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A dynamic framework for flood risk

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ABSTRACT

Long-term feedbacks between humans and floods may lead to complex phenomena such as coping strategies, levee effects, call effects, adaptation effects, and poverty traps. Such phenomena cannot be represented by traditional flood risk approaches that are based on scenarios. Instead, dynamic models of the coupled human-flood interactions are needed. This paper reviews the phenomena, feedbacks and model types associated with this kind of models. The paper concludes that the models may play an important role in integrated flood risk management by exploring a wider range of possible futures, including unexpected phenomena, than is possible when using scenarios.

Contents

1. Introduction

The city of Vienna has been grappling with flood issues for centuries. The centre of the city had been founded on a flood-proof terrace 15 m above the Danube in the first century, but as the city grew, lower parts of the landscape were settled and became thus prone to floods. Various attempts were made to protect the city from flooding [2]. A system of levees constructed in the second half of the 18th century was destroyed shortly after completion. For decades the responsible expert committees debated various protection variants without coming to an agreement. The February 1862 flood, which damaged large parts of the city of Vienna, acted as the immediate trigger to construct a new channel during 1870–1875, cutting through the many arms of the braided Danube (Fig. 1a,b), in order to increase the conveyance of the Danube and thus lower the water levels during floods. The Viennese used the opportunity to develop the newly protected areas. The cut-through channel did indeed prove efficient, as there was minimal damage during the large September 1899 flood. Vienna continued to grow, in particular on the area gained by the protection works due to its proximity to the city centre, so when the July 1954 flood struck, there was, again, considerable damage. A similar process to the one that occurred a century earlier started, and it was resolved to enhance the protection level of Vienna by constructing a relief channel on the former flood plain of the Danube to further increase the conveyance. The relief channel was constructed during

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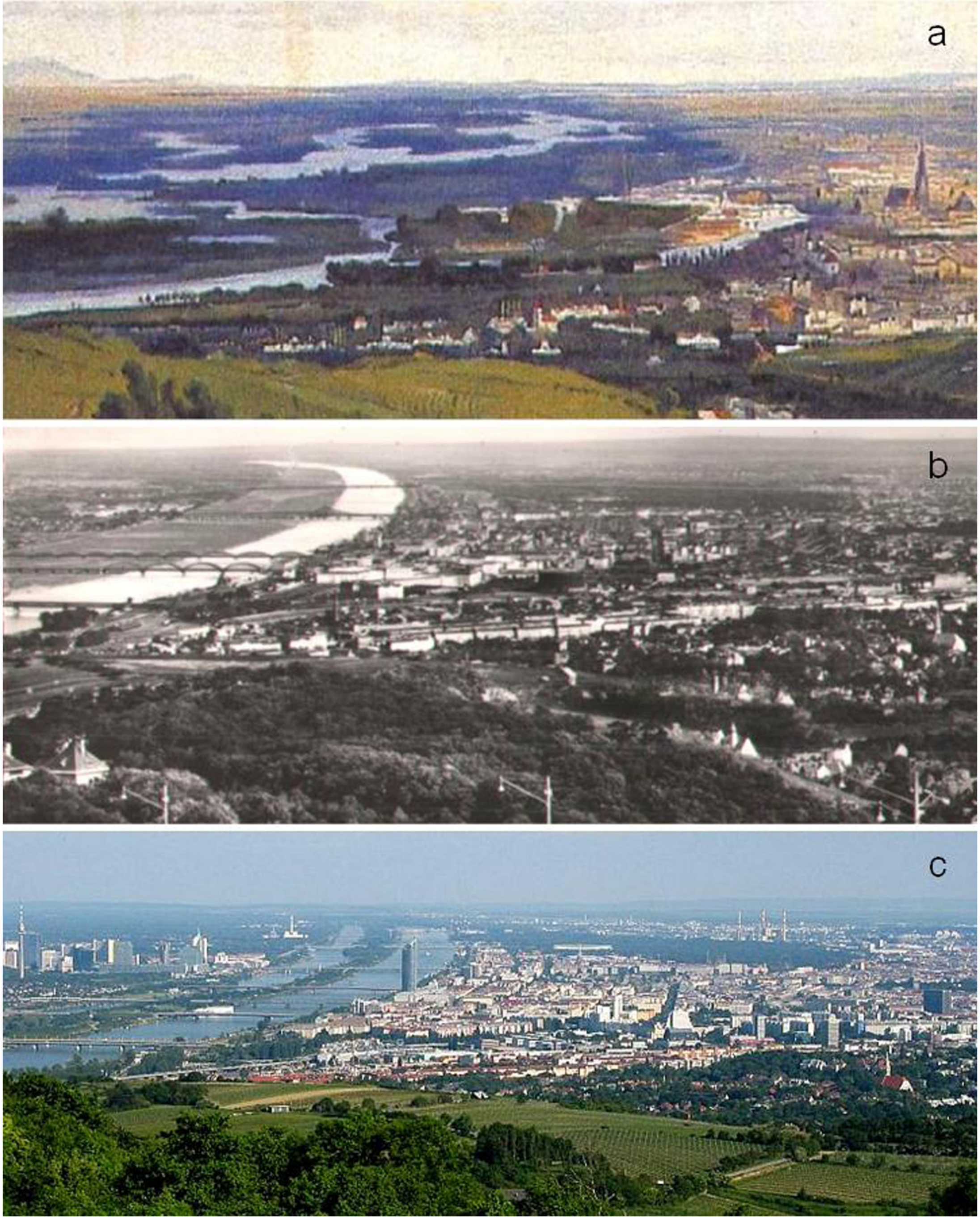

Fig. 1. City of Vienna and Danube from Kahlenberg. (a) Braided river around 1830 that did not allow development of the low areas. (b) Cut through channel around 1930, with some development in the north of the city (left and centre of photo). (c) Relief channel around 2015 when the north of the city had been further developed including a business district.

1972–1988. The enhanced protection boosted another wave of development, both for housing in the wider area north of the Danube and the development of the business centre of the city clustered around the UN facilities (Fig. 1c). The recent floods in August 2002 and June 2013, again, demonstrated the efficiency of the system [4].

The flood history of Vienna has been shaped by the interaction between urban development, flooding and flood protection measures. Protection works have been triggered by development but, conversely, development has been boosted by the existence of protection works when people saw the opportunity of building into protected zones. These feedbacks are not apparent if one looks at snapshots of the situation as is usually done in flood risk assessment. The 1870 planners in Vienna probably did not foresee that the development boosted by the protection will actually *increase* the potential for damage because of the incentive to place assets in areas that are protected to some safety level, but may be flooded if larger events occur. For long term planning it is therefore essential to consider the feedbacks between floods and people in a dynamic way.

Accounting for feedbacks within coupled human-flood systems goes beyond the traditional flood risk approach where either the effect of floods on humans is considered, e.g. through damage assessment [28] or, conversely, the effect of human actions on floods is considered, e.g. through analysing the effects of losing retention areas or land-use change on floods [37]; [34]. The launch of a new journal on Water Security is timely and presents an opportunity to reflect on a dynamic concept for flood risk involving a two-way coupling of processes associated with floods and people. A companion paper [38] puts forward a similar, dynamic concept for water security, i.e. for the case of droughts rather than floods.

Sivapalan et al. [36] proposed a framework for conceptualizing more generally such coupled systems, and Sivapalan and Blöschl [35] provided suggestions for more specifically framing and modelling these systems. Following the seven-step procedure of Sivapalan and Blöschl (Table 2 in [35]) we will in this paper first review phenomena of flood-people interactions published in the literature (Section 2), compare the feedback mechanisms of existing modelling studies (Section 3), review the various model types (Section 4), and finally discuss the implications for flood risk management (Section 5).

2. Phenomena of human-flood interactions

Phenomena of human-flood interactions such as those in Vienna abound around the world (Fig. 2). VanKoningsveld et al. [40] describe how the interactions between floods and people have shaped the Dutch society, its institutions and its flood protection system over the centuries. Changes in technology have affected the flood regime of the Yellow River, while the siltation of reservoirs during floods has affected society [9]. Central to these continuous interactions, or co-evolution, of humans and floods is the attempt of humans to minimise flood risk. Since flood risk is the combined effect of hazard (e.g. flood water levels and their probabilities), exposure (e.g. number of houses in flood prone areas), and vulnerability (e.g. the damage to a flooded building), humans attempt to alter one or more of these factors. Changing one of these factors may influence the others due to feedback mechanisms in the system, resulting in phenomena that are sometimes unexpected.

One of the phenomena of the Dutch human-flood system is the shift from coping strategies to protection strategies [40]. Settlements used to be on higher ground, thereby minimizing exposure, but as technology and cooperation advanced, people started to control the hazard by building dikes. Chen et al. [8] report a shift in the opposite direction, from flood protection to nature protection, between the 1960s and 1990s, in the Kissimmee River, Florida [8]. A similar shift towards nature protection is now occurring in the Netherlands as humans are giving more value to the environment. A change in priorities may also be brought about by threats other than floods. For example, in the Brisbane area, Australia, the management of a reservoir built in the 1970s for flood protection was modified to cope with droughts due to an extended drought period. When a catastrophic flood occurred in 2011, the reservoir was less effective for flood mitigation than foreseen in the initial design [15].

Krause [25] reports that the citizens of Gloucestershire, UK, have adapted to frequent, low intensity floods, and their social values are intertwined with their adaptation and protection measures. In the United States, society's values have played an important role in changing flood insurance policies between 2012 and 2014 [45]. Initially, the government changed the system to reflect local flood risk in the insurance fees. However, once citizens in flood prone areas realised that their insurance fees had dramatically increased, there was substantial political pressure to revert to the previous system of uniform fees across all contributors. Grelot and Barreteau [22] showed that an insurance system with fees independent of flood risk may result in people moving closer to the river, which is known as 'call effect', and consequently an increased risk, if no additional policies (such as land use regulation) are implemented. This phenomenon is similar to the 'levee effect' observed in Vienna,

Fig. 2. Examples of dynamic feedback phenomena between floods and people around the world.

which is the (unexpected) increase in exposure and/or vulnerability as more people move into the floodplain of a river because of a false sense of security following an increase in protection level [14,17,18,32,42,44]. Both of these are the result of feedbacks within the coupled human-flood system.

These kinds of phenomena, arising from the complexity of human-flood interactions, are inherent to flood systems and they often come as a surprise. Merz et al. [29] discuss two types of surprise. The first may arise from the complexity of the system dynamics, such as the levee effect. Adopting an integrated risk assessment approach with a long term perspective may help reduce the likelihood of this kind of surprise, in particular if one is able to shed light on the human-flood feedbacks. The second type of surprise may come from biased human perceptions. An example is the Vajont Dam disaster, Italy, where the overconfidence of the engineers in their ability to control the system resulted in a landslide that triggered a flood wave overtopping the crest of the dam [13,29]. A combination of the two types of surprise almost led to a disaster in the Lower Green River Valley, Washington [27]. Unexpected seepage in the dam has led to the decision of reducing its storage capacity to avoid structural failure, which in turn resulted into flood scenarios with water releases for which the flood control infrastructure downstream of the dam would not have been sufficient. In this case, one disaster was avoided (dam failure), but the possibility of another disaster (failure of flood control downstream) came as a surprise, resulting from complex system feedbacks and unexpected structural failure.

On the positive side, one interesting phenomenon is the 'adaptation effect', when frequent flooding results in increased preparedness and reduced vulnerability. For example, Kreibich and Thieken [26] noted an adaptation effect for the city of Dresden, Germany, where people implemented flood protection measures after the flood in 2002, thus reducing their vulnerability during the 2005/2006 floods. Citizens in the Upper Brahmaputra Plain have traditionally reduced the vulnerability to frequent floods by developing coping strategies [24] such as monitoring and strengthening of embankments during emergencies and the construction of raised platforms in regularly inundated villages. However this adaptation effect was brought out of balance by more recent flood control measures taken by the government. When the measures fail, people are no longer able to deal with floods in the same way as before due to changed flood characteristics.

While the adaptation effect can reduce society's vulnerability to floods, Di Baldassarre et al. [16] show that, in Africa, flood risk has been increasing in the past decades mainly due to an increase in exposure, i.e. due to a tendency of people to move to urban areas close to streams. They note that it is often the poorest people who do not have a choice or the means to protect themselves that live in the floodplains. If the economic situation is more favourable, people may move out of areas that have experienced floods, as illustrated by Collenteur et al. [11] for the US. Grames et al. [21] identified a similar difference between poor and rich economies by modelling the interactions between flood damage and economic growth for a range of hypothetical societies. According to their model, rich economies can afford building flood protection which allows them to develop higher living standards. Poor economies, on the other hand, lose part of their capital every time a flood occurs because they do not have the means to protect themselves from flooding. These poor economies are caught in a 'poverty trap': a lock-in situation that they may not be able to escape from.

3. Feedback mechanisms causing the phenomena

Once the phenomena have been identified and a perceptual model of the mechanisms involved has been developed, an important modelling step is the definition of the relevant variables. In the models reviewed here, the hydrology variable is always related to floods in some way while the societal aspects of the coupled system may be represented by different variables such as community sensitivity [8] and flood risk awareness [17]. Fig. 3 summarises the system components used by seven coupled human-flood models from the literature. The components are hydrology, economy, technology, politics, environment and society. For each of these components, specific variables have been chosen in the studies (shown in brackets in Fig. 3), depending on the specific focus and the interactions modelled. For example, in most of the cases described in Section 2 of this paper, floods affect society through damage, which is an economical variable, and in some cases society affects hydrology through building levees, which is a technological variable.

It is important to clearly specify the meaning of each variable in terms of process, spatial and temporal scales and unit. Damage, for example, can be expressed in monetary terms (Euros) and structural protection level in terms of levee height (m). In many instances in the literature, the variables represent stocks (such as capital, levee height, flood risk awareness) rather than fluxes. Choosing variables that are measurable is usually an advantage as these facilitate model parameter calibration and model testing when confronting them with measured data. Variables such as flood level are relatively easy to measure while variables representing society may be less easily measurable. Monetary variables may be more accessible than social variables such as flood awareness which require questionnaires to elicit response from people that have experienced floods [26].

Once the variables of the system have been specified in an unambiguous way, the interactions between these variables can be identified. The arrows in Fig. 3 show loop diagrams representing the interactions of variables of models from the literature, as presented by the authors of the original papers or, if the information was not available, interpreted by the authors of this paper. The arrows represent fluxes between the variables (stocks), as most equations are balance equations. The fluxes can be positive (i.e. increasing the influenced stock) or negative (i.e. decreasing the influenced stock). When two variables influence each other through fluxes, this results in a 'feedback loop'. In Fig. 3a, for example increasing vulnerability increases damage in case a flood occurs and this leads people to implement adaptation strategies to reduce their vulnerability [24]. Feedback loops can also involve more than two variables. In Fig. 3b, floods increase the awareness of flood risk, which results in a change of the dam operation to mitigate floods, which consequently affects flood discharges [15]. Also competing feedback loops may occur, like in Fig. 3f, where two loops connect hydrology and society, one additionally including economy and the other environment [8]. If both fluxes between two variables are negative, a negative feedback loop (or dampening feedback loop) will occur, such as between economy and society in Fig. 3c, where an increase in damage discourages people from settling in the damaged area which, in turn, decreases the potential damage [22]. Without other controls, the floodplain would eventually be abandoned. If both fluxes between two variables are positive, a positive feedback loop will occur, such as between economy and society in Fig. 3d [21]. Without other controls this behaviour will lead to exponential economic growth.

The different strategies to flood risk management represented in the models are reflected in the diagrams in Fig. 3. According to these models, society tries to minimise flood risk through decreasing hazard potential (e.g., through structural protection measures, Fig. 3b,d,e,f,g) or reducing exposure (e.g., through insurance policy, Fig. 3c), or reducing vulnerability (e.g., through individual measures, Fig. 3a). These actions are part of conventional flood risk assessment and management but they only reflect part of the

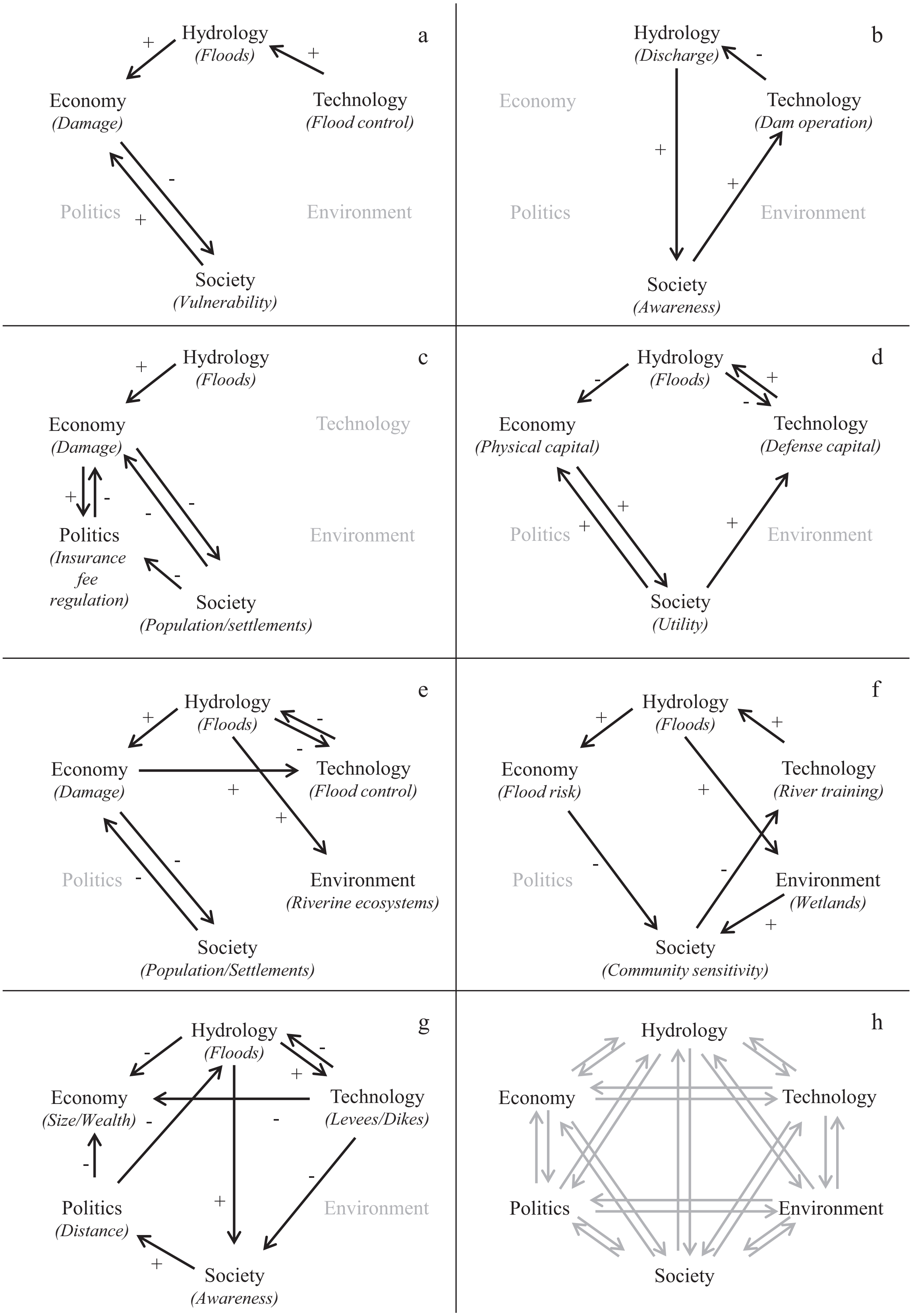

Fig. 3. System components, variables (in brackets) and feedback loops (arrows) for seven coupled human-flood models from the literature. All six system components are always shown to facilitate comparison. Positive (negative) connections are indicated with '+' ('−'). Feedback loops have been presented by the authors of the original papers or, if the information was not available, interpreted by the authors of this paper. a. Hazarika et al. [24], b. Di Baldassarre et al. [15], c. Grelot and Barreteau [22], d. Grames et al. [21], e. Liao [27], f. Chen et al. [8], g. Di Baldassarre et al. [17], h. Diagram with all possible connections.

possible connections in Fig. 3. In reality, human-flood systems are more complex and there are other connections such as public sensitivity to environmental issues (Fig. 3f) or the influence of regular flooding on the risk awareness of society (Fig. 3b,g). The coupled human-flood models represented in Fig. 3, analyse the system as a whole and may lead to the unexpected phenomena discussed in Section 2 (e.g., call effect in Fig. 3c, levee effect in Fig. 3e,g, adaptation effect in Fig. 3a, change in values in Fig. 3b,f). Ideally, scientists or flood risk managers should examine all possible connections between the system components (Fig. 3h) and implement the dominant ones for the real world situation in question. For example, when local managers are considering building a dam for flood protection and hydro-power generation, the hydrological, economic and technological aspects will be on their minds. However, they should also take into account the environment, society and politics. Otherwise, unexpected consequences may occur in the near or far future.

4. Models of feedbacks

Models that represent the dynamic phenomena and feedbacks of the previous sections may be classified, according to their complexity, into (a) system-of-systems models, and (b) stylised models [35].

System-of-Systems models (or coupled component models, [1]) consist of coupled, detailed models of the hydrologic and societal parts of the system. Typically, well established and tested models for each discipline are used, which enhances the credibility of the overall model. They are usually spatially explicit and can be tailored to specific, real-world management problems. Falter et al. [20], for example, coupled a set of models representing the complete flood risk chain: a weather generator, a hydrological model, a coupled 1D-2D hydrodynamic model and a flood loss model. While Falter et al. [20] did not include the impact of flood effects on societal processes, a more detailed model of social behaviour could be implemented as suggested by O'Connell and O'Donnell [30]. System-of-Systems models are amenable to practical problems, because of the local detail included. However, representing feedbacks may not be straightforward, because the disciplinary models may not have been designed for being integrated with other models. Also, understanding the overall system behaviour may be difficult because of the system complexity.

Stylised models, on the other hand, are simple/parsimonious models that directly couple the hydrologic and societal parts of the system. Feedbacks are built into the models during their development, e.g., starting from the loops in Fig. 3, and the models are used to understand how the feedbacks lead to the phenomena described in Section 2. Because of their relative simplicity, stylised models usually allow a clear understanding of the system behaviour but are not ideal for describing real-world management problems in specific cases. They are used for generalising the understanding of phenomena beyond individual case studies. These stylised models could be used to inform the development of more complex system-of-systems models. The outcomes of stylised models can inform the modeler which components should be represented in system-of-systems models and how these components should be connected. The system-of-systems models should be able to reproduce the same kind of feedbacks as the stylized models but can include more detail about the specific characteristics of the case study.

Most of the coupled human-flood models proposed in the literature are based on systems of a few coupled ordinary differential equations (termed 'system dynamic' models by [1]). For example, the model of Di Baldassarre et al. [17] and Viglione et al. [42] represents the evolution of four variables by four coupled non-linear differential equations. The equations are coupled in the sense that the change of one variable with time depends on some of the other variables. They are non-linear mainly due to threshold processes such as when a flood overtops a levee or the discharge exceeds a certain value like in the Kissimmee system of Chen et al. [8]. In system dynamic models, most differential equations are conceptual representations of the lumped system behaviour, i.e. one variable such as flood awareness is an aggregated, representative value of the entire domain.

In contrast, agent based models start from the behaviour of individuals (or small groups of people) termed agents. The modeller describes the interactions between agents through decision rules, and these interactions alter the agents' state [1]. In the model of Grelot and Barreteau [22], households decide to move into a floodplain based on the attractiveness of being close to the river and living in a populated area, they are discouraged if other houses in the area are dilapidated, and a percentage of the population leaves the floodplain in every time step. There is also a regulator (also an agent) determining the insurance fee based on the number of households and the potential flood damage. Even with very simple rules at the agent level, these models are able to simulate complex macro-scale consequences ('emergent patterns', [36] because of the number and heterogeneity of the agents. In Grelot and Barreteau [22], the introduction of an insurance system generates a call effect resulting in an increase of the risk taken by the households. While the upscaling through the interaction of agents is attractive, the output of agent based models and the aggregate system behaviour is sometimes difficult to understand because the connection between the variables is less clear at the macro-scale than for system dynamic models.

Both system dynamic and agent based models can be completely deterministic or may allow for stochasticity. Most of the coupled human-flood models reviewed in this paper are internally deterministic with external forcing that may be stochastic (i.e., flood occurrence and magnitude). However, stochasticity could be incorporated into the models. In system dynamic models, noise terms could be added to the ordinary differential equations making them stochastic, similar to models of eco-hydrology [33]. Examples of stochastic agent based models include the model of Dawson et al. [12] where the daily routine of individuals may or may not be interrupted (with a given probability) when they become aware of a flood, and the model of Grelot and Barreteau [22], where the population leaving the floodplain is selected randomly. The advantage of stochastic over deterministic models is their ability to represent the uncertainty associated with the connections between variables (i.e., with the feedbacks) as well as 'random' modifications of state variables not determined by the other variables in the model. The uncertainty in the outputs of the models then may be evaluated by uncertainty propagation methods.

Almost all coupled human-flood models published so far in the literature are descriptive models, in that they aim at describing the human – flood interactions as they are observed (or could be observed). The purpose is to understand the interactions, rather than searching for optimal policies/investments to minimise flood risk and/or maximise economic income. An exception is Grames et al. [21] who used a model in a prescriptive way. In this model, an economic decision maker interacts with the hydrological system by choosing how much to invest in flood defence in order to maximise the total economic income. O'Connell and O'Donnell [30] suggest that prescriptive coupled human-flood models may be more useful in determining appropriate flood investments than the traditional cost-benefit analysis, in particular if flood rich and flood poor periods occur.

All models reviewed in this paper have been developed starting from concepts derived from personal experience/observation of how the system works and comparisons with data have been performed in a qualitative way. For example, Ciullo et al. [10] com-

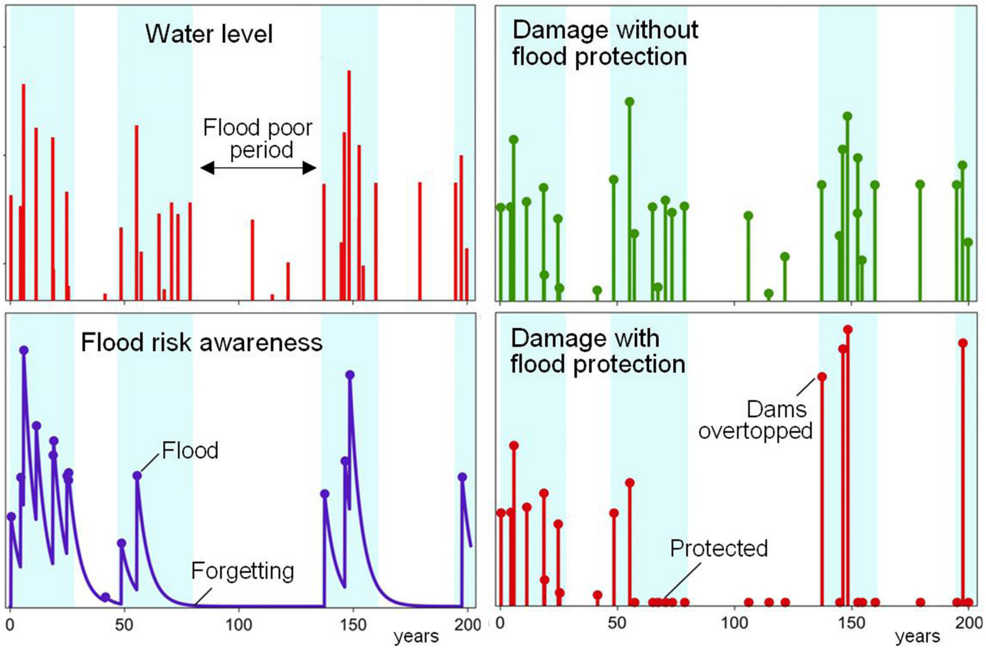

Fig. 4. Two scenarios of flood damage for a hypothetical city. Top right: Damage resulting from flood management options involving the choice of building close to or far away from a flood prone river but no levees. Bottom right: Damage resulting from flood management options also involving the construction of levees. For comparison, the top left panel shows the input flood water levels (for both cases) and the modelled flood risk awareness of the community for the case involving levees. Light blue areas indicate flood-rich periods, white areas flood-poor periods. Results from the model of Di Baldassarre et al. (2013b) and Viglione et al. (2014).

pared the outputs of the model of Di Baldassarre et al. [18] with data of population density, flood losses and levee heights in the city of Rome and in Bangladesh. In a similar way, Chen et al. [8] used flood series and data about wetland area to assess whether the model outputs are realistic. The next step for coupled human-flood modelling is the development of more formal methodologies to test and calibrate coupled human-flood models, perhaps based on Bayesian methods [43,41]. However, this poses a challenge, because the usual time-series fitting of hydrological models may not be the best option, since phenomena and feedbacks are of interest. New ways of testing how well the models reproduce observed patterns need to be developed, such as matching trajectories in the phase space of the model variables.

Starting from concepts and testing model outputs against data is one way of model development (i.e., a hypothesis testing approach). Alternatively, investigative data-based modelling could be performed starting from the data, without assuming a priori model structures. Data analyses that attempt to find relationships between the system components from data correlations (e.g., [16,11]) could be starting points for such models and may help bring coupled human-flood modelling to the next level. However, the lack of long-term data on individual system components poses a challenge for this type of methods. Comparative analyses could be of help, in the spirit of the PUB initiative [3], where the analysis in time is replaced by analyses in space [16], although the validity of this assumption in the context of co-evolutionary systems needs to be tested [31]. Comparative analyses may also become more wide spread thanks to the availability of new types of data [7]. Especially for coupled human-water systems this is more difficult than for hydrologic systems alone [35], but has the potential of boosting new insights and the development of new methodologies.

5. Implications for flood risk management

The European Flood Directive [19] explicitly requires the establishment of flood risk management plans that account for the complexity of the system as a whole. The underlying framework is termed ‘Integrated Flood Risk Management’ (IFRM), which implies integration between sectors (e.g., water management, transport, regional planning and tourism) and between upstream and downstream reaches in a river basin (i.e., the so called ‘solidarity principle’) [6]. IFRM seeks to reduce hazard and exposure at a regional scale by implementing a combination of various measures, such as structural (e.g., levees, polders) and non-structural (e.g., insurances, land-use zoning) measures. IFRM also seeks to reduce vulnerability through increasing people’s awareness of flood risk [39]. Implementation of the Flood Directive is well underway in most European countries. For the specific case of Vienna, as discussed in Section 1 of this paper, the main management measure is the relief channel, supported by non-structural measures such as warning, evacuation plans, and insurance.

Traditionally, decisions on what flood management measures to implement and to what level to protect have been highly political, since citizens may be directly affected and management measures can be very expensive. More recently, cost-benefit analyses are being performed, as stipulated in the Flood Directive. Typically, cost-benefit analyses compare a small number of scenarios to ascertain which scenarios are economically more favourable. However such scenarios do not usually take into account that the measures implemented will have an effect on the future flood risk because of the feedback loops in the system. Therefore the optimum combinations of measures chosen now may not be robust against the future evolution of the risk [5]. An alternative consists of adopting measures that are not optimal for a single future situation but are reasonable for a wide variety of different situations (termed robust, ‘low-regret’, or resilient approaches) [46]. For example, allowing floods to inundate into flood plains may be a more robust strategy than levees that will be overtopped once the protection level is exceeded. In practice, there is often a combination of a number of different measures and it is difficult to understand their interplay. A dynamic approach with coupled human-flood models can help explore the possible future situations that may arise because of the interplay between the system components.

Consider the flood damage simulations for a hypothetical city in Fig. 4. The simulations show the effect of two alternative flood risk management approaches over a period of two centuries using the model of Di Baldassarre et al. [17]. In the top right panel of Fig. 4 the options are to build close or far away from the river but there is no option to build levees. In the bottom right panel, the flood management options also involve the construction of levees. In this second case, the hazard has been decreased substantially after the construction of levees around year 50, however exposure has increased because of the levee effect and the consequences of the events around year 150 are catastrophic. In the top panel, instead, more floods have produced damage in the years before 150 and therefore exposure has not increased as much, which results in a lower damage for the big events around year 150. The levee effect is triggered by the flood awareness of the community which may be low during a period during which few floods occur [23]. When a flood rich period ensues (around year 130 in Fig. 4) the damage may be much larger than expected. Simulations such as those in Fig. 4 explore what could possibly happen and may therefore be used to advise decision making in the implementation of IFRM. They can show the consequences of a particular flood management decision and may help in comparing the measures that are being considered or show a need for additional measures. Simulations like in Fig. 4 could have informed flood risk management in the case of Vienna: additional measures (e.g. land use planning or flood zoning) could have been taken to reduce the increase in exposure that occurred as a result of the implemented structural measures.

Coupled human-flood modelling of many different systems around the world, such as those reviewed in this paper, may also be useful to inform IFRM at a particular location because they may provide a wider overview of the possible phenomena that have not occurred yet, but may occur. For example, for the Danube case, the levee effect has already occurred but other phenomena not yet observed such as the adaptation effect or a shift from flood risk concern to environmental concern may occur in the future. Stylised models, such as those reviewed here, could be used to investigate the effects of different feedback loops. The outcome of these models could then be the basis for building comprehensive and spatially explicit system-of-systems models to investigate the effects of alternative flood management decisions in more detail and support IFRM through a dynamic framework.

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References

[1] P. Blair, W. Buytaert, Socio-hydrological modelling: a review asking “why, what and how?”, Hydrol. Earth Syst. Sci. 20 (1) (2016) 443–478, http://dx.doi.org/10.5194/hess-20-443-2016.

[2] G. Blöschl, Two water problems of a big city, in: T. Hofmann, G. Blöschl, L. Lammerhuber, W.E. Piller, A.M.C. Şengör (Eds.), The Face of the Earth: The Legacy of Eduard Suess, Edition Lammerhuber, Vienna, 2014, pp. 34–39.

[3] G. Blöschl, M. Sivapalan, T. Wagener, A. Viglione, H.H.G. Savenije (Eds.), Runoff Prediction in Ungauged Basins-Synthesis Across Processes, Places and Scales, Cambridge Univ. Press, Cambridge, U.K., 2013, p. 465.

[4] G. Blöschl, T. Nester, J. Komma, J. Parajka, R.A.P. Perdigão, The June 2013 flood in the Upper Danube basin, and comparisons with the 2002, 1954 and 1899 floods, Hydrol. Earth Syst. Sci. 17 (2013) 5197–5212.

[5] G. Blöschl, A. Viglione, A. Montanari, Emerging approaches to hydrological risk management in a changing world, in: R. Pielke (Ed.), Climate Vulnerability: Understanding and Addressing Threats to Essential Resources, Academic Press, Elsevier Inc., Amsterdam, 2013, pp. 3–10.

[6] G. Blöschl, Z. Horváth, A.-.. Kiss, J. Komma, T. Nester, R.A.P. Perdigão, A. Viglione, J. Waser, Neue Methoden für das Hochwasserrisikomanagement (New methods for flood risk management), Österreichische Ingenieur- und Architekten-Zeitschrift (ÖIAZ) 160 (2015) 15–27.

[7] S. Ceola, F. Laio, A. Montanari, Satellite nighttime lights reveal increasing human exposure to floods worldwide, Geophys. Res. Lett. 41 (20) (2014) 7184–7190, http://dx.doi.org/10.1002/2014GL061859.

[8] X. Chen, D. Wang, F. Tian, M. Sivapalan, From channelization to restoration: sociohydrologic modeling with changing community preferences in the Kissimmee River Basin, Florida, Water Resour. Res. 52 (2) (2016) 1227–1244, http://dx.doi.org/10.1002/2015WR018194.

[9] Y. Chen, J.P.M. Syvitski, S. Gao, I. Overeem, A.J. Kettner, Socio-economic impacts on flooding: a 4000-year history of the yellow river, China, Ambio 41 (7) (2012) 682–698, http://dx.doi.org/10.1007/s13280-012-0290-5.

[10] A. Ciullo, A. Viglione, A. Castellarin, M. Crisci, G. Di Baldassarre, Socio-hydrological modelling of flood risk dynamics: comparing the resilience of green and technological systems, Hydrol. Sci. J. (2017), http://dx.doi.org/10.1080/02626667.2016.1273527.

[11] R.A. Collenteur, H. de Moel, B. Jongman, G. Di Baldassarre, The failed-levee effect: do societies learn from flood disasters?, Nat Hazards 76 (1) (2015) 373–388, http://dx.doi.org/10.1007/s11069-014-1496-6.

[12] R.J. Dawson, R. Peppe, M. Wang, An agent-based model for risk-based flood incident management, Nat. Hazards 59 (1) (2011) 167–189, http://dx.doi.org/10.1007/s11069-011-9745-4.

[13] G. Di Baldassarre, J.S. Kemerink, M. Kooy, L. Brandimarte, Floods and societies: the spatial distribution of water-related disaster risk and its dynamics, Wiley Interdisciplinary Reviews: Water 1 (April) (2014) 133–139, http://dx.doi.org/10.1002/wat2.1015.

[14] G. Di Baldassarre, M. Kooy, J.S. Kemerink, L. Brandimarte, Towards understanding the dynamic behaviour of floodplains as human-water systems, Hydrol. Earth Syst. Sci. 17 (8) (2013) 3235–3244, http://dx.doi.org/10.5194/hess-17-3235-2013.

[15] G. Di Baldassarre, F. Martinez, Z. Kalantari, A. Viglione, Drought and flood in the anthropocene: modelling feedback mechanisms, Earth Syst. Dyn. Discuss. 2016 (2016) 1–24, http://dx.doi.org/10.5194/esd-2016-65.

[16] G. Di Baldassarre, A. Montanari, H. Lins, D. Koutsoyiannis, L. Brandimarte, G. Blöschl, Flood fatalities in Africa: from diagnosis to mitigation, Geophys. Res. Lett. 37 (22) (2010), http://dx.doi.org/10.1029/2010GL045467.

[17] G. Di Baldassarre, A. Viglione, G. Carr, L. Kuil, J.L. Salinas, G. Blöschl, Socio-hydrology: conceptualising human-flood interactions, Hydrol. Earth Syst. Sci. 17 (8) (2013) 3295–3303, http://dx.doi.org/10.5194/hess-17-3295-2013.

[18] G. Di Baldassarre, A. Viglione, G. Carr, L. Kuil, K. Yan, L. Brandimarte, G. Blöschl, Debates – perspectives on socio-hydrology: capturing feedbacks between physical and social processes, Water Resour. Res. 51 (6) (2015) 4770–4781, http://dx.doi.org/10.1002/2014WR016416.

[19] European Union, Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks, Off. J. Eur. Union L 288 (27–34) (2007) 2007.

[20] D. Falter, K. Schröter, N.V. Dung, S. Vorogushyn, H. Kreibich, Y. Hundecha, et al., Spatially coherent flood risk assessment based on long-term continuous simulation with a coupled model chain, J. Hydrol. 524 (2015) 182–193.

[21] J. Grames, A. Prskawetz, D. Grass, A. Viglione, G. Blöschl, Modeling the interaction between flooding events and economic growth, Ecol. Econ. 129 (2016) 193–209, http://dx.doi.org/10.1016/j.ecolecon.2016.06.014.

[22] F. Grelot, O. Barreteau, Simulation of Resilience of an Insurance System to Flood Risk. *International Environmental Modelling and Software Society (iEMSs) 2012 International Congress on Environmental Modelling and Software Managing Resources of a Limited Planet: Pathways and Visions under Uncertainty, Sixth Biennial Meeting, Leipzig, Germany*, 2012.

[23] J. Hall, B. Arheimer, M. Borga, R. Brázdil, P. Claps, A. Kiss, T.R. Kjeldsen, J. Kriaučiūnienė, Z.W. Kundzewicz, M. Lang, M.C. Llasat, N. Macdonald, N. McIntyre, L. Mediero, B. Merz, R. Merz, P. Molnar, A. Montanari, C. Neuhold, J. Parajka, R.A.P. Perdigão, L. Plavcová, M. Rogger, J.L. Salinas, E. Sauquet, C. Schär, J. Szolgay, A. Viglione, G. Blöschl, Understanding flood regime changes in Europe: a state of the art assessment, Hydrol. Earth Syst. Sci. 18 (2014) 2735–2772, http://dx.doi.org/10.5194/hess-18-2735-2014.

[24] N. Hazarika, T. Tayeng, A.K. Das, Living in troubled waters: stakeholders' perception, susceptibility and adaptations to flooding in the Upper Brahmaputra plain, Nat. Hazards 83 (2) (2016) 1157–1176, http://dx.doi.org/10.1007/s11069-016-2366-1.

[25] F. Krause, “One Man's Flood Defense Is Another Man's Flood”: relating through water flows in Gloucestershire, England, Soc. Nat. Resour. 1920 (May) (2016) 1–15, http://dx.doi.org/10.1080/08941920.2015.1107787.

[26] H. Kreibich, A.H. Thieken, Coping with floods in the city of Dresden, Germany, Nat. Hazards 51 (3) (2009) 423–436, http://dx.doi.org/10.1007/s11069-007-9200-8.

[27] K.H. Liao, From flood control to flood adaptation: a case study on the Lower Green River Valley and the City of Kent in King County, Washington, Nat. Hazards 71 (1) (2014) 723–750, http://dx.doi.org/10.1007/s11069-013-0923-4.

[28] B. Merz, H. Kreibich, R. Schwarze, A. Thieken, Review article, Assessment of economic flood damage, NHESS 10 (2010) 1697–1724.

[29] B. Merz, S. Vorogushyn, U. Lall, A. Viglione, G. Blöschl, Charting unknown water – on the role of surprise in flood risk assessment and management, Water Resour. Res. 51 (2015) 6399–6416, http://dx.doi.org/10.1002/2014WR016259.

[30] P.E. O'Connell, G. O'Donnell, Towards modelling flood protection investment as a coupled human and natural system, Hydrol. Earth Syst. Sci. 18 (1) (2014) 155–171, http://dx.doi.org/10.5194/hess-18-155-2014.

[31] R.A.P. Perdigão, G. Blöschl, Spatiotemporal flood sensitivity to annual precipitation: evidence for landscape-climate coevolution, Water Resour. Res. 50 (2014) 5492–5509, http://dx.doi.org/10.1002/ 2014WR015365.

[32] M.J. Polo, C. Aguilar, A. Millares, Assessing risks for integrated water resource management: coping with uncertainty and the human factor, Iahs 364 (June) (2014) 285–291, http://dx.doi.org/10.5194/piahs-364-285-2014.

[33] I. Rodriguez-Iturbe, A. Porporato, F. Laio, L. Ridolfi, Plants in water-controlled ecosystems: active role in hydrologic processes and response to water stress: I. Scope and general outline, Adv. Water Resour. 24 (7) (2001) 695–705, https://doi.org/http://dx.doi.org/10.1016/S0309-1708(01)00004-5.

[34] S. Salazar, F. Francés, J. Komma, T. Blume, T. Francke, A. Bronstert, G. Blöschl, A comparative analysis of the effectiveness of flood management measures based on the concept of "retaining water in the landscape" in different European hydro-climatic regions, Nat. Hazards Earth Syst. Sci. 12 (2012) 3287–3306, http://dx.doi.org/10.5194/nhess-12-3287-2012.

[35] M. Sivapalan, G. Blöschl, Time scale interactions and the coevolution of humans and water. (2015), http://dx.doi.org/10.1002/2015WR017896.

[36] M. Sivapalan, H.H.G. Savenije, G. Blöschl, Socio-hydrology: a new science of people and water, Hydrol. Process. 26 (8) (2012) 1270–1276, http://dx.doi.org/10.1002/hyp.8426.

[37] D. Skublics, G. Blöschl, P. Rutschmann, Effect of river training on flood retention of the Bavarian Danube, J. Hydrol. Hydromech. 64 (4) (2016) 349–356, http://dx.doi.org/10.1515/johh-2016-0035.

[38] V. Srinivasan, M. Konar, M. Sivapalan, A dynamic framework for water security, Water Secur. 1 (2017) 12–20.

[39] A.H. Thieken, H. Kreibich, M. Müller, B. Merz, Coping with floods: preparedness, response and recovery of flood-affected residents in Germany in 2002, Hydrol. Sci. J. 52 (5) (2007) 1016–1037, http://dx.doi.org/10.1623/hysj.52.5.1016.

[40] M. VanKoningsveld, J.P.M. Mulder, M.J.F. Stive, L. VanDerValk, A.W. VanDerWeck, Living with sea-level rise and climate change: a case study of the Netherlands, J. Coastal Res. 242 (2008) 367–379, http://dx.doi.org/10.2112/07A-0010.1.

[41] A. Viglione, B. Merz, N. Viet Dung, J. Parajka, T. Nester, G. Blöschl, Attribution of regional flood changes based on scaling fingerprints, Water Resour. Res. 52 (2016) 5322–5340, http://dx.doi.org/10.1002/2016WR019036.

[42] A. Viglione, G. Di Baldassarre, L. Brandimarte, L. Kuil, G. Carr, J.L. Salinas, et al., Insights from socio-hydrology modelling on dealing with flood risk, J. Hydrol. 518 (PA) (2014) 71–82, http://dx.doi.org/10.1016/j.jhydrol.2014.01.018.

[43] A. Viglione, R. Merz, J.S. Salinas, G. Blöschl, Flood frequency hydrology: 3. A Bayesian analysis, Water Resour. Res. 49 (2013), http://dx.doi.org/10.1029/2011WR010782.

[44] A. Wałęga, Koncepcja socjohydrologii w analizie zagrożenia powodziowego, Acta Sci. Pol. Formatio Circumiectus 14 (3) (2015) 175–189.

[45] W.E. Walker, D.P. Loucks, G. Carr, Social responses to water management decisions, Environ. Processes 2 (3) (2015) 485–509, http://dx.doi.org/10.1007/s40710-015-0083-5.

[46] R.L. Wilby, S. Dessai, Robust adaptation to climate change, Weather 65 (7) (2010) 180–185.