systems

MDPI

Review

Floodplains and Complex Adaptive Systems—Perspectives on Connecting the Dots in Flood Risk Assessment with Coupled Component Models

Andreas Paul Zischg

Oeschger Centre for Climate Change Research, Institute of Geography, University of Bern, 3012 Bern, Switzerland; andreas.zischg@giub.unibe.ch; Tel.: +41-31-631-8839

Received: 10 December 2017; Accepted: 30 March 2018; Published: 5 April 2018

Abstract: Floodplains, as seen from the flood risk management perspective, are composed of co-evolving natural and human systems. Both flood processes (that is, the hazard) and the values at risk (that is, settlements and infrastructure built in hazardous areas) are dynamically changing over time and influence each other. These changes influence future risk pathways. The co-evolution of all of these drivers for changes in flood risk could lead to emergent behavior. Hence, complexity theory and systems science can provide a sound theoretical framework for flood risk management in the 21st century. This review aims at providing an entry point for modelers in flood risk research to consider floodplains as complex adaptive systems. For the systems science community, the actual problems and approaches in the flood risk research community are summarized. Finally, an outlook is given on potential future coupled component modeling approaches that aims at bringing together both disciplines.

Keywords: flood risk; floodplains; sensitivity analysis; coupled component modeling; complex adaptive systems

1. Introduction

Floods are one of the most damaging natural hazards, accounting for a majority of all economic losses from natural events worldwide [1]. Managing flood risks requires knowledge about hazardous processes and their impacts. Hence, risks resulting from floods are defined as functions of the probability of a flood event or scenario, respectively, and the related extent of damage [2,3]. The latter is computed in most cases by a function of the monetary value of the object affected by the flood and its vulnerability against the magnitude of the process scenario. In floodplains, these main factors of flood risk, the flood process, and the values at risk meet each other locally. From a physical perspective, floodplains are defined as areas of land adjacent to and formed by flowing water in times of floods. In addition, from a socioeconomic perspective, floodplains provide land for settlement, infrastructure, and other human activities. Floodplains and the main drivers for flood risks are evolving over time. Consequently, in natural hazards and risk research, an actual change in the paradigms can be observed. Risks are being more frequently analyzed from a dynamic rather than a static perspective [4,5]. Hence, many studies are dealing with changes of natural risks over recent decades and centuries [2,6–10]. In addition, research on climate changes and its impact is the focus of future changes in risks [11–20]. A few studies consider both the impacts of climatic changes to river flows and the future dynamics in the values at risk [21–26]. As drivers for changes in risk are not only varying in time, recent studies extend the dynamic framework of risk analysis toward a spatiotemporal framework [27–34]. Herein, the drivers of flood risk vary in space and time. Consequently, a few studies adopted the system dynamics approach to a spatial system dynamics approach for water resources systems and flood risk analyses [35–37]. Beside flood risk research, system dynamics modeling is also becoming an increasingly attractive approach in social sciences and earth system modeling [38–42].

In summary, the built environment in floodplains, whether the settlement area or the river channel, is subject to changes and co-evolutionary dynamics in both spheres. Floodplains are influenced by flood events and subsequent disruptive changes in the society, by governmental decisions as adaptation to these flood events, and individual agents. These co-evolutionary dynamics in the drivers for changes in flood risk influence future risk pathways, and could lead to emergent behavior. Hence, complexity theory and systems science potentially provide a sound theoretical framework for flood risk management as postulated by Helbing et al. [43] for other risks.

This short review aims at summarizing recent attempts in analyzing and modeling spatiotemporal changes in flood risk from a complex systems perspective and at giving an explorative outlook of future perspectives in considering floodplains as complex adaptive systems. With this, I am aiming at providing a summary of the prospective approaches for modeling the co-evolutionary dynamics and emergent behavior of floodplains and thus, an entry point for flood risk modelers to consider floodplains as complex adaptive systems. Moreover, I am aiming at providing a collection of relevant literature from the flood risk research community, and thus an entry point for the systems science community into flood risk research. The focus is placed on the approaches for modeling the co-evolutionary and spatiotemporal dynamics in the evolution of flood risks in floodplains.

2. Main Drivers of Evolving Risks in Floodplains

The spatiotemporal evolution of flood risk in floodplains is composed of several drivers that are intertwined with each other. In a reductionist approach, flood risk research is focusing on a single aspect of flood risk and their changes in space and time. However, constructivist perspectives in flood risk research are rather rare, and are more frequently present in the systems sciences. In this paper, I will summarize the main drivers of evolving flood risks in floodplains.

2.1. Changes in Flood Processes

Floods are either caused directly by rainfall onto the system under investigation (pluvial floods and surface water floods, for example) or by falling onto river catchments, resulting in a catchment outflow. The latter causes floods in downstream floodplains (riverine floods and lake floods). Thus, the boundary condition of floods in floodplains can either be rainfall, river flows, or both. Consequently, changes in flood processes, that is, changes in the frequency and magnitude of floods, are determined by these external influencing factors. In many studies, the changes in rainfall frequency and intensity are investigated, with a special focus on the effects of climatic changes [44,45]. In addition, changes in the incoming flow hydrographs are drivers of change in floodplains [46–48]. In mountainous areas, flood losses are also influenced by sediment transport and deposition processes [49].

However, the rivers themselves and their floodplains change over time [50–53]. These can be natural and gradual changes in the river morphodynamics and flood regime [54–57], changes in the adjacent vegetation [58], or disruptive changes by flood events [59], for example by levee failures [60]. Last but not least, anthropogenic interventions are more or less the most relevant driver of flood risk in a floodplain; that is, the construction of flood defenses such as levees and dams [61–63] or river restoration projects [64–66]. Furthermore, the construction of levees as flood protection measures in one floodplain can have adverse effects in downstream floodplains [67–71], and thus result in trade-offs between upstream and downstream floodplains [72,73]. Reviews on the impacts of land use changes and regulations on floods are given by Rogger et al. [74], Burby et al. [75], and O'Connell et al. [76]. Moreover, floodplains can be affected by land subsidence due to drainage or groundwater extraction. This results in increasing flood hazards and consequently, increasing flood risk [77].

2.2. Changes in Exposure and Vulnerability

In addition to changes in the natural environment (that is, the fluvial aspect of the floodplain), flood risks also change due to variations in the exposed values at risk and in their vulnerability. First of all, one of the most relevant drivers of flood risk is the increase in the values that are at risk due to economic development [78,79]. The growing of settlements and thus, the increase of residential buildings is related to population growth [80]. With it, the infrastructure increases as well. Infrastructure failures have wider impacts on the socioeconomic systems, and thus exhibit relevant interdependencies [81–84]. In economically active areas, floodplains are increasingly occupied by production facilities, as these require relatively flat compound areas for their construction that are not available in hilly areas [85]. Recent studies show that the number of buildings potentially affected by floods increased by up to 700% in the last century [31,78]. With economic development, the objects at risk and the infrastructure in the floodplains increase in terms of monetary value. This and higher object vulnerabilities [86,87] result in increased flood risks. Both factors compete with the opposing drivers of flood risk reduction measures by individuals and the public.

2.3. Adaptation in Governance

Changes in exposure and vulnerability are influenced by the action of individuals and by governmental interventions and regulations. On the one hand, local governments regulate land use with planning instruments. In several countries, the occupation and utilization of areas potentially affected by floods are not allowed or restricted. Moreover, governmental institutions and legislative entities are defining the basic principles and legislative frameworks for spatial planning in floodplains. On the other hand, land use regulations are binding the actions of the individuals and businesses. Hence, both the actions of individual agents and the public composed by a collection of agents result in the key interfering driving forces for changes in flood risk [88]. Often, the actions of individuals and governments are an adaptation to flooding events [89–92]. When a flood affects a relevant share of a house or the infrastructure of the floodplain, individuals urge the government to act. As a reaction to the flood event and requests by the population, the local government invests in flood protection measures [93–95]. If many communities are affected, the regional or national governments react by adapting the legislative or financial framework for flood risk management [96–99]. Individuals experiencing a flood event become aware and sensible to the hazard, and adapt by protecting their homes and workplaces from floods with object-based flood protection measures [100,101]. Moreover, governments try to inform and to sensitize residents in floodplains by aiming at increasing risk awareness [102]. These adaptations can be seen as social learning. Consequently, the following flood event will result in fewer losses. Hence, the vulnerability of values at risk and socioeconomic activities in floodplains might decrease due to the adaptation measures. Overall, this complexity calls for adaptive flood risk management strategies and integrative governance [103–117].

3. Characterization of Floodplains from the Viewpoint of Complex Adaptive Systems

Flood risk—as a quantitative variable of hazard, exposure, and vulnerability—is evolving in space and time. However, the quantification of flood risk in terms of expected losses in a specified time period summarizes all of the factors into one lumped variable. As the single factors in the risk formula are supposed to be co-evolutionary dynamics, it is interesting to have a look at the spatiotemporal evolution of the single drivers first and second to the evolution of the floodplain as a whole. The classical risk formula and the approaches in risk analyses enable a monitoring of the temporal development of the risks by periodically repeating a risk analysis [118]. However, these approaches do not provide a theoretical framework for a deeper understanding and for delineating management options from the behavior of the floodplain, including all drivers of change. As shown in Section 2, the factors influencing flood risk exhibit co-evolutionary dynamics with positive and negative feedback between each other. Moreover, signals from the natural process shaping floodplains as well as information processing between the local human agents and its collective in the form of governmental institutions in the floodplain lead to the complex behavior of a floodplain. Both the natural and the human systems adapt their behavior after flood events. The social system changes their behavior by learning from accidents and continuously adapting flood risk management strategies. Consequently, this adaptation leads to an emerging behavior of floodplains. Behavior in terms of vulnerability against floods and resilience changes remarkably with time. Following the overall complexity of the co-evolutionary dynamics in the drivers of flood risk and the emergent behavior, floodplains can be defined as complex adaptive systems [119,120]. As the actions of the individuals are difficult to predict, the future development paths of such a complex system as floodplains are difficult to predict as well. Hence, complex systems science might provide a helpful theoretical framework for the analysis and simulation of future development pathways of floodplains. However, the identification of emergent behavior, self-organization, and adaptation, as well as mapping complexity, remain a key challenge in flood risk research [121–124].

4. Prospective Approaches in Modeling Co-Evolutionary Dynamics in Floodplains

As the co-evolution of natural–human systems became more evident recently, the disciplines involved in flood risk research tried to collaborate with social sciences to implement human behavior in their models for analysis and prediction. There are mainly two research foci to mention in regard to the co-evolutionary dynamics in floodplains and the interactions between human and natural systems: the coupled human–natural systems approach, and the socio-hydrology approach [125]. The latter is a sub-discipline of socio-ecological systems research [126].

The research topic "coupled human–natural systems" (CHANS) mainly focus on wildlife habitats and landscape evolution [127]. An overview is given by Liu et al. [128]. However, there are some studies dealing with evolving floodplains and the role of individuals [129]. One focus in these models is an analysis of the resilience of the social systems in floodplains [130]. Another focus lays on vulnerability analysis, as exemplarily shown by Turner et al. [131]. The approach is also used to model flood protection investments [132]. The CHANS approach focuses on spatially explicit simulations of changes in systems by considering feedback mechanisms between human activities and the natural environment.

In 2013, the International Association of Hydrological Sciences launched a decade of focused research with the theme "Panta Rhei: Change in Hydrology and Society" [133–135]. Consequently, hydrological science attempted to analyze and model human behavior and their interlinkages with the natural environment, as well as co-evolutionary dynamics. These attempts are often termed as "socio-hydrology". This new focus aims at understanding the dynamics and co-evolution of coupled human–water systems [136] and the relationships between society and floods [137]. Soon after, conceptual articles followed and sharpened the research topic [138–148]. A review is given by Blair and Buytaert [125].

In parallel, different case studies described typically complex problems in floodplains from the "socio-hydrology" perspective [149–156]. A debate on socio-hydrology describes different points of views and discussions between research groups in this field [157–163]. In the wider field of socio-hydrology, a few studies focused on the dynamic behavior of floodplains as human–water systems [164] and on conceptualizing human–flood interactions [165,166]. The main topic herein is the relationship between the development paths of settlements and the construction of levees. In contrast to the CHANS approach, socio-hydrological models are based on system dynamics, and simulate system behavior mainly in a lumped way (that is, a way that is not spatially explicit). In geomorphology, similar tendencies in capturing and analyzing the co-evolution of socio-natural systems and the effects of human interventions on river morphology can be observed [167–169]. Hydrologic and geomorphic drivers in flood hazard evolution are compared by Slater et al. [170].

The unresolved challenges in socio-hydrology lie in the parameterization and validation of the models [163]. Spatially explicit models for the prediction of future pathways in floodplain evolution are still lacking [138,171,172]. Furthermore, there is still a lack of models that can predict potential adverse consequences for flood risk due to unintentional developments in the areas protected by levees [164]. This cannot be studied until the models explicitly consider space and time.

In the following sections, I will give a short overview of the three selected approaches that enable the consideration of the interactions between natural processes and human activities and describe the complex behavior of floodplains. I exemplarily selected one top–down modeling approach, one bottom–up modeling approach, and an approach that offers, in my opinion, a promising way to combine the two first mentioned options. The selection of modeling approaches is based on the classification of Kelly et al. [173]. The top–down modeling approaches aim to represent the system as a whole. The system behavior is represented by the interactions between the system components. Its design is mostly inferred by studying the overall behavior of the system. A model designed in this way can produce only deterministic results, and processes within the system are usually hard to analyze. In contrast, the bottom–up approach mainly focuses on representing the processes in a system. The overall behavior of the whole system results from the processes and their interactions. The latter approach is implemented mainly by explicitly considering space and time. A typical example of the first modeling technique is system dynamics. The most typical bottom–up modeling approach is agent-based models. A prospective approach of combining the benefits of both approaches is coupled component modeling.

4.1. System Dynamics

System dynamics (SD) is a computer simulation problem-solving approach with a foundation in the concepts of system feedbacks with the purpose of gaining insight into real-world system behavior [174]. System dynamics is based on the first computational experiments of Forrester [175] and on the system theory of Luhmann [176]. These approaches have recently been used in conceptualizing human–flood interactions [165], in vulnerability analyses [177], in modeling the feedbacks between flooding and economic growth [178], and to analyze upstream–downstream trade-offs in the internalization and externalization of flood risks [179].

However, system dynamic models are in most cases lumped models. Only a few studies deal with a spatial discretization of system dynamic models [180–183]. In flood risk research, these either deal with structural changes in flood risks [174] in general, the management of flood risk [111], or disaster management [184].

These approaches provide a potential for system conceptualization and thus a holistic analysis of floodplains. However, there is still a lack of methods for incorporating physically-based process models and linking them with the other modules in complex models. Moreover, the consideration of changes over time in system dynamic models is still a challenge. As an example, in studying the evolution of the flood risk of a specific floodplain, a modeler would build a system model at the macro level that incorporates the main drivers that change risk, such as river morphology, river engineering works, the dynamics in the exposure of houses, and finally, the risk management strategies. The modeler must know the present state of the system, the changes in these drivers, and the effects of the different risk reduction options. The system dynamics model would then quantitatively simulate the change in the overall flood risk in the floodplain within a certain time period. Thus, the outcome is quantitative, but aggregated in a lumped variable. The processes on the ground, that is, the spatiotemporal dynamics, are not modeled explicitly. However, the adaptive capacity can be studied because of the ability to consider flood risk management options and their effects.

4.2. Agent-Based Modeling

Agent-based modeling techniques (ABM) aim at simulating the behavior and decision-making of individuals (agents) and groups of individuals or institutions explicitly in space and time at the micro scale [125,173,185]. In (multi)agent models, the interactions between the agents are considered as well. The behavior of the agents is mostly determined by a set of rules. Agents can share common resources, compete, or react to a changing environment. Moreover, agents could be simulated as learning entities. The overall system behavior results in the sum of all actions, reactions, and interactions of the agents. Thus, this approach is preferably used in modeling complex adaptive systems. In hierarchical agent-based models, the effects of regulations by institutions could also be simulated [186]. Another benefit of this approach is the ability to consider time lags, memory, and legacy effects. Major challenges in developing agent-based models lie in their calibration and validation. In regards to flood risk management, agent-based models are being used for simulating the behavior of people in case of flooding. An example is the planning of evacuations [187–189], where pedestrians, cars, and crowding are considered. Another example is the assessment of flood risk management strategies under future climate changes [190]. In this example, institutional behavior is also modeled. In regards to the co-evolutionary dynamics and emergence in floodplains, ABMs can be used to model how individuals and institutions react to a changing environment. Exemplarily, which house owner is taking precautionary measures into account to protect their homes against increasing floods can be simulated. Herein, experience with former flood events, the availability bias, or other incentives could be considered. Furthermore, the role of institutions in changing the environment as a reaction to a flood event could be modeled in space and time. For example, where do governments invest in river engineering works?

4.3. Coupled Component Modeling

Coupled component models (CCM) are composed of specialized disciplinary models representing the parts of the system. Coupled models integrate sub-models to form a model chain that represents a whole system [125]. Synonymously, this type of model is often defined as an integrated environmental model [191,192]. Coupled component models have an advantage in that they are flexible regarding the level of integration, and are relatively transparent because the sub-models are in most cases validated in their specific discipline. Moreover, coupled component models are generally able to combine system dynamics and agent-based models. In such cases, the disciplinary and spatially explicit process models can simulate the (changing) boundary conditions of agent-based models. The outcomes of both results in the system behavior. The design of a CCM can be based on a causal loop diagram of SDs. Hence, instead of using stocks and flows, CCMs simulates the processes directly. However, the sub-models often use different spatial and temporal scales. Thus, the bridging of different scales in model coupling is challenging. Another advantage is that coupled component models can potentially combine both lumped and spatially explicit models. An overview of common coupled or integrated modeling approaches is given by Kelly et al. [173]. However, there is still a lack of integrating process-based models with socio-environmental models. As an example, a few studies showed how to couple system dynamics with agent-based models [193], physically-based models [194], or expert systems [195]. In regards to flood risk analysis, models for weather forecasts are coupled with hydrological models, inundation models, and with flood impact models (for example, flood loss models). An example of a complex modeling chain from rainfall to flood risk is given by Falter et al. [196] or Zischg et al. [197]. In addition, Saint-Geours et al. [198] and Thaler et al. [199] present an approach of incorporating risk management policies in coupled component models.

5. Conclusions and Outlook from a Modeler's Perspective

In this short review, I summarized the literature on modeling floodplains as complex adaptive systems. Beside this, there are other approaches that might be applicable in this context such as Bayesian networks, network theory, or knowledge-based models (that is, expert systems). I focused here on approaches that are applicable in predicting future pathways of flood risk evolution in floodplains. The literature review results in the first overview of modeling floodplains in their complexity and provides a few conclusions for further research that is needed in order to simulate the complex interactions between the natural processes and human actions. Flood risk is determined by several factors, and thus the coupling of models that are specified for selected drivers of flood risk change is needed.

Hitherto, in flood risk research, two main approaches of coupling models prevail. One of the most common approaches is the coupling of different models across specific domains. This is either done in a cascading approach or in a coupled modeling approach. In the first approach, changes in the boundary conditions of the model changes are analyzed from the viewpoint of the impacts to the studied system represented by the model chain. However, the studied system itself, which is represented by the sub-models in the model chain, changes contemporarily with the boundary conditions. In many cases, top–down model chains represent a system behavior that is relatively constant in time. One example of such a shortage is to study future flood risks without implementing the future system status of floodplains with their values at risk and the adaptation of flood risk management strategies over time. Moreover, the development of the studied system over time is influenced by its sensitivity to changes in the boundary conditions. This means that both changes in the boundary conditions and internal changes in the system predetermine the development path of a changing floodplain. Both drivers of change are interwoven, and a sound analysis of changes in complex environmental systems needs to consider them. Thus, a second main approach in model coupling is to study the sensitivity of floodplains. In this bottom–up approach, the focus is laid more on the internal behavior and change of the system rather than on the boundary conditions. In the coupled models, this is studied on the one hand by sensitivity analyses of the sub-modules in an isolated way, and on the other hand by sensitivity analyses of the whole model chain.

While both top–down and bottom–up modeling approaches offer a high potential for the development of methods and tools for the analysis of changes in complex environmental systems, a research gap is identified in bridging both approaches. Therefore, the main aim of future research in modeling floodplains as complex adaptive systems should be to integrate both approaches. This should lead to an extension of the capabilities of coupled component modeling. If the sensitivity of a hydro-geomorphic system is analyzed in detail and a model of adaptive behavior is developed (bottom–up approach), a subsequent analysis of the impacts of changing the boundary conditions (top–down), and consequently, a prediction of future development paths can be done more satisfyingly. This means that changes over time in the boundary conditions meet system-specific sensitivities and adaptive capabilities. Figure 1 schematizes a possible combination of top–down and bottom–up approaches in modeling floodplains as complex adaptive systems with a coupled component model.

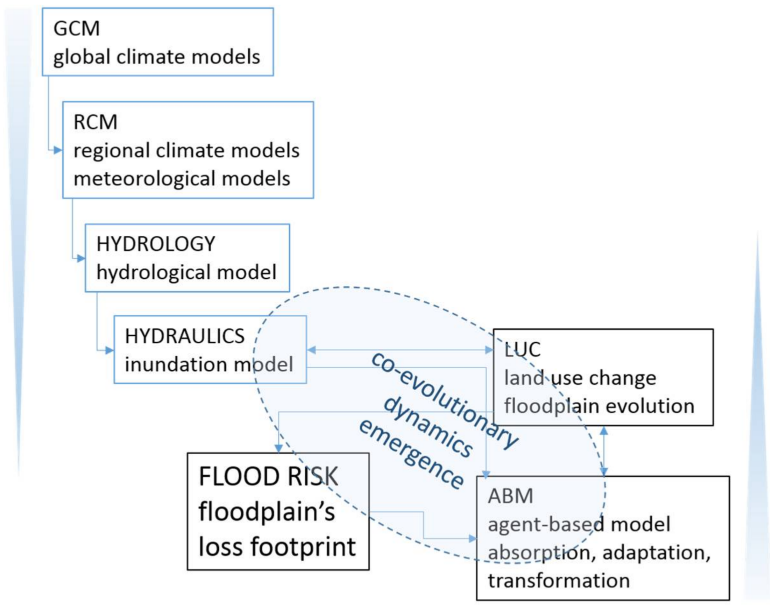

Figure 1. The proposed schema for merging top–down and bottom–up approaches in the framework of coupled component models.

Herein, coupled component models seem to promise the most flexible and robust approach for the prediction of future pathways of floodplain development. This modeling approach is modular; thus, the model chains can be extended step by step with sub-models that have already been validated in their specific domain of application. This modularity makes coupled component models more transparent, robust, and interpretable than lumped specific-purpose models. However, the coupling of already existing models remains a challenge, as they potentially address different scales in space and time. Moreover, coupled component models are preferred, as they consider explicitly spatial phenomena.

Before being applied in floodplain modeling, coupled component models have to be extended remarkably. In my opinion, especially the coupling of process models with agent-based models that simulate the interactions of individuals and institutions with the changing environment, offer a huge potential for extending the capabilities for simulating complex adaptive systems such as floodplains. Thus, the inclusion of the bottom–up modeling approach leads to a more holistic application for prediction purposes than process models alone. The combination of physics-based process models and ABMs offer a thorough simulation of the spatiotemporal dynamics in floodplains. In conclusion, the coupled component models have to be extended with agent-based models representing adaptive behavior sub-modules, and with capabilities for modeling the interactions between the sub-modules, such as feedbacks. This might lead to the capability of modeling adaptive behavior and emergent phenomena.

Acknowledgments: The research of the author is funded by the Swiss Mobiliar insurance.

Conflicts of Interest: The author declares no conflicts of interest. The funding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

References

1. United Nations International Strategy for Disaster Reduction (UNISDR). *Making Development Sustainable: The Future of Disaster Risk Management*; United Nations: Geneva, Switzerland, 2015.
2. Fuchs, S.; Keiler, M.; Zischg, A.; Bründl, M. The long-term development of avalanche risk in settlements considering the temporal variability of damage potential. *Nat. Hazards Earth Syst. Sci.* **2005**, *5*, 893–901. [CrossRef]
3. Haimes, Y.Y. On the complex definition of risk: A systems-based approach. *Risk Anal. Off. Publ. Soc. Risk Anal.* **2009**, *29*, 1647–1654. [CrossRef] [PubMed]
4. Mazzorana, B.; Levaggi, L.; Keiler, M.; Fuchs, S. Towards dynamics in flood risk assessment. *Nat. Hazards Earth Syst. Sci.* **2012**, *12*, 3571–3587. [CrossRef]
5. Merz, B.; Hall, J.; Disse, M.; Schumann, A. Fluvial flood risk management in a changing world. *Nat. Hazards Earth Syst. Sci.* **2010**, *10*, 509–527. [CrossRef]
6. Keiler, M.; Zischg, A.; Fuchs, S.; Hama, M.; Stötter, J. Avalanche related damage potential—Changes of persons and mobile values since the mid-twentieth century, case study Galtür. *Nat. Hazards Earth Syst. Sci.* **2005**, *5*, 49–58. [CrossRef]
7. Keiler, M. Development of the damage potential resulting from avalanche risk in the period 1950–2000, case study Galtür. *Nat. Hazards Earth Syst. Sci.* **2004**, *4*, 249–256. [CrossRef]
8. Keiler, M.; Sailer, R.; Jörg, P.; Weber, C.; Fuchs, S.; Zischg, A.; Sauermoser, S. Avalanche risk assessment; a multi-temporal approach, results from Galtür, Austria. *Nat. Hazards Earth Syst. Sci.* **2006**, *6*, 637–651. [CrossRef]
9. Achleitner, S.; Huttenlau, M.; Winter, B.; Reiss, J.; Plörer, M.; Hofer, M. Temporal development of flood risk considering settlement dynamics and local flood protection measures on catchment scale: An Austrian case study. *Int. J. River Basin Manag.* **2016**, *14*, 273–285. [CrossRef]
10. Himmelsbach, I.; Glaser, R.; Schoenbein, J.; Riemann, D.; Martin, B. Flood risk along the upper Rhine since AD 1480. *Hydrol. Earth Syst. Sci. Discuss.* **2015**, *12*, 177–211. [CrossRef]
11. Alfieri, L.; Bisselink, B.; Dottori, F.; Naumann, G.; de Roo, A.; Sa lamon, P.; Wyser, K.; Feyen, L. Global projections of river flood risk in a warmer world. *Earth Futur.* **2016**. [CrossRef]

12. Alfieri, L.; Burek, P.; Feyen, L.; Forzieri, G. Global warming increases the frequency of river floods in Europe. *Hydrol. Earth Syst. Sci.* **2015**, *19*, 2247–2260. [CrossRef]
13. Alfieri, L.; Feyen, L.; Di Baldassarre, G. Increasing flood risk under climate change: A pan-European assessment of the benefits of four adaptation strategies. *Clim. Chang.* **2016**. [CrossRef]
14. Arnell, N.W.; Gosling, S.N. The impacts of climate change on river flood risk at the global scale. *Clim. Chang.* **2016**, *134*, 387–401. [CrossRef]
15. Devkota, R.P.; Bhattarai, U. Assessment of climate change impact on floods from a techno-social perspective. *J. Flood Risk Manag.* **2015**. [CrossRef]
16. Hirabayashi, Y.; Mahendran, R.; Koirala, S.; Konoshima, L.; Yamazaki, D.; Watanabe, S.; Kim, H.; Kanae, S. Global flood risk under climate change. *Nat. Clim. Chang.* **2013**, *3*, 816–821. [CrossRef]
17. Hundecha, Y.; Merz, B. Exploring the relationship between changes in climate and floods using a model-based analysis. *Water Resour. Res.* **2012**, *48*, 3331. [CrossRef]
18. Kundzewicz, Z.W.; Kanae, S.; Seneviratne, S.I.; Handmer, J.; Nicholls, N.; Peduzzi, P.; Mechler, R.; Bouwer, L.M.; Arnell, N.; Mach, K.; et al. Flood risk and climate change: Global and regional perspectives. *Hydrol. Sci. J.* **2014**, *59*, 1–28. [CrossRef]
19. Merz, B.; Aerts, J.; Arnbjerg-Nielsen, K.; Baldi, M.; Becker, A.; Bichet, A.; Blöschl, G.; Bouwer, L.M.; Brauer, A.; Cioffi, F.; et al. Floods and climate: Emerging perspectives for flood risk assessment and management. *Nat. Hazards Earth Syst. Sci.* **2014**, *14*, 1921–1942. [CrossRef]
20. Alfieri, L.; Feyen, L.; Dottori, F.; Bianchi, A. Ensemble flood risk assessment in Europe under high end climate scenarios. *Glob. Environ. Chang.* **2015**, *35*, 199–212. [CrossRef]
21. Bouwer, L.M.; Bubeck, P.; Aerts, J.C.J.H. Changes in future flood risk due to climate and development in a Dutch polder area. *Glob. Environ. Chang.* **2010**, *20*, 463–471. [CrossRef]
22. Jongman, B.; Koks, E.E.; Husby, T.G.; Ward, P.J. Increasing flood exposure in the Netherlands: Implications for risk financing. *Nat. Hazards Earth Syst. Sci.* **2014**, *14*, 1245–1255. [CrossRef]
23. Jongman, B.; Ward, P.J.; Aerts, J.C.J.H. Global exposure to river and coastal flooding: Long term trends and changes. *Glob. Environ. Chang.* **2012**, *22*, 823–835. [CrossRef]
24. Liu, J.; Hertel, T.W.; Diffenbaugh, N.S.; Delgado, M.S.; Ashfaq, M. Future property damage from flooding: Sensitivities to economy and climate change. *Clim. Chang.* **2015**, *132*, 741–749. [CrossRef]
25. Löschner, L.; Herrnegger, M.; Apperl, B.; Senoner, T.; Seher, W.; Nachtnebel, H.P. Flood risk, climate change and settlement development: A micro-scale assessment of Austrian municipalities. *Reg. Environ. Chang.* **2016**, *42*, 125. [CrossRef]
26. Winsemius, H.C.; Aerts, J.C.J.H.; van Beek, L.P.; Bierkens, M.F.; Bouwman, A.; Jongman, B.; Kwadijk, J.C.; Ligtvoet, W.; Lucas, P.L.; van Vuuren, D.P.; et al. Global drivers of future river flood risk. *Nat. Clim. Chang.* **2015**, *6*, 381–385. [CrossRef]
27. Ahmad, S.S.; Simonovic, S.P. Spatial and temporal analysis of urban flood risk assessment. *Urban Water J.* **2013**, *10*, 26–49. [CrossRef]
28. Aubrecht, C.; Fuchs, S.; Neuhold, C. Spatio-temporal aspects and dimensions in integrated disaster risk management. *Nat. Hazards* **2013**, *68*, 1205–1216. [CrossRef]
29. Cammerer, H.; Thieken, A.H.; Verburg, P.H. Spatio-temporal dynamics in the flood exposure due to land use changes in the Alpine Lech Valley in Tyrol (Austria). *Nat. Hazards* **2013**, *68*, 1243–1270. [CrossRef]
30. Früh-Müller, A.; Wegmann, M.; Koellner, T. Flood exposure and settlement expansion since pre-industrial times in 1850 until 2011 in north Bavaria, Germany. *Reg. Environ. Chang.* **2015**, *15*, 183–193. [CrossRef]
31. Fuchs, S.; Röthlisberger, V.; Thaler, T.; Zischg, A.; Keiler, M. Natural Hazard Management from a Coevolutionary Perspective: Exposure and Policy Response in the European Alps. *Ann. Am. Assoc. Geogr.* **2016**, *107*, 1–11. [CrossRef] [PubMed]
32. Röthlisberger, V.; Zischg, A.; Keiler, M. Spatiotemporal aspects of flood exposure in Switzerland. *E3S Web Conf.* **2016**, *7*, 8008. [CrossRef]
33. Röthlisberger, V.; Zischg, A.P.; Keiler, M. Identifying spatial clusters of flood exposure to support decision making in risk management. *Sci. Total Environ.* **2017**, *598*, 593–603. [CrossRef] [PubMed]
34. Fuchs, S.; Keiler, M.; Sokratov, S.; Shnyparkov, A. Spatiotemporal dynamics: The need for an innovative approach in mountain hazard risk management. *Nat. Hazards* **2013**, *68*, 1217–1241. [CrossRef]

35. Ahmad, S.; Simonovic, S.P. Modeling Dynamic Processes in Space and Time—A Spatial System Dynamics Approach. In Proceedings of the World Water and Environmental Resources Congress 2001, Orlando, FL, USA, 20–24 May 2001; pp. 1–20.
36. Ahmad, S.S.; Simonovic, S.P. System dynamics and hydrodynamic modelling approaches for spatial and temporal analysis of flood risk. *Int. J. River Basin Manag.* **2015**, *13*, 443–461. [CrossRef]
37. Ahmad, S.; Simonovic, S.P. Spatial System Dynamics: New Approach for Simulation of Water Resources Systems. *J. Comput. Civ. Eng.* **2004**, *18*, 331–340. [CrossRef]
38. Bentley, R.A.; Maddison, E.J.; Ranner, P.H.; Bissell, J.; Caiado, C.; Bhatanacharoen, P.; Clark, T.; Botha, M.; Akinbami, F.; Hollow, M.; et al. Social tipping points and Earth systems dynamics. *Front. Environ. Sci.* **2014**, *2*. [CrossRef]
39. Brinke, W.B.M.; Knoop, J.; Muilwijk, H.; Ligtvoet, W. Social disruption by flooding, a European perspective. *Int. J. Disaster Risk Reduct.* **2017**, *21*, 312–322. [CrossRef]
40. Von Elverfeldt, K.; Embleton-Hamann, C.; Slaymaker, O. Self-organizing change? On drivers, causes and global environmental change. *Geomorphology* **2016**, *253*, 48–58. [CrossRef]
41. Fraternali, P.; Castelletti, A.; Soncini-Sessa, R.; Vaca Ruiz, C.; Rizzoli, A.E. Putting humans in the loop: Social computing for Water Resources Management. *Environ. Model. Softw.* **2012**, *37*, 68–77. [CrossRef]
42. Donges, J.F.; Winkelmann, R.; Lucht, W.; Cornell, S.E.; Dyke, J.G.; Rockström, J.; Heitzig, J.; Schellnhuber, H.J. Closing the loop: Reconnecting human dynamics to Earth System science. *Anthr. Rev.* **2017**, *4*, 151–157. [CrossRef]
43. Helbing, D.; Brockmann, D.; Chadefaux, T.; Donnay, K.; Blanke, U.; Woolley-Meza, O.; Moussaid, M.; Johansson, A.; Krause, J.; Schutte, S.; et al. Saving Human Lives: What Complexity Science and Information Systems can Contribute. *J. Stat. Phys.* **2015**, *158*, 735–781. [CrossRef] [PubMed]
44. Gobiet, A.; Kotlarski, S.; Beniston, M.; Heinrich, G.; Rajczak, J.; Stoffel, M. 21st century climate change in the European Alps—A review. *Sci. Total Environ.* **2014**, *493*, 1138–1151. [CrossRef] [PubMed]
45. Arheimer, B.; Lindström, G. Climate impact on floods: Changes in high flows in Sweden in the past and the future (1911–2100). *Hydrol. Earth Syst. Sci.* **2015**, *19*, 771–784. [CrossRef]
46. Hollis, G.E. The effect of urbanization on floods of different recurrence interval. *Water Resour. Res.* **1975**, *11*, 431–435. [CrossRef]
47. Hooke, J.M. Human impacts on fluvial systems in the Mediterranean region. *Geomorphology* **2006**, *79*, 311–335. [CrossRef]
48. Muñoz, L.A.; Olivera, F.; Giglio, M.; Berke, P. The impact of urbanization on the streamflows and the 100-year floodplain extent of the Sims Bayou in Houston, Texas. *Int. J. River Basin Manag.* **2017**, *7*, 1–9. [CrossRef]
49. Staffler, H.; Pollinger, R.; Zischg, A.; Mani, P. Spatial variability and potential impacts of climate change on flood and debris flow hazard zone mapping and implications for risk management. *Nat. Hazards Earth Syst. Sci.* **2008**, *8*, 539–558. [CrossRef]
50. Sear, D.A.; Newson, M.D. Environmental change in river channels: A neglected element. Towards geomorphological typologies, standards and monitoring. *Detect. Environ. Chang. Sci. Soc.* **2003**, *310*, 17–23. [CrossRef]
51. Brierley, G.J.; Fryirs, K.A. The Use of Evolutionary Trajectories to Guide 'Moving Targets' in the Management of River Futures. *River Res. Appl.* **2016**, *32*, 823–835. [CrossRef]
52. Marani, M.; Rigon, R. Self-Organized River Basin Landscapes—Fractal and Multifractal Characteristics. *Water Resour. Res.* **1994**, *30*, 3531–3539. [CrossRef]
53. Pinter, N.; Thomas, R.; Wlosinski, J.H. Assessing flood hazard on dynamic rivers. *Eos Trans. AGU* **2001**, *82*, 333. [CrossRef]
54. Church, M.; Ferguson, R.I. Morphodynamics: Rivers beyond steady state. *Water Resour. Res.* **2015**, *51*, 1883–1897. [CrossRef]
55. Coulthard, T.J.; Van De Wiel, M.J. Quantifying fluvial non linearity and finding self organized criticality? Insights from simulations of river basin evolution. *Geomorphology* **2007**, *91*, 216–235. [CrossRef]
56. Hall, J.; Arheimer, B.; Borga, M.; Brázdil, R.; Claps, P.; Kiss, A.; Kjeldsen, T.R.; Kriaučiūnienė, J.; Kundzewicz, Z.W.; Lang, M.; et al. Understanding flood regime changes in Europe: A state-of-the-art assessment. *Hydrol. Earth Syst. Sci.* **2014**, *18*, 2735–2772. [CrossRef]
57. Herget, J.; Dikau, R.; Gregory, K.J.; Vandenberghe, J. The fluvial system—Research perspectives of its past and present dynamics and controls. *Geomorphology* **2007**, *92*, 101–105. [CrossRef]

58. Corenblit, D.; Davies, N.S.; Steiger, J.; Gibling, M.R.; Bornette, G. Considering river structure and stability in the light of evolution: Feedbacks between riparian vegetation and hydrogeomorphology. *Earth Surf. Process. Landf.* **2014**, *40*, 189–207. [CrossRef]
59. Guan, M.; Carrivick, J.L.; Wright, N.G.; Sleigh, P.A.; Staines, K.E.H. Quantifying the combined effects of multiple extreme floods on river channel geometry and on flood hazards. *J. Hydrol.* **2016**, *538*, 256–268. [CrossRef]
60. Croke, J.; Denham, R.; Thompson, C.; Grove, J. Evidence of Self-Organized Criticality in riverbank mass failures: A matter of perspective? *Earth Surf. Process. Landf.* **2015**, *40*, 953–964. [CrossRef]
61. Di Baldassarre, G.; Castellarin, A.; Brath, A. Analysis of the effects of levee heightening on flood propagation: Example of the River Po, Italy. *Hydrol. Sci. J.* **2009**, *54*, 1007–1017. [CrossRef]
62. French, J.R. Hydrodynamic Modelling of Estuarine Flood Defence Realignment as an Adaptive Management Response to Sea-Level Rise. *J. Coast. Res.* **2008**, *2*, 1–12. [CrossRef]
63. Pinter, N.; Thomas, R.; Wlosinski, J.H. Regional Impacts of Levee Construction and Channelization, Middle Mississippi River, USA. In *Flood Issues in Contemporary Water Management*; Marsalek, J., Watt, W.E., Zeman, E., Sieker, F., Eds.; Springer: Dordrecht, The Netherlands, 2000; pp. 351–361.
64. Dixon, S.J.; Sear, D.A.; Odoni, N.A.; Sykes, T.; Lane, S.N. The effects of river restoration on catchment scale flood risk and flood hydrology. *Earth Surf. Process. Landf.* **2016**, *41*, 997–1008. [CrossRef]
65. Surian, N.; Rinaldi, M. Morphological response to river engineering and management in alluvial channels in Italy. *Geomorphology* **2002**, *50*, 307–326. [CrossRef]
66. Kiss, T.; Fiala, K.; Sipos, G. Alterations of channel parameters in response to river regulation works since 1840 on the Lower Tisza River (Hungary). *Geomorphology* **2008**, *98*, 96–110. [CrossRef]
67. Pinter, N.; van der Ploeg, R.R.; Schweigert, P.; Hoefer, G. Flood magnification on the River Rhine. *Hydrol. Process.* **2006**, *20*, 147–164. [CrossRef]
68. Ward, P.J.; Renssen, H.; Aerts, J.C.J.H.; van Balen, R.T.; Vandenberghe, J. Strong increases in flood frequency and discharge of the River Meuse over the late Holocene: Impacts of long-term anthropogenic land use change and climate variability. *Hydrol. Earth Syst. Sci.* **2008**, *12*, 159–175. [CrossRef]
69. Gregory, K.J. The human role in changing river channels. *Geomorphology* **2006**, *79*, 172–191. [CrossRef]
70. Tobin, G.A. The Levee Love Affair: A Stormy Relationship? *J. Am. Water Resour. Assoc.* **1995**, *31*, 359–367. [CrossRef]
71. Van Triet, N.K.; Dung, N.V.; Fujii, H.; Kummu, M.; Merz, B.; Apel, H. Has dyke development in the Vietnamese Mekong Delta shifted flood hazard downstream? *Hydrol. Earth Syst. Sci.* **2017**, *21*, 3991–4010. [CrossRef]
72. Ryffel, A.N.; Rid, W.; Grêt-Regamey, A. Land use trade-offs for flood protection: A choice experiment with visualizations. *Ecosyst. Serv.* **2014**, *10*, 111–123. [CrossRef]
73. Salzmann, N.; Huggel, C.; Nussbaumer, S.U.; Ziervogel, G. *Climate Change Adaptation Strategies—An Upstream-Downstream Perspective*; Springer: Cham, Switzerland, 2016.
74. Rogger, M.; Agnoletti, M.; Alaoui, A.; Bathurst, J.C.; Bodner, G.; Borga, M.; Chaplot, V.; Gallart, F.; Glatzel, G.; Hall, J.; et al. Land-use change impacts on floods at the catchment scale—Challenges and opportunities for future research. *Water Resour. Res.* **2017**, *53*, 5209–5219. [CrossRef] [PubMed]
75. Burby, R.J.; French, S.P. Coping With Floods: The Land Use Management Paradox. *J. Am. Plan. Assoc.* **2007**, *47*, 289–300. [CrossRef]
76. O'Connell, P.E.; Ewen, J.; O'Donnell, G.; Quinn, P. Is there a link between agricultural land-use management and flooding? *Hydrol. Earth Syst. Sci.* **2007**, *11*, 96–107. [CrossRef]
77. Carisi, F.; Domeneghetti, A.; Gaeta, M.G.; Castellarin, A. Is anthropogenic land subsidence a possible driver of riverine flood-hazard dynamics? A case study in Ravenna, Italy. *Hydrol. Sci. J.* **2017**, *6*, 1–16. [CrossRef]
78. Fuchs, S.; Keiler, M.; Zischg, A. A spatiotemporal multi-hazard exposure assessment based on property data. *Nat. Hazards Earth Syst. Sci.* **2015**, *15*, 2127–2142. [CrossRef]
79. Elmer, F.; Hoymann, J.; Düthmann, D.; Vorogushyn, S.; Kreibich, H. Drivers of flood risk change in residential areas. *Nat. Hazards Earth Syst. Sci.* **2012**, *12*, 1641–1657. [CrossRef]
80. Morales, A.P.; Gil-Guirado, S.; Cantos, J.O. Housing bubbles and the increase of flood exposure. Failures in flood risk management on the spanish south-eastern coast (1975–2013). *J. Flood Risk Manag.* **2015**, *11*, S302–S313. [CrossRef]

81. Hasan, S.; Foliente, G. Modeling infrastructure system interdependencies and socioeconomic impacts of failure in extreme events: Emerging R & D challenges. *Nat. Hazards* **2015**, *78*, 2143–2168. [CrossRef]
82. Little, R.G. Controlling Cascading Failure: Understanding the Vulnerabilities of Interconnected Infrastructures. *J. Urban Technol.* **2002**, *9*, 109–123. [CrossRef]
83. Gonzva, M.; Barroca, B.; Gautier, P.-É.; Diab, Y. Modeling disruptions causing domino effects in urban guided transport systems faced by flood hazards. *Nat. Hazards* **2017**, *86*, 183–201. [CrossRef]
84. Pescaroli, G.; Alexander, D. Critical infrastructure, panarchies and the vulnerability paths of cascading disasters. *Nat. Hazards* **2016**, *82*, 175–192. [CrossRef]
85. Nicholls, S.; Crompton, J.L. The effect of rivers, streams, and canals on property values. *River Res. Appl.* **2017**, *36*, 773. [CrossRef]
86. Adger, W.N. Vulnerability. *Glob. Environ. Chang.* **2006**, *16*, 268–281. [CrossRef]
87. Posey, J. The determinants of vulnerability and adaptive capacity at the municipal level: Evidence from floodplain management programs in the United States. *Glob. Environ. Chang.* **2009**, *19*, 482–493. [CrossRef]
88. Wiering, M.; Liefferink, D.; Crabbé, A. Stability and change in flood risk governance: On path dependencies and change agents. *J. Flood Risk Manag.* **2017**. [CrossRef]
89. Kreibich, H.; Müller, M.; Thieken, A.H.; Merz, B. Flood precaution of companies and their ability to cope with the flood in August 2002 in Saxony, Germany. *Water Resour. Res.* **2007**, *43*, 41. [CrossRef]
90. Kuhlicke, C. The dynamics of vulnerability: Some preliminary thoughts about the occurrence of 'radical surprises' and a case study on the 2002 flood (Germany). *Nat. Hazards* **2010**, *55*, 671–688. [CrossRef]
91. Guthrie, R. The catastrophic nature of humans. *Nat. Geosci.* **2015**, *8*, 421–422. [CrossRef]
92. Reilly, A.C.; Guikema, S.D.; Zhu, L.; Igusa, T. Evolution of vulnerability of communities facing repeated hazards. *PLoS ONE* **2017**, *12*, e0182719. [CrossRef] [PubMed]
93. Thomi, L.; Zischg, A.; Suter, H. *Was Macht Hochwasserschutzprojekte Erfolgreich? Eine Evaluation der Risikoentwicklung, des Nutzens und der Rolle privater Geldgeber*; Geographisches Institut: Bern, Switzerland, 2015.
94. White, G. *Human Adjustment to Floods*; University of Chicago: Chicago, IL, USA, 1945.
95. James, L.A.; Marcus, W.A. The human role in changing fluvial systems: Retrospect, inventory and prospect. *Geomorphology* **2006**, *79*, 152–171. [CrossRef]
96. Hartmann, T. *Clumsy Floodplains: Responsive Land Policy for Extreme Floods/by Thomas Hartmann*; Ashgate: Farnham, UK, 2011.
97. Ison, R.L.; Collins, K.B.; Wallis, P.J. Institutionalising social learning: Towards systemic and adaptive governance. *Environ. Sci. Policy* **2015**, *53*, 105–117. [CrossRef]
98. Kjeldsen, T.R.; Prosdocimi, I. Assessing the element of surprise of record-breaking flood events. *J. Flood Risk Manag.* **2016**, *19*, 83. [CrossRef]
99. Wiering, M.; Kaufmann, M.; Mees, H.; Schellenberger, T.; Ganzevoort, W.; Hegger, D.L.T.; Larrue, C.; Matczak, P. Varieties of flood risk governance in Europe: How do countries respond to driving forces and what explains institutional change? *Glob. Environ. Chang.* **2017**, *44*, 15–26. [CrossRef]
100. Collenteur, R.A.; Moel, H.; de Jongman, B.; di Baldassarre, G. The failed-levee effect: Do societies learn from flood disasters? *Nat. Hazards* **2015**, *76*, 373–388. [CrossRef]
101. Gallopín, G.C. Linkages between vulnerability, resilience, and adaptive capacity. *Glob. Environ. Chang.* **2006**, *16*, 293–303. [CrossRef]
102. White, G.F.; Kates, R.W.; Burton, I. Knowing better and losing even more: The use of knowledge in hazards management. *Environ. Hazards* **2001**, *3*, 81–92.
103. Klijn, F.; Kreibich, H.; Moel, H. de; Penning-Rowsell, E. Adaptive flood risk management planning based on a comprehensive flood risk conceptualisation. *Mitig. Adapt. Strateg. Glob. Chang.* **2015**, *20*, 845–864. [CrossRef]
104. Klinke, A.; Renn, O. Adaptive and integrative governance on risk and uncertainty. *J. Risk Res.* **2012**, *15*, 273–292. [CrossRef]
105. Koontz, T.M.; Gupta, D.; Mudliar, P.; Ranjan, P. Adaptive institutions in social-ecological systems governance: A synthesis framework. *Environ. Sci. Policy* **2015**, *53*, 139–151. [CrossRef]
106. Kruse, S.; Pütz, M. Adaptive Capacities of Spatial Planning in the Context of Climate Change in the European Alps. *Eur. Plan. Stud.* **2013**, *22*, 2620–2638. [CrossRef]
107. Hurlimann, A.C.; March, A.P. The role of spatial planning in adapting to climate change. *WIREs Clim. Chang.* **2012**, *3*, 477–488. [CrossRef]

108. Hasselman, L. Adaptive management intentions with a reality of evaluation: Getting science back into policy. *Environ. Sci. Policy* **2017**, *78*, 9–17. [CrossRef]
109. Lawrence, J.; Reisinger, A.; Mullan, B.; Jackson, B. Exploring climate change uncertainties to support adaptive management of changing flood-risk. *Environ. Sci. Policy* **2013**, *33*, 133–142. [CrossRef]
110. Mori, K.; Perrings, C. Optimal management of the flood risks of floodplain development. *Sci. Total Environ.* **2012**, *431*, 109–121. [CrossRef] [PubMed]
111. Simonovic, S.P. Managing flood risk, reliability and vulnerability. *J. Flood Risk Manag.* **2009**, *2*, 230–231. [CrossRef]
112. Priest, S.J.; Penning-Rowsell, E.C.; Suykens, C.; Lang, M.; Klijn, F.; Samuels, P. Promoting adaptive flood risk management: The role and potential of flood recovery mechanisms. *E3S Web Conf.* **2016**, *7*, 17005. [CrossRef]
113. Prenger-Berninghoff, K.; Cortes, V.J.; Sprague, T.; Aye, Z.C.; Greiving, S.; Głowacki, W.; Sterlacchini, S. The connection between long-term and short-term risk management strategies for flood and landslide hazards: Examples from land-use planning and emergency management in four European case studies. *Nat. Hazards Earth Syst. Sci.* **2014**, *14*, 3261–3278. [CrossRef]
114. Smit, B.; Wandel, J. Adaptation, adaptive capacity and vulnerability. *Glob. Environ. Chang.* **2006**, *16*, 282–292. [CrossRef]
115. Thaler, T. Moving away from local-based flood risk policy in Austria. *Reg. Stud. Reg. Sci.* **2016**, *3*, 329–336. [CrossRef]
116. Van der Pol, T.D.; van Ierland, E.C.; Gabbert, S. Economic analysis of adaptive strategies for flood risk management under climate change. *Mitig. Adapt. Strateg. Glob. Chang.* **2015**. [CrossRef]
117. Birkmann, J.; Bach, C.; Vollmer, M. Tools for Resilience Building and Adaptive Spatial Governance. *Raumforsch. Raumordn.* **2012**, *70*, 293–308. [CrossRef]
118. Zischg, A.; Schober, S.; Sereinig, N.; Rauter, M.; Seymann, C.; Goldschmidt, F.; Bäk, R.; Schleicher, E. Monitoring the temporal development of natural hazard risks as a basis indicator for climate change adaptation. *Nat. Hazards* **2013**, *67*, 1045–1058. [CrossRef]
119. Miller, J.H.; Page, S.E. *Complex Adaptive Systems: An Introduction to Computational Models of Social Life*; Miller, J.H., Page, S.E., Eds.; Princeton University Press: Princeton, NJ, USA, 2007.
120. Mitchell, M. *Complexity: A Guided Tour*; Oxford University Press: Oxford, UK, 2009.
121. Birdsey, L.; Szabo, C.; Falkner, K. Identifying Self-Organization and Adaptability in Complex Adaptive Systems. In Proceedings of the 2017 IEEE 11th International Conference on Self-Adaptive and Self-Organizing Systems (SASO), Tucson, AZ, USA, 18–22 September 2017; pp. 131–140.
122. Bras, R.L. Complexity and organization in hydrology: A personal view. *Water Resour. Res.* **2015**. [CrossRef]
123. Kirschke, S.; BORCHARDT, D.; Newig, J. Mapping Complexity in Environmental Governance: A comparative analysis of 37 priority issues in German water management. *Environ. Policy Gov.* **2017**, *3*, 101. [CrossRef]
124. Weis, S.W.M.; Agostini, V.N.; Roth, L.M.; Gilmer, B.; Schill, S.R.; Knowles, J.E.; Blyther, R. Assessing vulnerability: An integrated approach for mapping adaptive capacity, sensitivity, and exposure. *Clim. Chang.* **2016**, *136*, 615–629. [CrossRef]
125. Blair, P.; Buytaert, W. Socio-hydrological modelling: A review asking "why, what and how?". *Hydrol. Earth Syst. Sci.* **2016**, *20*, 443–478. [CrossRef]
126. Schlüter, M.; Mcallister, R.R.J.; Arlinghaus, R.; Bunnefeld, N.; Eisenack, K.; Hölker, F.; Milner-Gulland, E.J.; Müller, B. New horizons for managing the environment: A review of coupled social-ecological systems modeling. *Nat. Resour. Model.* **2012**, *25*, 219–272. [CrossRef]
127. Werner, B.T.; McNamara, D.E. Dynamics of coupled human-landscape systems. *Geomorphology* **2007**, *91*, 393–407. [CrossRef]
128. Liu, J.; Dietz, T.; Carpenter, S.R.; Folke, C.; Alberti, M.; Redman, C.M.; Ouyang, Z.; Deadman, P.; Kratz, T.; Provencher, W. Coupled human and natural systems. *Ambio* **2007**, 639–649.
129. Noël, P.H.; Cai, X. On the role of individuals in models of coupled human and natural systems: Lessons from a case study in the Republican River Basin. *Environ. Model. Softw.* **2017**, *92*, 1–16. [CrossRef]
130. Folke, C. Resilience: The emergence of a perspective for social–ecological systems analyses. *Glob. Environ. Chang.* **2006**, *16*, 253–267. [CrossRef]

131. Turner, B.L.; Matson, P.A.; McCarthy, J.J.; Corell, R.W.; Christensen, L.; Eckley, N.; Hovelsrud-Broda, G.K.; Kasperson, J.X.; Kasperson, R.E.; Luers, A.; et al. Illustrating the coupled human-environment system for vulnerability analysis: Three case studies. *Proc. Natl. Acad. Sci. USA* **2003**, *100*, 8080–8085. [CrossRef] [PubMed]
132. O'Connell, P.E.; O'Donnell, G. Towards modelling flood protection investment as a coupled human and natural system. *Hydrol. Earth Syst. Sci.* **2014**, *18*, 155–171. [CrossRef]
133. McMillan, H.; Montanari, A.; Cudennec, C.; Savenije, H.; Kreibich, H.; Krueger, T.; Liu, J.; Mejia, A.; van Loon, A.; Aksoy, H.; et al. Panta Rhei 2013–2015: Global perspectives on hydrology, society and change. *Hydrol. Sci. J.* **2016**, 1–18. [CrossRef]
134. Kreibich, H.; Krueger, T.; van Loon, A.; Mejia, A.; Liu, J.; McMillan, H.; Castellarin, A. Scientific debate of Panta Rhei research—How to advance our knowledge of changes in hydrology and society? *Hydrol. Sci. J.* **2016**, 1–3. [CrossRef]
135. Montanari, A.; Young, G.; Savenije, H.H.G.; Hughes, D.; Wagener, T.; Ren, L.L.; Koutsoyiannis, D.; Cudennec, C.; Toth, E.; Grimaldi, S.; et al. "Panta Rhei—Everything Flows": Change in hydrology and society—The IAHS Scientific Decade 2013–2022. *Hydrol. Sci. J.* **2013**, *58*, 1256–1275. [CrossRef]
136. Sivapalan, M.; Savenije, H.H.G.; Blöschl, G. Socio-hydrology: A new science of people and water. *Hydrol. Process.* **2012**, *26*, 1270–1276. [CrossRef]
137. Di Baldassarre, G.; Kemerink, J.S.; Kooy, M.; Brandimarte, L. Floods and societies: The spatial distribution of water-related disaster risk and its dynamics. *WIREs Water* **2014**, *1*, 133–139. [CrossRef]
138. Pande, S.; Sivapalan, M. Progress in socio-hydrology: A meta-analysis of challenges and opportunities. *WIREs Water* **2016**, *4*, e1193. [CrossRef]
139. Elshafei, Y.; Sivapalan, M.; Tonts, M.; Hipsey, M.R. A prototype framework for models of socio-hydrology: Identification of key feedback loops and parameterisation approach. *Hydrol. Earth Syst. Sci.* **2014**, *18*, 2141–2166. [CrossRef]
140. Gupta, H.V.; Nearing, G.S. Debates-the future of hydrological sciences: A (common) path forward? Using models and data to learn: A systems theoretic perspective on the future of hydrological science. *Water Resour. Res.* **2014**, *50*, 5351–5359. [CrossRef]
141. Liu, D.; Tian, F.; Lin, M.; Sivapalan, M. A conceptual socio-hydrological model of the co-evolution of humans and water: Case study of the Tarim River basin, western China. *Hydrol. Earth Syst. Sci.* **2015**, *19*, 1035–1054. [CrossRef]
142. Garcia, M.; Portney, K.; Islam, S. A question driven socio-hydrological modeling process. *Hydrol. Earth Syst. Sci.* **2016**, *20*, 73–92. [CrossRef]
143. Mount, N.J.; Maier, H.R.; Toth, E.; Elshorbagy, A.; Solomatine, D.; Chang, F.-J.; Abrahart, R.J. Data-driven modelling approaches for socio-hydrology: Opportunities and challenges within the Panta Rhei Science Plan. *Hydrol. Sci. J.* **2016**, *61*, 1192–1208. [CrossRef]
144. Seidl, R.; Barthel, R. Linking scientific disciplines: Hydrology and social sciences. *J. Hydrol.* **2017**, *550*, 441–452. [CrossRef]
145. Sivapalan, M.; Konar, M.; Srinivasan, V.; Chhatre, A.; Wutich, A.; Scott, C.A.; Wescoat, J.L.; Rodríguez-Iturbe, I. Socio-hydrology: Use-inspired water sustainability science for the Anthropocene. *Earth Futur.* **2014**, *2*, 225–230. [CrossRef]
146. Sivapalan, M.; Blöschl, G. Time scale interactions and the coevolution of humans and water. *Water Resour. Res.* **2015**, *51*, 6988–7022. [CrossRef]
147. Viglione, A.; Di Baldassarre, G.; Brandimarte, L.; Kuil, L.; Carr, G.; Salinas, J.L.; Scolobig, A.; Blöschl, G. Insights from socio-hydrology modelling on dealing with flood risk—Roles of collective memory, risk-taking attitude and trust. *J. Hydrol.* **2014**, *518*, 71–82. [CrossRef]
148. Wesselink, A.; Kooy, M.; Warner, J. Socio-hydrology and hydrosocial analysis: Toward dialogues across disciplines. *WIREs Water* **2016**, *4*, e1196. [CrossRef]
149. Fuchs, S.; Karagiorgos, K.; Kitikidou, K.; Maris, F.; Paparrizos, S.; Thaler, T. Flood risk perception and adaptation capacity: A contribution to the socio-hydrology debate. *Hydrol. Earth Syst. Sci.* **2017**, *21*, 3183–3198. [CrossRef]
150. Lu, Z.; Wei, Y.; Xiao, H.; Zou, S.; Xie, J.; Ren, J.; Western, A. Evolution of the human–water relationships in the Heihe River basin in the past 2000 years. *Hydrol. Earth Syst. Sci.* **2015**, *19*, 2261–2273. [CrossRef]

151. Di Baldassarre, G.; Saccà, S.; Aronica, G.T.; Grimaldi, S.; Ciullo, A.; Crisci, M. Human-flood interactions in Rome over the past 150 years. *Adv. Geosci.* **2017**, *44*, 9–13. [CrossRef]
152. Gaál, L.; Szolgay, J.; Kohnová, S.; Parajka, J.; Merz, R.; Viglione, A.; Blöschl, G. Flood timescales: Understanding the interplay of climate and catchment processes through comparative hydrology. *Water Resour. Res.* **2012**, *48*, 383. [CrossRef]
153. Mao, F.; Clark, J.; Karpouzoglou, T.; Dewulf, A.; Buytaert, W.; Hannah, D. HESS Opinions: A conceptual framework for assessing socio-hydrological resilience under change. *Hydrol. Earth Syst. Sci.* **2017**, *21*, 3655–3670. [CrossRef]
154. Reynard, E.; Bonriposi, M.; Graefe, O.; Homewood, C.; Huss, M.; Kauzlaric, M.; Liniger, H.; Rey, E.; Rist, S.; Schädler, B.; et al. Interdisciplinary assessment of complex regional water systems and their future evolution: How socioeconomic drivers can matter more than climate. *WIREs Water* **2014**, *1*, 413–426. [CrossRef]
155. Sofia, G.; Roder, G.; Dalla Fontana, G.; Tarolli, P. Flood dynamics in urbanised landscapes: 100 years of climate and humans' interaction. *Sci. Rep.* **2017**, *7*, 40527. [CrossRef] [PubMed]
156. Westerberg, I.K.; Di Baldassarre, G.; Beven, K.J.; Coxon, G.; Krueger, T. Perceptual models of uncertainty for socio-hydrological systems: A flood risk change example. *Hydrol. Sci. J.* **2017**. [CrossRef]
157. Di Baldassarre, G.; Viglione, A.; Carr, G.; Kuil, L.; Yan, K.; Brandimarte, L.; Blöschl, G. Debates-Perspectives on socio-hydrology: Capturing feedbacks between physical and social processes. *Water Resour. Res.* **2015**, *51*, 4770–4781. [CrossRef]
158. Gober, P.; Wheater, H.S. Debates-Perspectives on socio-hydrology: Modeling flood risk as a public policy problem. *Water Resour. Res.* **2015**, *51*, 4782–4788. [CrossRef]
159. Loucks, D.P. Debates-Perspectives on socio-hydrology: Simulating hydrologic-human interactions. *Water Resour. Res.* **2015**, *51*, 4789–4794. [CrossRef]
160. Montanari, A. Debates-Perspectives on socio-hydrology: Introduction. *Water Resour. Res.* **2015**, *51*, 4768–4769. [CrossRef]
161. Sanderson, M.R.; Bergtold, J.S.; Heier Stamm, J.L.; Caldas, M.M.; Ramsey, S.M. Bringing the "social" into socio-hydrology: Conservation policy support in the Central Great Plains of Kansas, USA. *Water Resour. Res.* **2017**, *53*, 6725–6743. [CrossRef]
162. Sivapalan, M. Debates-Perspectives on socio-hydrology: Changing water systems and the "tyranny of small problems"-Socio-hydrology. *Water Resour. Res.* **2015**, *51*, 4795–4805. [CrossRef]
163. Troy, T.J.; Pavao-Zuckerman, M.; Evans, T.P. Debates-Perspectives on socio-hydrology: Socio-hydrologic modeling: Tradeoffs, hypothesis testing, and validation. *Water Resour. Res.* **2015**, *51*, 4806–4814. [CrossRef]
164. Di Baldassarre, G.; Kooy, M.; Kemerink, J.S.; Brandimarte, L. Towards understanding the dynamic behaviour of floodplains as human-water systems. *Hydrol. Earth Syst. Sci.* **2013**, *17*, 3235–3244. [CrossRef]
165. Di Baldassarre, G.; Viglione, A.; Carr, G.; Kuil, L.; Salinas, J.L.; Blöschl, G. Socio-hydrology: Conceptualising human-flood interactions. *Hydrol. Earth Syst. Sci.* **2013**, *17*, 3295–3303. [CrossRef]
166. Ciullo, A.; Viglione, A.; Castellarin, A.; Crisci, M.; Di Baldassarre, G. Socio-hydrological modelling of flood-risk dynamics: Comparing the resilience of green and technological systems. *Hydrol. Sci. J.* **2016**, *62*, 880–891. [CrossRef]
167. Ashmore, P. Towards a sociogeomorphology of rivers. *Geomorphology* **2015**, *251*, 149–156. [CrossRef]
168. Keiler, M. Geomorphology and Complexity–inseparably connected? *Z. Geomorphol. Suppl. Issues* **2011**, *55*, 233–257. [CrossRef]
169. Temme, A.J.A.M.; Keiler, M.; Karssenberg, D.; Lang, A. Complexity and non-linearity in earth surface processes—Concepts, methods and applications. *Earth Surf. Process. Landf.* **2015**, *40*, 1270–1274. [CrossRef]
170. Slater, L.J.; Singer, M.B.; Kirchner, J.W. Hydrologic versus geomorphic drivers of trends in flood hazard. *Geophys. Res. Lett.* **2015**, *42*, 370–376. [CrossRef]
171. Srinivasan, V.; Sanderson, M.; Garcia, M.; Konar, M.; Blöschl, G.; Sivapalan, M. Prediction in a socio-hydrological world. *Hydrol. Sci. J.* **2016**, *62*, 338–345. [CrossRef]
172. Lane, S.N. Acting, predicting and intervening in a socio-hydrological world. *Hydrol. Earth Syst. Sci.* **2014**, *18*, 927–952. [CrossRef]
173. Kelly, R.A.; Jakeman, A.J.; Barreteau, O.; Borsuk, M.E.; ElSawah, S.; Hamilton, S.H.; Henriksen, H.J.; Kuikka, S.; Maier, H.R.; Rizzoli, A.E.; et al. Selecting among five common modelling approaches for integrated environmental assessment and management. *Environ. Model. Softw.* **2013**, *47*, 159–181. [CrossRef]

174. Neuwirth, C.; Peck, A.; Simonović, S.P. Modeling structural change in spatial system dynamics: A Daisyworld example. *Environ. Model. Softw.* **2015**, *65*, 30–40. [CrossRef] [PubMed]
175. Forrester, J.W. *Urban Dynamics*; Massachusetts Institute of Technology Press: Boston, MA, USA, 1969.
176. Luhmann, N. *Soziale Systeme*; Suhrkamp: Frankfurt, Germany, 1987.
177. Rougé, C.; Mathias, J.-D.; Deffuant, G. Vulnerability: From the conceptual to the operational using a dynamical system perspective. *Environ. Model. Softw.* **2015**, *73*, 218–230. [CrossRef]
178. Grames, J.; Prskawetz, A.; Grass, D.; Blöschl, G. Modelling the interaction between flooding events and economic growth. *Proc. IAHS* **2015**, *369*, 3–6. [CrossRef]
179. Roos, M.M.D.; Hartmann, T.T.; Spit, T.T.J.M.; Johann, G.G. Constructing risks—Internalisation of flood risks in the flood risk management plan. *Environ. Sci. Policy* **2017**, *74*, 23–29. [CrossRef]
180. Wingo, P.; Brookes, A.; Bolte, J. Modular and spatially explicit: A novel approach to system dynamics. *Environ. Model. Softw.* **2017**, *94*, 48–62. [CrossRef]
181. Neuwirth, C. System dynamics simulations for data-intensive applications. *Environ. Model. Softw.* **2017**, *96*, 140–145. [CrossRef]
182. Neuwirth, C.; Hofer, B.; Peck, A. Spatiotemporal processes and their implementation in Spatial System Dynamics models. *J. Spat. Sci.* **2015**, *60*, 277–288. [CrossRef]
183. ElSawah, S.; Pierce, S.A.; Hamilton, S.H.; van Delden, H.; Haase, D.; Elmahdi, A.; Jakeman, A.J. An overview of the system dynamics process for integrated modelling of socio-ecological systems: Lessons on good modelling practice from five case studies. *Environ. Model. Softw.* **2017**, *93*, 127–145. [CrossRef]
184. Simonovic, S.P. *Systems Approach to Management of Disasters*; John Wiley & Sons: Hoboken, NJ, USA, 2011.
185. Heppenstall, A.; Malleson, N.; Crooks, A. "Space, the Final Frontier": How Good are Agent-Based Models at Simulating Individuals and Space in Cities? *Systems* **2016**, *4*, 9. [CrossRef]
186. Malanson, G.P.; Walsh, S.J. Agent-based models: Individuals interacting in space. *Appl. Geogr.* **2015**, *56*, 95–98. [CrossRef]
187. Dawson, R.J.; Peppe, R.; Wang, M. An agent-based model for risk-based flood incident management. *Nat. Hazards* **2011**, *59*, 167–189. [CrossRef]
188. Lumbroso, D.; Davison, M. Use of an agent based model and Monte Carlo analysis to estimate the effectiveness of emergency management interventions to reduce loss of life during extreme floods. *J. Flood Risk Manag.* **2016**, *11*, S419–S433. [CrossRef]
189. Dressler, G.; Müller, B.; Frank, K.; Kuhlicke, C. Towards thresholds of disaster management performance under demographic change: Exploring functional relationships using agent-based modeling. *Nat. Hazards Earth Syst. Sci.* **2016**, *16*, 2287–2301. [CrossRef]
190. Jenkins, K.; Surminski, S.; Hall, J.; Crick, F. Assessing surface water flood risk and management strategies under future climate change: Insights from an Agent-Based Model. *Sci. Total Environ.* **2017**, *595*, 159–168. [CrossRef] [PubMed]
191. Laniak, G.F.; Olchin, G.; Goodall, J.; Voinov, A.; Hill, M.; Glynn, P.; Whelan, G.; Geller, G.; Quinn, N.; Blind, M.; et al. Integrated environmental modeling: A vision and roadmap for the future. *Environ. Model. Softw.* **2013**, *39*, 3–23. [CrossRef]
192. Welsh, W.D.; Vaze, J.; Dutta, D.; Rassam, D.; Rahman, J.M.; Jolly, I.D.; Wallbrink, P.; Podger, G.M.; Bethune, M.; Hardy, M.J.; et al. An integrated modelling framework for regulated river systems. *Environ. Model. Softw.* **2013**, *39*, 81–102. [CrossRef]
193. Martin, R.; Schlüter, M. Combining system dynamics and agent-based modeling to analyze social-ecological interactions—An example from modeling restoration of a shallow lake. *Front. Environ. Sci.* **2015**, *3*, 1166. [CrossRef]
194. Malard, J.J.; Inam, A.; Hassanzadeh, E.; Adamowski, J.; Tuy, H.A.; Melgar-Quiñonez, H. Development of a software tool for rapid, reproducible, and stakeholder-friendly dynamic coupling of system dynamics and physically-based models. *Environ. Model. Softw.* **2017**, *96*, 410–420. [CrossRef]
195. Zischg, A.; Fuchs, S.; Keiler, M.; Meißl, G. Modelling the system behaviour of wet snow avalanches using an expert system approach for risk management on high alpine traffic roads. *Nat. Hazards Earth Syst. Sci.* **2005**, *5*, 821–832. [CrossRef]
196. Falter, D.; Schröter, K.; Dung, N.V.; Vorogushyn, S.; Kreibich, H.; Hundecha, Y.; Apel, H.; Merz, B. Spatially coherent flood risk assessment based on long-term continuous simulation with a coupled model chain. *J. Hydrol.* **2015**, *524*, 182–193. [CrossRef]

197. Zischg, A.P.; Felder, G.; Weingartner, R.; Quinn, N.; Coxon, G.; Neal, J.; Freer, J.; Bates, P. Effects of variability in probable maximum precipitation patterns on flood losses. *Hydrol. Earth Syst. Sci. Discuss.* **2018**, in review. [CrossRef]
198. Saint-Geours, N.; Bailly, J.-S.; Grelot, F.; Lavergne, C. Multi-scale spatial sensitivity analysis of a model for economic appraisal of flood risk management policies. *Environ. Model. Softw.* **2014**, *60*, 153–166. [CrossRef]
199. Thaler, T.; Zischg, A.; Keiler, M.; Fuchs, S. Allocation of risk and benefits—Distributional justices in mountain hazard management. *Reg. Environ. Chang.* **2018**, *18*, 353–365. [CrossRef]