Perceptual models of uncertainty for socio-hydrological systems: a flood risk change example

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Motivation and aim of this commentary

Characterising, understanding and better estimating uncertainty related to changing socio-hydrological systems are key concerns for the IAHS scientific initiative "Panta Rhei: Change in Hydrology and Society" (Montanari et al., 2013; McMillan et al., 2016). New types of questions and uncertainties come into focus when the hydrological system is expanded to a changing socio-hydrological system (Fig. 1). These add to the already significant uncertainty about how to deal with uncertainty in hydrology (Juston et al., 2014; Nearing et al., 2016; Montanari, 2007; Brown, 2010; Brugnach et al., 2008; Beven, 2012; 2016). This second order uncertainty is not surprising since many of the uncertainties that we have to deal with in both hydrology and socio-hydrology result from a lack of knowledge about processes, boundary conditions and the limitations of data, which means that there can be no right answer. Consequently, any analysis of uncertainty will depend on the person who is doing the analysis and their perceptions of what is important. Eliciting and discussing different peoples' perspectives can therefore expand our knowledge about uncertainty – as well as reduce our exposure to surprises (Merz et al, 2015). For similar reasons, many authors have argued for an open and explicit treatment of uncertainty in environmental research and risk assessment (Stirling, 2010; Refsgaard et al., 2007; Beven, 2012; Brown, 2010; Juston et al., 2013; Spiegelhalter and Riesch, 2011).

A perceptual model is a qualitative (and personal) summary of our knowledge about a system and its complexities, which evolves over time (Beven, 1991). It is useful in any analysis, and is therefore not necessarily related to the use of a conceptual or mathematical model or to management decision support (e.g. McGlynn et al., 2002; Ocampo et al., 2006). Here we suggest developing a *perceptual model of uncertainty* that is complementary to the perceptual model of a socio-hydrological system. It summarises the uncertainties inherent in our knowledge about the system and aims at making all relevant uncertainty sources – and different perceptions thereof – explicit in a structured way. Such a model would be particularly useful in a collaborative field like socio-hydrology, by helping structuring dialogue, communication, and understanding about uncertainty between researchers and stakeholders focusing on different aspects of the coupled system – such as social scientists and hydrologists (Faulkner et al., 2007; Krueger et al., 2016).

We expect any perceptual model to be application-specific. Here we suggest a general methodological approach for identifying and assessing sources of uncertainty that aims to be applicable to complex coupled socio-hydrological systems. We apply our methodology to a flood risk example, where mapping uncertainty about causal phenomena and system response in terms of future flood-generating processes, exposure and vulnerability is central to modelling, reducing and managing risk (Beven et al., 2014; Merz et al., 2015). We believe that the method can be useful as a way of building consensus about uncertainty related to flood risk change – while openly recognizing ignorance and the diversity of perspectives on risk and uncertainty arising from inter- or trans-disciplinary work (van der Sluijs et al., 2010).

#Fig. 1 approximately here#

The nature and characteristics of uncertainty

We first shortly review how uncertainty has been defined in the literature to provide a background to the categories we propose to describe the nature of uncertainty in the perceptual model. Many authors propose to differentiate between uncertainty that arises because of imperfect knowledge (epistemic uncertainty) and aleatory uncertainty that is a result of inherent, stochastic variability (Walker et al., 2003; Ferson et al., 2004; Koutsoyiannis, 2010; Rougier and Beven, 2013). In practice, uncertainty estimates often contain aspects of both these types of uncertainty, e.g., Refsgaard et al. (2007) give the example of the uncertainty in a 100-year flood estimate that depends both on the methods of data collection and analysis (epistemic) and the natural weather variability (aleatory). However, there is disagreement in the literature as to whether epistemic and aleatory are useful labels. Nearing et al. (2016), for example, argue that all uncertainty is fundamentally epistemic and that processes only appear inherently random (aleatory) because we do not understand the underlying processes. Brown (2004) provides a wider definition of uncertainty as *a state of confidence in knowledge*, occurring along the spectrum between certainty and *indeterminacy* (recognising that there are things we cannot know). In between these extremes there may be both *bounded* uncertainty (we know all possible outcomes but not necessarily all corresponding probabilities) and *unbounded* uncertainty (we do not know all possible outcomes and corresponding probabilities). For example, in flood risk analysis we know the possible flood inundation depths over a Digital Terrain Model through physical reasoning, though we often do not know the probability of a certain depth in a particular location for a given flood scenario. This is a case of bounded uncertainty without all probabilities known. Other cases of bounded uncertainty may be constructed where we are more confident we know the complete probability distribution over all possible states of the system (bounded uncertainty with all probabilities known). An example of unbounded uncertainty in the case of flood risk would be the ways of responding to flooding that inhabitants in flood prone areas continuously invent against the background of the regulatory, economic and political systems. We can imagine a set of possible responses even if they have never been observed before, but we just do not know what people's ingenuity will come up with next, let alone attaching probabilities to these possibilities. An example of indeterminable uncertainty (i.e.

things we cannot know and that will therefore always lead to an element of surprise) is the timing of flood events happening in the distant future.

This wider definition of uncertainty as a state of confidence in knowledge is useful as it incorporates the conditional nature of uncertainty as dependent on the methods and people used to estimate it – including the underlying framing of the research problem that we bring to the analysis (see also Brugnach et al., 2008). It puts focus on social influences such as ambiguity of language and scientific philosophy, and psychological factors such as cognitive biases or heuristics in uncertainty treatment (Brown, 2010; Kahneman et al., 1982). It also highlights the role of ignorance (lack of awareness), i.e. that we are really not aware of how imperfect our knowledge is and that we may thus be surprised when "unknown unknowns" occur (Brown, 2010; Merz et al., 2015; Di Baldassarre et al., 2016). Ignorance is personal and can be actively constructed by ignoring extraneous information (that others might find relevant) in closing a problem (Brown, 2010).

A perceptual model of uncertainty

In the same way that a perceptual model of hydrological processes is a qualitative (and personal) summary of the complexity of hillslope and catchment responses – a perceptual model of uncertainty is a similar qualitative summary of uncertainty. The perceptual model of processes is (at least implicitly) the foundation for any mathematical description of hillslope and catchment responses (and for an appreciation of the limitations of a mathematical description). This could also be the case for the perceptual model of uncertainty, and it should likewise evolve over time as we learn about, reduce and expand different uncertainties. In cases where different research and/or stakeholder groups are involved (e.g. scientists, flood warning officers, and floodplain residents), it would be useful for each group to develop their own perceptual models first, and then compare and discuss them.

Our approach to building the perceptual model consists of three steps: 1) Identifying uncertainty in the framing of the studied system and problem; 2) Identifying uncertainty sources in the socio-hydrological system; and 3) Defining the nature, interactions and relative importance of the uncertainty sources. These steps are described in further detail in the following sections. In Table 1 we list a set of general questions to help identify the relevant uncertainty sources (that depend on the application) and investigate their characteristics.

1) Identifying uncertainty in the framing of the studied system and problem

The first step in building the perceptual model of uncertainty is to define the coupled socio-hydrological system under study (Fig. 1) and the particular problem to be addressed. Starting with hydrological systems, these are open systems but they need to be approximated by a closed system to be able to apply mass, energy and momentum balance equations (Beven, 2006). How the system is defined and closed, i.e. which system properties and cross-boundary fluxes are considered and which are ignored, therefore constitutes an important source of uncertainty (Brown, 2010). For example, Graham et al. (2010), study how deep-seepage processes affect water balance closure and show that explicit consideration of uncertainty about different fluxes and flow pathways is needed to draw robust conclusions. Uncertainties about the cross-boundary fluxes that affect the boundary conditions of the system should therefore be identified, including identification of those fluxes that are being excluded. Moving to social systems, we first need to decide which of the systems coupled to hydrology should be included – i.e. which cultural, political and economic systems should be considered? Coupled systems that may potentially be important but have been left out of the analysis should be noted as a source of uncertainty. Then we need to consider how we delineate social systems given the diversity of human impacts and the disparity of social boundaries, e.g. administrative regions, which often do not correspond to river basins (Moss, 2012), how we define social entities (e.g. individuals, groups, practices), and how we relate these to each other and their environment/the hydrological system (e.g. through communication, power, economic exchange). Acknowledging uncertainty in the framing of the research problem itself would be a necessary part of this first step of building the perceptual model, incorporating perspectives of scientists from different disciplines and non-academic stakeholders. This includes recognition of different philosophical research foundations in social and natural sciences, including different views on reality, knowledge and research aims (Owusu, 2016; Krueger et al., 2016).

2) Identifying the uncertainty sources in the socio-hydrological system

The uncertainty sources are application-specific, but would generally include uncertainties in hydrological and social data, process representations, socio-hydrological impacts of hydrological events, and societal response to hydrological events (Table 1 and 2). Non-stationarity of uncertainty in space and time is important to consider, not least when it comes to uncertainty in hydrological and social data – e.g. discharge data uncertainty characteristics vary temporally because of changing river-bed conditions (Westerberg et al., 2011). Uncertainties related to drivers and feedbacks within the system mainly relate to the interplay between social processes and hydrological dynamics, e.g. seasonal and permanent migration patterns in areas affected by flood events (Penning-Rowsell et al., 2013). Conceptual models can be used a tool to explore and learn about such uncertainties, e.g. to what extent socio-hydrological developments are path-dependent so that the history of events exerts control over future behaviour (Beven, 2015; Viglione et al., 2014). Long-term socio-hydrological predictions can be used as tools to explore uncertainties related to possible future system states and boundary conditions, by investigating alternative, plausible and co-evolving trajectories of the coupled human-water system under different conditions (Srinivasan et al., 2016). Finally, we must remember that there may be uncertainty sources that we are not aware of, and that surprises emerging from unknown unknowns or incorrect formulations of emergent behaviour (unforeseen consequences) can play a major role in shaping the actual dynamics of socio-hydrological systems (Di Baldassarre et al, 2016). Merz et al. (2015) suggest approaches such as spatial, temporal and causal information expansion to reduce the potential for surprise in flood risk systems.

3) Defining the nature, interactions and relative importance of the uncertainty sources

For each identified uncertainty source in steps 1 and 2, we propose that the nature of the uncertainty is classified in three classes according to whether it is 1) Bounded, 2) Unbounded, or 3) Indeterminable (Table 1 and 2). Here the bounded category could be further sub-divided according to whether the probabilities associated to the possible states are known or are problematic to define (as discussed in the section The nature and characteristics of uncertainty above). Any interactions between the uncertainty sources are then analysed (see example in Table 2) – this will be an important aspect to consider in any prediction of future change. For example, uncertainties in how the system is closed will directly interact with the uncertainties related to future flood risk. The final step in building the perceptual model is to assess the relative importance of the different uncertainty sources in relation to the formulated research problem. We propose that a quantitative or qualitative scale is first agreed upon and that the importance of each source is then ranked independently by the relevant researchers and stakeholders before the rankings are shared, discussed and potentially reconciled (see van der Sluijs et al. (2005) for a similar approach for model-based assessments). This is expected to help prioritise research efforts and generate a better understanding of the importance of uncertainties from different viewpoints. For example, a political ecologist and a hydrologist may have very different views on the importance of uncertainty sources related to the effectiveness of flood control measures like planting of riparian forests or blocking of upland drainage channels to create wetlands. For the latter, a hydrologist may focus on uncertainty related to flow pathways in the wetlands in relation to their moisture state and position in the landscape. A political ecologist, instead, may focus on uncertainty related to the particular rationality underlying this flood control measure and whether this is contested by local knowledge and creates conflicts with local communities' livelihoods. This is important since political consequences may arise from closing the system in a particular way or using particular uncertainty representations at the expense of competing ones in a decision-making context. Zeitoun et al. (2016), for example, argue that a probabilistic representation of uncertainty where it is not warranted (in the case of unbounded uncertainty) will lead to water security policies that are vulnerable to those uncertainties that the probabilistic representation leaves out and too inflexible in the face of future surprises.

#Table1 approximately here#

A flood risk example

We now present an example of the methodological approach proposed above (steps 1–3) for the analysis of changes in flood risk, defined here as a combination of hazard, exposure and vulnerability. Our example is generic and therefore lists a set of typical uncertainty sources, questions and areas to be assessed in an application to a particular flood risk case. In practical applications the distinction between bounded and unbounded for some uncertainty sources may be different depending on the type of information available. Hydrological studies have focused on the uncertainty in the hazard component, which is mainly caused by the existence of various climate projections and numerous downscaling techniques (e.g. Prudhomme and Davies, 2009). Meanwhile, socio-economic studies have emphasized the role of socio-economic trends in increasing a society's exposure (e.g. Hallegatte et al., 2014). Lastly, it has been shown how changes in society's vulnerability driven by the experience of past flood events can significantly reduce flood damage (e.g. Mechler and Bouwer, 2014). Policy and decision makers have often complained about the lack of clarity about these different sources of uncertainty and the relative importance of knowledge gaps. Moreover, many authors have argued that the spatial and social distribution of risk is often overlooked as measures of flood risk reduction for some might lead to increased flood risk for others (e.g. Collins, 1999).

When building a perceptual model of uncertainty for flood risk change analyses, the socio-hydrological cycle depicted in Fig. 1 can be used as a starting point by clarifying the propagation of the various sources of uncertainty. By following the feedback loop of Fig. 1 from the top-left (*Regional/global climate change*), the diagram can be used to describe how uncertainty in climate change projections affect the estimation of changes in flood hazard (*Hydrology*), which are then experienced by society (*Impacts and Perceptions*), which in turn can respond by changing its vulnerability or exposure (*Policies and Measures*) as well as by introducing new structural measures, which again alter the flood hazard. The influence of hydrology on impacts/perceptions and impacts/perceptions on society are likely to be the most uncertain feedbacks in this loop. Sometimes the feedback can go beyond the system boundaries such as for example the floods in Thailand in 2011, which had worldwide consequences for the manufacturing industry because of global supply chain limitations (Haraguchi and Lall, 2015). Table 2 lists the main sources of uncertainty following the three steps of developing the perceptual model (Table 1) and the feedback loop of the socio-hydrological cycle (Fig. 1).

Many of the sources of uncertainty have unbounded characteristics and relate to how we actively close the system we study (Table 2). This will allow some stakeholders to push certain representations of uncertainty (or neglect some sources of uncertainty altogether) if this fits their interests. For example, emphasising or not the uncertainty of nature-based solutions for flood risk mitigation such as blocked drains, or beaver dams (Nyssen et al., 2011). A situation of uncertainty is often a welcome state for all parties as it allows enlisting a selective interpretation of the unknown into one's pre-existing political agenda (Milman and Ray, 2011). The advantage of being explicit about sources of uncertainty, and their perceived importance, in this context is to facilitate an open discussion of how to address each source – as well as the meaning of the resulting uncertainty estimates. Agreement on what sources of uncertainty are to be considered, and assumptions about their nature, will also provide an audit trail that can later be reviewed and reconsidered as necessary (Beven et al., 2014).

#Table2 approximately here#

Summary

Identifying, characterising, and discussing the uncertainties inherent in our understanding of socio-hydrological systems through a perceptual uncertainty model is a first step to assessing uncertainty in system outcomes. It can raise awareness not only about different sources of uncertainty, but also about different perceptions of uncertainty and can thus help us deal with and eventually reduce uncertainty about uncertainty treatment. We demonstrated how this concept can be applied to flood risk change analysis, but it can be extended to many other areas in socio-hydrology. We posit that open and explicit consideration of uncertainty does not only contribute to the production of more robust and reliable conclusions in socio-hydrology, but that it is an essential part of building trust and possibly consensus between actors in water and risk management – notwithstanding the political forces that will work against trust and consensus and that may benefit from particular perceptions of uncertainty or from ignoring it.

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TABLES

Table 1. The different steps and questions to be addressed in building the perceptual model of uncertainty

Step in building the perceptual model	**Questions to address**
1) Identifying uncertainty in the framing of the studied system and problem	What uncertainties are related to identifying the boundaries of each coupled system?
	What potentially important coupled systems have been left out of the analysis?
	What uncertainties are related to cross-boundary fluxes?
	Is the framing of the research problem different between different researchers and stakeholders?
2) Identifying uncertainty sources in the socio-hydrological system	What uncertainties are there in process representations?
	What uncertainties are there in the data used to study the system?
	Is there spatial and temporal variability in some uncertainties and what is known about it?
	What uncertainties are related to drivers and feedbacks within the system?
	What uncertainties are there related to future boundary conditions?
3) Defining the nature, interactions and relative importance of the uncertainty sources	What is the nature of the uncertainty; is it 1) Bounded, 2) Unbounded, or 3) Indeterminable?
	Which uncertainty sources interact with each other?
	What is the relative importance of the different uncertainty sources from the perspective of different scientists and stakeholders?
	Does the selection and exclusion of particular uncertainty sources have consequences for policy and risk management?

Table 2. Sources of uncertainty in flood risk change analysis and their characteristics. Relative importance (last column) is left blank as these issues should be openly discussed to reflect different opinions and perspectives from different disciplines and stakeholders.

Source of uncertainty	**Nature of uncertainty**			**Interactions with other sources**	**Relative importance**
	Bounded	**Unbounded**	**Indeterminable**		
1) Uncertainty in the framing of the studied system and research problem					
1.1) System boundary: closing the socio-hydrological system	Measurement error in defining divide for river basins from digital terrain model Where are the administrative boundaries?	Are there processes that make the divide non-stationary? What fluxes need to be considered to close the system and study flood characteristics? What coupled systems that may potentially be important have been excluded from the analysis? What alters the frequency and magnitude of floods? Who is affected by floods – large-scale/global impacts? Who responds to them?		1.2	
1.2) Research problem framing		Which socio-hydrological aspects need to be considered?		1.1	
2) Uncertainty sources in the socio-hydrological system					
2.1 Hydrology: Data					
2.1.1 Extreme precipitation: Observation	Gauge errors, radar reflectivity residuals	Neglect of, or incorrect corrections for, gauge errors and		1.1	

		radar error estimates. Errors associated with lack of knowledge of spatial heterogeneity. Data processing errors, unrecorded limitations of past data.			
2.1.2 Extreme precipitation: Spatial distribution	Residuals for any storm given choice of interpolation method	Choice of interpolation method might not be appropriate for all storms, unobserved cells, non-stationary spatial covariance characteristics		1.1, 2.1.1	
2.1.3 River discharge	Water level observation errors, rating curve errors	Data processing errors, unrecorded limitations of past data, extrapolation of rating curve, non-stationarity of measurement conditions		1.1	
2.2 Hydrology: Process representation					
2.2.1 Flood-generation processes: Contributing source area	Variability of the source area contributing to peak flow			1.1 to 2.1.3, 2.2.2	
2.2.2 Flood-generation processes: Event propagation along the river		Effect of upstream flood-protection measures on downstream flooding		1.1 to 2.2.1	
2.3 Impacts and Perceptions					
2.3.1 Flood damage	Error in estimated direct losses to infrastructure	Discrimination between direct and indirect, as well as tangible and intangible losses		1.1, 1.2	
2.3.2 Risk perception	Limited sample for surveys and interviews	Assumptions on the link between flood perception and flood awareness		1.1,1.2, 2.5.1	
2.4 Society: Data					

2.4.1 Human population and socio-economic indicators: Observation	Error in population and gross domestic product data	What happens between two censuses, temporary versus permanent migration		1.1, 1.2	
2.4.2 Human population and socio-economic indicators: Spatial distribution	Errors in spatial data of human population dynamics	Official demographic data cannot properly account for informal human settlements		1.1, 1.2, 2.4.1	
2.5 Society: Process representation					
2.5.1 Vulnerability generating processes	Vulnerability gap (proportion of population living below certain threshold of well-being)	Relationship between flood awareness and flood preparedness		1.1, 1.2, 2.3.2	
2.6 Measures and policies					
2.6.1 Human response to floods and feedbacks	Error in estimated migration patterns	Informal changes in governance and institutions		1.1, 1.2	
2.6.2 Human impact on floods	Error in estimated impact of structural measures, such as major reservoirs, on flood attenuation	Informal processes affecting floods, such as individual measures of protection and regulation of minor structures		1.1, 1.2	
3) Uncertainty in regional/global climate change and socio-economic trends					
3.1 Future flood hazard	Parameterization of flood inundation models	Realism of climate change scenarios, downscaling to hydrological extremes	Surprises in future flood-generating processes	1.1, 1.2	
3.2 Future vulnerability to floods		Change in human vulnerability, e.g. similar events can lead to different losses (adaptation and learning effect versus forgetting and levee effects). Technical innovations? Rapid changes in socio-economic conditions? Future	Unpredictable timing of future events (will e.g. lead to different losses if it happens on Sunday morning or Friday	1.1, 1.2	

		focus on sustainability and environment?	evening). Unexpected technical paradigm shifts		

FIGURE

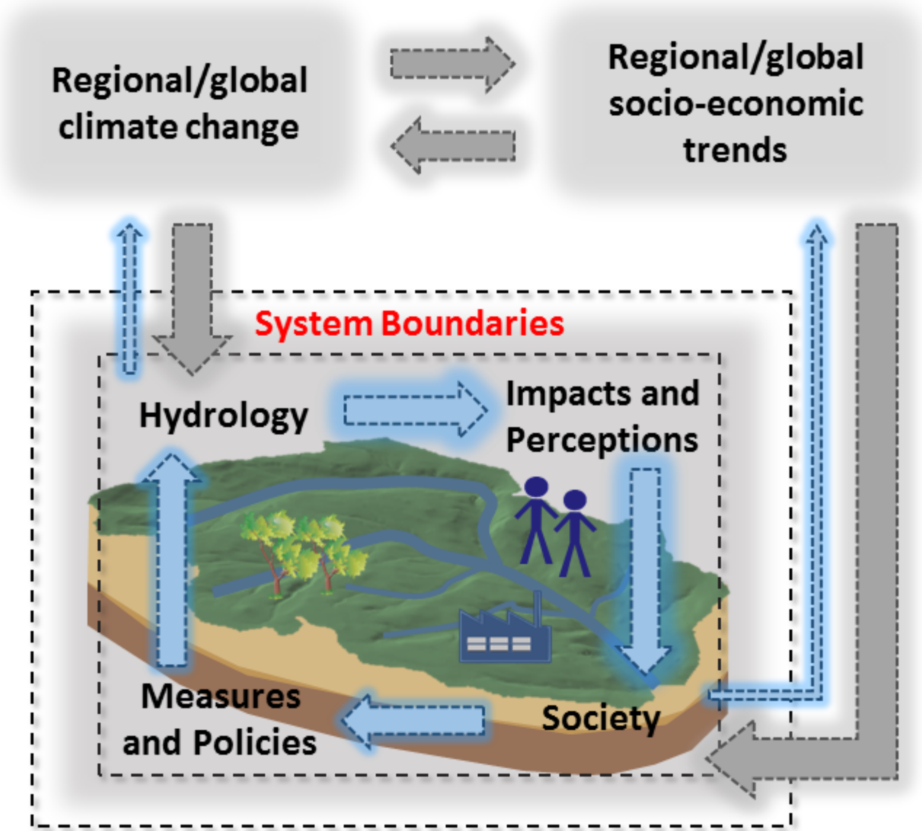

Fig. 1. Uncertainty in the socio-hydrological cycle. The diagram show the internal feedback loop between hydrological and social processes and illustrates the associated uncertainty (thicker arrows indicate more uncertain interactions). It also shows drivers and feedbacks with large-scale (global) climate and socio-economic trends.