard vs. flood-exposure dynamics

Consistently with previous investigations performed for the Po river (see e.g. Montanari, 2012; Zanchettini et al., 2008), the results of trend detection analyses performed along the study reach 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 1917–1921 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 hydraulic model (e.g. quasi-2D) may represent a suitable and effective tool for an approximated quantitative assessment of direct damages to residential settlements over large geographical areas. In 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-protected floodplain (i.e. C-Buffer). Fig. 6 shows a significant variation of economic losses associated with compartments 8 and 20 (see also Figs. 1 and 7), which are the most urbanized compartments and are characterized by large towns. Generalized expansion of urban areas notwithstanding, the number of exposed inhabitants decreased in all C-Buffer compartments but 8 and 20, where it remained the same (compartment 8) or increased (compartment 20) during the study period (see Fig. 9). This result might be a consequence of inaccuracies of land-use maps adopted in 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 seen through changes in land-use and land-cover of a specific region, increasing the built-up and paved area (Sudhira and Ramachandra, 2007), without a corresponding increase of inhabitants (see also Fig. 8). In fact, the birth and growth of residential settlements in rural areas is a common phenomenon in Northern Italy, even though expansion of metropolitan areas is definitely more evident (ISTAT, 2008; Settis, 2012). ISTAT (2008) found that the urban areas mapped during the 2001 census covered nearly the 6.4% of the Italian territory with an increase of about 15% compared to 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.

7.2. Main assumptions and limitation of the proposed simplified approach for flood-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 urban areas, and in particular for residential buildings, since a series of other direct (e.g. chattel, furniture, stocks, etc.) and indirect (e.g. economic losses indirectly related to the loss of private houses) costs are not considered and economically quantified. The estimate provided by AE represents the present real estate market value of a given building type, that is more an expression of the overall economic well-being of a specific area rather than the actual economic loss in case of a flood event. This bias is expected to be more significant for the productive infrastructures (i.e. 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, and the day of work interruption) strongly influence the overall damages associated to inundation events.

Finally, using an averaged economic value for all urban assets within a given compartment may 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 overall economic value use of urban settlements within the compartment. Consequently, averaging the economic value over all residential areas in the compartment would increase the economic value also of rural residential areas situated in the lowland portion of the compartment, with the paradox that a correct land-use development policy may increase the risk in the flood-prone areas. This limitation can be easily overcome by constructing different HVCs for different municipalities (or economically 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 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 analysis of the urban development over the period of interest is considered exclusively in terms of elevation, that is considering in which part of the compartment the urban area expanded (i.e. in areas that are more or less prone-to-floods), without considering its economic development during the last 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).

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 levee systems may encourage the economic and social growth on the floodplain areas, leading to the 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 economic losses associated with a given inundation scenario (see Fig. 6), the "levee effect" paradigm is not supported by the associate population dynamics. Considering Fig. 8, the population growth on the area closer to the river appears comparable with the one measured in the remaining part of the basin (i.e. Emilia-Romagna and Lombardy) until 1950. Starting from the 50s, people moved from the floodplains toward the major cities and settled far away from the main river, causing a significant decrease of number of people exposed to floods. The "shock"

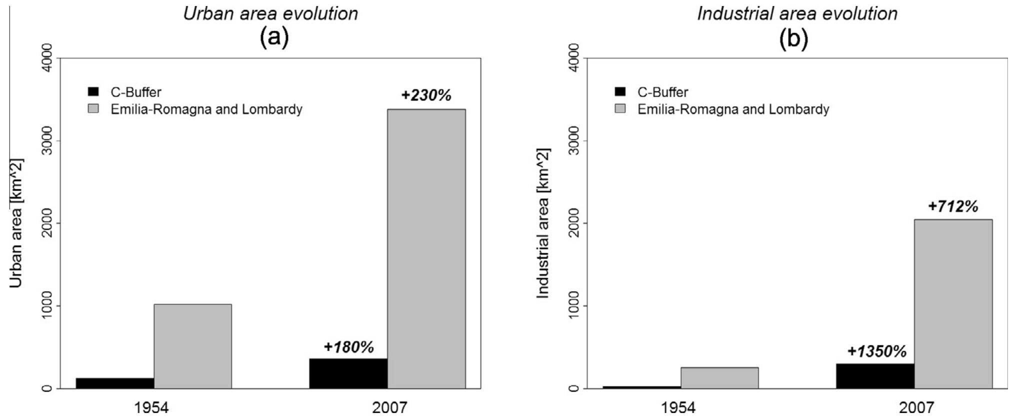

Fig. 10. Evolution over the last half-century of the overall extent of urban (panel a) and industrial (panel b) areas in the C-Buffer (black bars) and in Emilia-Romagna plus Lombardy regions (gray bars).

induced by the flood disaster occurred in the 1951 to the floodplain socioeconomic system (see e.g., Amadio et al., 2013; Di Baldassarre et al., 2013) is clearly visible in Fig. 8. Together with an increased flood-risk awareness resulted from the 1951 inundation event, the rapid industrial and economic growth that characterized the aftermath of the II World War is undoubtedly another important driver that attracted people from rural areas toward richer and more industrialized areas, such as large cities.

Fig. 10 further investigates the levee paradox in the study area. Panel (a), in particular, 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 the last fifty years (increase of about 180%), while the growth rate observed in Emilia-Romagna and Lombardy districts is higher than or equal to 230%. Even though the urban development in the flood-prone area is evident and representative of a levee-effect, it appears to be less pronounced than in other parts of the basin. These findings seem to support the idea that the expansion of residential areas is related mainly to social and economic drivers, than to the proximity to the water, that no longer represents a peculiarity of favorable development conditions in developed society (Di Baldassarre et al., 2013). A different behavior could otherwise be expected considering the industrial sector, where the availability of a large amount of fresh water still represents a key element for developing productive activities. Panel (b) of Fig. 10 confirms these considerations for the study area. Referring to the results of a preliminary investigation, panel (b) of Fig. 10 compares the extent and growth rate of industries in the C-Buffer and in the Emilia-Romagna and Lombardy districts, showing an opposite trend relative to what can be observed for residential areas. Even though industrial areas grew over 712% in Emilia-Romagna and Lombardy, the industrial activities experienced a higher grow-rate (1350%) in the areas closer to the river (i.e. C-Buffer). The presence of a levee system, together with the proximity to abundance of fresh water, is evidently an incentive to 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 the objective of specific future analyses.

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 et al., 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 to 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, and stores (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 land-use 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).

The analysis points out a significant growth of the extension of residential areas over the study region, with a consequent increase in the expected damage that is almost doubled relative to the considered inundation scenario (recurrence interval ~500 years). On the contrary, the number of exposed inhabitants showed only marginal modifications during the study period. These findings offer important elements to further the discussion on the existence and importance of the "levee effect" (or 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 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). Despite our study focused on the development of urban settlements only, different evidences seem to arise from preliminary analysis performed relative to the industrial asset, from which we have noticed in the C-Buffer a greater growth rate than the one occurred in the rest of Emilia-Romagna and Lombardy districts. However, further investigations are needed addressing this specific point for getting a more definite answer concerning the existence and entity of a call-effect relative to industrial activities in the study area during the last fifty years. Further analyses are also required to enable the 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 indicators of the expected losses (see also Section 5.2).

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 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 Directive 2007/60 further promotes this process requiring the Member States to identify flood-risk mitigation plans in order to reduce the adverse consequences (e.g. number of people affected, damages, etc.) of a given inundation event. In this context, keeping in mind all the assumptions that were previously highlighted, the combination of HVCs (and HICs) with inundation scenarios computed 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).

Acknowledgements

The study was carried out as part of the activities of the working group Anthropogenic and climatic controls on water availability (ACCuRAcY) of scientific decade 2013–2022 of IAHS, entitled "Panta Rhei – Everything Flows" – Change in Hydrology and Society (see Montanari et al., 2013). The authors are extremely grateful to the Interregional Agency for the Po River (Agenzia Interregionale per il Fiume Po, AIPO, Italy) and Po River Basin Authority (Autorità di Bacino del Fiume Po, Italy) allowing access to their high resolution DTM of River Po and GIS layers used in the analysis. Finally, the Authors acknowledge the appropriateness and the usefulness of anonymous Reviewers' comments.

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