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

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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.

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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.