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Insights from socio-hydrology modelling on dealing with flood risk – Roles of collective memory, risk-taking attitude and trust

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SUMMARY

The risk coping culture of a community plays a major role in the development of urban floodplains. In this paper we analyse, in a conceptual way, the interplay of community risk coping culture, flooding damage and economic growth. We particularly focus on three aspects: (i) collective memory, i.e., the capacity of the community to keep risk awareness high; (ii) risk-taking attitude, i.e., the amount of risk the community is collectively willing to be exposed to; and (iii) trust of the community in risk reduction measures. To this end, we use a dynamic model that represents the feedback between the hydrological and social system components. Model results indicate that, on the one hand, by under perceiving the risk of flooding (because of short collective memory and too much trust in flood protection structures) in combination with a high risk-taking attitude, community development is severely limited because of high damages caused by flooding. On the other hand, overestimation of risk (long memory and lack of trust in flood protection structures) leads to lost economic opportunities and recession. There are many scenarios of favourable development resulting from a trade-off between collective memory and trust in risk reduction measures combined with a low to moderate risk-taking attitude. Interestingly, the model gives rise to situations in which the development of the community in the floodplain is path dependent, i.e., the history of flooding may lead to community growth or recession.

1. Introduction

1.1. Floodplains as human–water systems

People have lived close to rivers since the earliest times and this has been for very good reasons. Rivers have been the first transport corridors. The preferences for being close to the river extended into times when waterways were navigated and the economy developed along the rivers. Settlements close to rivers had very clear economic and military advantages. Controlling the rivers meant controlling the most important transport and communication routes. Floodplains along the rivers were also attractive because of the fertility of the land and the easy access to irrigation water. For a collection of all of these reasons, major cultures have developed along rivers such as, for example, those settled in Mesopotamia (Tigris and Euphrates), Egypt (Nile), Pakistan (Indus) and China (Yellow River). Even today, numerous societies live deeply connected to rivers and are dependent on them in many ways, such as in the Netherlands and in Bangladesh.

However, there is a dilemma. While floodplains have always been attractive settlement areas, living in the floodplains involves the risk of river flooding. On the one hand, from an economic perspective and for other benefits, it is advantageous to settle as close as possible to rivers. On the other hand, from the perspective of avoiding flood damage, it is advantageous to settle at a distance from the river that is safe from flooding. These competing objectives lead to a tradeoff situation in making flood coping decisions.

There are a number of ways communities have dealt with flooding. As technology advanced in history, structural measures have become increasingly important, such as building levees for flood protection and river training to increase the capacity of the river channels (Remo et al., 2012). More modern societies have a broader spectrum of flood risk management options, usually conceptualised as the flood risk management cycle consisting of four phases: mitigation, preparedness, response, and recovery (e.g., Thieken et al., 2007; Merz et al., 2010). While flood risk mitigation focuses on alleviating the frequency of floods and their damage, preparedness, response, and recovery aim to reduce vulnerability (Blöschl

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et al., 2013). The vulnerability perspective is broader and involves perception of citizens or communities, such as worry or fear (Slovic, 1987), social values (Slovic et al., 1979; Dake, 1991), and affects (Slovic et al., 2007).

The adoption of one flood risk management option or another has several implications, not only from the technical and economic, but also from the social and political viewpoint. People have shaped the river system in various ways through structural flood protection measures. River training and river straightening, increasing the conveyance of rivers and building levees will, locally, mitigate the flood risk, but further downstream the loss of retention areas may actually increase the flood risk (Di Baldassarre et al., 2009). Also, human activities in and near floodplains may involve land use changes that may affect flooding (Blöschl, 2007). Conversely, the river system and the nature of its floods will shape local society. Positive effects include additional economic and social opportunities (trade, agriculture, jobs) that would not exist further away from the river, but flood damage and the costs of construction and maintenance of flood defense systems will affect the economy. There are therefore feedbacks between riverine societies and fluvial processes (Di Baldassarre et al., 2013a,b). Over centuries, these feedbacks may lead to a co-evolution of people and rivers (Sivapalan et al., 2012).

1.2. Flood risk coping culture

The way people deal with floods, and therefore the feedbacks involved, are ultimately controlled by the risk coping culture of a particular society (Pfister, 2011; Shrubsole, 2001). “Risk culture” (Moore, 1964; Douglas and Wildavsky, 1982; Thompson et al., 1990;Rohr, 2007, among others) is a very broad concept used to better understand how different communities live and cope with risk. Risk coping cultures differ depending on a number of social, economic, political and technical aspects and their reciprocal interactions (Handmer, 2001; Baana and Klijnb, 2004). These cultures can be considered as prototypes of responses to risk, which underline different views about the risk and its management, but also about nature and society. This paper analyses flood risk coping culture, with focus on the community dynamics. Thus, we investigate the community’s behaviour – as a whole – in coping with flood risk and do not address the individual response of citizens, which, indeed, might deviate from the community dynamic or even drive it (see, e.g., the different theoretical frameworks in Slovic et al., 1979; Slovic, 2000; Douglas and Wildavsky, 1982; Beck, 1992; Johnson and Covello, 1987; Jasanoff, 1998; Strydom, 2002). In particular, we focus on three main components that contribute in shaping flood risk culture: collective memory, risk-taking attitude and trust. Although these three factors do not by themselves comprehensively explain the complex process of building up a flood risk culture, we identify them as the leading characteristics of this process.

Occurrence of floods tends to increase peoples’ recognition that their property is in an area that is potentially at risk of flooding (Burningham et al., 2008), both at the scales of individuals and communities (November et al., 2009), which is one of the main reasons why flood coping actions are taken. Floods people have experienced personally may be much more relevant for driving risk coping behaviour than information on historic floods (Tversky and Kahneman, 1973; Pagneux et al., 2011). In particular, the emotional and affective processes involved (including fear and powerlessness) as well as the tangible and intangible losses may be more important than the cognitive assessments of those risks (Loewenstein et al., 2001; Terpstra, 2011). Hazards interact with psychological, social, institutional, and cultural processes in ways that may result into the amplification of the risk perception and of the social response to the risk (Kasperson et al., 1988; Jasanoff, 1998). Frequent events ensure that the perception of risk remains high (Bradford, 2012) and, conversely, long periods without floods will serve to diminish awareness (Burn, 1999). The memory of floods tends to be short, i.e., people tend to forget quickly (Pfister, 2011). The capacity of the community to keep awareness high is referred to as *collective memory*. Collective memory is intended here as the opposite of forgetfulness, i.e., the time scale at which awareness is lost, and is one major aspect that influences how people live and choose to cope with flood risks at the community scale.

Another attitude that is relevant both at the scales of individuals and communities is the *risk-taking attitude*, i.e., the amount of risk a community is collectively willing to expose themselves to. Cameron and Shah (2012) showed how risk preferences have important implications for economic development. For example, these preferences may affect decisions on building constraints which in their own turn influence urban and industrial development, especially in areas characterised by scarce land availability. They also noted that risk aversion is influenced by subjective beliefs of the probability of a disaster to occur (also see Kahneman and Tversky, 1979; Tversky and Kahneman, 1992 for a theoretical discussion of risk-taking/risk-aversion attitudes). Risk preferences at the community level are very crucial for decisions about flood risk mitigation. For example, a community might be aware of the risk but decide to settle close to the river due to a number of different reasons among which the trade-offs between high safety standards and economic growth (Kahn, 2005; de Moel et al., 2011), and, more in general, between public and private benefits (Beatley, 1989; Beatley, 1999; Burby, 1998; Gregory, 2002). The risk-taking behaviour itself is related to a number of cultural factors as well as experience of personal threat to life (Ben-Zur and Zeidner, 2009).

One other aspect of risk coping culture is the *trust* in risk reduction measures, which plays a central role for risk management in present societies (Slovic, 1993). A review of Wachinger et al. (2013) suggests that personal experience of a natural hazard and trust, or lack of trust, in authorities and experts have the most substantial impact on risk perception. A higher level of trust in flood protection measures tends to reduce citizens’ perceptions of flood likelihood, which may hamper their flood preparedness intentions (Terpstra, 2011). Trust also lessens the amount of dread evoked by flood risk, which in turn impedes flood preparedness intentions. For instance, trust in flood protection works is one of the causes of the so called “levee effect” (White, 1945; Burton and Cutter, 2008; Di Baldassarre et al., 2009; Ludy and Kondolf, 2012) and it may increase the feeling of safety, favour a delegation of responsibility to the authorities in charge of building and monitoring the structural devices, and, in this way, encourages the neglect of personal engagement in risk mitigation actions (Scolobig et al., 2012). However, there are also studies that conclude that higher level of trust may lead to more effective preventive actions (Samaddar et al., 2012).

1.3. Research question

Given that collective memory, risk-taking attitude and trust are important controls on how communities deal with flood risk, and therefore are fundamental characteristics of the risk coping culture of communities, it would be of interest to understand their influence on floodplain community development in clearly defined settings. The aim of this paper is to gain insight into the effect of these factors on the evolution of flood risk management measures and the economic development of communities at the time scales of centuries. We analyse a hypothetical setting of a city at a river where a community evolves, making choices between flood management options on the floodplain. The analyses are based on an extension of the socio-hydrology model of Di Baldassarre et al. (2013b) that represents the most important feedbacks between

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the economic, political, technological and hydrological processes of the evolution of that community.

The paper is organised as follows. Section 2 presents the conceptualised socio-hydrology model. Section 3 presents a sensitivity analysis of the economic wealth and damage with respect to the three model parameters that represent collective memory, risk-taking attitude and trust. The results are discussed in Section 4. As a mnemonic device of the three factors we use animals: long collective memory is associated to elephants while short collective memory to cicadas (from the Aesop's fable); risk-taking attitude is associated to lions while risk-avoiding attitude to rabbits; and trust is associated to dogs while lack of trust to cats.

2. Conceptualised socio-hydrology

In order to address the research question, i.e., to gain insight into the effect of collective memory, risk-taking attitude and trust on the evolution of a community in a floodplain, we extend the conceptual model formulated in Di Baldassarre et al. (2013b) regarding two aspects: (i) we include the stochasticity of the hydrology of floods (Section 2.1) and (ii) we reformulate the conceptual model in a non-dimensional way (Section 2.2) to reduce its dimensionality, i.e., to reduce the number of free parameters.

2.1. Hydrological forcing

We model the time series of high water levels above bankfull depth as a marked point stochastic process defined by two random variables: the arrival time between the events and the magnitude of the peak events. We assume that subsequent peaks are independent, that the number of occurrences per unit time is Poisson-distributed, and that the probability density function of the flood peaks is a generalised Pareto (see e.g. Claps and Laio, 2003). We measure time t in non-dimensional form as scaled by the mean time between flooding events. Therefore for every $t > 0$ the number of arrivals in the time interval $[0, t]$ follows a Poisson distribution with mean t and the sequence of inter-arrival times is modelled by an exponential random variable having unit mean:

$$P(T \leqslant t) = 1 - e^{-t} \tag{1}$$

The distribution of the magnitude of the high water levels is modelled in non-dimensional form as a generalised Pareto distribution with minimum equal to 0 and mean equal to 1, i.e., the mean flood water level is considered as characteristic height. The cumulative distribution function is

$$P(W \leqslant w | \Upsilon(t) = 0) = 1 - \left[1 - \frac{\theta_3}{1 + \theta_3} w\right]^{1/\theta_3} \tag{2}$$

where θ_3 is the shape parameter of the distribution (Grimaldi et al., 2011). The distribution is defined for $0 \leqslant w < \infty$ if $\theta_3 < 0$ and for $0 \leqslant w \leqslant 1 + 1/\theta_3$ if $\theta_3 > 0$. In the following analyses, we use $\theta_3 = 0.28$, i.e., the non-dimensional high water levels cannot exceed the value 4.57. Figs. 1a and 2a show two examples of time series of high water levels above bankfull depth $W(t)$ from this stochastic model (for a timespan of length 50, 50 events are expected on average). To give an order of magnitude, the high water levels above bankfull depth can be seen as being given by floods of ~10 years return period, but could vary depending on the morphology of the stream and surrounding floodplain.

2.2. Conceptual model of human–flood interactions

We conceptualise the dynamics of a human–flood system in a floodplain in a simplified way, as in Di Baldassarre et al. (2013b), through four differential equations:

$$\begin{cases} \dfrac{dG}{dt} = \rho_E(1 - D)G - \Delta(\Upsilon(t)) \cdot \left(FG + \gamma_E R\sqrt{G}\right) & \text{Economy} \quad (3a) \\ \dfrac{dD}{dt} = \left(M - \dfrac{D}{\lambda_P}\right) \dfrac{\varphi_P}{\sqrt{G}} & \text{Politics} \quad (3b) \\ \dfrac{dH}{dt} = \Delta(\Upsilon(t))R - \kappa_T H & \text{Technology} \quad (3c) \\ \dfrac{dM}{dt} = \Delta(\Upsilon(t))S - \mu_S M & \text{Society} \quad (3d) \end{cases} \tag{3}$$

where all variables involved are indicated with capital letters (for brevity we omit to indicate that they vary in time t), parameters are indicated with Greek letters and Δ is a nonperiodic Dirac comb that is always 0 except when $\Upsilon(t) = 0$ (i.e., when flooding occurs), in which case it is $+\infty$ with integral equal to 1. The system of equations is analogous to the one proposed in Di Baldassarre et al. (2013b) with the difference that all variables and parameters of the model are non-dimensionalised by (i) a characteristic time – the mean time between flooding events; (ii) a characteristic height – the mean flood water level; and/or (iii) a characteristic length – the distance of the settlement from the river at which there is no economic growth. Tables 1 and 2 summarise the meaning of the variables and parameters in the system and, for consistency, their definition in the original notation of Di Baldassarre et al. (2013b) is also provided.

The variation of the size/wealth of the settlement in time in Eq. (3a) is called here *Economy* equation. $G(t)$ is the size of the settlement at time t scaled by the squared distance of no growth, which correlates to number of people, wellbeing and wealth (e.g., larger settlement = higher wealth). Eq. (3a) states that the speed of changes in settlement size is driven by two main components: (i) the growth rate due to the external economy and the distance of the community to the river and (ii) the shock due to flooding, which is due to the damages and to the cost of raising the protection levels, which we assume to happen, eventually, after flooding events. The parameter ρ_E is the extrinsically driven maximum growth rate at the river scaled by the rate of flooding. Therefore the growth rate is linearly related to the distance D of the community to the river. The distance of the settlement center of mass to the river is scaled by the distance of no growth, i.e., if the community moves beyond the distance $D = 1$ the growth is negative. If a flood happen, i.e., $\Upsilon(t) = 0$, and if it causes flooding, i.e., $F > 0$ (it leads to inundation and consequently damages), the settlement area shrinks because of destruction of proportion F and of costs of raising the dikes of a quantity R. In our conceptualisation, flooding events cause sudden changes in settlement size, which is determined by the Dirac comb function. The parameter γ_E is the cost, in terms of reduction of the settlement's area, for unit height and width of dike raising. In Figs. 1b and 2b there are two examples of evolution of G in time, one showing an overall growth of the settlement and the other an overall shrinkage. The sudden changes of G due to flooding damages are clearly visible in the figures.

The proportion of settlement area damaged during a flood event is defined by the *Hydrology* equation:

$$F = \begin{cases} 1 - \exp\left(-\dfrac{W + \xi_H H_{-}}{\alpha_H D}\right) & \text{if } W + \xi_H H_{-} > H_{-} \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

This is not a differential equation but acts as an event-forcing into the differential equations and is coupled with them because it depends on the state variables H and D (where H_{-} is the height of the levees immediately before the flooding event). F can be 0 (when levees are not overtopped) meaning that not every flood results in flooding. F has a maximum equal to 1, i.e., total destruction of the settlement, that is approached when the flood water level is

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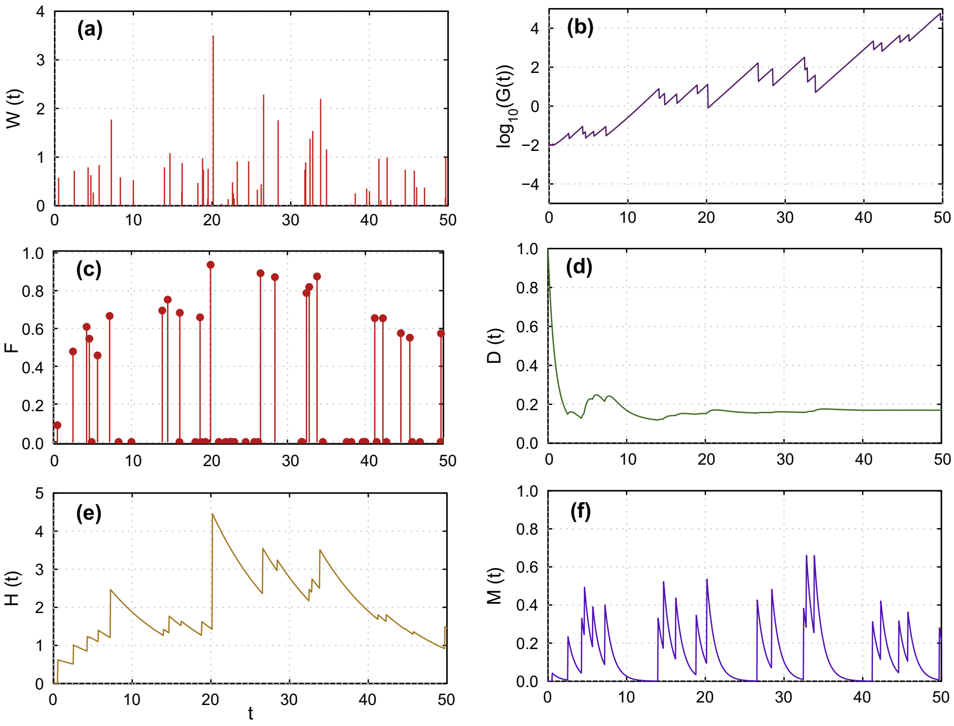

Fig. 1. One possible evolution of the settlement and socio-hydrology of floods: (a) high water levels $W(t)$; (b) size/wealth of the settlement $G(t)$; (c) relative flood damages F; (d) distance of the settlement from the river $D(t)$; (e) flood protection levels $H(t)$; and (f) flood risk awareness $M(t)$.

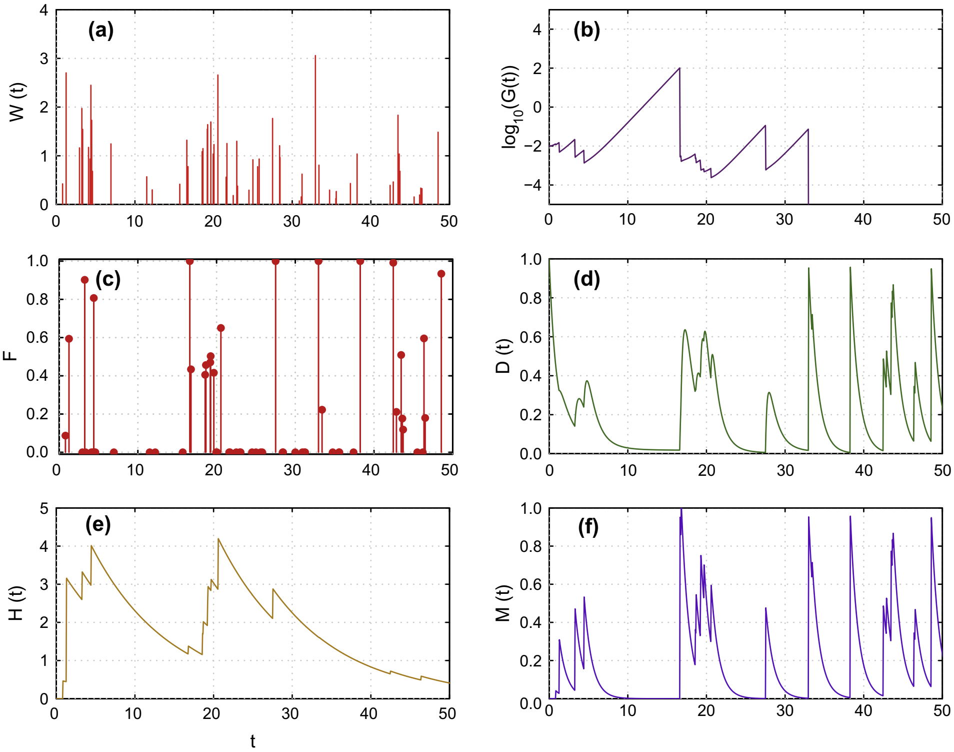

Fig. 2. One possible evolution of the settlement and socio-hydrology of floods (same parameters as in Fig. 1): (a) high water levels $W(t)$; (b) size/wealth of the settlement $G(t)$; (c) relative flood damages F; (d) distance of the settlement from the river $D(t)$; (e) flood protection levels $H(t)$;and (f) flood risk awareness $M(t)$.

extremely high and/or the distance from the river approaches 0. Examples of values of F are shown in Figs. 1c and 2c. The parameter ξ_H represents how much the heightening of dikes translates into heightening of water levels W because of reduced flood attenuation and/or altered flood conveyance associated to the presence of levees (Di Baldassarre et al., 2009; Remo et al., 2012; Heine and Pinter, 2012). The parameter α_H is instead related to the slope of the floodplain, i.e., if α_H is high for a given water level the

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Table 1

Variables of the dynamic system and their initial conditions (IC) in this paper. For consistency, their definition in the original notation of Di Baldassarre et al. (2013b) is also provided (Orig.), where λ_E (L) is the critical distance from the river beyond which the settlement can no longer grow and θ_W (L) is the mean flood water level.

	Description	Eq.	Orig.	Domain	Type	IC
F	Intensity of flooding	(4)	(F)	Hydrology	Event	0
G	Size of the human settlement scaled by the squared distance of no growth as a measure of wealth	(3a)	(G/λ_E^2)	Economy	State	10^{-2}
D	Distance from the river scaled by the distance of no growth	(3b)	(D/λ_E)	Politics	State	1
R	Amount by which the levees are raised after flooding scaled by the mean flood water level	(5)	(R/θ_W)	Technology	Event	0
H	Flood protection level height scaled by the mean flood water level	(3c)	(H/θ_W)	Technology	State	0
S	Shock magnitude	(6)	(S)	Society	Event	0
M	Flood risk awareness	(3d)	(M)	Society	State	0

Table 2

Parameters of the dynamic system and their values in this paper. For consistency, their definition in the original notation of Di Baldassarre et al. (2013b) is also provided (Orig.), where λ_E (L) is the critical distance from the river beyond which the settlement can no longer grow, κ_W (1/T) is the rate of flooding and θ_W (L) is the mean flood water level.

	Description	Eq.	Orig.	Domain	Values
ξ_H	Proportion of additional high water level due to levee heightening	(4)	(ξ_H)	Hydrology	0.5
α_H	Parameter related to the slope of the floodplain and the resilience of the human settlement	(4)	$(\alpha_H \cdot \lambda_E/\theta_W)$	Hydrology	10
ρ_E	Maximum relative growth rate scaled by the rate of flooding	(3a)	(ρ_E/κ_W)	Economy	1
γ_E	Cost for unit height R and width $\sqrt{G}$ of levee raising	(3a)	$(\gamma_E \cdot \theta_W/\lambda_E)$	Economy	$5 \cdot 10^{-3}$, ∞
λ_P	Distance at which people would accept to live when they remember past floods whose total consequences were perceived as a total destruction of the settlement scaled by the distance of no growth	(3b)	(λ_P/λ_E)	Politics	0–5
φ_P	Rate by which new properties can be built	(3b)	$(\varphi_P/(\kappa_W \lambda_E^2))$	Politics	0.1
ε_T	Safety factor for levees rising	(5)	(ε_T)	Technology	1.1
κ_T	Rate of that decay of levees scaled by the rate of flooding	(3c)	(κ_T/κ_W)	Technology	0.1
α_S	Proportion of shock after flooding if levees are risen	(6)	(α_S)	Society	0–1
μ_S	Memory loss rate scaled by the rate of flooding	(3d)	(μ_S/κ_W)	Society	0.01–10

damage reduces a lot with distance, if $\alpha_H = 0$ the damage is the maximum possible whatever the water level and the distance of the settlement from the river are.

The raising of levees/dikes because of flooding of the settlement is modelled as:

$$R = \begin{cases} \varepsilon_T(W + \xi_H H_- - H_-) & \text{if } (F > 0) \\ & \text{and } (FG_- > \gamma_E R\sqrt{G_-}) \\ & \text{and } (G_- - FG_- > \gamma_E R\sqrt{G_-}) \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

We assume that, if flooding has happened, two decisions may be taken: (i) to rise the dikes at a level equal or greater than the water level of the flood just experienced or (ii) not to rise the dikes (and eventually move away). The decision to rise the dikes is triggered by the incentive and the ability of doing it. People (or decision makers) have an incentive to raise the dikes if the damages of the just happened flood (i.e., FG_-) have been greater than the cost of protecting the settlement from such a flood (i.e., $\gamma_E R\sqrt{G_-}$). In any case, they will raise the dikes if they are able to do it: if the costs in terms of urban area (i.e., $\gamma_E R\sqrt{G_-}$) are lower than the wealth left after flooding (i.e., $G_- - FG_-$). The parameter ε_T in Eq. (5) is generally greater or equal to 1 and includes a safety factor, i.e., the level of protection is higher than what would be necessary to avoid the just experienced event (Werner and McNamara, 2007).

The variation of the distance of the settlement from the river in time in Eq. (3b) is called here *Politics* equation. The speed of movement towards and away from the river is driven by the incentive to move in that direction and by the ability to move. The awareness to flood risk M (i.e., the accumulated worry of past floods) pushes the people/decision makers to settle away from the river, i.e., the urban growth happens at distances from the river greater than the center of mass of the settlement, thus increasing D. However societies can tolerate flooding because of the benefits of being close to the river. This is modelled in Eq. (3b) by the term $-D/\lambda_P$ where λ_P is the distance (scaled by the distance of no growth) at which the decision makers assume people would tolerate to live when they remember past floods whose total consequences may be perceived as a total destruction of the settlement (i.e., $M = 1$). Therefore if the center of mass of the village is at $D \geqslant \lambda_P$ and $M \leqslant 1$, people are pushed to settle closer to the river. Notice that λ_P is a parameter related to political behaviour rather than a economic one. Decision makers may select the tolerance level based on economic reasoning but also, and in our opinion this is the case in the real world, on political reasoning (i.e., in order to be re-elected in the future). In this paper we relate λ_P to the attitude of a community to be risk-averse and, consequently, $1/\lambda_P$ is used here as a measure of risk-taking attitude of the community (see Section 2.3).

The last term in Eq. (3b) defines the ability of moving the center of mass of the settlement. We assume that larger urban areas/more wealthy settlements are less capable of moving because resettling large groups of people is more time consuming than resettling small groups. The term $\varphi_P/\sqrt{G}$ could be seen, for a squared settlement, as the speed of its center of mass if a slice with edge $\sqrt{G}$ is removed from, e.g., the side close to the river and resettled to the side far from the river. The parameter φ_P can be therefore seen as a flux parameter and defines the rate by which new properties can be built. Figs. 1d and 2d show the dynamics of D for a growing and a shrinking settlement respectively. The movement of the center of mass of the settlement away from the river happens after flooding has occurred proportionally to the size of the settlement. For instance in Fig. 1d the settlement grows to a size for which no movement of the center of mass is actually visible.

The variation of protection level in time in Eq. (3c) is called here *Technology* equation. The speed of construction of flood protection is driven by the incentive and ability of raising dikes as defined in Eq. (5) above. Here $H(t)$ represents the height of the levees/dikes at time t scaled by the mean flood water level, which can be seen as a measure of the protection level from flooding of the settlement, and when $H(t) = 1$ the settlement is protected from the average flood water level only. Dikes are raised only if a flooding event has just happened and the choice is related to that event and not to the memory of previous events (Werner and McNamara, 2007). If risen, the dikes are brought to a level equal or greater to the water level of the last experienced flood. The second term in

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Eq. (3c) represents the decay of the structural measures with time and the parameter κ_T is the rate of decay scaled by the rate of flooding, which depends on the technology used and may embed maintenance costs. If $\kappa_T = 1$, on average, when the flood arrives the levee has decayed to 37% of the initial value. In this paper we have set $\kappa_T = 0.1$ for all simulations, meaning that, on average, when the flood arrives the levee has decayed to 90% of the initial value. Figs. 1e and 2e show the temporal evolution of protection measures in two cases. In particular, in the case of Fig. 2e at a certain point in time levees are no more raised because the community cannot afford it any more (the value of G is too small, see Fig. 2b).

The change in awareness is defined in Eq. (3d) and is called here the *Society* equation. This is very similar to Eq. (3c) and describes the balance between the psychological shocks S experienced by people during events and their forgetfulness, where the parameter μ_S is the memory loss rate scaled by the rate of flooding. If $\mu_S = 1$, on average, when the flood arrives the people remember 37% of what they remembered at the previous flood while if $\mu_S = 0.1$ they still remember 90% of it. In this paper we consider $1/\mu_S$ as a measure of collective memory of the community (see Section 2.3), intended as ability to keep the awareness to flood risk even when time has passed from the last experienced flooding event. The awareness to flood risk M is a measure of perceived number of flood events experienced and still remembered. The accumulated awareness is schematised as a linear reservoir, i.e., greater inflows lead to greater outflows. The accumulation of awareness occurs instantly following flood events as shocks. Figs. 1f and 2f show the evolution in time of the awareness to flood risk of the community in two cases. The shocks magnitude is defined as:

$$S = \begin{cases} \alpha_S F & \text{if } (R > 0) \\ F & \text{otherwise} \end{cases} \tag{6}$$

which goes from 0 to 1 similarly to the proportion of damages F produced by the flood event. If no additional protection measures are built after the event (i.e., $R = 0$), the shock is equal to F. If protection measures are built, i.e., dikes are raised of a level R, the shock may be less than F and the amount of (false) sense of protection corresponds to $1 - \alpha_S$ in our model, which we use as measure of trust the community has that the new protection measures will prevent future flooding (see Section 2.3). If the parameter α_S is 0, we assume that the people perceive the building of additional protection levels as a total remedy, they feel safe from future events like the one that just occurred. Normally $\alpha_S > 0$, meaning that the remedy is not enough to cancel the shock due to the recent flood. In the limiting case $\alpha_S = 1$, which means the society keep its awareness at the maximum level notwithstanding the construction of additional protection levels.

2.3. Sensitivity analysis

Three parameters of the model in Eqs. (1)–(6) are related in this paper to the risk coping culture of the community: (i) the collective memory of the community is quantified by $1/\mu_S$; (ii) the risk-taking attitude by $1/\lambda_P$; and (iii) the trust by $1 - \alpha_S$. Note that other parameters could be related to the culture of safety too, such as for example the safety factor ε_T, but their range of variability and therefore influence is much lower than the aforementioned three. Therefore we analyse in Section 3 the combined effect of the three parameters allowing them to vary between the following limits:

μ_S from 0.01 to 4.6, i.e., on average, when the flood arrives the people remember 99% ($\mu_S = 0.01$) or 1% ($\mu_S = 4.6$) of what they remembered at the previous flood;

λ_P from 0.33 to 3, i.e., the community is willing to settle at one third or three times the distance of no economic growth if what people remember corresponds to one event of total destruction of the settlement (i.e., if $M = 1$);

α_S from 0 to 1, i.e., from perceived total remediation to no remediation at all by levees building after a flooding event has occurred.

Fig. 3 illustrates the 3D space of risk coping culture we investigate. Each face of the cube corresponds to high/low values of collective memory, risk-taking attitude and trust and is represented, for mnemonic purposes, by animals. Long and short collective memories are associated to elephant (e.g., $\mu_S = 0.01$ or $1/\mu_S = 100$) and cicada (e.g., $\mu_S = 4.6$ or $1/\mu_S = 0.217$). Risk-taking and risk-avoiding attitudes are associated to lion (e.g., $\lambda_P = 0.33$ or $1/\lambda_P = 3$) and rabbit (e.g., $\lambda_P = 3$ or $1/\lambda_P = 0.33$). Trust and lack of trust are associated to dog (e.g., $\alpha_S = 0$ or $1 - \alpha_S = 1$) and cat (e.g., $\alpha_S = 1$ or $1 - \alpha_S = 0$).

3. Results

For each scenario, i.e., triplet of parameters μ_S, λ_P and α_S, 1000 time series of high water levels $W(t)$ are generated from the stochastic model of Eqs. (1) and (2) for the time span $t \in [0, 200]$ and are used as input to the dynamic model. The results are shown for particular slices of Fig. 3 in Sections 3.1, 3.2 and 3.3, and for the entire risk coping culture space in Section 3.4.

3.1. Green society: collective memory and risk-taking attitude

Consider first a simplified version of the model representing a green society that never build levees, for which $\gamma_E = \infty$ and the technology Eq. (3c) disappears from the system. In this particular case trust ($1 - \alpha_S$) does not play any role, because no protection measures are built, therefore the sensitivity of the model is assessed against collective memory ($1/\mu_S$) and risk-taking attitude ($1/\lambda_P$).

Fig. 4 shows the evolution in time of the size/wealth $G(t)$ of the settlement where collective memory increases from right to left and risk-taking attitude increases from top to bottom. Every small rectangle in Fig. 4 contains the trajectories of the 1000 simulations for each scenario. Clearly there are two extremes which cause the quick shrinkage of the settlement: (i) when the community does

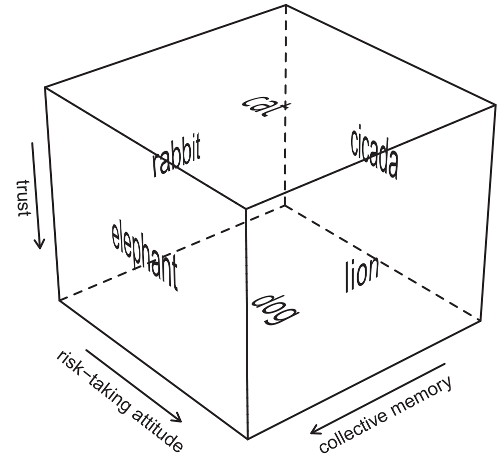

Fig. 3. Risk coping culture space. Animals are used for mnemonic purposes: elephant = long collective memory; cicada = short collective memory; lion = risk-taking attitude; rabbit = risk-avoiding attitude; dog = trust; and cat = lack of trust. The cube is sliced and filled with the results of the sensitivity analysis of Section 3.

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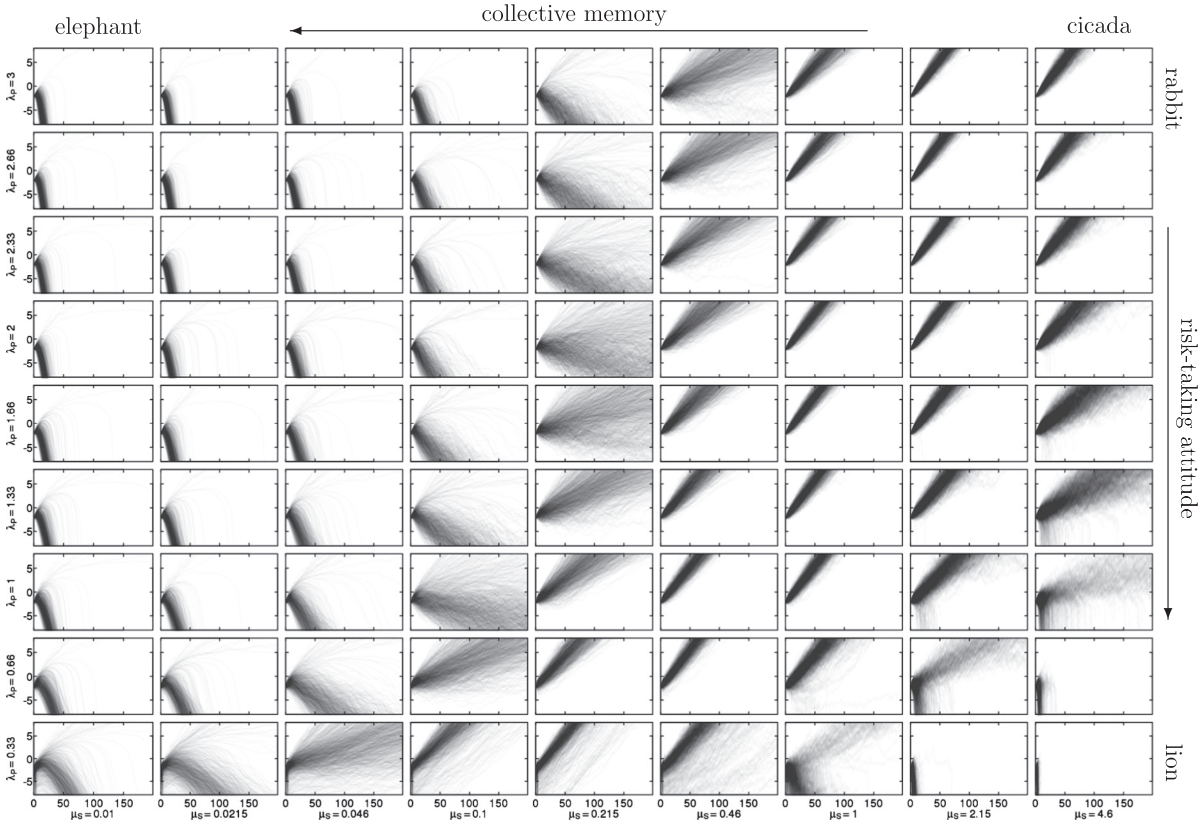

Fig. 4. Evolution of the size/wealth G of the settlement in time t for 1000 simulations for each scenario with $\gamma_E=\infty$, i.e., green society. Different combinations of μ_S and λ_P are considered (their values are printed on the axes) in order to assess the sensitivity of the system to collective memory and risk-taking attitude of the community.

not forget (elephant) and is willing to move far away (rabbit) because does not feel safe near the river and (ii) when the community forgets very quickly (cicada) and is too risk taking feeling safe close to the river (lion). In these upper-left and bottom-right regions of Fig. 4 all simulations show $G(t)$ pointing down and very quickly vanishing. There is instead an optimal central region in Fig. 4 where all the simulations consistently give an increase of G with time (wealth-growth), which corresponds to intermediate values of collective memory and risk-taking attitude. More specifically, the optimal growth occurs if the community is quite brave but remembers (lion–elephant) or quite forgetful but risk-avoiding (cicada–rabbit). Interestingly, there are transition scenarios where some of the simulations result in growing G and others in decreasing G. These communities are particularly sensitive to the sequence of flooding events (to their stochasticity, since the statistics of flooding is always the same).

3.2. Techno society: collective memory and risk-taking attitude

We consider as techno society the case in which the community also builds levees. We model it by setting $\gamma_E=0.005$, i.e., building levees is very cheap and the community will do it from the beginning of its development, which corresponds to use the entire system of differential equations, including the technology Eq. (3c). In this section the sensitivity of the model is assessed against collective memory and risk-taking attitude. The value of α_S is kept always equal to 0.5, i.e., only half of the shock due to flooding is retained by the community if new protection measures are built. This corresponds to investigate one horizontal slice in the middle of the cube in Fig. 3.

Fig. 5 is analogous to Fig. 4 and shows the evolution in time of the size/wealth $G(t)$ of the settlement for μ_S from 0.01 to 4.6 (left to right) and for λ_P from 0.01 to 2.66 (from bottom to top). Also in the techno society there are two extremes which cause the quick shrinkage of the settlement and they are analogous to those in Fig. 4: (i) when the community does not forget (elephant) and is willing to move far away (rabbit) because does not feel safe near the river and (ii) when the community forgets very quickly (cicada) and is too risk-taking feeling safe close to the river (lion). Compared to the green society, the optimal central region where all the simulations consistently give an increase of G with time is placed more on the left of the graph, i.e., in the techno society the required collective memory is higher than in the green society. Also, the evolution trajectories are more interesting here (because of having one equation more in the dynamic system and therefore more feedbacks and complexity). There are cases where the stochasticity of flooding can lead to two alternative evolution (continuous growth or shrinkage) but not situations in between. One example is the case with $\mu_S=1$ and $\lambda_P=1$. Figs. 1 and 2 belong to this scenario. The sequence of flooding events in Fig. 1c is more evenly distributed in time than the one in Fig. 2c, where long periods without damages when the settlement is still small (Fig. 2b) result in very low awareness (Fig. 2b) and settling too close to the river (Fig. 2d). The sequence of flooding determines a path dependent development of the community. In other cases, situation of no-growth nor shrinkage are allowed or even are the only ones (see the case with $\mu_S=0.46$ and $\lambda_P=0.33$).

Fig. 6 is analogous to Fig. 5 but shows the damages $F(t)$ in time. When the community does not forget (elephant) and/or is willing to move far away (rabbit) the damages are low (F always much lower than 1), while when the community forgets very quickly (cicada) and/or is too risk taking feeling safe close to the river (lion) the damages are high (F approaches 1). Fig. 6 is useful to interpret the evolution of $G(t)$ in Fig. 5. The cause of the collapse of

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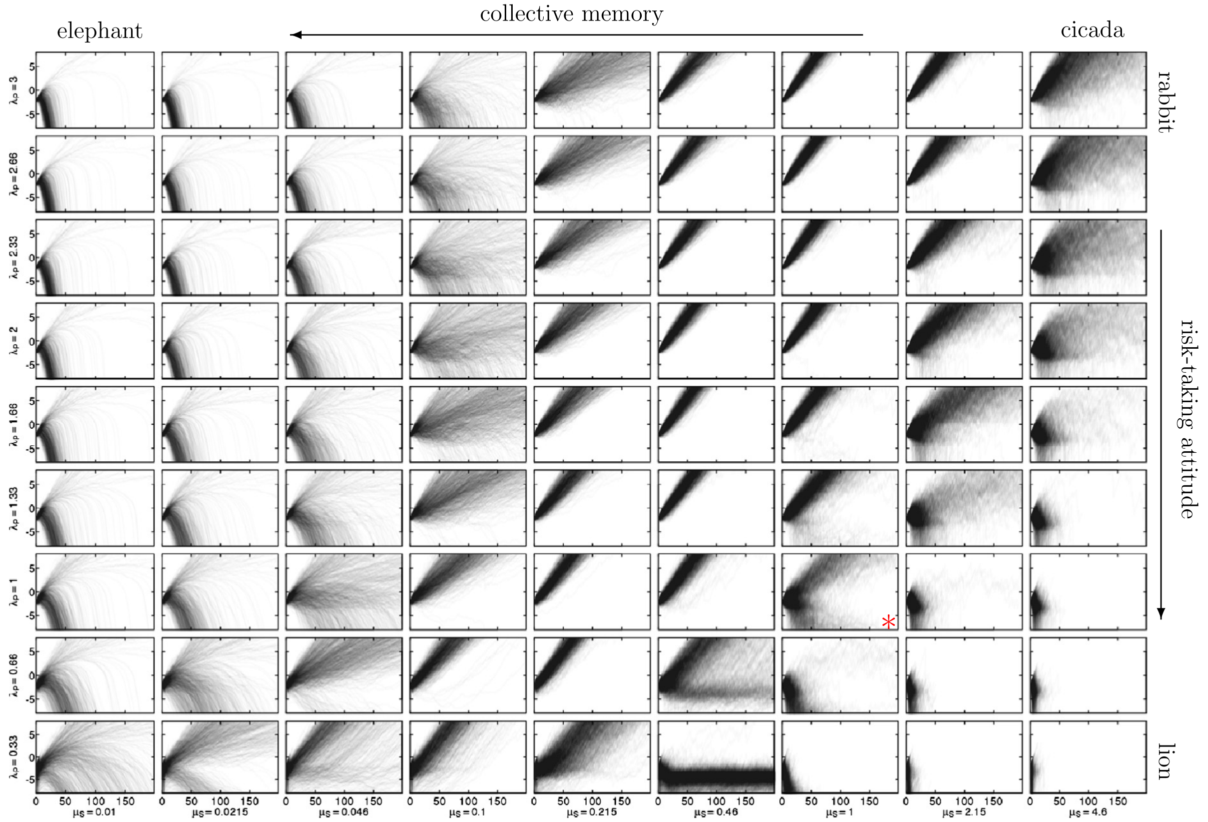

Fig. 5. Evolution of the size/wealth G of the settlement in time t for 1000 simulations for each scenario with $\gamma_E = 0.005$, i.e., techno society. Different combinations of μ_S and λ_P are considered (their values are printed on the axes) in order to assess the sensitivity of the system to collective memory and risk-taking attitude of the community. The value of α_S is 0.5 for all simulations. The cases in Figs. 1 and 2 belong to the panel marked with an asterisk.

settlements in the upper-left region of the two figures is economic: because of their fear, the communities tend to settle too far away from the river (at a distance $D > 1$) which results in economic recession. In the bottom-right region, instead, the cause of the collapse of settlements is flooding: the communities are risk-taking and at the same time forgetful, thus essentially committing suicide.

3.3. Techno society: collective memory and trust

In the techno society, also trust in the protection measures plays a role. Fig. 7 illustrates the sensitivity of the model to the remediation parameter α_S for different values of μ_S and with $\lambda_P = 1$ (the distance perceived as safe is the no-growth distance). Different degrees of collective memory and trust are considered. Also in Fig. 7 (like in Figs. 4 and 5) the upper-left and bottom-right regions are critical, i.e., all simulations show $G(t)$ pointing down and very quickly vanishing. These are two extremes: (i) when the community does not forget (elephant) and has no trust in the remedy provided by building new protection measures (cat) and (ii) when the community forgets very quickly (cicada) and has too much trust in the remedy provided by building new levees (dog). The cause of the collapse of settlements in the upper-left region of the two figures is economic: because of their skepticism, the communities tend to build up their risk awareness at every flooding event and to settle too far away from the river (at a distance $D > 1$) which results in economic recession. In the bottom-right region, instead, the cause of the collapse of settlements is flooding: the communities are forgetful and trust too much the remedy provided by additional protection measures, thus essentially committing suicide. There is instead an optimal central region in Fig. 7 where all the simulations consistently give an increase of G with time (wealth-growth), which corresponds to intermediate values of collective memory and trust. More specifically, the optimal growth occurs if the community remembers and trusts the remedies (dog–elephant) or forgetful but skeptical (cat–cicada). Interestingly, there are transition scenarios where bifurcations can happen, even though the hydrological forcing is statistically the same. These communities are particularly sensitive to the sequence of flooding events, such as those in Figs. 1 and 2.

3.4. Techno society: collective memory, risk-taking attitude and trust

Figs. 4–7 represent slices of the 3D space of Fig. 3. In order to grasp the three-variate effect of collective memory, risk-taking attitude and trust on the development of settlements in a floodplain, additional simulations have been done and the results are summarised in Fig. 8. Considering the values of μ_S, λ_P and α_S in a range slightly larger than in the previous sections, a total of 4500 scenarios have been simulated by sampling the parameters uniformly over these ranges. This correspond to fill the 3D space of Fig. 3 uniformly with points. In Fig. 8 we have plotted only the scenarios for which the settlement still existed at time $t = 200$ and the size of the points is proportional to the slope of the line connecting the value of $\log_{10}(G(t))$ at the beginning and at the end of the simulation, i.e., big points correspond to high overall growth of the settlement while small points to small growth or even shrinkage of the settlement. Fig. 8 shows a 3D perspective and three side views of the space occupied by these points. Small collective memory and high risk-taking attitude result in the collapse of the settlement no matter the level of trust. This can be attributed to the community perceiving the risk of flooding to be very low (due to their very limited capacity to retain their awareness of past floods that informs

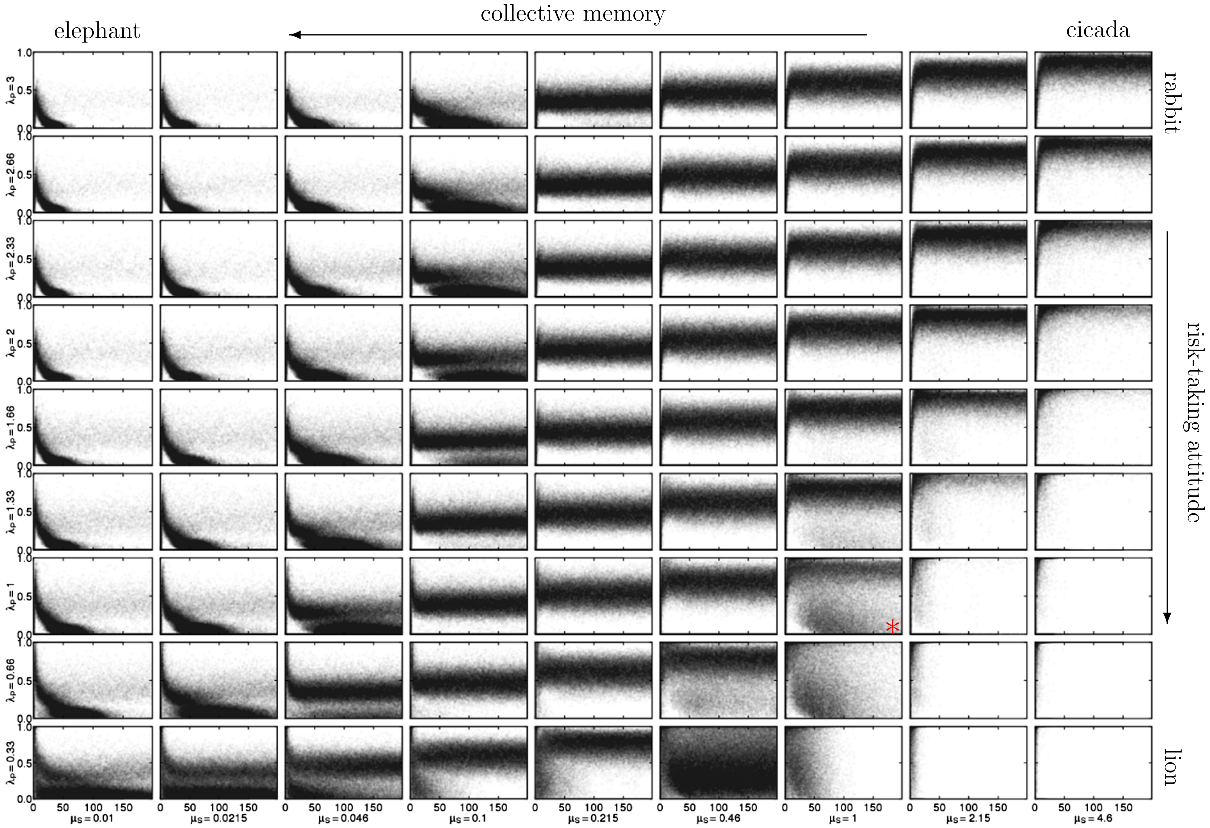

Fig. 6. Temporal sequence of the flooding damages F for 1000 simulations for each scenario with $\gamma_E = 0.005$, i.e., techno society. Different combinations of μ_S and λ_P are considered (their values are printed on the axes) in order to assess the sensitivity of the system to collective memory and risk-taking attitude of the community. The value of α_S is 0.5 for all simulations. The cases in Figs. 1 and 2 belong to the panel marked with an asterisk.

their understanding of future flood risk, coupled with a willingness to gain benefits from living close to the river, with no care for the hazard this presents to their community). Situations with high collective memory and low risk-taking attitude may result in overall growth of the community if the level of trust is high. In this situation, the communities perceive the risk of flooding to be higher than it really is and are unwilling to take risks, but their high trust in the flood protection engineering allows them to move themselves close to the river. In contrast, high collective memory and a low level of trust in the flood protection structures result in the collapse of the settlement no matter what the risk-taking attitude. In this situation, the perceived risk is considered to be so high that even if the communities are not aware of how probable is a future flood they cannot be persuaded to move close to the river. Situations with low collective memory and high levels of trust may result in the overall growth of the community if the risk-taking attitude is low. In such a scenario, the communities perceive the risk of flooding to be lower than it actually is, but nonetheless they remain cautious of what the river might do in the future and choose to stay further away from it.

4. Discussion and conclusions

The socio-hydrology model proposed by Di Baldassarre et al. (2013b) has been used to get some insights on the three identified key features of the risk coping culture of a community: collective memory, risk-taking attitude and trust in protection works. Different hypotheses related to these features have been developed in order to build the model presented in this paper. The awareness that flooding occurred in the past drives the community's belief that flooding will occur again in the future. The belief that flooding will happen in the future is shaped by (i) the actual occurrence of flooding in the past, combined with (ii) social processes of communicating and retaining knowledge of that flooding (which results in the collective memory, i.e., the capacity of the community to keep risk awareness high). The combination of these two aspects contributes to whether the community perceives the actual risk to be higher or lower than it really is. The assumption we are making is that if people remember, they take action because they believe in the possibility that flooding will happen again if no action is taken. This is consistent with, for example, Loewenstein et al. (2001), Pagneux et al. (2011) and Cameron and Shah (2012), who suggest that emotional reactions and memory of past events, rather than cognitive assessments of risks, often drive behaviour. This is opposed to the assumption that if a major flood happened, people believe that an event of the same magnitude will not happen again in the nearest future (Marchi et al., 2007).

The risk-taking attitude accounts for the preference of a community to settle more or less close to a river, depending on a number of contextual factors among which are the trade-offs between high safety standards and economic growth (Kahn, 2005; de Moel et al., 2011). The risk-taking attitude controls the balance between risk perception and action (Kahneman and Tversky, 1979; Tversky and Kahneman, 1992). For example, a community might perceive a high risk (believe a flood will occur), but be willing to take a chance that flooding will not happen in the time frame they are concerned with. Therefore, they disregard the consequences of flooding and settle close to the river (see e.g., Willis et al., 2011). The degree of trust of a community that the protection measures (dykes/levees) will prevent flooding from occurring is analysed by assuming that people feel that flooding is less likely (perceive lower risk) when protection measures are built (Ludy and Kondolf, 2012).

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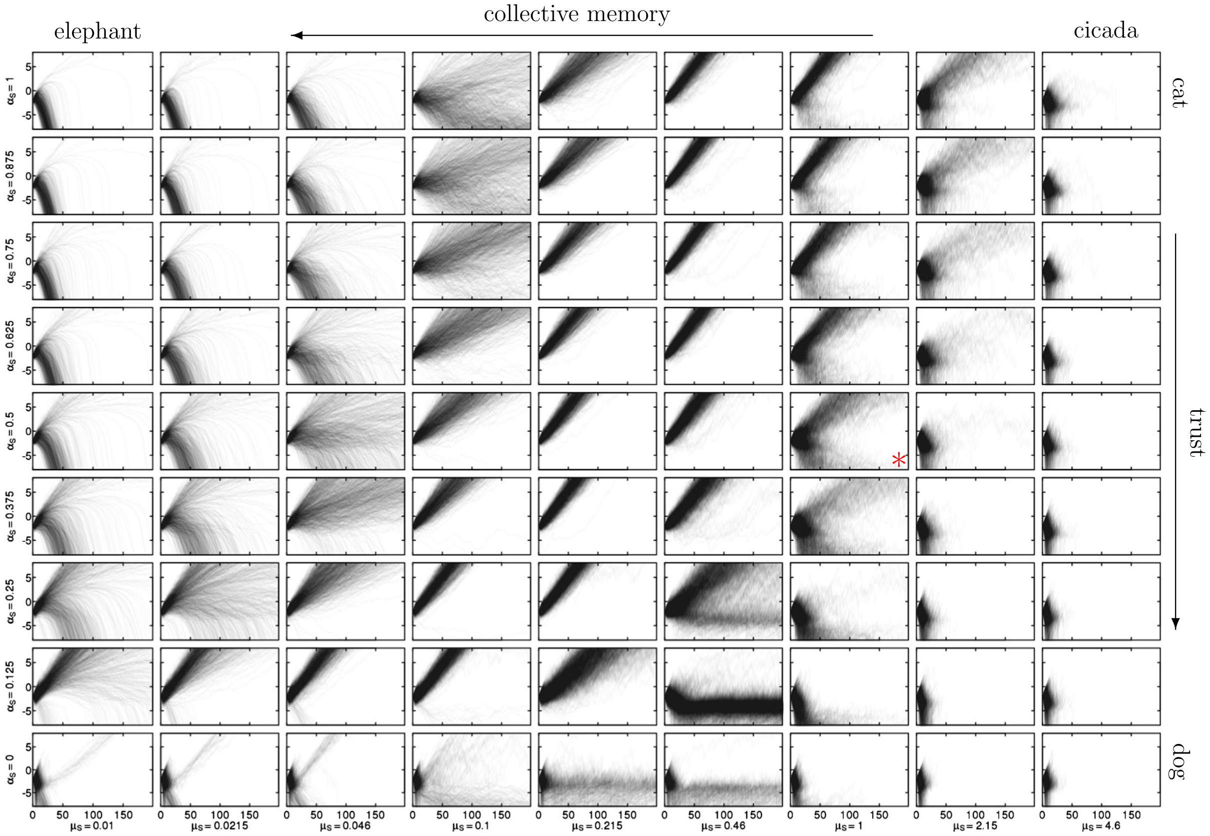

Fig. 7. Evolution of the size/wealth G of the settlement in time t for 1000 simulations for each scenario with $\gamma_E = 0.005$, i.e., techno society. Different combinations of μ_S and α_S are considered (their values are printed on the axes) in order to assess the sensitivity of the system to collective memory and trust. The value of λ_P is 1 for all simulations. The cases in Figs. 1 and 2 belong to the panel marked with an asterisk.

The belief that flooding will happen in the future is shaped by society itself (engineers, politicians, etc. who communicate the reliability of the structures to the community). The degree of trust in the protection structures leads the community to either perceive the actual risk to be higher than it really is (low level of trust), or perceive the actual risk to be lower than it really is (high level of trust).

The simulations conducted in this paper show that there are good and bad combinations of the three factors under study – collective memory, risk-taking attitude and trust – related to the risk coping culture with respect to floods. On one hand, by under perceiving the risk of flooding (because of short collective memory and too much trust in flood protection structures) in combination with a high risk-taking attitude, community development is severely limited because of destruction caused by flooding. On the other hand, high perceived risk (long memory and lack of trust in flood protection structures) relative to the actual risk leads to lost economic opportunities and recession. There are many optimal scenarios for economic growth, but greater certainty of economic growth can be achieved by ensuring the community has accurate risk perception (memory neither too long nor too short and trust in flood protection neither too great nor too low) combined with a low to moderate risk-taking attitude. Our model suggests that memory of past floods and trust in flood protection structures can work either together to mutually reinforce a perception of high or low flood risk, or against each other to balance the community's perception of the risk. In the real world, this suggests that high trust in structural protection measures (which is one of the causes of the levee effect) will only be detrimental for a community's development if coupled with short memory and a high risk-taking attitude.

Interestingly, the model gives rise to situations in which the development of the community in the floodplain is path dependent, i.e., decisions that community makes following flooding events are limited by the decisions they have made as a response to past flood events (Pierson, 2000; Garrelts and Lange, 2011). Model results suggest that, in some circumstances, the sequence of flooding controls the development of the community, e.g., its growth or recession. This path dependency has implications from two perspectives. (1) From the perspective of an individual event, path dependency implies that the past event interarrival times and ordering affect the impact of that flooding event. Beven (1981) illustrated this concept for the case of erosion and transportation events, where the impact is termed 'geomorphic effectiveness'. In that case, the path dependency was related to the variability of river bank cumulative erosion given variable timing of intense storms. The results of the present paper suggest that the concept is more generally applicable to flood impacts. In the socio-hydrological context, the path dependency is related to the interplay between the economic evolution of the community and the timing of the flooding. (2) From the perspective of the ensemble of floods, path dependency implies that their exceedence probabilities (their marginal distributions) are not uniquely related to their potential impact, even if the vulnerability conforms to the same dynamics. This is important for flood design and flood risk management as it challenges the traditional paradigm of using the exceedence probabilities of floods (their marginal distributions) without considering time sequence. For a more complete understanding of potential flood impacts over long time periods, it may be necessary to develop indicators that account for the path dependency.

Future work is also needed to look at risk coping culture in a nonstationary way. In this work collective memory, risk-taking attitude and trust are considered to be stationary over time. However they undoubtedly shift through time, i.e., culture evolves. It

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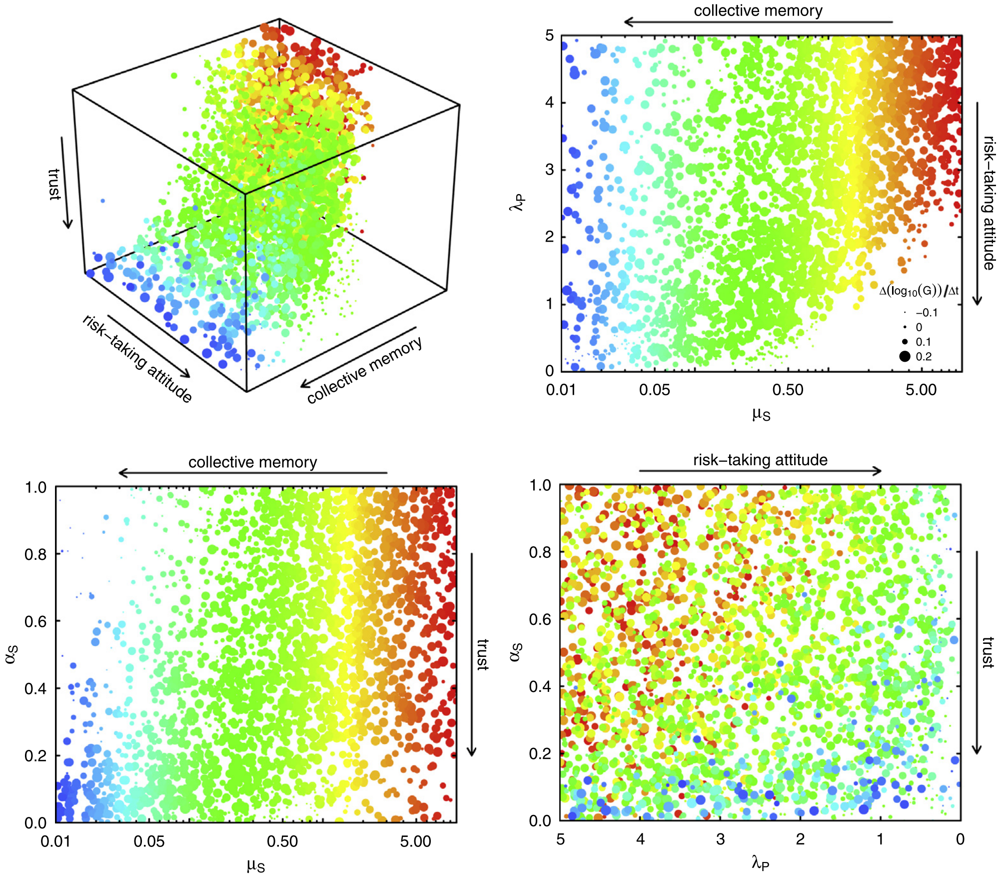

Fig. 8. Overall settlement growth in the risk coping culture space of Fig. 3. From a total of 4500 scenarios uniformly distributed in the cube, only the scenarios for which the settlement still existed at time $t = 200$ are plotted as points and the size of the points is proportional to the slope of the line connecting the value of $\log_{10}(G(t))$ at the beginning and at the end of the simulation. The colour scale, with colours going from red for short collective memory to blue for long collective memory, has been chosen in order to facilitate the 3D visualisation, i.e., the red points are behind, the blue ones are in front. Along with the 3D space, also three views of the cube from above, from the right and from the left are respectively shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

would be of interest to use an analogous conceptual framework to investigate how communities adjust (or may adjust) toward developing a suitable culture for their environment.

Also, this paper has considered the community as one entity. Further work could focus on which role different agents inside the community (e.g., institutions and public) have in the process of decision making (including flood risk management as well as other decisions about the economic evolution of the community) (Johnson and Covello, 1987; Slovic, 2000; Strydom, 2002) and could be based on a similar mathematical framework. It is worth mentioning that such frameworks (as the one in this paper) are not intended to be predictive tools or descriptive models of reality, but rather conceptualisations of interacting factors that drive community response to flooding. One of their strengths is their capacity to analyse different parts of the system and explore feedbacks. Additionally, they create a basis for discussion among researchers from different disciplines such as natural and social sciences, which is one of the goals of socio-hydrology (Sivapalan et al., 2012; Montanari et al., 2013).

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