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Human-flood interactions in Rome over the past 150 years

Giuliano Di Baldassarre[1], Smeralda Saccà[2], Giuseppe Tito Aronica[2], Salvatore Grimaldi[3], Alessio Ciullo[4], and Massimiliano Crisci[5]

[1]Uppsala University, Department of Earth Sciences, Uppsala, Sweden
[2]University of Messina, Dipartimento di Ingegneria Civile, Informatica, Edile, Ambientale e Matematica Applicata, Messina, Italy
[3]Tuscia University, DIBAF Department, Viterbo, Italy
[4]Deltares, Delft, the Netherlands
[5]Institute for Research on Population and Social Policies of the Italian National Research Council (CNR-IRPPS), Roma, Italy

Correspondence to: Giuliano Di Baldassarre (giuliano.dibaldassarre@geo.uu.se)

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Abstract. Throughout history, the socio-economic development of the city of Rome has been intertwined with the magnitude and frequency of flooding events from the Tiber, one of Italy's largest rivers. Ancient Rome mostly developed on the hills, while the Tiber's floodplain was mainly exploited for agricultural purposes. A few small communities did settle in the riparian areas of the Tiber, but they had a relatively peaceful relationship with the frequent occurrence of flooding events. Instead, numerous people live nowadays in modern districts in the Tiber's floodplain, unaware of their exposure to potentially catastrophic flooding. This research work aims to explore the dynamics of changing flood risk between these two opposite pictures of ancient and contemporary Rome. To this end, we carried out a socio-hydrological study by using long time series of hydrological (extreme flood events) and social (human population dynamics) processes, along with information about human interactions with the environment (flood defence structures). The historical analysis showed how human and water systems have been co-evolving over time, while being abruptly altered by the occurrence of an extreme flood event in 1870, just before Rome became the capital of a recently unified Italy. The outcomes of this study were then compared to the results of a socio-hydrological model simulating the dynamics emerging from the mutual shaping of floods and societies.

1 Premise

Economic losses and fatalities caused by floods have dramatically increased in many regions of the world over the past decades (UN-ISDR, 2016). This trend is expected to worsen, as population growth, economic development, and urbanization will likely increase the potential damage, while the frequency and magnitude of flood events might be enhanced by hydrological change (Jongman et al., 2014; Alfieri et al., 2016).

Much progress has been made in making quantitative assessments of flood risk at local and global scales (Di Baldassarre et al., 2009; Winsemius et al., 2015), but there is still a lack of fundamental understanding of the role of feedbacks between social and hydrological processes (Sivapalan et al., 2012; Montanari et al., 2013; Van Loon et al., 2016). In a rapidly changing world, this lack of knowledge is of serious concern as it limits the interpretation of past risk changes as well as the projections of future possibilities. Thus, it makes difficult (if not impossible) to plan appropriate and sustainable measures for flood risk reduction for long term horizons (Di Baldassarre et al., 2013a).

To fill this knowledge gap about human-flood interactions and their role in shaping the dynamics of flood risk, a great opportunity is offered by interdisciplinary frameworks including political ecology, environmental history, social-ecological systems, ecological economics, and socio-hydrology (Swyngedouw, 1999; Aldrete, 2007; Liu et al., 2007; Ostrom, 2009; Kallis and Norgaard, 2010; Sivapalan et al., 2012).

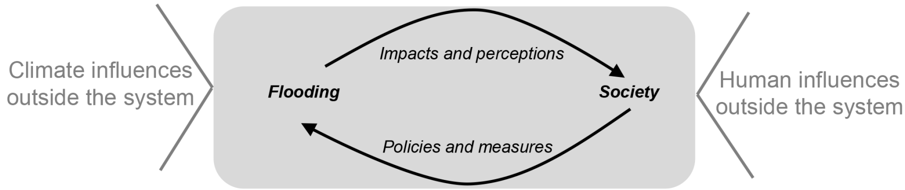

Figure 1. Socio-hydrology of floods in Rome. The figure shows drivers of global/regional change operating at larger scale, i.e. climatic and human influences outside the system (e.g. climate change, economic growth, regional trends) and the four elements of the feedback loop (internal interactions between flooding and society; grey area), which are the main focus of this study.

Here we show an initial attempt to uncover the interplay of hydrological and social processes in the city of Rome over the past 150 years, by means of both historical data analysis and socio-hydrological modelling.

2 Historical analysis

About 2700 years ago, the King of Alba Longa, Amulius, abandoned to die the newborn twins Romulus and Remus in the Tiber river. Luckily, flooding occurred at the same time and Amulius did not manage to leave them in the main river channel. Instead, he had to abandon them in the calmer waters of the floodplain. A she-wolf ("lupa", in Italian) rescued and breastfed the twins. Some years after, Romulus and Remo founded the city of Rome and Romulus was the first King of Rome.

This is only a myth about the origins of Rome, but it shows the long "love-hate relationship of Rome and the Tiber" (Aldrete, 2007). Indeed, the socio-economic development of the historical city of Rome -close to one of the largest Italian rivers, the Tiber- has been intertwined with the magnitude and frequency of flooding events. The ancient Rome mostly developed on the (seven) hills, while the Tiber's floodplain was mainly exploited for agricultural purposes. A few small communities did settle in the riparian areas of the Tiber, but they had a relatively peaceful relationship with the frequent occurrence of flooding events. Nowadays, large population live in contemporary districts in the Tiber's floodplain, mostly unaware of their exposure to potentially catastrophic flooding. To get insights about the dynamics of changing flood risk between these two extreme pictures of the ancient and contemporary Rome, an historical data analysis and a socio-hydrological modelling exercise were performed.

Here we investigate the city of Rome and its relationship with flooding from the Tiber river, by treating them as a coupled human-water system (Di Baldassarre et al., 2013a), and we use the unique set of historical information available in Rome to uncover how the impacts and perceptions of floods have shaped human society in terms of demography, while policies and measures of disaster risk reduction have in turn shaped the frequency of floods (Fig. 1).

Rome is a rare case study with reliable and long time series of hydrological and social data (Calenda et al., 2009; Adrete, 2007). By referring to the four elements of the feedback loop of Fig. 1, this study used the following sources of data and information and explored flood risk dynamics in Rome across the past centuries: (i) *Flooding*, hydrological data, such as river flows, high water levels and flood extent maps; (ii) *Impacts and perceptions*, local data about damage caused by floods (post-event studies); risk perception analysis (survey); (iii) *Society*, demographic data (census and population registers) and other proxies of social vulnerability to flooding (urban development maps); (iv) *Policies and measures*, inventory strategies of risk reduction (flood walls), urban planning, or sustainable water management.

Figure 2a shows high water levels in Rome in the period 1800–2000, the construction of flood walls and human population in Tiber's floodplain areas. Information about Rome's population dynamic is derived from population register data sources and censuses (Crisci, 2010; Casacchia and Crisci, 2013). In particular, demographic data were disaggregated by districts (so-called "zone toponomastiche"), and the ones adjacent to the river were defined as Tiber's floodplain (Fig. 2b).

One of the most striking results of this study is that while human and water systems have been interacting over centuries in Rome (Aldrete, 2007), they were abruptly altered at the end of the 19th Century by the coincidence of a large flood event with a major historical and political changes. Devastating flooding occurred in Rome the 27 December 1870, only three months after the city was annexed to the Italian Kingdom and one month before Rome became the new capital of the State. The coincidence of these events triggered a debate at the top level, including the Italian Risorgimento hero Giuseppe Garibaldi, about different options for flood defence in Rome. Eventually, following the examples of other European capitals such as London and Paris, high flood walls ("muraglioni"; in Italian) were built to protect floodplain areas. This process increased the level of flood protection and in turn facilitated the development of new urban districts in the Tiber's floodplain ("levee effect"; White, 1945). As flooding was prevented over the past decades by the presence of levees, it was not possible to survey changes in the social memory of flooding. Thus, interviews were made by ask-

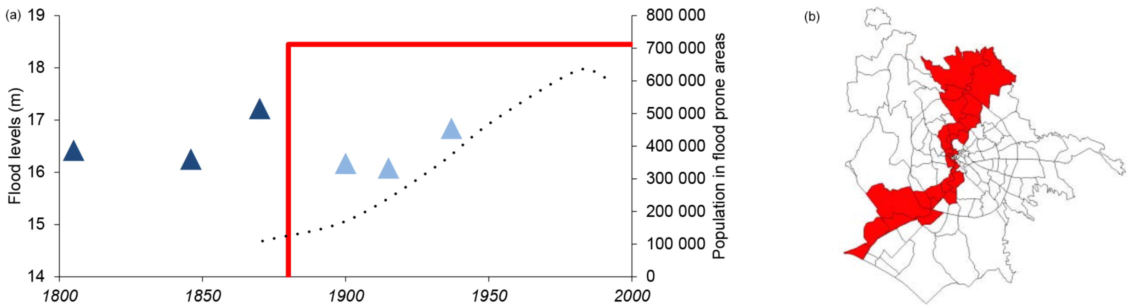

Figure 2. Human-flood interactions in Rome. **(a)** High water levels in Rome in the period 1800–2000 (blue triangles, darker when leading to major flooding); Construction of flood walls (solid red line), which followed the large 1870 flooding and then prevented major flooding in Rome for many decades; Increase of human population in Tiber's floodplain areas (dotted black line). **(b)** Map of Rome's census districts and areas considered as part of Tiber's floodplain (highlighted in red).

ing people whether they remembered the most recent events of high water levels. 82 % of the respondents could remember the 2014 event, while only 9 % remembered the 1986 event. By assuming an exponential decay of social memory, we found a half-life value about 2.5 years.

3 Socio-hydrological modelling

Lastly, we use a recently developed model of human-flood interactions (Di Baldassarre et al., 2015) to see whether the dynamics of flood risk observed in Rome are consistent with the trajectories simulated by this model. The model is based on the concept of social memory (Di Baldassarre et al., 2013b, 2015; Viglione et al., 2016), which is assumed to be built after the experience of extreme flood events and then exponentially decay over time. This hypothesis is based on empirical evidence of risk preparedness being maximum after floods and then vanishing over time (Hanak, 2011), as well as studies about individual and collective memory consolidation (Anastasio et al., 2012). It is worth noting that the modelling approach is based on a lumped conceptualization, which does not take into account the spatial variability of flooding and considers a binary subdivision of Rome between floodplain and other areas.

As the socio-hydrological model uses a relative population density from 0 to 1, Tiber's floodplain population values are normalized by using a theoretical maximum value, which is estimated based on expert judgment and assumed to be ranging between 10^6 and 2×10^6. Figure 3 shows the model results in term of high water levels, flood protection level, social memory and population density in the floodplain, while Table 1 reports the parameters values that were derived via expert judgement without any efforts to perfectly fit the data (Ciullo et al., 2016). As initial conditions, we assumed all variables starting from null values. Note that the assumed parameter for the memory decay rate was found consistent with the outcomes of the survey as it is plausible to assume that the decay of the memory of high water events that do not result into flooding (observed half-life about 2.5 years; see Sect. 2) is faster than the decay of flooding events (assumed half-life about 11.5 years; see Table 1). For more details about the model of human-flood interactions and the parameters the reader can refer to Di Baldassarre et al. (2015).

The exercise shows that the socio-hydrological model can capture the increasing floodplain population density in Rome that occurred in the 20th Century after the construction of flood walls (Fig. 3d). The uncertainty bounds in the observation result from the aforementioned range in the estimation of a theoretical maximum value (Ciullo et al., 2016). The model explains this dynamic effect through social memory. In particular, memory is lower and lower during the 20th Century (Fig. 3c) because high water levels (Fig. 3a) were below the level of flood walls (Fig. 3b) and did not produce any major flooding.

4 Concluding remarks

This brief communication described an initial attempt to explore flood risk changes in Rome by combining empirical and theoretical (modelling) research. While the results presented here suggest that the concept of social memory can help explain the emerging dynamic of risk, i.e. levee effect, the model remains a falsifiable hypothesis that needs to be tested further in a variety of case studies across scales and along gradients of social and hydrological conditions. More specifically, the comparison of model results and observations presented here is not meant to be a validation exercise. Socio-hydrological models, such as the one used here, are still at an early stage and the focus is mainly on exploring the generic mechanisms underlying the dominant dynamics of human-water systems (Sivapalan et al., 2012; Di Baldassarre et al., 2016). We think that only when the theory in this emerging field is more consolidated, one might start building more complex models around specific test sites, perform calibration and validation, and then use the model to explore future trajectories. Doing this at this early stage would

Table 1. Parameters of the socio-hydrological model used in the experiment. More details about the model and its variables can be found in Di Baldassarre et al. (2015).

Parameter	Description	Values
α_H	Parameter related to flood depth-damage curve	30
ξ_H	High water level enhancement due to presence of flood walls	0 (not considered)
ρ_D	Mean relative growth rate	0.003 years^{-1}
κ_T	Protection level decay rate	0 (not considered)
α_D	Ratio between preparedness and awareness	20
ε_T	Safety factor for flood walls	1.1
μ_S	Memory loss rate (half-life)	0.06 years^{-1} (11.5 years)

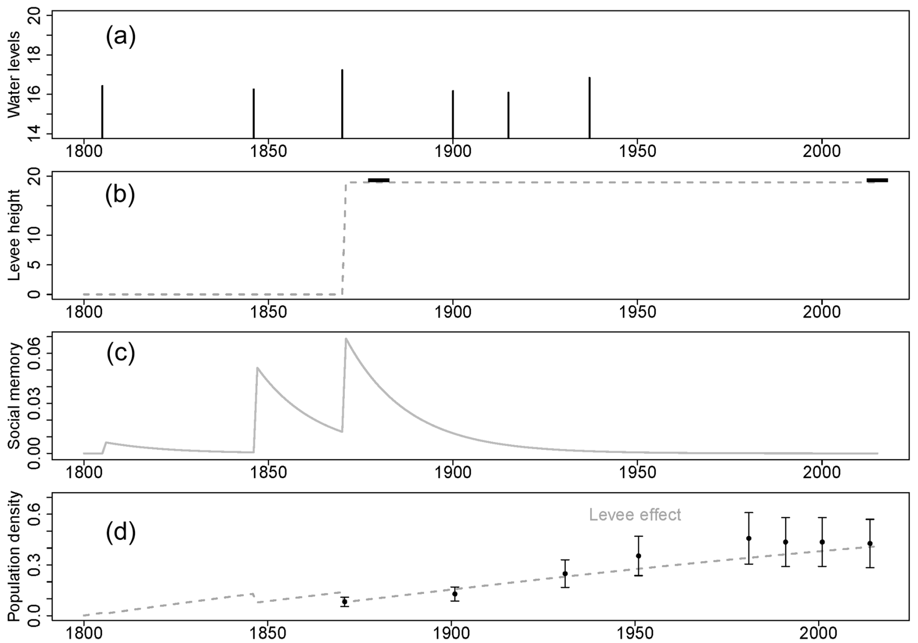

Figure 3. Comparing observations (in black) and model results (in grey) of human-flood interactions in Rome. Observed population density is expressed with boxplots representing the uncertainty in the (unavoidably arbitrary) estimation of a theoretical maximum value of floodplain population.

jeopardize the process of advancing understanding of the co-evolution of human and water systems.

Moreover, while this study focused on the internal feedback mechanisms between floods and societies in Rome, it should be mentioned that other external drivers of change (climate, economic growth, regional trends) can have a major role in the dynamics of flood risk. For instance, floodplain population in Rome significantly increased over the period of 150 years analysed here, but this trend has slightly changed over the past decades (Fig. 2a). This is not related to flood risk. Instead, it can be attributed to more investments in Rome's suburban areas, within a process known as urban diffusion, which started in the 1970's as more and more inhabitants from central and semi-central neighbourhoods of the city moved out and spread over the whole metropolitan area of Rome (Crisci, 2016).

5 Data availability

Both data and model code (in R) are enclosed here as Supplement.

The Supplement related to this article is available online at doi:10.5194/adgeo-5-9-2017-supplement.

Competing interests. The authors declare that they have no conflict of interest.

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