Hydrological risk: modeling flood memory and human proximity to rivers

Elena Ridolfi, Elena Mondino and Giuliano Di Baldassarre

ABSTRACT

Recent literature in sociohydrology has shown the important role of flood memory in shaping hydrological risk. In this paper, we present a system dynamics model of human–flood interactions that simulates how the river proximity of human settlements is altered by changes in flood memory. We also compare our model outcomes with an unprecedented dataset consisting of historical and archeological observations of human settlements in the Czech Republic that have been affected by major flood events. This comparison allows us to evaluate the potentials and limitations of our sociohydrological model in capturing essential features of flood risk changes, including the process of resettling farther and closer to the river. Our results show that the accumulation (and decay) of collective memory has potential in explaining temporal changes of flood risk driven by the occurrence (or absence) of major events. As such, this study contributes to advancing knowledge about the complex dynamics of human–water systems, while providing useful insights in the field of flood risk reduction.

Key words | collective memory, flood risk, sociohydrology, system dynamics

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HIGHLIGHTS

- We explore how flood memory shapes human settlements and their proximity to rivers.
- We develop a system dynamics model of human–flood interactions that simulates how the settlements' proximity to rivers is altered by changes in flood memory.
- We validate the model using a dataset of settlements location spanning eight centuries.
- Relocation of a community is effective in flood risk mitigation if flood memory is sustained in time.

INTRODUCTION

Throughout history, floods have been a major concern for numerous communities that have settled in the proximity of rivers (Ramesh 2013; Rosbjerg *et al.* 2013). UNISDR (2015) reported that floods are the most deadly and costly among all natural hazards: between 1995 and 2015 floods affected more than 2 billion people, causing more than 150,000 fatalities. Flood risk is increasing in many parts of the world because of climatic and socio-economic changes, such as growing population in flood-prone areas (Di Baldassarre *et al.* 2010). Humans have also increasingly altered the frequency and magnitude of hydrological extremes (i.e. both floods and droughts) through levees, reservoirs and land-use changes (Van Loon *et al.* 2016).

Most human societies adapt and respond to flood risk using a combination of hard and soft measures. Hard protection measures include large infrastructures, such as levees,

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which aim to decrease the frequency of floods. These structures tend to increase people's complacency and often enable intense urbanization of flood-prone areas. This process is widely known as the 'levee effect' (White, 1945), and it can lead to catastrophic outcomes when hard protection measures eventually fail, as seen in 2005 in New Orleans, USA (Kates *et al.* 2006). Soft adaptation measures aim at raising flood risk awareness and preparedness in the population living in flood-prone areas through, e.g. community education programs (Scolobig *et al.* 2012), or reducing flood exposure using risk-avoiding strategies, such as resettling away from rivers (e.g., Mård *et al.* 2018).

The process of resettling farther from the river as an informal (e.g. migration) or formal (e.g. relocation plan) response to flooding has been described in many cases around the world (e.g., Penning-Rowsell *et al.* 2013; Hino *et al.* 2017; Kreibich *et al.* 2017; Arnall 2019). Planned or spontaneous relocation can reduce flood losses substantially. For instance, after the occurrence of disastrous flooding in the Mekong Delta in 2000, many people were encouraged to move to flood-safe areas and when a similar flood occurred in 2011, fatalities were reduced by 77% (Kreibich *et al.* 2017). Yet, it has also been shown that communities relying heavily on structural protection measures, such as levees, tend to stay in the same area after major flooding and respond by improving these structural protection measures, e.g. repairing, reinforcing or raising levees (Mård *et al.* 2018). Indeed, relocation after flooding is difficult, if not impossible, as it encounters resistance especially when high levels of structural protection are in place (Hino *et al.* 2017).

When dealing with the process of resettlement, the role of collective memory of floods is key (Viglione *et al.* 2014). Indeed, resilience can be strongly affected by society's flood memory. It was found that a long interarrival time between flood events can fade the memory that the community built after the occurrence of a flood (Ullberg 2017). On the other hand, high levels of flood memory may lead to an appropriate response to disasters, jogging risk awareness and thus prompting preparedness (see e.g. Scolobig *et al.* 2012).

The accumulation of collective memory has been broadly investigated in sociology, anthropology, history, neurosciences and psychology (Anastasio *et al.* 2012). The term collective memory was first introduced in the mid-1920s by the French sociologist Maurice Halbwachs (1925), from whom a large tradition of memory studies originates (see e.g. Roediger & Wertsch 2008; Brown *et al.* 2009; Olick 2009). However, there is no clear definition of the concept itself, and the only defining characteristic is that 'it is a form of memory that transcends individuals and is shared by a group' (Wertsch & Roediger 2008). While individual memory is one's personal memory of a previous experience, collective memories can be seen as the remembering of the same experience but not necessarily in the same way (Van Dijck 2007). This feature of collective memory is particularly fitting in the framework of disaster risk, as different individuals are affected by – and experience – the same event differently. Collective memory has indeed been the subject of numerous disaster studies, especially in relation to remembering the past in the wake of new events (Madsen & O'Mullan 2013). Within flood risk, some scholars have also dealt with the effects of memory in terms of real-life decision-making (e.g., Del Missier *et al.* 2013). McEwen *et al.* (2017) investigated the role of flood memory in generating strategies to better deal with flood risk. In their study, flood memory is considered as a process that develops both at the individual and at the community level, accounting for diverse sources of materialized memories in formal and informal archives, documentaries or involving different types of technologies. While the majority of studies on the subject are theoretical, some scholars employed empirical methods to investigate and assess collective memory. Choi *et al.* (2014) conducted an experiment on words recalling. Madsen & O'Mullan (2013) conducted a community-based participatory project focused on exploring and enhancing resilience. The present paper aims at providing a temporal dimension to the study of collective memory, by exploring how it changes over time and how disastrous events affect it. Exploring the temporal dimension is particularly important as the memory is sustainable only when it creates and supports conditions for its inter- and intra-generational progress, contributing to an increase in the associated lay knowledge, which, in turn, may foster the adoption of flood mitigation strategies. Flood memories furnish a stage to develop and share lay knowledge, increasing social learning and thus fostering the actions to build social resilience to future risk (McEwen *et al.* 2017). While flood memory is linked to remembering and forgetting a flood event, the concept of lay knowledge refers to what we interpret and what we learn from personal experiences (Popay 2018). Being the result of understanding, explaining and assigning meaning to events occurring in a person's life, the concept of lay knowledge also includes the transmission of anecdotes and stories to comprehend, describe and then recognize circumstances of everyday life (Ullberg 2017). Flood memory can be seen as a personal and local preparation of sustained resilience (McEwen *et al.* 2017). Garde-Hansen *et al.* (2017) argued that collective memory of flooding has a key role in the individual's sense of future preparedness. In this regard, the understanding of how flood memory develops into lay knowledge is of utmost importance to create learning opportunities and increase communities' resilience.

Very little research has been done on the role of memory on collective decisions and more specifically on its impact on risk mitigation strategies' planning and actuation (Fanta *et al.* 2019). There still remains the key question of how long flood events remain in our collective memory. To this end, Fanta *et al.* (2019) explored how the spatial distribution of human settlements has been influenced by the occurrence of flood events in 1,293 settlements in the Czech Republic across eight centuries. They observed that after the occurrence of a disastrous flood, new human settlements were often built farther from the river. Yet, human settlements again started to develop closer and closer to the river after a few decades. They attributed this outcome to the social processes of learning and forgetting: as long as the reminiscence of the flood event is still fresh in the memories of eyewitnesses, most establishments are built in flood-safe places. As flood memory decays over time, river proximity resumes, and a larger portion of the newly built human settlements develops in flood-prone areas.

Studies focusing on long-term memory of flood events are rare (Tschakert *et al.* 2010); therefore, the study of the development of settlements in the aftermath of several extreme flood events occurring in a time window of several centuries offers interesting insights into the role of collective memory on the community's decisions and its evolution in time. In turn, the behavior of the community provides information on the evolution of the flood mitigation strategies implemented by that community.

Di Baldassarre *et al.* (2013a) argued that a sociohydrological approach can help unravel changes in flood risk generated by the interactions and feedback mechanisms between hydrological, technical and social processes. In this context, recent progress in sociohydrology (Sivapalan *et al.* 2012; Pande & Sivapalan 2017; Di Baldassarre *et al.* 2019) has contributed to a better understanding of the human–flood interactions (Di Baldassarre *et al.* 2013b; Sivapalan & Blöschl 2015). System dynamics models, in particular, have proven to be useful tools for unraveling the risks generated by the interplay of flood and human systems (Viglione *et al.* 2014), thus providing opportunities to better interpret past risk changes while exploring future trajectories of flood risk (Alonso Vicario *et al.* 2020; Ridolfi *et al.* 2020). Yet, empirical information about feedback mechanisms between human and water systems is only rarely available and, as a result, the role of water in urbanization patterns is one of the 23 Unsolved Problems in Hydrology (UPH) identified by the initiative of the International Association of Hydrological Sciences (IAHS; Blöschl *et al.* 2019). In this paper, we aim to explore how flood memory shapes human settlements and their proximity to rivers. To this end, we first develop a system dynamics model of human–flood interactions and then evaluate its potential and limitations by using an unprecedented dataset consisting of historical observations of flood events and changes in human settlements collected in the Czech Republic by Fanta *et al.* (2019). By building and testing our sociohydrological model, we contribute jointly to behavioral sciences, in terms of accumulation and decay of collective memory, and to hydrology and natural hazards in terms of flood risk modeling.

MODELING FLOOD LOSSES, MEMORY AND HUMAN SETTLEMENTS

We conceptualize human–flood interactions in a simplified way, building upon sociohydrological models that have been proposed over the past years (a review in Di Baldassarre *et al.* 2019). We hypothesize that when a damaging flood event occurs, the collective memory of floods (M) is built up. Similar to previous studies (Di Baldassarre *et al.* 2013b; 2015; Viglione *et al.* 2014; Grames *et al.* 2016; Ciullo *et al.* 2017;

Yu *et al.* 2017; Barendrecht *et al.* 2019), we assume that the higher the losses, the higher the accumulation of memory, and thus the tendency to settle on flood-safe ground. The latter is modeled, for the first time, by increasing the vertical distance (H) of the center of the human settlement from the river. Flood memory is assumed to decay over time, consistently with consolidated literature (Anastasio *et al.* 2012). As such, the benefits of settling close to the river (e.g. trading, transportation, energy production, water access) gain more weight and flood memory decreases until the next flood event that builds the flood memory up and, as a result, human proximity to rivers eventually increases again. This conceptualization is depicted by the causal loop in Figure 1.

Our conceptualization above is translated into a system dynamics model by considering a series of flood events with different magnitudes and irregular time intervals to represent a time series of peak over threshold of flood levels, $W(t)$ [L]; see more details in Viglione *et al.* (2014). To simulate the dynamics of human settlements, we assume resettling as the primary risk reduction strategy, i.e. no structural measures such as levees are built. Flood severity is described by the unitless variable $F(t)$ [.], which is the proportion of damage caused to the settlement by a high value of $W(t)$, ranging from 0 (no losses) to 1 (total destruction). The variable is given by the following equation (time dependence is omitted for brevity) describing the flood system:

$$F = 1 - \exp\left(-\frac{W}{\alpha H}\right) \qquad \text{if} \quad W > 0, \tag{1}$$

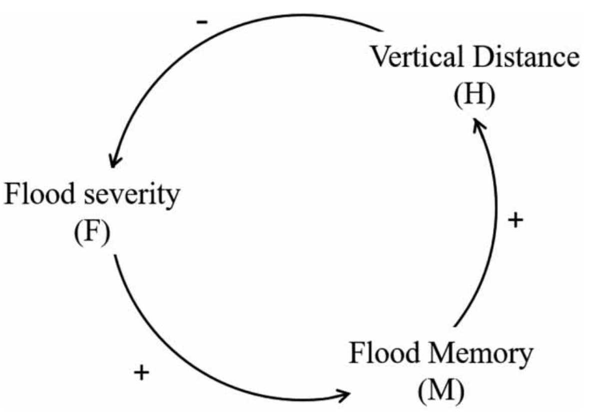

Figure 1 | Causal loop considering the interaction between flood memory, vertical distance from the river and flood severity.

where α is a unitless parameter related to the topographic characteristics of the floodplain (Di Baldassarre *et al.* 2013b), which determines to what extent flood damage reduces by increasing the vertical distance between the center of the human settlement and the river. Note that a near-total destruction of the settlement can occur if the water level is extremely high or if the vertical distance to the river is about zero.

The flood system (Equation (1)) is fully coupled with the human system:

$$\begin{cases} \dfrac{dH}{dt} = \varphi\left[M - \dfrac{H}{\lambda}\right] \\ \dfrac{dM}{dt} = \Delta(\psi(t)) \cdot F - \mu M \end{cases} \tag{2}$$

This system represents how the spatial distribution of human settlements, schematized in a lumped way using the vertical distance H [L] of its center of mass from the river, is altered by the occurrence of flood losses (F) by means of changes in the unitless collective memory of floods (M).

When flooding occurs, the collective memory $M[.](t)$ is built in the community, which witnesses the event. This abrupt change in memory is modeled via the Dirac comb $\Delta(\psi(t))$, which is a function always equal to zero, but assuming the value of 1 at the time of flood occurrences. This term represents the increase of memory, which is assumed proportional to flood losses (F). The solution for M is a bounded piecewise continuous function. From the equations' solutions, M is a continuous decreasing function between two consecutive floods; while where M is discontinuous (i.e. when the flood occurs), it never exceeds 1. Flood memory decays to one-half of its initial value in a given time named half-life τ [T]:

$$\mu = \frac{ln(2)}{\tau} \tag{3}$$

The parameter μ [T^{-1}] describes the decay rate of flood memory: the longer the time passes from the event, the weaker are the memories of it. The assumptions above are not only based on previous sociohydrological models (Di Baldassarre *et al.* 2013b, 2015; Viglione *et al.* 2014; Grames *et al.* 2016; Ciullo *et al.* 2017; Yu *et al.* 2017; Barendrecht *et al.* 2019) but also on recent findings in anthropology, history, neuroscience and psychology (Anastasio *et al.* 2012).

In our model, memory M accumulates when people experience flood losses (F). As a consequence, the community tends to settle on higher grounds. This process is schematized by variations of the vertical distance H [.](t) of the center of the settlement from the river. H increases abruptly because of the occurrence of a major flooding since flood memory builds up. Then, H tends to decrease since flood memory decays over time (Figure 1). The latter tendency reflects the fact that proximity to the river is often beneficial for e.g. trading, agriculture, transportation and access to water resources (Di Baldassarre *et al.* 2013b). The parameter λ [L] represents the critical vertical distance from the river beyond which the settlement can no longer grow. The parameter φ [L T^{-1}] represents the velocity by which human settlements can grow.

CASE STUDY

We apply our model to the Vltava region (Czech Republic). The Vltava River is the largest river of the Czech Republic with a length of 430 km and a drainage area of 28,090 km^2, extending over one third of the entire Czech Republic. The river rises in southwestern Bohemia, crosses Bohemia and thus Prague and finally flows into the Elbe. Seven disastrous flood events were identified; they occurred in 1118, 1342, 1432, 1501, 1655, 1784 and 1845. We considered extreme events since they probably had an influence on settlement evolution rather than small floods. The water levels of the seven flood events were retrieved from literature. In Prague, the 1118 flood reached 6 m, while in 1342 the water level ranged between 4 and 5 m (Kundzewicz 2019); in 1432 it ranged between 3.4 and 4 m, while in 1501, 1655, 1784 and 1845 it reached 5.1, 4.9, 5.7 and 5.7 m, respectively (Brazdil *et al.* 2006) (Figure 2(a)).

To investigate the influence of flood events on the vertical distance from the river of newly established settlements, we analyzed a dataset of 1,293 individual towns and villages. The raw dataset consisting of the establishment date of each settlement and its location was retrieved by the freely available dataset published by Fanta *et al.* (2019). They also provided details on the dataset, the case study, and on the identification, dating and location of settlements. To date the establishment of a human settlement, they used a combination of historical and archeological dating. Since the shape and the boundaries of settlements are difficult to define clearly, the settlements are represented by data points corresponding to the vertical distance from the river of their historical center.

We then analyzed the raw data as follows. We calculated the average vertical distance from the river of the settlements in the Vltava region one generation before and one and two generations after each flood (boxplots in Figure 2(c)). One generation is considered to be 25 years long, since this is the average time during which a child grows up and may have children. The settlements established within 25 and 1 year before the flood represent generation −1, the ones established within the flood year and up to 25 years after representing generation 1, and those established within 25 and 50 years after the flood represent generation 2. Then, we used the data on the average vertical distance to validate our model.

As we are interested in the possible trajectories of settlements establishment from the river, the parameters of the model vary within a range rather than assuming a deterministic value. According to literature, the parameter related to flood depth-damage curve (i.e., α) varies between 0.01 (Di Baldassarre *et al.* 2013b) and 10 (Di Baldassarre *et al.* 2015). The vertical distance from the river at which the settlement does not have any increase in benefit (i.e., λ) varies between 4 and 24 m. These are, respectively, the minimum and maximum 75th percentile of vertical distances of newly established settlements among all flood events (Figure 2(c)). The change in distance from the river per year (i.e., φ) varies between 0.5 and 5 m yrs^{-1} as we assume that the rate by which the new settlements were established may depend on several factors, such as availability of materials and distance to collect them and thus may be not deterministic.

In the past, many scholars modeled the half time of flood memory using diverse time windows ranging from 1 to 15 years (e.g., ICPR 2002; Di Baldassarre *et al.*, 2013, 2015; Viglione *et al.* 2014; Ciullo *et al.* 2017; Barendrecht *et al.* 2019). It represents the time during which the flood memory decays to one-half of its initial value in the society

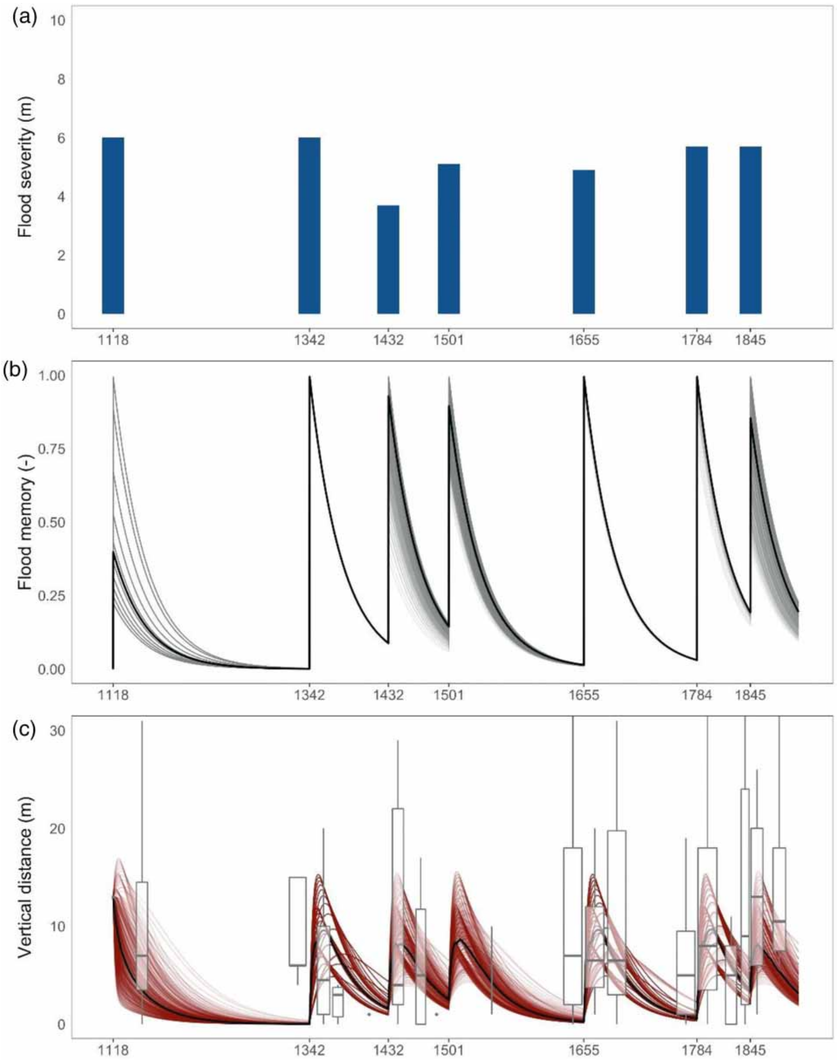

Figure 2 | Outcomes of the sociohydrological model in terms of (a) flood severity, (b) flood memory, (c) vertical distance of settlements from the river (red envelope), the median of the envelope (black curve) and the average vertical distance from the river of the settlements observed in the Vltava region one generation (i.e., 25 years) before and one and two generations after each flood (boxplots). Some boxplots consist in a single dot when there was only one point in the corresponding 25 years.

that experienced the flood. It is used to investigate the potential of flood memory in informing and changing flood risk management. Ridolfi *et al.* (2020) showed that depending on the attitude of a specific society toward flood risk, the flood memory may vary largely (i.e. from 2 to 15 years). As we are interested in the possible trajectories of settlements establishment from the river, we did not assign a specific value to parameters, but rather parameters vary in an interval. On the basis of literature values, half time of flood memory here varies between 5 and 15 years. Parameters ranges are reported in Table 1.

MODEL APPLICATION AND RESULTS

Model results are compared with historical observations in order to assess whether changes in flood memory can explain the observed dynamics of human settlements. As we are interested in the possible trajectories of settlements establishment from the river, results are presented in terms of envelopes. This is in agreement with the trajectories of observed newly established settlements. The vertical distance is compared with a statistical summary of historical observations by Fanta *et al.* (2019) represented by boxplots (Figure 2(c)).

Table 1 | Parameters of the sociohydrological model and their range of variation

Parameter	Description	Range	Unit
α	Parameter related to flood depth-damage curve	0.01–10, by = 0.5	[–]
λ	Vertical distance from the river at which the settlement does not have any increase in benefit	4–24, by = 4	[m]
φ	Change in distance from the river per year	0.5–5, by = 0.5	[m yrs^{-1}]
τ	Years in which the memory reduces to half its initial value	{5,10,15}	[yrs]

Figure 2 shows model results in terms of flood memory (panel b) and vertical distance from the river of the center of the human settlements (panel c). Here we describe the results starting from $t = 0$ (year 1118) and progressing over time until the year 1900. The initial conditions of model variables are presented in Table 2. We assume that at the beginning of the simulation, i.e. at time $t = 0$ in Figure 2(b), people have no memory of past flood events, i.e. $M(t = 0)$ is set to zero. According to the dataset of vertical distance of newly established settlements, at time $t = 0$, the average vertical distance of settlements is 13 m, Figure 2(c). As the first disastrous flood hits the human settlements in 1118, memory rises (Figure 2(b)) at the community level as many people become conscious of living in a flood-prone area. As a result, new settlements are built farther away from the river and, specifically, on higher ground (Figure 2(c)). Model results are compared with the statistical distribution of observed data represented by boxplots for each generation, i.e. one before and two after each flood (Figure 2(c)). As we move in time, no major flooding occurs for some decades and flood memory decays, halving its initial value in time. Thus, the tendency to re-settle close to the river resumes until the occurrence of a second flood in 1342, which jogs the memory of the community. As a consequence, the vertical distance of the new settlements from the watercourse increases again as new settlements tend to be established on flood-safe areas, i.e. higher ground. This process repeats in time with a similar pattern for each of the seven major floods (Figure 2). Low memory levels lead the communities to establish new settlements in the river proximity, as their risk awareness lowers with time. Because of the flood memory decay, the memory is often close to zero when an extreme event occurs. As a consequence, the new settlements are close to the river when they are hit. The relocation of a community is effective in mitigating flood risk only if communities' memory of past floods and awareness of flood risk are kept alive and sustained in time. This unprecedented dataset allows us to disentangle the link between flood memory and societal behavior in terms of settlements establishment. From the model results, we can observe that the envelopes well describe the behavior of settlements changes across time, thus the parameterization of the model well suits the behavior of the communities settled in the case study area. Historical data show that these communities forget relatively quickly (i.e. from 5 to 15 years) and the forgetfulness causes the adoption of a risk-taking approach (feeling safe near the river). The combination of the two behaviors (i.e. the attitude toward flood risk and the collective memory) influences the growth of communities. It was found that a wealth growth is associated with societies that either pursue a risk-taking attitude (such as settling in a flood-prone area) together with strategies to maintain the flood memory in time or tend to forget but adopt risk-avoiding strategies (such as relocation; Viglione et al. 2014). The parameter related to flood depth-damage curve (i.e., α) varies between 0.01 and 10, suggesting that the proportion of damage caused to the settlements (F), can vary largely. The vertical distance from the river can hinder the development of the settlements when the distance itself reaches its critical value (i.e. λ). The critical value varies between 4 and 24 m, confirming that the proximity to rivers is often the result of a trade-off that may depend on the specific community.

Table 2 | Variables of the human–flood system and their initial conditions in the modeling exercise presented here

Variable	Description	Initial condition	Unit
F	Flood severity	6	[m]
H_v	Vertical distance	13	[m]
M	Flood memory	0	[.]

It is worth noting that regarding three flood events (i.e., 1342, 1655 and 1845), the newly established settlements are on average built farther from the river before the occurrence of the event as opposed to the general behavior that the flood prompts the establishment on higher ground. This behavior could be caused by events other than floods and could be related to the need to move on higher ground to increase the protection from invasions by enemies or to increase the control over a territory. For instance, in 1631 and 1648, Prague was invaded by Saxons and Swedes, respectively. Moreover, the area is rich in mining quarries that may have led the communities to settle in their proximity. In this regard, the change in distance from the river per year (i.e., φ) varies between 0.5 and 5 m yrs^{-1} and it may depend on the availability of materials, which may not be constant over time. The data related to the position of settlements across time and historical events thus reveal that there may have been many factors that led communities to move and settle on higher ground. However, Figure 2 shows, in general terms, that the model captures the essential features of resettling farther and closer to the river depending on the time passed from the last disastrous flood event. In this regard, flood memory can be considered as one of the main drivers influencing the human proximity to rivers and thus society's exposure to flooding.

DISCUSSION

Concerning the real-world case study we explore here, we can infer that societies respond to flood occurrence by adopting strategies to avoid flood risk (such as relocation). The comparison of model results and the statistical analysis of observed data, i.e. a synthesis of settlements relocation across centuries, shows the capability of the proposed model to capture the dynamics due to the mutual feedback between social and hydrological processes.

Human settlements located in the proximity of rivers are often the result of a trade-off. Floodplain areas have often offered both benefits (e.g. economic growth) and potential costs (e.g. flood risk). In our conceptualization, weights in this trade-off continuously change over time depending on the collective memory of floods. From a statistical analysis of observed data, it is interesting to observe that within two generations from the flood event, the center of human settlements returns closer to the river (Figure 2). This dynamic can be explained via decays of flood memory. We consider that this decay is not only happening at the individual level (everyone tends to forget; Anastasio *et al.* 2012) but also at the collective level as, for instance, there may be a reduction over time of eyewitnesses in the community, as some people leave and others die. Fanta *et al.* (2019) argue that the process of forgetting may be ascribed to the death of the eyewitnesses that experienced the flood. They can foster the lay knowledge of flood risk as they can be considered the custodian of the information regarding the occurrence of the flood, e.g. the magnitude, the stroked areas, the damages. Their death ends the process of horizontal (intra-generational) and vertical (inter-generational) transmission of this information. The experience of flooding can underpin the creation and nurturing of collective memory.

The collective memory of floods can play a major role in mitigating risk and boosts the adoption of flood reduction practices at the individual and community level. Owusu *et al.* (2015), for example, showed how public education and promotion campaigns have had a key role in raising communities' awareness, resulting in personal strategies and attitudes towards flooding and property-level flood protection. Communities promoting inclusive and participatory approaches substantially reduce flood losses. People engaged in forward-looking plans and characterized by risk monitoring behavior cope better with flood risk and increase the resiliency of the environment (Ridolfi *et al.* 2020). Flood risk communication is key for flood risk assessment, which should comprehend social, economic, cultural and political perspectives to be ground-based and thus adequate to the specific case for an effective flood risk management (Buchecker *et al.* 2013). Wheater (2006) argues that the level and type of flood protection measures may depend on the social perception of what is an acceptable risk, and the answer to this question may evolve in time at the society level. Societies that adopt hard protection measures, such as levees, increase the level of protection and thus lower the (estimated) risk. Nevertheless, they experience higher losses: the exposed value of the protected areas increases because of the false sense of safety generated by the presence of levees. On the other hand, societies that adopt soft protection measures, such as relocation, can be more resilient. They can adopt approaches aiming at reducing risk-minimizing losses (Ciullo *et al.* 2017). Yet, public perception of risk is often low and a greater effort is required to raise awareness and preparedness, in case flood events occur (Mondino *et al.* 2020).

CONCLUSIONS

We explored the evolution of collective flood memory in time and its implication in terms of resettlements using an unprecedented dataset of settlements' location spanning eight centuries in the Czech Republic.

A new sociohydrological model was introduced to simulate the role of flood memory in influencing human proximity to rivers and thus society's exposure to flooding. Results show that the proposed sociohydrological model could reproduce the essential features of changes in human settlements driven by major flood events by representing the process of accumulation and decay of flood memory. As such, the parameterization of the model is suitable to describe the behavior of communities' resettlements in the Vltava Region. Results suggest that flood events are likely to be the main driver of resettlements processes and confirm our fundamental assumption: flood memory – as a primary mechanism of human–flood interactions – has the potential to explain the spatial and temporal changes of human settlements driven by the (non-)occurrence of major flooding events and thus the dynamics of flood risk.

Anastasio *et al.* (2012) state that the structures that enable collective memory are represented by collective levels and comprehend museums, monuments, people, transcriptions among others. Collective memory consolidates with a similar process of individual memory. In this sense, public education and promotion campaigns also have a key role in raising communities' awareness and may result in personal strategies and attitudes towards flooding and property-level flood protection (Owusu *et al.* 2015). In fact, communities promoting inclusive and participatory approaches substantially reduce flood losses. This suggests the need to keep promoting educational programs to keep the flood memory alive within communities.

This work has a number of limitations. The human response to floods is complex and uncertain as it depends on many other aspects – such as economic interests, cultural values and historical events – that were not considered here. Moreover, changes in both collective memory and vertical distance from the river are influenced by numerous factors and thus are more complex than what is described in our model. As such, the concept of flood memory alone cannot adequately describe the complexity of the processes that lead to translate societal perceptions into policy action (Gober & Wheater 2015), especially because other variables involved, such as risk awareness and preparedness, have been shown to be multifaceted and non-trivial in various contexts (Scolobig *et al.* 2012). Still, it has been shown that being aware of exposure to flood risk remains a necessary step to be prepared to face the occurrence of a flood event (Kreibich *et al.* 2017).

Despite its simplicity, the model presented here is able to reproduce the key features of the dynamics generated by the interplay between floods and society. The process of resettling farther and closer to the river depending on the collective flood memory allowed us to perform a further step in disentangling the relationship between societal and hydrological processes. Adaptation strategies such as resettling farther from the river may have a key role in reducing flood risk. However, a flood risk-averse attitude requires programs that sustain memory and awareness over time. As the link between societal perception and flood mitigation strategies is still not fully understood, testing the hypotheses of our model can inspire future research to further unravel the role of collective memory in shaping the dynamics of flood risk over time.

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DECLARATION OF INTEREST

The authors declare no competing interest.

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AUTHOR CONTRIBUTIONS

ER: conceptualization, model development, data analysis, writing, editing; EM: data analysis, visualization, editing; GDB: conceptualization, model development, editing.

DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories. Data are available at https://www.nature.com/articles/s41467-019-09102-3#Sec12.

REFERENCES

Alonso Vicario, S., Mazzoleni, M., Bhamidipati, S., Gharesifard, M., Ridolfi, E., Pandolfo, C. & Alfonso, L. 2020 Unravelling the influence of human behaviour on reducing casualties during flood evacuation. *Hydrological Sciences Journal*. doi: 10.1080/02626667.2020.1810254.

Anastasio, T. J., Ehrenberger, K. A., Watson, P. & Zhang, W. 2012 *Individual and Collective Memory Consolidation, Analogous Processes on Different Levels*. The MIT Press, Cambridge, MA/London.

Arnall, A. 2019 Resettlement as climate change adaptation: What can be learned from state-led relocation in rural Africa and Asia? *Climate and Development* **11** (3), 253–263. doi: 10.1080/17565529.2018.1442799.

Barendrecht, M. H., Viglione, A., Kreibich, H., Merz, B., Vorogushyn, S. & Blöschl, G. 2019 The value of empirical data for estimating the parameters of a socio-hydrological flood risk model. *Water Resources Research* **55**, 1312–1336. https://doi.org/10.1029/2018WR024128.

Blöschl, G. *et al.* 2019 Twenty-three unsolved problems in hydrology (UPH) – a community perspective. *Hydrological Sciences Journal* **64** (10), 1141–1158. https://doi.org/10.1080/02626667.2019.1620507.

Brazdil, R., Kotyza, O. & Dobrovolný, P. 2006 July 1432 and August 2002 – two millennial floods in Bohemia? *Hydrological Sciences Journal* **51** (5), 848–863.

Brown, A. D., Gutman, Y., Freeman, L., Sodaro, A. & Coman, A. 2009 Is an interdisciplinary field of memory studies possible? *International Journal of Politics, Culture and Society* **22**, 117–124.

Buchecker, M., Salvini, G., Di Baldassarre, G., Semenzin, E., Maidl, E. & Marcomini, A. 2013 The role of risk perception in making flood risk management more effective. *Natural Hazards and Earth System Sciences* **13**, 3013–3030. https://doi.org/10.5194/nhess-13-3013-2013.

Choi, H., Blumen, H. M., Congleton, A. R. & Rajaram, S. 2014 The role of group configuration in the social transmission of memory: evidence from identical and reconfigured groups. *Journal of Cognitive Psychology* **26** (1), 65. (80). doi: 10.1080/20445911.2013.862536.

Ciullo, A., Viglione, A., Castellarin, A., Crisci, M. & Di Baldassarre, G. 2017 Socio-hydrological modelling of flood-risk dynamics: comparing the resilience of green and technological systems. *Hydrological Sciences Journal* **62** (6), 880–891. https://doi.org/10.1080/02626667.2016.1273527.

Del Missier, F., Mäntylä, T., Hansson, P., De Bruin, W. B., Parker, A. M. & Nilsson, L. G. 2013 The multifold relationship between memory and decision making: an individual-differences study. *Journal of Experimental Psychology: Learning Memory and Cognition* **39** (5), 1344–1364. https://doi.org/10.1037/a0032379.

Di Baldassarre, G., Montanari, A., Lins, H., Koutsoyiannis, D., Brandimarte, L. & Bloeschl, G. 2010 Flood fatalities in Africa: from diagnosis to mitigation. *Geophysical Research Letters* **37**, L22402. doi:10.1029/2010GL045467.

Di Baldassarre, G., Kooy, M., Kemerink, J. S. & Brandimarte, L. 2013a Towards understanding the dynamic behaviour of floodplains as human-water systems. *Hydrology and Earth System Sciences* **17**, 3235–3244. https://doi.org/10.5194/hess-17-3235-2013.

Di Baldassarre, G., Viglione, A., Carr, G., Kuil, L., Salinas, J. L. & Blöschl, G. 2013b Sociohydrology: conceptualising human-flood interactions. *Hydrology and Earth System Sciences* **17** (8), 3295–3303. https://doi.org/10.5194/hess-17-3295-2013.

Di Baldassarre, G., Viglione, A., Carr, G., Kuil, L., Yan, K., Brandimarte, L. & Blöschl, G. 2015 Debates – perspectives on sociohydrology: capturing feedbacks between physical and social processes. *Water Resources Research* **51**, 4770–4781. https://doi.org/10.1002/2014WR016416.

Di Baldassarre, G., Sivapalan, M., Rusca, M., Cudennec, C., Garcia, M., Kreibich, H., Konar, M., Mondino, E., Mård, J., Pande, S., Sanderson, M. R., Tian, F., Viglione, A., Wei, J., Wei, Y., Yu, D. J., Srinivasan, V. & Blöschl, G. 2019 Sociohydrology: scientific challenges in addressing the sustainable development goals. *Water Resources Research* **55**, 6327–6355. https://doi.org/10.1029/2018WR023901.

Fanta, V., Šálek, M. & Sklenicka, P. 2019 How long do floods throughout the millennium remain in the collective memory?

Nature Communications **10** (1). https://doi.org/10.1038/s41467-019-09102-3.

Garde-Hansen, J., McEwen, L., Holmes, A. & Jones, O. 2017 Sustainable flood memory: remembering as resilience. *Memory Studies* **10** (4), 384–405.

Gober, P. & Wheater, H. S. 2015 Debates – perspectives on sociohydrology: modeling flood risk as a public policy problem. *Water Resources Research* **51** (6), 4782–4788. https://doi.org/10.1002/2015WR016945.

Grames, J., Prskawetz, A., Grass, D., Viglione, A. & Blöschl, G. 2016 Modeling the interaction between flooding events and economic growth. *Ecological Economics* **129**, 193–209. https://doi.org/10.1016/j.ecolecon.2016.06.014.

Halbwachs, M. 1925 *Les Cadres Sociaux de la Mémoire, Paris, Presses Universitaires de France, 1952, Originally Published in Les Travaux de L'Année Sociologique*. F. Alcan, Paris.

Hino, M., Field, C. B. & Mach, K. J. 2017 Managed retreat as a response to natural hazard risk. *Nature Climate Change* **7** (5), 364–370. https://doi.org/10.1038/nclimate3252.

International Commission for the Protection of the Rhine (ICPR). 2002 *Non Structural Flood Plain Management – Measures and Their Effectiveness*. ICPR, Koblenz.

Kates, R. W., Colten, C. E., Laska, S. & Leatherman, S. P. 2006 Reconstruction of New Orleans after Hurricane Katrina: a research perspective. *Proceedings of the National Academy of Sciences of the United States of America* **103**, 14653–14660.

Kreibich, H., Di Baldassarre, G., Vorogushyn, S., Aerts, J. C. J. H., Apel, H., Aronica, G. T., Arnbjerg-Nielsen, K., Bouwer, L. M., Bubeck, P., Caloiero, T., Chinh, D. T., Cortès, M., Gain, A. K., Giampá, V., Kuhlicke, C., Kundzewicz, Z. W., Llasat, M. C., Mård, J., Matczak, P., Mazzoleni, M., Molinari, D., Dung, N. V., Petrucci, O., Schröter, K., Slager, K., Thieken, A. H., Ward, P. J. & Merz, B. 2017 Adaptation to flood risk: results of international paired flood event studies. *Earth's Future* **5**, 953–965. https://doi.org/10.1002/eft2.232.

Kundzewicz, Z. W. 2019 *Changes in Flood Risk in Europe*. CRC Press, London, UK.

Madsen, W. & O'Mullan, C. 2013 Responding to disaster – applying the lens of social memory. *Australian Journal of Communication* **40** (1), 57–70.

Mård, J., Di Baldassarre, G. & Mazzoleni, M. 2018 Nighttime light data reveal how flood protection shapes human proximity to rivers. *Science Advances* **4** (8), 1–8. https://doi.org/10.1126/sciadv.aar5779.

McEwen, L., Garde-Hansen, J., Holmes, A., Jones, O. & Krause, F. 2017 Sustainable flood memories, lay knowledges and the development of community resilience to future flood risk. *Transactions of the Institute of British Geographers* **42** (1), 14–28. https://doi.org/10.1111/tran.12149.

Mondino, E., Scolobig, A., Borga, M., Albrecht, F., Mård, J., Weyrich, P. & Di Baldassarre, G. 2020 Exploring changes in hydrogeological risk awareness and preparedness over time: a case study in northeastern Italy. *Hydrological Sciences Journal* **65** (7), 1049–1059. 10.1080/02626667.2020.1729361.

Olick, J. K. 2009 Between chaos and diversity: is social memory studies a field? *International Journal of Politics, Culture and Society* **22**, 249–252.

Owusu, S., Wright, G. & Arthur, S. 2015 Public attitudes towards flooding and property-level flood protection measures. *Natural Hazards* **77** (3), 1963–1978. https://doi.org/10.1007/s11069-015-1686-x.

Pande, S. & Sivapalan, M. 2017 Progress in socio-hydrology: a meta-analysis of challenges and opportunities. *WIRES Water* **4**, e1193. doi: 10.1002/wat2.1193.

Penning-Rowsell, E. C., Sultana, P. & Thompson, P. M. 2013 The 'last resort'? Population movement in response to climate-related hazards in Bangladesh. *Environmental Science and Policy* **27**, S44–S59. https://doi.org/10.1016/j.envsci.2012.03.009.

Popay, J. 2018 What will it take to get the evidential value of lay knowledge recognised? *International Journal of Public Health* **63** (9), 1013–1014. 12.2018.

Ramesh, A. 2013 *Response of Flood Events to Land use and Climate Change. Springer Thesis*, Springer.

Ridolfi, E., Albrecht, F. & Di Baldassarre, G. 2020 Exploring the role of risk perception in influencing flood losses over time. *Hydrological Sciences Journal* **65** (1), 12–20. 10.1080/02626667.2019.1677907.

Roediger, H. L. & Wertsch, J. V. 2008 Creating a new discipline of memory studies. *Memory Studies* **1** (1), 9–22.

Rosbjerg, D., Bloschl, G., Burn, D. H., Castellarin, A., Croke, B., Di Baldassarre, G., Iacobellis, V., Kjeldsen, T. R., Kuczera, G., Merz, R., Montanari, A., Morris, D., Ouarda, T. B. M. J., Ren, L., Rogger, M., Salinas, J. L., Toth, E. & Viglione, A. 2013 Prediction of floods in ungauged basins. In: *Runoff Prediction in Ungauged Basins: Synthesis Across Processes, Places and Scales* (G. Bloschl, M. Sivapalan, A. Viglione, T. Wagener & H. Savenije, eds). Cambridge University Press, Cambridge, UK, pp. 189–225. https://doi.org/10.1017/CBO9781139235761.

Scolobig, A., De Marchi, B. & Borga, M. 2012 The missing link between flood risk awareness and preparedness: findings from case studies in an Alpine. *Natural Hazards* **63**, 499–520. doi:10.1007/s11069-012-0161-1.

Sivapalan, M. & Blöschl, G. 2015 Time scale interactions and the coevolution of humans and water. *Water Resources Research*. Blackwell Publishing Ltd. https://doi.org/10.1002/2015WR017896.

Sivapalan, M., Savenije, H. H. G. & Blöschl, G. 2012 Socio-hydrology: a new science of people and water. *Hydrological Processes* **26** (8), 1270–1276.

Tschakert, P., Sagoe, R., Ofori-Darko, G. & Nii Codjoe, S. 2010 Floods in the Sahel: an analysis of anomalies, memory, and anticipatory learning. *Climatic Change* **103**, 471–502. https://doi.org/10.1007/s10584-009-9776-y.

Ullberg, S. 2017 Forgetting flooding?: post-disaster livelihood and embedded remembrance in suburban Santa Fe, Argentina. *Nature and Culture* **12** (1), 27–45. doi:10.2307/26430632.

UNISDR 2015 *The Human Cost of Weather Related Disasters 1995–2015*.

Van Dijck, J. 2007 *Mediated Memories in the Digital Age*. Stanford UP, Stanford, CA. Print.

Van Loon, A., Gleeson, T., Clark, J., Van Dijk, A. I. J. M., Stahl, K., Hannaford, J., Di Baldassarre, G., Teuling, A. J., Tallaksen, L. M., Uijlenhoet, R., Hannah, D. M., Sheffield, J., Svoboda, M., Verbeiren, B., Wagener, T., Rangecroft, S., Wanders, N. & Van Lanen, H. A. J. 2016 Drought in the Anthropocene. *Nature Geoscience* **9**, 89–91. https://doi.org/10.1038/ngeo2646.

Viglione, A., Di Baldassarre, G., Brandimarte, L., Kuil, L., Carr, G., Salinas, J. L., Scolobig, A. & Blöschl, G. 2014 Insights from sociohydrology modelling on dealing with flood risk – roles of collective memory, risk-taking attitude and trust. *Journal of Hydrology* **518**, 71–82. https://doi.org/10.1016/J.JHYDROL.2014.01.018.

Wertsch, J. V. & Roediger III, H. L. 2008 Collective memory: conceptual foundations and theoretical approaches. *Memory* **16** (3), 318–326. doi: 10.1080/09658210701801434.

Wheater, H. S. 2006 Flood hazard and management: a UK perspective. *Philosophical Transactions of the Royal Society A* **364**, 2135–2145. doi:10.1098/rsta.2006.1817.

White, G. F. 1945 Human adjustments to floods. Research paper no. 29, Department of Geography Research, Chicago University, Chicago, IL, USA.

Yu, D. J., Sangwan, N., Sung, K., Chen, X. & Merwade, V. 2017 Incorporating institutions and collective action into a sociohydrological model of flood resilience. *Water Resources Research* **53**, 1336–1353. https://doi.org/10.1002/2016WR019746.

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