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Key Points:
- A novel approach to explore flood risk changes is developed
- The approach explains the dynamics emerging from human-flood interactions
- Green societies tend to be less affected by increasing flood frequency

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Debates—Perspectives on socio-hydrology: Capturing feedbacks between physical and social processes

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Abstract In flood risk assessment, there remains a lack of analytical frameworks capturing the dynamics emerging from two-way feedbacks between physical and social processes, such as adaptation and levee effect. The former, "adaptation effect", relates to the observation that the occurrence of more frequent flooding is often associated with decreasing vulnerability. The latter, "levee effect", relates to the observation that the non-occurrence of frequent flooding (possibly caused by flood protection structures, e.g. levees) is often associated to increasing vulnerability. As current analytical frameworks do not capture these dynamics, projections of future flood risk are not realistic. In this paper, we develop a new approach whereby the mutual interactions and continuous feedbacks between floods and societies are explicitly accounted for. Moreover, we show an application of this approach by using a socio-hydrological model to simulate the behavior of two main prototypes of societies: green societies, which cope with flooding by resettling out of flood-prone areas; and technological societies, which deal with flooding also by building levees or dikes. This application shows that the proposed approach is able to capture and explain the aforementioned dynamics (i.e. adaptation and levee effect) and therefore contribute to a better understanding of changes in flood risk, within an iterative process of theory development and empirical research.

1. Introduction

The impact of floods has dramatically increased in many regions of the world over the past decades [*Aerts et al.*, 2014; *Dankers et al.*, 2014; *Di Baldassarre et al.*, 2010]. This trend looks set to worsen in the near future, as rapid urbanization continues to swell the size of the population living on floodplains above the current size of one billion, while flood levels might increase due to climate change and sea level rise [*Hinkel et al.*, 2014; *Jongman et al.*, 2014].

While much progress has been made in making quantitative assessments of flood risk, there remains a lack of fundamental understanding of the interplay between physical and social processes. As a result, the current analytical frameworks cannot capture (or explain) the dynamics emerging from this interplay.

A first type of dynamics, termed here the "adaptation effect," relates to the observation that the occurrence of more frequent flooding is often associated with decreasing societal vulnerability. There is empirical evidence (Figure 1) that the impacts of a flood event are lower when that event occurs shortly after a similar flood. For instance, the damages of the 1995 flood at the Meuse River were much lower than those in 1993, even though their magnitudes were similar [*Wind et al.*, 1999]. More examples of the adaptation effect have been described by the literature [*Penning-Rowsell*, 1996; *IPCC*, 2012; *Mechler and Bouwer*, 2014] and are summarized in Figure 1. This effect can be mainly attributed to the enhanced coping and adaptation capacities gained by the community during their earlier experience of flooding. Besides informal dynamics, flood risk management policy also responds to flood events [*Johnson et al.*, 2005; *Pahl-Wostl et al.*, 2013; *Penning-Rowsell et al.*, 2006]. Early warning systems, community engagement programs to raise awareness to flood risk, and changes to land use planning are examples of adaptation measures that often occur at the local or central government level following a flood event.

A second type of dynamics, the so-called "levee effect" [*Montz and Tobin*, 2008], relates to the observation that the nonoccurrence of frequent flooding (possibly caused by flood protection structures, e.g., levees) is

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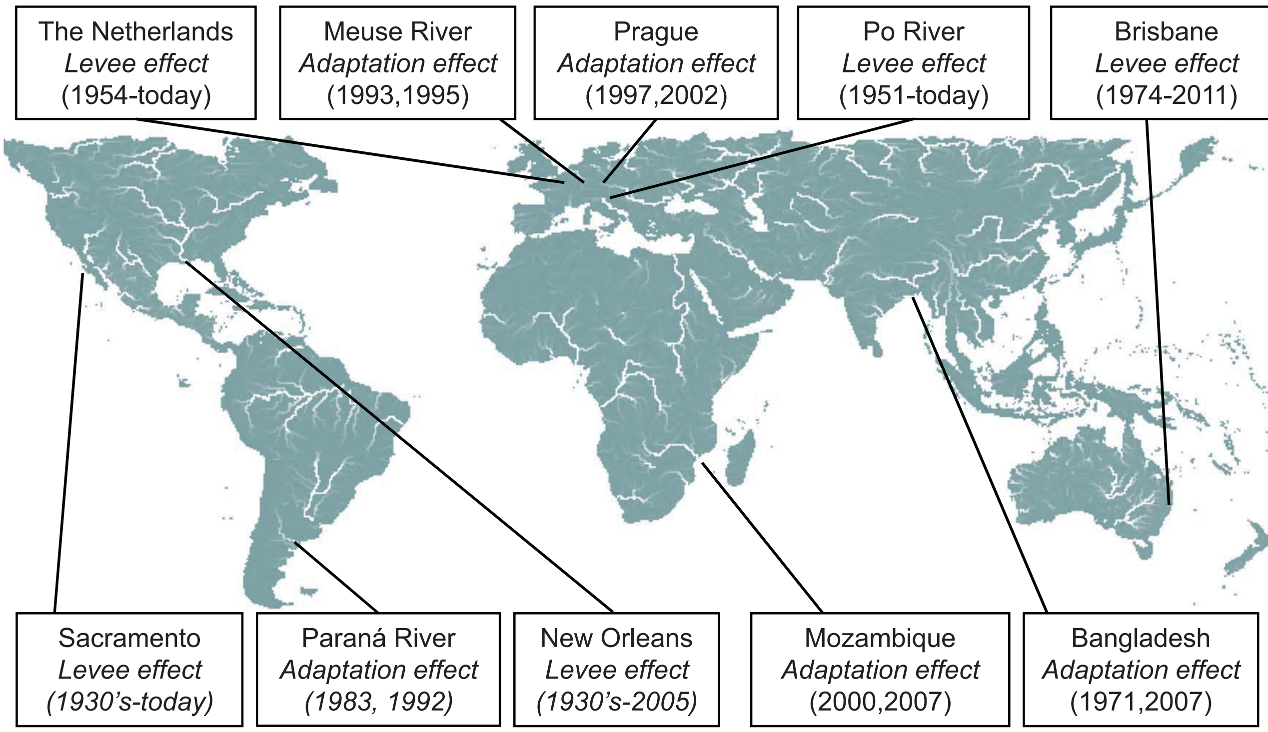

Figure 1. Adaptation and levee effects. Examples of generic dynamics observed in diverse floodplains and deltas around the world. For adaptation effects, the boxes indicate the years of two similar flood events, whereby the second led to a significantly lower reported damage. For levee effects, the boxes indicate the period in which levees have been significantly raised while the exposure and vulnerability of the "protected" society have remarkably increased.

often associated with increasing vulnerability to flooding. There is empirical evidence that flood control structures tend to promote an increase in the vulnerability (including exposure) of societies and, paradoxically, this often results in increasing flood risk [*Burton and Cutter*, 2008; *Ludy and Kondolf*, 2012]. An example is the case of New Orleans, where the process of building and raising levees has led to a shift from frequent, small flooding to rare, but catastrophic disasters [*Kates et al*., 2006]. More examples of levee effect have been described by the literature [*Kates et al*., 2006; *de Moel et al*., 2011; *Ludy and Kondolf*, 2012; *IPCC* 2012; *Bohensky and Leitch*, 2014; *Di Baldassarre et al*., 2013a] and are summarized in Figure 1.

These two types of dynamics emerging from the interplay between physical and social processes have been widely observed (Figure 1) in numerous floodplains and deltas around the world. Yet, current methods cannot capture (or explain) these dynamics. As a result, current projections of future flood risk are unrealistic.

Changes in flood risk are typically assessed by comparing scenarios of climate change and socioeconomic development [*Apel et al*., 2008; *Winsemius et al*., 2013]. For each scenario, flood risk is estimated as a combination of the probability of flooding (i.e., hazard) and the potential flood damages to society (i.e., exposure, vulnerability or resilience). Flood policies, such as the implementation of flood protection measures (e.g., levees), are treated as an external forcing to the physical system; while the damages triggered by the physical system are treated as an external forcing to the human system (Figure 2, top). This traditional approach does not account for the interplay between physical and human systems. Hence, it cannot capture the above dynamics, i.e., adaptation and levee effects. For instance, conventional methods would consistently suggest that flood-rich periods would lead to more flood damages. However, the aforementioned adaptation effect shows that this is not necessarily the case. Similarly, current methods would consistently suggest that the implementation of flood protection measures would lead to less flood damages, but the levee effect shows that this is not always the case.

To better understand how floods have changed in the past, and anticipate future changes of flood risk, we propose here a novel approach that explicitly considers the coupled dynamics of floods and societies. This paper also shows an application of this novel approach to highlight its potentials as well as its limitations.

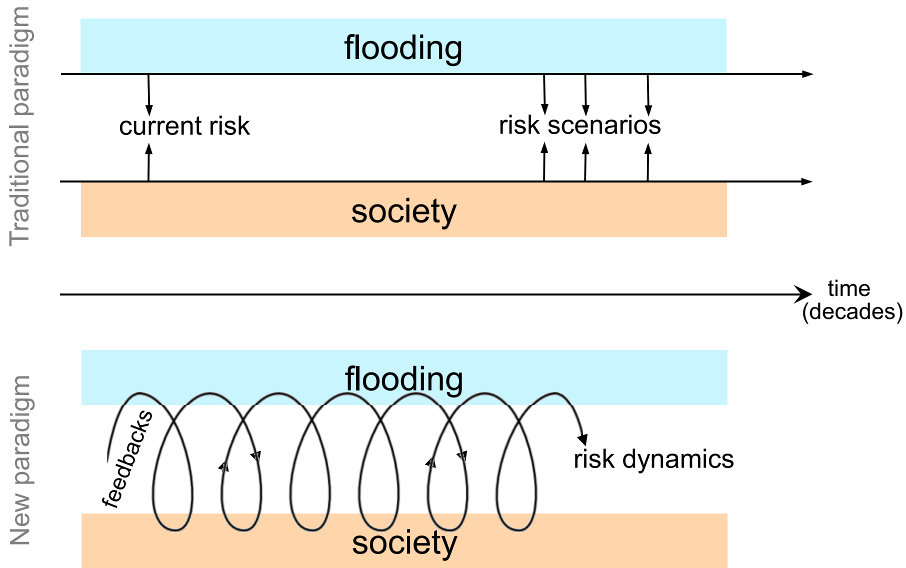

Figure 2. Changes in flood risk. Current approaches are based on scenarios: for each time slice, flood risk is estimated as a combination of the probability of flooding and the potential damages to society; (top) adaptation and levee effects cannot be captured. (bottom) We propose a novel approach that captures the coupled dynamics of floods and societies and the long-term behavior emerging from the mutual interactions and feedbacks between social and physical systems.

2. A Novel Approach to Explore Changes in Flood Risk

The bottom plot of Figure 2 shows a schematic representation of our approach, which draws from emerging interdisciplinary frameworks, such as socioecological systems, complex system theories, and socio-hydrology [*Liu et al.*, 2007; *Werner and McNamara*, 2007; *Ostrom*, 2009; *Sivapalan et al.*, 2012; *Srinivasan et al.*, 2012; *Di Baldassarre et al.*, 2013b; *Montanari et al.*, 2013]. The proposed approach explicitly account for the dynamics of risk by capturing the continuous interactions and mutual feedbacks between flooding and society. To this end, floodplains are treated as nonlinear, fully coupled physical-human systems.

Several different methods have been recently proposed for studying the dynamics of complex systems. In the social sciences, one of the most common methods is based on statistical analysis of empirical research data, such as surveys and interviews [*Brown*, 2007]. In this context, interesting methods have been developed to combine the strengths of qualitative and quantitative data [*Jick*, 1979; *Driscoll et al.*, 2007]. This method relies on extensive and robust empirical data, which can be expensive and time consuming to collect. Moreover, the resulting narratives can be vague and therefore difficult (if not essentially impossible) to validate or falsify.

A second method, which has gathered increasing momentum in social sciences, is agent-based modeling [e.g., *Evans and Kelly*, 2004]. These models operate by prescribing rules on how individuals and/or institutions (the agents) interact, and therefore allow heterogeneity to be included. They compute the interactions at the microlevel which leads to observed behavior at higher levels [*Gilbert*, 2008; *Gilbert and Terna*, 2000]. The disadvantage of these models is that they can become extremely complex and opaque [*Turchin*, 2003], results might be difficult to interpret, and they are often not generalizable [*Janssen and Ostrom*, 2006].

In a third method, a number of hypotheses about the fundamental processes and interactions driving the behavior of the system are explicitly formalized (in mathematical terms) using a set of differential equations. The strength of this method is its transparency, flexibility, and ability to capture the dynamics emerging from interacting processes. This type of modeling has proved to be useful where empirical data are limited [*Brown*, 2007]. Moreover, differential equations for dynamic modeling have been recognized as being appropriate for understanding complex systems and it has been widely used in neoclassic economic models.

While the use of differential equations for dynamic modeling is more popular in physical and natural sciences, there are also several examples of their use in the social science literature. *Nefedov* [2004] developed an

Table 1. Time Varying Variables of the Dynamic Model and Initial Conditions Used in the Experiment

	Units	Description	Domain	Type	Initial Conditions
F		Relative flood damage	Hydrology	Event	0
D		Population density	Demography	State	0.1
H	[*L*]	Flood protection level	Technology	State	0 m
M		Societal memory of floods	Society	State	0

economic-demographic model for ancient China. The model showed how a series of failed harvests could initially be managed by the state through grain reserves, but would eventually lead to catastrophic population decline due to famine. In a similar way, *Turchin and Korotayev* [2006] developed a coupled model for early modern England showing how population growth leads to war but with a time delay. More recently, *Van Emmerik et al*. [2014] develop a socio-hydrologic model to understand the competition for water resources between environmental health and agricultural development in the Murrumbidgee River Basin (Australia), while *Liu et al*. [2015] simulated the coevolution of humans and water in the Tarim River basin (China). Although these models have been compared with empirical data, the approach is not without critics from the social sciences. One critique is that strong and robust social theories are needed to underlie any mathematically based socioecological model, but the theories are often underdeveloped or contested [*Tainter*, 2004]. Another issue is that these models can be too site specific. There are large gaps in our understanding of how human-physical systems function and in this sense, model building is particularly valuable for exploring how variables effect system functioning and can aid in the development of theories [*Brown*, 2007]. Hence, an iterative process of theory, model development, and empirical research seems appropriate.

In this context, our novel approach to decipher changes in flood risk is based on capturing coupled dynamics of floods and societies (Figure 2). To this end, we developed a set of differential equations for dynamic modeling. Our model is a mathematical formalization of general, plausible hypotheses about human-flood interactions, which were derived from a number of stylized facts [*Kaldor*, 1957]. The model does not attempt to perfectly schematize the dynamics of a specific case study, which would be impossible to generalize. Thus, the proposed framework (Figure 2) uses socio-hydrological modeling as explorative tools to support the understanding of changes in flood risk emerging from human-flood interactions. In particular, modeling contributes to theory development of societal response to flooding as it allows the exploration of long-term trajectories emerging from the continuous feedbacks between physical and social processes. Moreover, within an iterative process of empirical research, modeling, and theory development, stylized modeling provides useful insights about the types of data that we need to collect, if we are to better understand human-flood interactions and resulting changes in flood risk.

3. Modeling Feedbacks Between Physical and Social Processes

To show the implementation of the proposed approach, we develop socio-hydrological modeling and simulate the feedbacks between physical and social processes. The model presented here is a new version of the one described in *Di Baldassarre et al*. [2013b] and [*Viglione et al*., 2014].

We conceptualize the human-flood interactions by considering a community that settles and develops in a coastal or river flood-prone area (urbanizing delta or floodplain) to gain associated economic benefits, e.g., trading. However, the occurrence of flooding causes losses and displacement of people. After experiencing an event, the community is shocked and builds memory (*M*) of flooding. People respond by reducing population density (*D*, ranging between 0 and 1) in the floodplain, and they can respond by building or heightening levees (*H*) to protect the floodplain (i.e., nonstructural and structural measures). As the memory of flooding decays with time [*Di Baldassarre et al*., 2013b; *Viglione et al*., 2014], the tendency to resettle closer to the river and increase population density in the floodplain resumes.

Our conceptualization considers a time series of peak-over threshold of natural high water levels, $W(t)$, which are typically a sequence of impulses with different magnitudes and nonregular time arrivals [*Viglione et al*., 2014]. Empirical evidence shows that, when levees are built, high water levels tend to be exacerbated

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Table 2. Time Invariant Parameters of the Dynamic Model, Values Used in the Experiment and Reference[a]

	Units	Description	Domain	Values and References
α_H	[L]	Parameter related to relationship between flood water levels to relative damage	Hydrology	10 m *Penning-Rowsell et al.* [2010]
ξ_H		Proportion of flood level enhancement due to presence of levees	Hydrology	0.2 *Heine and Pinter* [2012]
ρ_D	[T^{-1}]	Maximum relative growth rate	Demography	0.03 year^{-1} *Me-Bar and Valdez* [2003]
α_D		Ratio preparedness/awareness	Demography	5 *Scolobig et al.* [2012]
ε_T		Safety factor for levee heightening	Technology	1.1 *Da Deppo et al.* [2004]
κ_T	[T^{-1}]	Protection level decay rate	Technology	2e-05 year^{-1} *Di Baldassarre et al.* [2013]
μ_S	[T^{-1}]	Memory loss rate	Society	0.06 year^{-1} (Figure 5) 0.24 yr^{-1} (Figure 6a and 6b) 0.12 year^{-1} (Figures 6c and 6d) 0.03 year^{-1} (Figures 6e and 6f 0.015 year^{-1} (Figures 6g and 6h) *Di Baldassarre et al.* [2013]

[a]References are provided to justify the choice of the parameters.

for a combination of physical reasons, including reduced flood attenuation and decreased conveyance area [*Heine and Pinter*, 2012; *Di Baldassarre et al*., 2010, 2013b]. Thus, if levees are built, we simulate the human impact on flood levels by expressing the actual high water levels as $W+\xi_H H$, whereby H is the flood protection level, e.g., height of levees, while ξ_H is the proportion of flood level enhancement due to the presence of levees. If the actual high water levels are less than the flood protection level they do not cause flooding. Otherwise, they can lead to flooding (overtopping), and the relative flood damage F (ranging between 0 and 1) depends on the actual high water levels, as expressed by the *Hydrology* equation:

$$F=1-\exp\left(-\frac{W+\xi_H H_-}{\alpha_H}\right) \quad \text{if } W+\xi_H H_- > H_- \tag{1}$$

In this paper, time varying variables are in capital letters (Table 1) and, for brevity, the time has not been indicated in the equations. Time invariant parameters are in Greek with subscript indicating the domain they belong to (Table 2). H_- (with the "minus" subscript) is the flood protection level immediately before the flooding event.

We consider here two prototypes of floodplain management systems (Figure 3): (i) green societies, which rely only on nonstructural measures reducing the potential adverse consequences of flooding (a "living with floods" policy [*Di Baldassarre et al*., 2014]); and (ii) technological societies, which rely also on structural measures, such as levees or dikes, to reduce the probability of flooding (a "fighting floods" policy [*Di Baldassarre et al*., 2014]). Technological societies are assumed to increase their flood protection level by building or raising levees after the experience of flooding events. The amount of levee heightening (R) is assumed to be proportional to the difference between the actual high water level, which has led to flooding, and the flood protection level:

$$R=\begin{cases} \varepsilon_T(W+\xi_H H_- - H_-) & (technosociety) \\ 0 & (greensociety) \end{cases} \tag{2}$$

It should be noted that humans typically apply a combination of these two management systems, although several societies tend to have a dominant behavior similar to either green or technological societies [*Viglione et al*., 2014]. Anyhow, combination of structural and nonstructural measures, and shifts from green to technological societies (and vice versa), can be schematized by adding a parameter to the conceptual model as shown elsewhere [e.g., *Di Baldassarre et al*., 2013b]. For the sake of simplicity, we refer here only to these two extreme prototypes of management systems.

The *Hydrology* equation (1), which simulates the impact of the human system on the flood system, is coupled to three differential equations (3) that model the (simultaneous) impact of the flood system on the human system (two-way feedback):

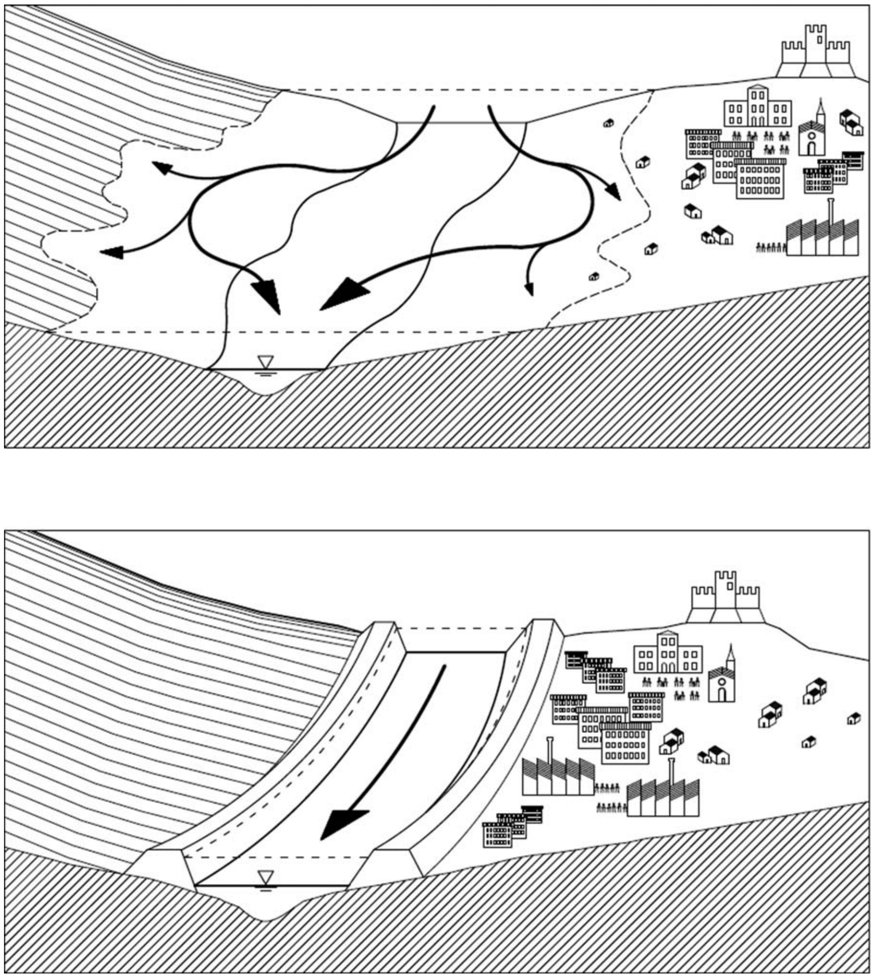

Figure 3. Schematic representation of (top) green and (bottom) technological societies.

$$
\begin{cases}
\dfrac{dD}{dt} = \rho_D(1-D(1+\alpha_D M)) - \Delta(\psi(t)) \cdot FD_- \\
\dfrac{dH}{dt} = \Delta(\psi(t))R - \kappa_T H \\
\dfrac{dM}{dt} = \Delta(\psi(t))FD_- - \mu_s M
\end{cases}
\tag{3}
$$

The three differential equations schematize the gradual coevolution over time of *Demography*, *Technology*, and *Society* as well as the way they are all abruptly altered by the sudden occurrence of flooding events (Figure 4). In case of flooding, the reduction of population density due to people displacement immediately after the event as well as the contemporaneous building of societal memory and heightening of levees (for the technological society) are modeled as instantaneous. This

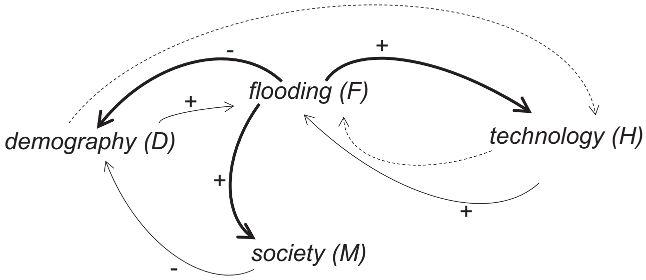

Figure 4. Socio-hydrological modeling: loop diagram showing how hydrological, demographic, technologic, and social processes are all interlinked and gradually (continuous thin arrows) coevolve, while being abruptly (continuous thick arrows) altered by the sudden occurrence of flooding events. Dashed arrows indicate control mechanisms.

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is done via a nonperiodic Dirac comb $\Delta(\psi(t))$ that is always 0 except when $\psi(t)=0$, in which case it is infinite with integral equal to 1. Since $\psi(t)$ is defined as a function whose roots are located at times t of flooding occurrences, the following terms of the set of partial differential equations (3) exist only immediately after the occurrence of flooding events: $-FD_{-}$ (flood losses, express as abrupt reduction of population density), $+R$ (increasing flood protection level, such as levee heightening), and $+FD_{-}$ (accumulation of memory, proportional to flood losses).

Table 1 shows the time varying variables of the dynamic system (F, D, H ad M), while Table 2 summarizes the model parameters, the values used in the modeling exercise, and references to the literature. More details about the empirical research and the case studies supporting these hypotheses are also reported in *Di Baldassarre et al*. [2013b].

Compared to a previous version of the model [*Di Baldassarre et al*., 2013b; *Viglione et al*., 2014], this new conceptualization can be more easily compared to real-world observations as it uses population density in

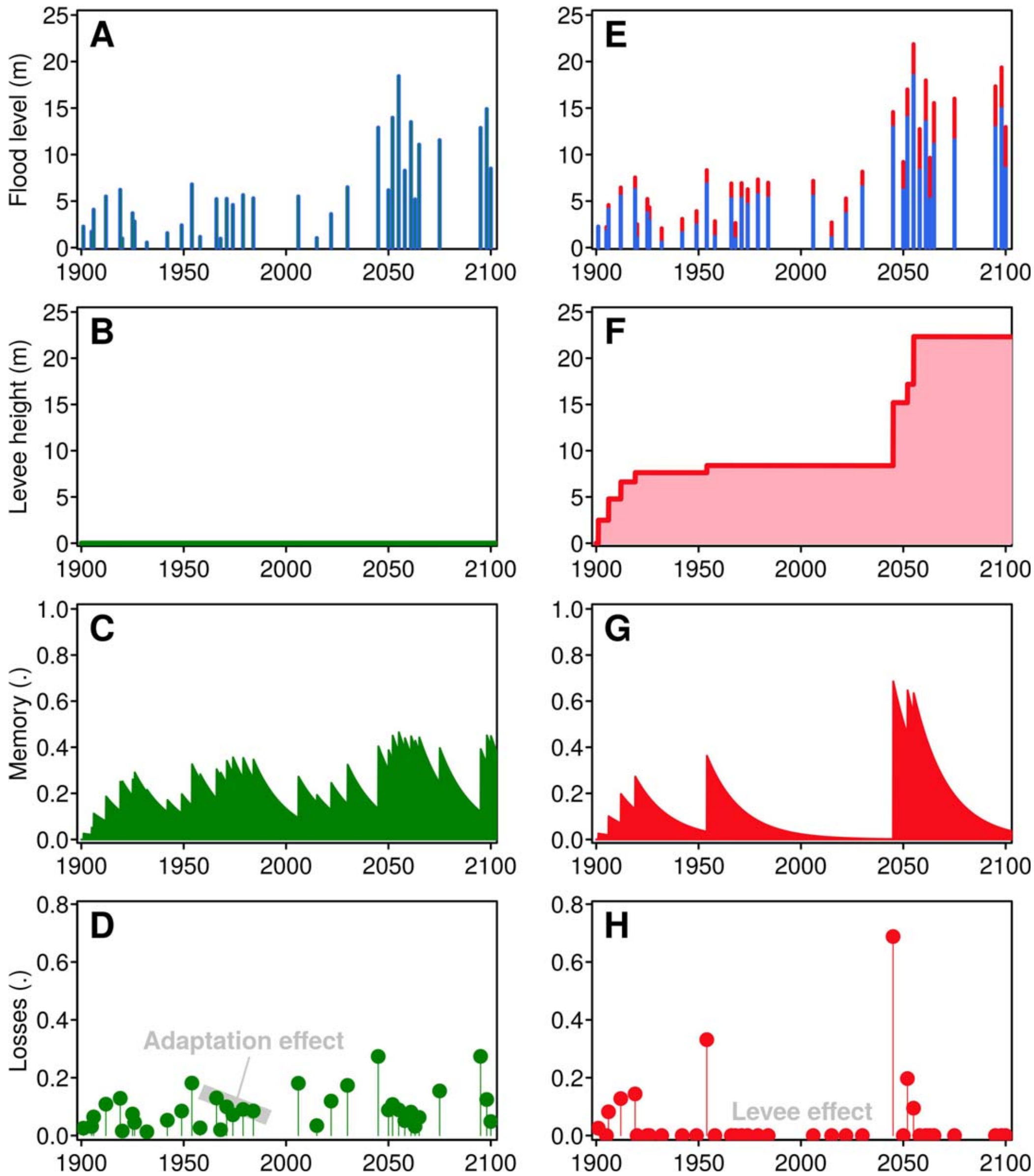

Figure 5. Coupled dynamics of floods and societies in response to increasing flood levels. Effect on green society: (a) actual high water levels, (b) levee heights, (c) memory, and (d) flood losses. Effect on technological society: (e) actual high water levels (note the enhancement due to the presence of levees, which is highlighted in red), (f) levee heights, (g) memory, and (h) flood losses.

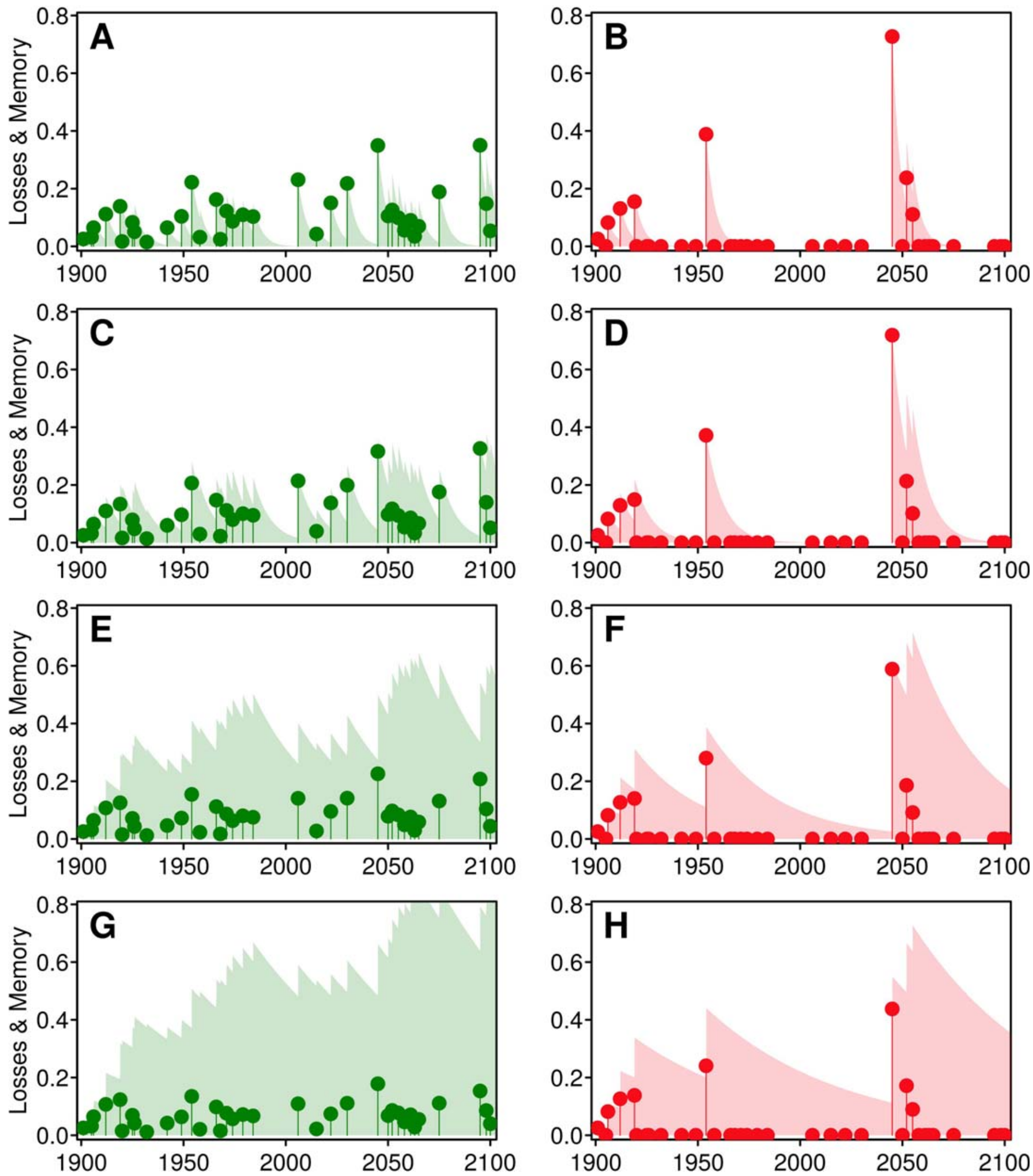

Figure 6. Sensitivity to memory loss rate. (left) Flood losses (green dots) and memory (green shaded area) in green societies. (right) Flood losses (red dots) and memory (red shaded area) in technological societies. The memory loss rate decreases from Figure 6a (6b) to Figure 6g (6h) (see Table 2).

the floodplain instead of community's wealth and average distance from the river. Moreover, the model presented here is simpler than the original one (4 versus 5 variables, 7 versus 11 parameters). While it schematizes different social processes (e.g., population change instead of economic growth), it still captures the essential dynamics emerging from the interplay between floods and societies, such as adaptation and levee effect (see below). Thus, it allows the application of the proposed approach to explore flood risk changes.

This model provides a mathematical formalization of plausible hypothesis (stylized facts) about the feedbacks between physical and social processes. Four subcomponents of the system are accounted for (hydrology, demography, technology, and society; Figure 4) by means of simple equations (1–3) characterized by a similar level of reduced complexity. The main focus of this model is to capture the interplay, i.e., the interactions and feedbacks between physical and social processes (Figure 4). Hence, this model does not aim to accurately and precisely simulate hydrologic, demographic, technologic, and societal processes. Moreover, the lumped nature of the dynamic model unavoidably neglects some potentially significant aspects related to the spatial heterogeneity of human societies and physical processes.

This model aims to support a better understanding of coupled human-flood systems by allowing the exploration of plausible trajectories of flood risk dynamics and the identification of the types of data that we need to collect to study human-flood interactions. Thus, this stylized model does not attempt to make quantitative predictions of future flood risk, which are believed to be unrealistic anyhow, as discussed in the introductory section.

4. Application of the Novel Approach

To show an example of the implementation of the novel approach, we use this model to explore the impact of increasing frequency and magnitude of flood levels (Figure 5a), which can be plausibly caused by climate change or sea level rise [e.g., *Hinkel et al*., 2014; *Jongman et al*., 2014]. To this end, we simulate the behavior of the aforementioned prototypes of risk management systems: green societies and technological societies. Both green and technological societies have the same initial and boundary conditions as well as model parameters (Tables 1 and 2). They only differ in the way humans adjust to flooding events (equation (2)) as technological societies build or heighten flood protection structures (e.g., levees), while green societies cope with floods only by reducing population density in flood-prone areas. The initial conditions and the parameter values used in the numerical experiment are reported in Tables 1 and 2.

Figure 5 summarizes the results of the experiment. The most striking result is that the model is able to capture the dynamics emerging from the interactions and feedbacks between floods and societies, i.e., adaptation and levee effects.

The adaptation effect dominates the dynamics of the green society during the years between 1950 and 1980, when the occurrence of a sequence of similar flood levels (Figure 5a) leads to decreasing losses (Figure 5d). This response occurs as the society builds up memory with each flood experience (Figure 5c) and consequently adapts by reducing the speed of urban development (i.e., population density growth rate) in flood-prone areas, which in turn reduces the damage of future events.

For the technological society, the levee effect emerges between 1955 and 2045 when a series of moderate flood levels (Figure 5e) does not cause any flood damage (Figure 5h) as inundation is prevented by the presence of levees (Figure 5f). However, this lack of flooding leads to a loss of flood memory (Figure 5g) and the society, unaware of the risks, develops and urbanizes the flood-prone areas. When an exceptionally high flood level occurs in 2048, the levees are overtopped and the damage to the technological society is dramatic (Figure 5h). Moreover, it is interesting to note the enhancement of flood levels (Figure 5e) due to the presence of flood protection structures, i.e., feedback on the hydrology of floods.

By analyzing the entire time series, the green society experiences flood losses more frequently. However, despite the trend in flood levels, these losses remain limited (between 5 and 25%; Figure 5d). In contrast, the technological society exhibits a dramatically high flood loss after a long period of nonoccurrence of flooding (around 70%; Figure 5h). These losses can be catastrophic. For instance, the empirical study of historical disasters around the world performed by *Me-Bar and Valdez* [2003] showed that population recovery time increases very rapidly for losses above 60%. And, in some instances, these high losses might lead to collapse.

To test the robustness of this outcome, we perform a sensitivity analysis, whereby the coupled dynamics of floods and societies are investigated by testing two different model structures (the one presented here and the one described in *Di Baldassarre et al*. [2013b]) and by altering (increasing or decreasing) the parameters of the green and technological societies. The results of the sensitivity analysis shows that different parameterizations lead to the same outcome: despite increasing flood frequency and magnitude, green societies are affected by relatively small flood losses, while technological societies are prone to rare flooding with catastrophic losses. This behavior is caused by the role of societal memory. In green societies, memory is often refreshed by experiencing frequent, small floods. In contrast, in technological societies, the memory of flooding decays quickly as many flood levels do not produce any damage at all. The long flood-poor periods, which are artificially induced by the construction of levees in technological societies, have a major effect on the dynamics of flood risk with potentially catastrophic effects.

Figure 6 shows, as an example, the sensitivity to memory loss rate (Table 2). In the case of higher memory loss rates, the losses in the technological society becomes larger, while in case of lower memory loss rates, the technological society deals better with increasing floods. This shows that efforts to raise risk awareness are crucial and extremely important, especially for technological societies where the presence of flood protection structures leads to a rapid decay of the memory of flooding and therefore higher vulnerability and exposure of societies.

5. Discussion and Conclusions

This study has demonstrated the capability of the proposed approach to capture two types of dynamics, i.e., adaptation and levee effects, which have been widely observed worldwide, but that traditional methods are unable to explain. We also showed how these dynamics can emerge from the interplay between physical and social processes, and highlighted the crucial role of societal memory and technology in shaping this complex interplay.

A better understanding of the coupled dynamics of floods and societies provides useful insights for flood risk management. In exploring future flood risk, many studies focus on the danger of flood-rich periods. However, this study shows that flood-poor periods should also be of serious concern, particularly for societies relying on flood protection structures, as they tend to lower the memory of flooding and therefore increase societal vulnerability. This suggests that attention needs to be directed to maintaining and raising risk awareness on a long-term basis.

Moreover, the modeling exercise showed that green societies tend to be less affected by increasing flood frequency and magnitude than technological societies. Populated deltas and floodplains in developing countries have dynamics similar to green societies and often exhibit adaptation effects (Figure 1). Bangladesh, for instance, is a typical example of a society living with floods [*Di Baldassarre et al*., 2014], with people responding to regular flooding by locating their homes on higher grounds and adjusting their economic activities to benefit from high water, e.g., through farming systems and fisheries. *Mechler and Bouwer* [2014] have recently demonstrated how the societal vulnerability to flooding in Bangladesh has significantly decreased over the past decade. We interpret it as an example of adaptation effect. Our study shows that this type of society is less prone to catastrophic events in case of increasing frequency or magnitude of floods. However, as the urbanization and industrialization of floodplains typically favor economic growth, many developing countries (including Bangladesh) are planning to build more and more structures for flood protection. A dynamic approach, such as the one proposed here, can be used to explore plausible future trajectories and consider a variety of trade-offs between the need for economic growth and disaster risk reduction to achieve sustainable development in a rapidly changing environment.

Many urbanized floodplains and deltas in Western countries have a behavior similar to technological societies [*Di Baldassarre et al*., 2013b]. Our study shows that although this type of society may not experience flooding for very long periods, when flooding does occur it will have devastating consequences. New Orleans is a case in point. The city is still struggling to recover from the unexpected 2005 flooding [*Myers et al*., 2008; *Adams*, 2012]. Larger floodplain societies, such as the Netherlands, have high levels of protection that make the probability of flooding nearly zero. However, if flooding does occur the consequences can be dramatic and can potentially lead to societal collapse. In some regions, such as in the Netherlands and California, societies have realized that continually raising levees is no longer sustainable and are gradually adopting an adaptive policy of giving some room back to the river [*Vis et al*., 2003; *Opperman et al*., 2009].

In conclusion, we showed how the interactions between human and physical systems can be investigated, and demonstrated that changes in flooding and changes in societies are deeply intertwined. If we are to explore the impact of global changes on urbanizing deltas or floodplains, it will prove necessary to go beyond traditional scenarios and capture relevant dynamics driving changes in flood risk, such as adaptation and levee effects. To this end, there is still a need to gain further insights into the interplay between physical and social processes. Along with empirical research across scales and places, stylized models such as the one presented here are promising explorative tools that can help explore socio-hydrological dynamics and contribute to theory development.

6. Postscript: Comments on the Other Papers in the Debate

To address the "big problems" that arise in Anthropocene, *Sivapalan* [2015] discusses the need to go beyond the "tyranny of small problems" and suggests socio-hydrology as the way forward. We fully agree on the fact that the study of the dynamic interplay between water and human systems will not only broaden hydrological sciences, but also contribute to better coping with water-related issues in a rapidly changing world. In this paper, we have shown that dynamic modeling can offer interesting perspectives and contribute to enhance our knowledge of water-society interactions within an iterative process of theory development and empirical research.

Loucks [2015] talks about socio-hydrological models as a stakeholder engagement tool and rightfully discusses the tremendous challenges associated with this type of exercise. Societal response to hydrological changes is very complex and highly unpredictable as it strongly depends on economic interests and cultural values. In this context, we fully agree with *Gober and Wheater* [2015] on the fact that, for instance, changes in societal memory are much more complex than modeled in our paper. They are also driven by, e.g., media, which can amplify or attenuate perceptions of risk, and policy entrepreneurs, who can make efforts to keep flood risk high on the public agenda. Yet, empirical research shows that the experience of flooding events is (unfortunately) still the main driver of changes in risk awareness and their actual translations into actions, e.g., *Scolobig et al*. [2012].

Troy et al. [2015] focus on socio-hydrological modeling and discuss trade-offs between generality, precision and realism. As there is still a need to develop fundamental knowledge of socio-hydrological processes, we think that, at this stage, there is still a need to formalize general and realistic hypotheses capturing the basic mechanisms driving the dynamics of coupled human-water systems. We agree with *Troy et al*. [2015] about the need to test these hypotheses and validate models. In our opinion, the evaluation (validation or falsification) of socio-hydrological models should not only be based on fitting data of specific test sites (which can be easily achieved given a sufficient number of parameters), but also on diagnosing whether the model is able to represent emerging behaviors, such as adaptation and levee effects, within an iterative process of empirical research and theory development. These dynamics are generic macroscale mechanisms that may occur anywhere in the world in the spirit of *Sivapalan*'s [2015] "big problems." This paper showed an example of model diagnosis of such generic mechanisms. First, we collected empirical evidence about common dynamics of flood risk around the world (Figure 1) and showed that current methods are unable to capture them. Then, we proposed a novel approach based on the formulation of simple, plausible hypotheses about the coevolution of fundamental variables of the coupled human-water system. Lastly, we tested the capability of these hypotheses to capture and explain the above dynamics emerging from the interactions between physical and social processes.

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