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How to embrace uncertainty in participatory climate change risk management — A roadmap

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Key Points:

- Successful climate change risk management requires embracing multiple uncertainties
- We present a detailed, yet flexible roadmap for participatory climate change risk management processes with stakeholders and scientists
- We suggest an uncertainty framework and practical methods for addressing the relevant uncertainties

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Abstract The Earth's future depends on how we manage the manifold risks of climate change (CC). It is state-of-the-art to assume that risk reduction requires participatory management involving a broad range of stakeholders and scientists. However, there is still little knowledge about the optimal design of participatory climate change risk management processes (PRMPs), in particular with respect to considering the multitude of substantial uncertainties that are relevant for PRMPs. To support the many local to regional PRMPs that are necessary for a successful global-scale reduction of CC risks, we present a roadmap for designing such transdisciplinary knowledge integration processes. The roadmap suggests ways in which uncertainties can be comprehensively addressed within a PRMP. We discuss the concept of CC risks and their management and propose an uncertainty framework that distinguishes epistemic, ontological, and linguistic uncertainty as well as ambiguity. Uncertainties relevant for CC risk management are identified. Communicative and modeling methods that support social learning as well as the development of risk management strategies are proposed for each of six phases of a PRMP. Finally, we recommend how to evaluate PRMPs as such evaluations and their publication are paramount for achieving a reduction of CC risks.

1. Introduction

Today, all societies need to manage the numerous risks of anthropogenic climate change (CC), i.e., potential future negative impacts of hazardous events or trends that are due to CC. The Intergovernmental Panel on Climate Change (IPCC) proposes to address the persistent uncertainties of future CC and its impacts by iterative risk management [*IPCC*, 2014a; *Jones et al.*, 2014]. Due to magnitude, complexity, uncertainty, and ambiguity of CC risks, risk management requires the cooperation of a broad range of scientists and stakeholders [*Mimura et al.*, 2014]. The challenge is to design transdisciplinary or participatory processes (PP) that enable a productive and meaningful integration of scientific and stakeholder knowledge of the human-environment systems of interest as well as consideration of the various legitimate concerns and values of all stakeholders [*Renn et al.*, 2011]. While PPs have gained increasing popularity in risk governance and environmental management and are prescribed, for example, by European Union regulations on water and flood management, there is still the need for learning about how to best implement PPs [e.g., *Stokols*, 2006; *Blackstock et al.*, 2007; *Renn et al.*, 2011; *Lang et al.*, 2012; *Klenk and Wyatt*, 2015; *Scholz and Steiner*, 2015].

Scientific projections of the future state of the planet are an important element of participatory CC risk management. However, risk management is hampered by uncertainties concerning future climate and physical hazards caused by CC, characterization of exposure, and vulnerability to these hazards as well as effectiveness and costs of risk management strategies. Scientific projections with small uncertainties would allow rather straightforward adaptation decisions. For example, the height of dykes could be increased by the amount that is computed by quantitative flood projections or assisted migration of species to habitats that are computed to be more suitable for them in the future could be started. However, the prevailing large uncertainties, in particular at the local and regional scales that are of interest for risk management [e.g., *Fatichi et al.*, 2016], prevent this type of risk management. These uncertainties are due to our limited understanding of the human system and the Earth system as well as of their interactions, and include limited knowledge of the state of our world and of interactions of system components. The long time frames that must be taken into account in CC risk management due to delayed responses of the physical system to emission changes increase uncertainties in exposure and vulnerability. Thus, CC has added epistemic uncertainty to the ontological uncertainty inherent in climate-related hazards like floods that is due to the stochastic nature of weather (for definitions of epistemic and ontological uncertainty, see Section 2.2). To achieve an effective, efficient, and fair CC risk management, it is necessary that all participants in the management process have a clear understanding of the multiple uncertainties and that all legitimate interpretations of these uncertainties are considered [*Van Asselt and Rotmans*, 2002].

This is not easily accomplished. A significant body of literature exists on classification of types and levels of uncertainty relevant for decision-making [e.g., *Van Asselt and Rotmans*, 2002; *Ascough et al.*, 2008; *Kwakkel et al.* 2010; *Stirling*, 2010]. However, uncertainty in scientific statements is often interpreted differently by stakeholders and scientists. Given the restricted scientific literacy of many practitioners, they may interpret uncertainty statements as expression of ignorance, which hampers consideration of scientific evidence in decision-making. Scientists may not understand the meaning and relevance of certain types of uncertainties to stakeholders, and interpretations of uncertainties in projected climate and CC impacts differ even among scientists [*Wesselink et al.*, 2015]. Not everything relevant for CC risk management is equally uncertain, and some uncertainties can be characterized better than others. Enormous scientific efforts have been made to understand and partially quantify uncertainties in projections of CC and its many potential hazards. For example, it is well established that hazards that are driven mainly by temperature changes suffer from less uncertainty than hazards that are mainly driven by changes in less predictable precipitation changes. A set of plausible emissions scenarios and multi-model ensembles of climate scenarios has been produced. Those ensembles are increasingly used as input to ensembles of impact models (e.g., hydrological models) such that hazards caused by CC (e.g., a decrease in water availability [*Schewe et al.*, 2014]) can now be assessed regarding their uncertainty. Characterization of uncertainties in vulnerability and exposure is less advanced than characterization of hazard uncertainties. Differences in uncertainties and in our knowledge about them should be fully accounted for when deciding on risk management measures.

While there is broad agreement that insufficient consideration of uncertainties will lead to suboptimal decisions [*Bastin et al.*, 2013], little information is available on how to best address and explore the diversity of uncertainties, and on their significance for participatory risk management. Publications on PPs rarely document or discuss how uncertainties were treated. For example, analyzing 23 participatory scenario planning processes, *Oteros-Rozas et al.* [2015] found that uncertainty was mentioned in the PP description in only 16 cases and only in relation to the drivers of change; uncertainty about the causal relations within the systems of consideration or other types of uncertainty were not mentioned. Scenario generation is a suitable method for dealing with uncertainty about future conditions [e.g., *Stirling*, 2010], but it frequently remains the only instance when uncertainties are dealt with in PPs.

Many local to regional PPs will have to occur to achieve a global-scale reduction of CC risks. The objective of this paper is to provide a roadmap for the design of participatory CC risk management processes (PRMP) in which CC risks are assessed and risk management measures are identified. The roadmap focuses on how to address the many uncertainties that are relevant for PRMPs. It is designed to support those who seek to set up a PRPM by providing (1) a possible structure for such a process, (2) suggestions for dealing with different types of uncertainties throughout the PRMP, and (3) information on specific participatory methods that may be applied depending on the characteristics of the PRMP (problem framing, data availability, participants, and temporal or financial management constraints). Given the large number of methods that may be suitable in PRMPs, methods cannot be presented in any detail, and the list of methods is not exhaustive. The roadmap may also inform social and natural scientists who increasingly participate in PRMPs. It is not suitable for PPs that exclusively aim at identifying local to regional CC mitigation options as in this case no CC risk assessment would be required.

While a number of synthesis papers on PPs include treatment of uncertainties, in particular in participatory modeling [e.g., *Kelly et al.*, 2013; *Hamilton et al.*, 2015; *Voinov et al.*, 2016], a synthesis on how uncertainty might be dealt with specifically in participatory CC risk management processes is lacking. Focusing on a specific (while still very broad) problem field allows us to address the complex and diverse uncertainty issues that are particular to this problem field. We can therefore give more specific guidance on how uncertainty issues relevant for CC risk management are best addressed than has been possible in the synthesis papers without a thematic focus. This paper is based on our experiences with inter- and transdisciplinary knowledge integration [*Döll and Krol*, 2002; *Romero-Lankao et al.*, 2013; *Düspohl and Döll*, 2016], with modeling of CC impacts [*Döll*, 2009] and as co-authors of IPCC reports [e.g., *Romero-Lankao et al.*, 2014; *Jiménez Cisneros et al.*, 2014]. *Voinov et al.* [2016] proposed to work toward a "Good Practice Guide" for participatory assessments to which we wish to contribute with this paper. As a multidisciplinary author team composed of a hydrologist and a sociologist, we also aim at a balanced and comprehensive treatment of both the natural and social science aspects of CC risks and their management.

In the following section, we introduce CC risks and their participatory management and propose a framework for categorizing uncertainties that are important in CC risk management. In Section 3, we present a roadmap for the design of PRMPs that aim at a transdisciplinary generation and integration of system, target, and transformation knowledge (see Section 2.1 for a definition of these knowledge types) about the management of CC risks. In our presentation of the roadmap, we follow the prototypical PRMP phases of preparation (framing/scoping), introduction, risk identification, risk assessment, risk evaluation and identification of risk management strategy. In Section 4, we address the topic of PRMP evaluation. Finally, we draw conclusions and identify research needs.

2. Uncertainty in Participatory Management of CC Risks

2.1. CC Risks and Their Participatory Management

CC risks are a function of (1) the physical hazards caused by CC, (2) the exposure of humans or assets to the hazard, and (3) their vulnerability to the hazard [*IPCC*, 2014a] (Table 1). Vulnerability is a function of both sensitivity and adaptive capacity. CC risks can be reduced by reducing greenhouse gas emissions, i.e., by CC mitigation, and by adaptation to CC [*IPCC*, 2014a]. An example is the risk of water rationing due to groundwater scarcity caused by CC, where the physical hazard is a decrease of groundwater recharge due to CC. If this hazard actually materializes, it has the potential to create negative impacts. The actual impacts will depend not only on the magnitude of the hazard but also on the number of people relying on groundwater for their water supply (exposure), the degree of water scarcity as well the dependence of the population on groundwater for their water supply (sensitivity) and the adaptive capacity, i.e., the ability water users have to draw on income and water infrastructures to respond to and avoid the negative impacts of decreases in groundwater recharges [*Döll*, 2009; *Romero-Lankao et al.*, 2013]. Risk management by CC mitigation (Table 1) reduces CC and thus the hazard (here the groundwater recharge decrease), while adaptation to CC (Table 1) may reduce the hazard (e.g., by decreasing soil sealing) as well as exposure (e.g., by relocation of the population), or sensitivity (e.g., by reducing water demand); it may also enhance adaptive capacity (e.g. by education).

An assessment of exposure and vulnerability should tease out the relative influence of exposure, sensitivity, and adaptive capacity across different social groups. Collaboration among social and natural scientists is necessary to achieve a good assessment of CC risks, combining the natural scientists' expertise on physical hazards and biophysical factors contributing to exposure and vulnerability with the social scientists' expertise on exposure and social vulnerability [*Rothman et al.*, 2014]. Furthermore, expertise of social scientists is needed for the analysis of risk-related concerns of the public and of risk governance. In addition, an interdisciplinary collaboration can illuminate the dual nature of risk as an actual potential for physical change and harm on the one hand and as a social construction on the other hand [*Renn*, 2008]. Scholars have used risk frameworks to discuss challenges to CC risk management in terms of thresholds between tolerable and intolerable risks, conditioned by the frequency and intensity of adverse impacts, which will increase in the absence of strong mitigation efforts [*IPCC*, 2014b, 2014c]. They have also highlighted the highly variable degree to which CC hazards impose risks upon diverse actors in relation to their unique circumstances, livelihoods, perceptions, values, and priorities. Scholars divide this variation into three categories: *acceptable risks* considered sufficiently minimal by stakeholders that risk reduction efforts are not justified; *tolerable risks* or conditions where adaptive risk-reduction efforts are necessary to bring risks from such hazards as droughts, or flooding to within reasonable levels; and *intolerable risks* related to high frequency, intensity, or duration of impacts, caused by unchecked emissions, for which no amount of adaptation effort will alleviate the threats imposed to livelihoods and/or values [*Renn*, 2008; *Dow et al.*, 2013]. The dual components of risk are dynamic, with many risks progressing over time from acceptable to intolerable.

The systemic and dual nature of CC risks, i.e., their complexity, uncertainty, and ambiguity, prevents the determination of a CC risk as a function of a well-defined probability of hazard occurrence and the

Table 1. Concepts and Terms Central for PRMPs

Concept or term	Explanation
Risk	The potential for consequences (impacts) where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values [*Agard et al.*, 2014]. CC risk for each social group depends on the CC-related hazard as well as on exposure and vulnerability of the group
Hazard	The potential occurrence of a natural or human-induced physical event or trend that may cause negative impacts such as disease and damage to property and ecosystems [*Agard et al.*, 2014]
Exposure	The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected by the hazard [*Agard et al.*, 2014]
Vulnerability	The propensity or predisposition to be adversely affected; encompasses sensitivity to hazard and lack of capacity to cope and adapt [*Agard et al.*, 2014]
(Coping/adaptive) capacity	The ability of systems, institutions, and individuals to adjust to potential damage, to take advantage of opportunities, or to respond to consequences [*Agard et al.*, 2014]
Adaptation	The process of adjustment to actual or expected climate and its effects, which seeks to moderate harm, reduce vulnerability or exploit beneficial opportunities [*Agard et al.*, 2014]
CC mitigation	Reduction of greenhouse gas emissions
Deliberation	Open exchange of knowledge and arguments (factual, normative, and subjective knowledge claims) free of coercion of any kind that allows people to come to a rationally motivated agreement (discourse theory and discourse ethics of *Habermas* [1981]). Oriented toward the common good and toward finding the best possible consensus (not compromise) about potential actions based on knowledge about consequences and an agreement on basic human values and moral standards [*Renn*, 2008, p. 298]
Social learning	Learning by communicative interactions among individuals, including cognitive learning (acquisition of new or the structuring of existing knowledge), normative learning (shift in value or paradigm), relational learning (improved understanding of others' mindsets, enhanced trust, and ability to cooperate) [*Baird et al.* 2014] as well as new or changed relations among the individuals and new or changed actions [*Beers et al.*, 2016]. Convergence of perspectives on problems and their solutions [*Van der Wal et al.*, 2014]

CC, climate change; PRMPs, participatory climate change risk management processes.

potential negative impact, as has been done traditionally and remains to be suitable for simple risks [*Renn et al.*, 2011]. Instead, the state-of-the-art is to apply iterative, adaptive, and participatory risk analysis and management [*Jones et al.*, 2014]. This type of risk management is consistent with concepts of adaptive resource management [*Holling*, 1978] including adaptive water management [*Pahl-Wostl et al.*, 2007a], risk governance [*Renn et al.*, 2011] and transdisciplinary research [*Siew and Döll*, 2012]. It is a process of iteratively planning, implementing, and modifying strategies for managing risks in the face of uncertain change. Adaptive management involves adjusting policies in response to observations of their effect and changes in the system [*Agard et al.*, 2014]. Participation refers to the inclusion of a broad range of stakeholders in CC risk management. CC risk management can be conceptualized as the iteration of (1) a preparatory framing (or problem definition) phase which includes the determination of the scope of the specific CC risk management process, (2) an analysis phase comprising risk identification, assessment, and evaluation as well as the development of a risk management strategy and decision-making, and (3) an implementation and subsequent monitoring phase at the end of which the new knowledge on the state of the world and the effectiveness of the implemented measures is assessed, feeding into the next problem definition phase. In this paper, we restrict ourselves to phases 1 and 2.

Participatory CC risk management is consistent with the shift from traditional state-centric and hierarchical approaches to policymaking, supported by scientific expert opinion, to multi-level governance systems including multi-actor alliances of governmental actors and actors from civil society in addition to scientists [*Renn*, 2008]. PPs enable transdisciplinary integration of diverse system knowledges (how does the system work?), target knowledges (which different problem perspectives, values and goals exist?) and transformation knowledges (how to achieve common goals?) [Conference of the Swiss Scientific

Academies/ProClim-, 1997]. A study of the United States Environmental Protection Agency/Science Advisory Board [2001, p. 3] found that “an adequate treatment of science is possible in stakeholder processes, but typically only if substantial financial resources, adequate time, and high-quality staff are available from the outset to allow the necessary deliberation and provide the necessary support on an iterative basis through ongoing interaction with the stakeholders.” Stakeholders learn together how to best deal with risks. This social learning occurs in processes in which stakeholders are connected “in flexible networks that allow them to develop the capacity and trust they need to collaborate in a wide range of formal and informal relationships ranging from formal legal structures and contracts to informal, voluntary agreements” [*Pahl-Wostl et al.*, 2007b]. Participation is assumed to improve not only the quality but also the legitimacy and effectiveness of developed CC risk management strategies that typically need to be implemented by a broad range of stakeholders. Stakeholders include governments/agencies, private sector/industries, civil society/non-governmental organizations, and the general public at various levels from local to global. In PPs, mostly representatives of organizations (such as non-governmental organizations or private companies) participate, even though involvement of the general public, i.e., of individual citizens, should also occur in some form.

In PRMPs, identified risks are assessed and evaluated taking into account the uncertainty of hazards (as derived by climate and impact models), exposure, and vulnerability. After the preliminary identification of risk management options, their robustness with respect to the prevailing uncertainties is investigated, mostly using scenario methods. A widely proposed and applied type of adaptation in the face of climate-related uncertainty are “no-regret/low-regret” measures that do not rely on specific risk scenarios but increase the resilience of the social-ecological system. However, *Dilling et al.* [2015] point out that “no-regret/low-regret” strategies that aim at adapting to current climate variability may even increase CC risks if future dynamics of vulnerability and consequences of adaptation are not taken into account. A number of practical approaches for identifying robust and/or flexible adaptive risk management strategies in the face of large uncertainties have been proposed and applied in some cases (e.g., Robust Decision Making—RDM, [*Groves et al.*, 2014], Dynamic Adaptive Policy Pathways—DAPP, [*Haasnoot et al.*, 2013], and turning points for adaptation measures, [*Werners et al.*, 2013] [see also *Jones et al.*, 2014; *Maier et al.*, 2016; *Kwakkel et al.*, 2016, for a comparison of RDM and DAPP].

In many cases, CC merely exacerbates unsustainable conditions and existing or future risks, e.g., groundwater depletion, loss of biodiversity or floods. Then, the still relatively new CC risks may open up a deadlocked discussion by providing an incentive for new thinking in the face of an external threat.

2.2. Uncertainty Framework

There are many terms that imply aspects of uncertainty (e.g., ignorance, imprecision, ambiguity, and risk), and the term *uncertainty* can have different meanings to different people in different contexts. It is therefore necessary to use a common framework and classification of uncertainty-related terms to discuss and deliberate uncertainty in PRMPs. To devise such a framework, it is helpful to imagine the situation in which there was no uncertainty: (1) future CC impacts are accurately quantified with precision and everyone agrees with this quantification, and (2) optimal risk (or rather impact) management measures can be determined positively and unambiguously in a way that everyone finds fair and optimal. All deviations from this unachievable ideal are uncertainties. We propose to apply an uncertainty framework that slightly modifies the framework of *Kwakkel et al.* [2010] and extends it by using elements and ideas from the uncertainty classifications of *Ascough et al.* [2008] and *Bijlsma et al.* [2011]. Due to its comprehensiveness and terminological clarity, this framework is suitable for addressing uncertainty in PRMPs.

In our framework, three dimensions of uncertainty are used: position, nature, and level of uncertainty (Figure 1). These three dimensions were proposed by *Kwakkel et al.* [2010] who, however, used the term “location” instead of “position,” which may cause misinterpretation as a geographical location. *Position* refers to where the specific uncertainty occurs within the whole participatory risk management process. Within any computational modeling, which is most likely to be part of the PRMP, positions are (1) demarcation of the system boundary, (2) conceptual model, (3) computational model including algorithms, parameters and input variables, (4) coding, and (5) post-processed output [*Kwakkel et al.*, 2010]. Uncertainty of observational and statistical data, often listed in other classifications [*Ascough et al.*, 2008], can be related to uncertainty of input variables of the computational model. However, PRMPs include many

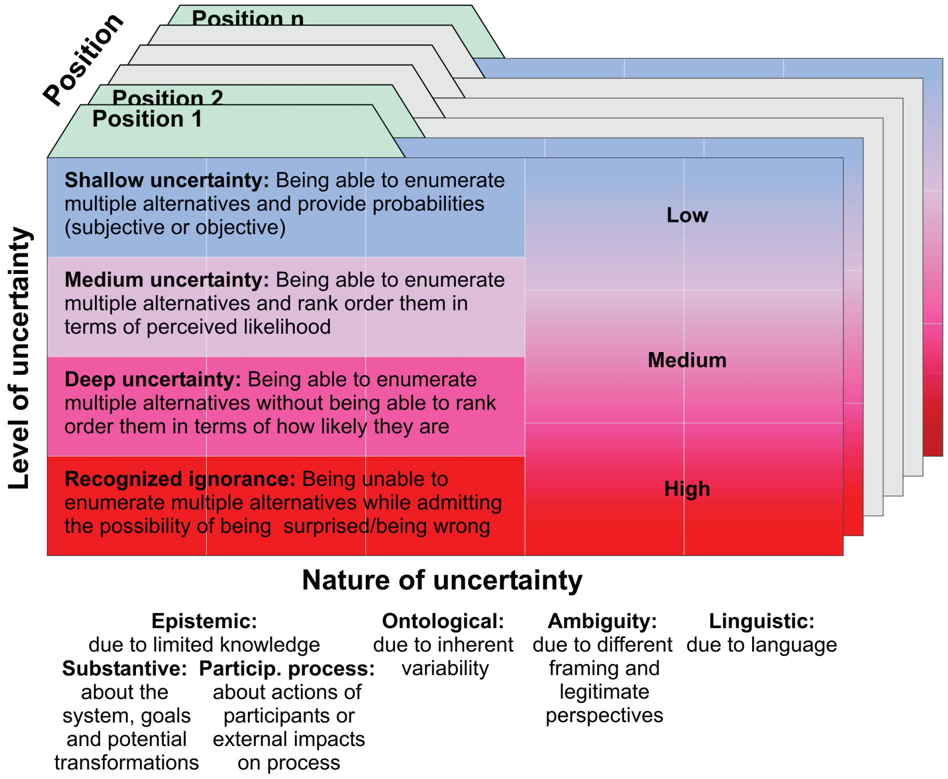

Figure 1. Description of an uncertainty according to its position, nature and level [based on *Kwakkel et al.*, 2010; *Ascough et al.*, 2008; *Bijlsma et al.*, 2011].

other components beyond modeling where uncertainties matter. These positions of uncertainty may be described in a nested way. A supra-ordinate position is, for example, the modeling of the climate system, with the five positions of Kwakkel *et al.* [2010] listed above being its pertaining subordinate positions. Another example of a supra-ordinate position of an uncertainty is the effectiveness of adaptation measures where subordinate positions include process understanding and quantitative relations between cause and effect.

We classify the *nature* of the uncertainty into four categories: (1) epistemic uncertainty, (2) ontological uncertainty, (3) ambiguity, and (4) linguistic uncertainty (Figure 1). *Epistemic uncertainty* is caused by limited knowledge. Following *Bijlsma et al.* [2011], we distinguish two types of epistemic uncertainties relevant in PRMPs and PPs in general: *Substantive uncertainty* is limited knowledge about the substance (content, subject matter) of the problem under consideration, i.e., limited system, target, and transformation knowledge. *Participatory process-related uncertainty* refers to uncertainties within the PP. Somewhat modifying the definitions and terminology of *Bijlsma et al.* [2011], we define PP-related uncertainty as consisting of lack of knowledge about how participants of a PP will act within the PP (internal PP-related uncertainty), and of lack of knowledge how the PP will be impacted by external actions, e.g., by governance actions at a higher level (external PP-related uncertainty). *Bijlsma et al.* [2011] found that PP-related uncertainty was very important for the course of a PP and that there was a low tolerance for PP-related uncertainty in their case study. *Ontological uncertainty*, also called random, stochastic, aleatory or variability uncertainty, refers to the inherent variability of human or natural systems [*Ascough et al.*, 2008]. In PRMPs, relevant ontological uncertainties are due to the stochastic nature of weather that makes it impossible to predict the occurrence of a certain weather hazard or weather-related hazard such as a flood event. In addition, there is a randomness in the composition of the participants of the PRMP regarding their knowledge base, attitudes, and relations, as well as in the governance conditions of the PRMP, e.g., the current political climate [*Ascough et al.*, 2008]. *Ambiguity* is uncertainty arising from multiple legitimate perspectives on the problem under consideration (including its severity, justification, and wider meaning) such that even in the absence of epistemic uncertainty not everybody should or could agree [*Renn*, 2008; *Kwakkel et al.*, 2010; *Renn et al.*, 2011]. Ambiguity exists when stakeholders frame the problem or interpret knowledge differently due to different value systems, expectations, experiences, and forms of knowledge [*Renn*, 2008; *Kwakkel et al.*, 2010]. It remains even after epistemic uncertainty about target knowledge, i.e., knowledge about goals and values of the stakeholders, could be reduced during the PRMP. *Linguistic uncertainty* arises because our language is vague, equivocal, under-specified, and context-dependent, and the meaning of words can change over time [*Regan et al.*, 2002; *Ascough et al.*, 2008]. *Carey and Burgman* [2008] found that explicit treatment of this uncertainty changed the agreement on risks among workshop participants. In case of discussions among participants that do not share the same mother tongue, linguistic uncertainty can be expected to be particularly large. Differences in culturally appropriate ways of communication increase linguistic uncertainty, too.

The nature of an uncertainty affects how it should be handled. Different from ontological uncertainty, the other types of uncertainty may be reduced by human action. Epistemic uncertainty may be reduced by research, ambiguity by specific participatory methods within the PRMP, and linguistic uncertainty by agreed-upon terminology, precise wording, and quantification. So once the position of an uncertainty is defined, its nature should be identified.

In the last step, participants of the PRMP need to address the *level* or degree of an uncertainty, which may range from certainty (deterministic knowledge) to total ignorance. *Kwakkel et al.* [2010] proposed four levels (shallow, medium and deep uncertainty, and recognized ignorance) which differ by the way in which the likelihood of the occurrence of an outcome can be assigned (see explanation in Figure 1). We suggest to use these four levels of uncertainty for describing epistemic and ontological uncertainty, and use levels low, medium, and high to describe the degree of ambiguity and linguistic uncertainty (Figure 1).

PRMPs integrate general systems knowledge about CC processes, risks, and risk management (e.g., about the general impact of CC on agricultural yields or water availability for cities) with knowledge on local conditions (e.g., local precipitation change and number of people living in floodplains). Therefore, uncertainties in knowledge about local conditions and in general systems knowledge need to be considered in PRMPs. IPCC reports, which assess the state of knowledge about CC risks and their management and are therefore a central source for general systems knowledge about CC processes, qualify the findings by a description of their certainty. To avoid linguistic uncertainty in the description of certainty, a calibrated uncertainty language is used in the reports that is common to all IPCC working groups [*Mastrandrea et al.*, 2011]. The IPCC author teams first assessed the amount of evidence (limited, medium, robust) for the specific finding as well as the scientific agreement (low, medium, high) about the finding. If possible, the author teams then evaluated the level of confidence in the finding (very low, low, medium, high, and very high). If confidence could be evaluated, the author teams determined in a third step whether there was enough information available for a probabilistic quantification of the uncertainty of a finding. In this case, the certainty of the finding was described by its likelihood, ranging from exceptionally unlikely (0–1% probability) to virtually certain (99–100%) [*Mastrandrea et al.*, 2011, their table 1].

3. Roadmap for a Comprehensive Treatment of Uncertainties in PRMPs

Consistent with the prototypical phases of participatory risk governance processes [*Renn*, 2008], we have structured the PRMP into a preparation phase and a main phase that includes risk identification, assessment, and evaluation as well as the development of a risk management strategy, with the addition of an introductory phase (Figure 2). Risk identification and evaluation are not included within the risk assessment phase to clearly show their importance. The roadmap explores uncertainties and suggests methods to address them. The core of the PRMP is a series of workshops in which stakeholders, scientists (technical experts), and PP experts collaborate. PP experts are scientists or consultants with experience in PP methods. Collaboration within the workshops should be supported through diverse participatory methods as well as through input to the workshop by PP experts, natural scientists, and social scientists (Figure 2). This input may comprise the results of surveys, focus groups, interviews, data analysis, modeling and literature reviews. The roadmap offers guidance for the design and organization of the PRMP, including: schedule, selection of participants, and choice of applied participatory methods, all of which depend on the specific setting of the PRMP and the available resources.

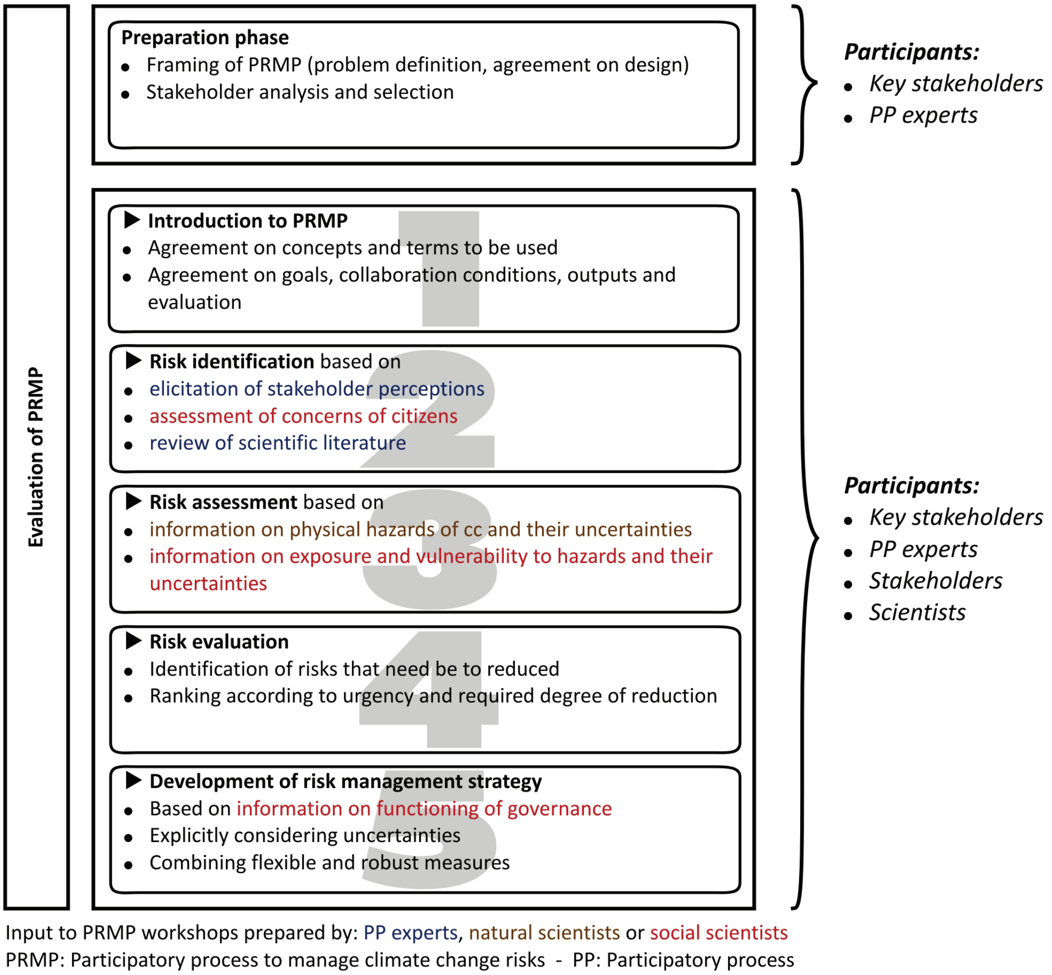

Figure 2. Phases of transdisciplinary knowledge integration in a PRMP, also specifying external inputs to the PRMP workshops by PP experts, natural scientists and social scientists.

3.1. PRMP Preparation Phase

Participants in the preparation phase are key stakeholders (including governmental organizations with remit over CC risk management) and PP experts. Goals are (1) to frame the problem to be addressed, i.e., to agree on scope and objectives to be revisited in the risk identification phase, (2) to identify other stakeholders to be invited, and (3) to agree on the design of the PRMP including a preliminary time plan and organizational issues. While communication with the general public about the PRMP should be agreed on in the preparatory phase, methods and uncertainties of communication with the public are beyond the scope of this paper.

3.1.1. Uncertainties

Substantive epistemic uncertainty (Figure 1) regarding systems, target, and transformation knowledge can be addressed by eliciting the diverse knowledges of stakeholders and scientists; therefore, selection of participants in the PRMP should aim at covering a broad range of knowledge and knowledge types. Ambiguity (Figure 1) arising from different problem perspectives should not be avoided when selecting participants (even if this may make the PRMP more “difficult”) but should be embraced to promote social learning and to make the outcome of the PRMP more likely to be implemented. However, under certain political conditions, not all potential stakeholders can be included in the PRMP. In addition, a certain randomness in the composition of participants cannot be avoided. Barriers to participation mean that some knowledge is always excluded and this carries uncertainties with it. Due to illness and other random events, some knowledge may be missing at decisive moments of the PRMP. Due to a chance encounter at the coffee machine,

Table 2. Main PRMP Participatory Modeling Methods

Modeling Method	Type	Addressed Uncertainties	Applicability in PP Phases	Examples
Causal network[a] /concept map	Qualitative	None	3	[*Düspohl and Döll*, 2016]/[*Catenacci and Giupponi*, 2013]
Actor modeling (based on perception graphs)	Semi-quantitative	Ambiguity (eliciting stakeholder's framing and system, target and transformation knowledge)	2, 3, 5	[*Titz and Döll*, 2009; *Düspohl and Döll*, 2016]
Actor-based modeling	Semi-quantitative	Deep substantive epistemic uncertainty by scenarios of drivers and other model input	3, 5	[*Döll et al.*, 2013]
Bayesian Network modeling	Quantitative probabilistic	Shallow substantive epistemic (as uncertainty in expert belief and output is explicitly quantified) Deep substantive epistemic uncertainty by scenarios of drivers and other model input	3, 5	[*Richards et al.*, 2013; *Catenacci and Giupponi*, 2013; *Düspohl and Döll*, 2016]
(Coupled) component modeling (or integrated modeling)	Quantitative deterministic	Substantive epistemic (only if effect of structural and parameter uncertainties quantified by Monte Carlo method) Deep substantive epistemic uncertainty by scenarios of drivers and other model input	3, 5	[*Rutledge et al.*, 2008; *Schewe et al.*, 2014; *Haasnoot et al.*, 2014]

PP, participatory processes; PRMPs, participatory climate change risk management processes.
Data requirements increase from top to bottom. Some of these and other methods are discussed in *Kelly et al.* [2013] and *Voinov et al.* [2016].
[a] Also basis for actor, actor-based, and Bayesian Network modeling.

two participants may develop a new idea. Unforeseeable political developments external to the PRMP may change its course and relevance. All this causes deep ontological uncertainty (Figure 1).

3.1.2. Methods

A rapid appraisal can be performed for a preliminary understanding of the local CC risks and their management [*Beebe*, 1995]. A stakeholder analysis is indispensable to understand the relationships between groups that will impact the CC risk management and be impacted by it. Based on key stakeholder(s)' knowledge, literature, and focus groups, potential stakeholders can be classified according to their stakes, interest in PRMP, importance, political clout, and networks including power relationships [*Grimble*, 1998]; an influence-interest matrix can be set up. *Reed et al.* [2009] discuss the strengths and weaknesses of various stakeholder analysis methods. Stakeholder analysis is a type of actor analysis [*Hermans and Thissen*, 2009] that is concerned with influence, interest, and networks. It is state of the art that a stakeholder analysis is required for achieving an optimal selection of participants of the ensuing main phase of the PRMP including the development of risk management strategies. We suggest to complement the stakeholder analysis with an actor analysis in which the diverse actor perceptions and perspectives are elicited, modeled and analyzed ("actor modeling" in Section 3.2.2.2 and Table 2). In actor modeling, only participants in the main phase are included and are interviewed before phase 1 of the PRMP (Figure 2). Actor modeling forms the basis for the generation of a shared problem framing and perception in CC risk management.

3.2. PRMP Main Phase

3.2.1. Phase 1: Introduction

Participants of the main phase of the PRMP should include, besides key stakeholders and PP experts, approximately 15 stakeholders and five scientists. If the PRMP group is larger, participatory methods might have to be adapted to enable active participation of all stakeholders, and the PRMP becomes more costly. Objectives of this phase are to (1) introduce the rationale for undertaking a PP to advance CC risk management and to clarify concepts and terms, (2) to introduce and revise the objectives and scope of the PRMP, and (3) to agree on the conditions for collaboration within the PRMP.

3.2.1.1. Uncertainties

While ambiguity can arise from the concurrent presence of multiple valid and occasionally conflicting ways of framing CC risks, linguistic uncertainty can arise when scientists and stakeholders operate with different terms and languages. Another important uncertainty that is best addressed in this phase is PP-related epistemic uncertainty due to uncertain behavior of PRMP participants and uncertain impacts on the PRMP by external conditions.

3.2.1.2. Methods

Phase 1 consists of a sequence of presentations and discussions during a workshop with all participants. First, objectives and scope of the PRMP are presented by the key stakeholder(s). To decrease linguistic uncertainty, the PP experts then introduce the concept of a participatory, iterative, and adaptive management of CC risks (Section 2.1 and Figure 2) including a number of important terms (Table 1). Because in complex problem fields like CC risks, good decision-making requires fully embracing uncertainty, a goal of the PRMP is to explore the many uncertainties that are relevant for finding the best strategies for risk management. The PP experts present the uncertainty framework (Section 2.2 and Figure 1) and stakeholders share their understanding of uncertainty such that a common understanding of different uncertainties and their various aspects can be achieved.

Two discussion phases follow: (1) A discussion about the underlying rationale for PPs according to *Habermas* [1981] and *Renn* [2008]: In contested problem fields such as CC, the best (effective, efficient, legitimate, reflective, and morally right) actions can be identified only through deliberation (comp. Table 1) and negotiation by all stakeholders. The PRMP is designed as an analytic-deliberative process [*Stern and Fineberg*, 1996] that combines scientific expertise with deliberation among all participants. (2) A discussion of objectives and scope of the PRMP, and a potentially necessary enlargement of the participant group, with agreed modifications to be implemented in the PRMP.

To reduce PP-related epistemic uncertainty, the PP experts present a proposal for a “memorandum of understanding” that clearly defines the objectives and scope of the PRMP, the role of the different participants as well as the rules of communication and collaboration [see *Renn*, 2008, pp. 318–320; *Voinov et al.*, 2016, pp. 214–215]. It includes also a list of planned outputs, e.g., joint reports by scientists and stakeholders, papers including their potential co-authors, websites, and social media output. In addition, ways of communication with other stakeholders not included in PRMP and with the public must be discussed. Participants then discuss and modify the memorandum, and finally agree on it as the basis for their joint effort. They also discuss and agree on the time plan of the PRMP.

3.2.2. Phase 2: Risk Identification

The objective of this phase is to identify perceived CC risks, relevant to the stakeholders taking part in the PRMP and—preferably—to the general public.

3.2.2.1. Uncertainties

While scientific knowledge on general CC risks is well developed, and key risks have been identified and described by world regions [*IPCC*, 2014a], substantive epistemic uncertainties remain at the scale of risk management units such as river basins, in particular in developing countries where little information exists at the local scale. A major concern is uncertainty from lack of identification of all risks relevant to scientists, stakeholders, and the general public. For risk identification, ambiguity arises from different stakeholder perspectives and from unacknowledged substantive differences among different knowledge systems that need to be considered in the PRMP. For instance, participants might come from different knowledge traditions (engineers and indigenous communities) or have different stakes on the CC risk issue (e.g., farmers associations and governmental agencies).

3.2.2.2. Methods

To support the identification of all relevant perceived risks, PP experts prepare a preliminary list of risks by synthesizing the results of the following three studies (Figure 2): (1) elicitation of the problem perception of each of the stakeholders involved in the PP in the form of a perception graph, the central element of actor modeling (Table 2), performed by the PP experts, (2) a concern assessment in which the concerns of the general public are determined [*Renn*, 2008], performed by social scientists, and (3) a review of the scientific literature, performed by the PP experts or scientists. These studies are done before the start of the main phase of the PRMP. They help to reduce epistemic uncertainty regarding risks and to better understand epistemic uncertainty and ambiguity. The synthesis is provided to the PRMP participants before the workshop in which they discuss the results, jointly agree on CC risks to be assessed in the next phase, and acknowledge the difficulties of bringing together knowledges (i.e., different types of knowledge) that have different political valences [*Brugnach and Ingram*, 2012].

Actor modeling has the unique capacity to show ambiguity in PPs because perception graphs, derived for each of the stakeholders, show the diverse system, target, and transformation knowledges of the stakeholders, i.e., their problem perceptions and values (Table 2). Perception graphs are directed acyclic graphs that relate stakeholder goals (e.g., the reduction of specific CC risk) with influencing factors, options for action by specified actors and external factors (e.g., change of climatic variables) ([*Bots*, 2007]; actor modeling software DANA at http://dana.actoranalysis.com/). They are semi-quantitative, as factors, utility of goal achievement and causal relations are all expressed on a scale of 7. Perception graphs are constructed during interviews with one or more stakeholders [*Titz and Döll*, 2009]. The guiding questions to stakeholders should include what and who may prevent successful risk management. Elicitation could be introduced by providing information on plausible local CC and related hazards. The various goals included in the stakeholders' perception graphs serve to compile risks in the risk identification phase. Furthermore, perception graphs and their analysis support risk assessment and identification of risk management measures.

Renn [2008, p. 366] suggests concern assessment as an important element of risk governance and management. Concern assessment is a purely scientific assessment (in parallel to a scientific risk assessment done by social and natural scientists) that provides sound knowledge about concerns, expectations, and worries that individuals or groups who do not participate in the PRMP may associate with the hazard. For example, while economists and engineers see water problems best solved through allocation mechanisms, ecologists and indigenous communities might see watershed conservation as the primary concern [*Brugnach and Ingram*, 2012]. While some might consider nuclear energy to be a safe and proven alternative to mitigate climate risks, others might fear its potential negative impacts. As a result, people often put forward conflicting framings of and approaches to the same climate risk concerns [*Romero-Lankao and Gnatz*, 2014].

3.2.3. Phase 3: Risk Assessment

In this phase, CC risks identified in phase 2 are assessed with respect to their magnitude and uncertainty in hazard, exposure and vulnerability.

3.2.3.1. Uncertainties

Substantive epistemic uncertainties in CC risks are apparent at many positions of the social-ecological system, and concern physical hazards, exposure, and vulnerability (Table 3). At the beginning of the causal chain of physical hazards, there is deep uncertainty (Figure 1) in future greenhouse gas emissions and their complex societal drivers. However, this type of uncertainty only becomes important for projections for the second half of the 21st century because near-term climate is strongly conditioned by past greenhouse gas emissions [*IPCC*, 2013]. Dynamics of future hazards are also directly affected by societal activities and processes, e.g., dyke construction, land development, or political turmoil. This likewise leads to deep uncertainty in future hazards, exposure, and vulnerability. The level of all the other uncertainties listed in Table 3 can be characterized as shallow to medium (Figure 1). Except for the change in climatic variables, the uncertainty level depends on local knowledge, data, and modeling capacity. Substantive epistemic uncertainty about CC also affects the way in which ontological uncertainty of hazards that is due to the stochastic nature of weather can be quantified. Due to CC, probabilities of, e.g., flood occurrence can no longer be determined from observations ["Stationarity is dead," *Milly et al.*, 2008].

Table 3. Positions of Substantive Epistemic Uncertainty in Assessing CC Risks, Related to Physical Hazards and to Exposure and Vulnerability

Uncertain Knowledge About	Physical Hazards (Examples Relevant to Freshwater-Related CC Risks)	Exposure and Vulnerability (Examples Relevant to Freshwater-Related CC Risks)
Future human activities	affecting greenhouse gas emissions (Representative concentration pathways) affecting hazard by CC adaptation or other developments (Expansion of urban areas, waste water treatment)	affecting exposure (Land use) affecting vulnerability (Income, water infrastructure, risk perception)
Functioning of	the climate system as simulated by climate models (Climate model structure and parameters, bias-correction, downscaling) the physical system affected by climate change as simulated by impact models (Hydrological model structure and parameters)	the social-ecological system: Vulnerability and its societal and ecological drivers (Capacity of farmers to switch to irrigated farming, adaptability of water users' networks and water management institutions) technological systems (Resilience of water supply and flood protection infrastructure)
Current conditions	(Groundwater recharge, stormflow drainage)	(Number of people living in floodplain, or with access to piped drinking water and sanitation)
Coarse spatial aggregation	(Water management units are smaller than one grid cell of a typical climate model)	(Socio-economic data do not distinguish between people living within the floodplain and outside)
Coarse temporal aggregation	(Climate change projections cannot be reasonably made for a particular year)	(Only decadal census track data on people, buildings and infrastructure available but conditions in developing countries change within a decade)

CC, climate change.

Uncertainty of CC risks is obviously higher than uncertainty of CC hazards, which is due to uncertainties in how economic conditions, land use change, demographic dynamics, perceptions, and governance shape current and future exposure and vulnerability. Like hazard estimation, estimation of vulnerability and exposure is affected by ontological uncertainty, related to the dynamics of everyday life. For example, exposure to hazards may be affected by commuting. It is important to address in this phase of the PRMP the uncertainties of any model output and other information, and their relevance for risk assessment. Identification of dominant uncertainties is recommended.

3.2.3.2. Methods

Risk assessment for simple systems can be done by identifying the probability of a hazard and the magnitude of its impacts. However, the deep und non-quantifiable uncertainties in the dynamics of future hazards, exposure, and vulnerability due to the deep uncertainty in human behavior and its societal drivers (e.g., economic, demographic, cultural and political) make this type of risk assessment impossible. These deep uncertainties can instead be addressed by risk scenarios, i.e., by the descriptions of plausible future risk developments without an assigned probability. Risk scenarios are based on alternative greenhouse gas emissions and socio-economic futures, where the former mainly drive the hazard, while the latter mainly drive future exposure and vulnerability.

The substantive epistemic uncertainty in the causal links between emissions and hazards (due to modeling including bias-correction and downscaling, Table 3) can be considered to be at a medium level, thus allowing some sort of ranking. *Clark et al.* [2016] even suggested that a probabilistic characterization of hydrological hazard uncertainties is possible by a thorough analysis and combination of the uncertainties in the individual computational steps. Currently, CC hazards under a given emissions scenario are estimated best by the analysis of the output of multi-model ensembles that include climate models and, depending on the hazard, impact models such as agricultural yield or hydrological models (e.g., www.isimip.org). Assuming that each output data set is equally likely and that the outputs represent the total probability space, a probability function of future CC hazards under a given emissions scenario can be estimated but this function is itself highly uncertain [*Döll et al.*, 2015]. This approach for considering epistemic uncertainty of future drivers is called "top-down," while the "bottom-up" way is to first identify a threshold for a hazard that, if exceeded and if considered intolerable by stakeholders, will require some action [*Jones et al.* 2014].

In the bottom-up approach, the ensemble of climate or hazard scenarios can be used to determine the likelihood of threshold exceedance.

With multi-model output, maps of changes of, e.g., renewable groundwater resources for different exceedance probabilities can be generated [*Crosbie et al.*, 2013], where the probabilities address different degrees of risk aversion of the water managers [*Döll et al.*, 2015]. According to *IPCC* [2014a, p. 9], "assessment of the widest possible range of potential impacts, including low-probability outcomes with large consequences, is central to understanding the benefits and trade-offs of alternative risk management actions." Therefore, not only multi-model ensemble means should be analyzed but also low-likelihood hazardous trends that may have strong negative impacts due to high exposure and vulnerability.

PRMPs are best supported by local integrated models of CC risks that are driven by (1) a number of CC scenarios covering the plausible local range of CC and (2) by a number of socio-economic scenarios. Such models first compute future CC hazards, exposure, and vulnerability based on scenarios of the drivers and then combine hazards, exposure, and vulnerability to estimate CC risk. In addition, the models should be able to compute the effects of potential risk management measures such that they can be used to support strategy development in phase 5. While natural scientists contribute knowledge and data about physical hazards, social scientists do the same for exposure and vulnerability (Figure 2).

A number of methods exist for integrated modeling in support of PRMPs (Table 2). Which model type is appropriate for a specific PRMP depends mainly on the availability of knowledge, data, and models. While the output of coupled component models may be most informative for a PRMP, such a modeling method is only appropriate in case of good knowledge, extensive data, and existing component models. This type of modeling is so involved that it is difficult for participants to take part in it. At the other extreme, qualitative causal networks or concept maps (Table 2) can easily be constructed in a participatory manner by the stakeholders and allow stakeholders to share, increase and harmonize their systems knowledge but they do not provide any quantitative information. They are a good basis for many types of modeling. Perception graphs of the different stakeholders can be synthesized into one joint perception graph as representation of the social-ecological system under consideration. This joint graph can form the basis for actor-based modeling [*Döll et al.*, 2013] or Bayesian Network modeling [*Düspohl and Döll*, 2016]. Bayesian Networks have many advantages for PRMPs. A number of different disciplinary domains can be easily integrated, the links between factors can be quantified even if only expert beliefs are available, and uncertainty is made explicit by using probabilities to describe states and links. However, results of Bayesian Networks are in general less specific and tangible than results of, e.g., (coupled) disciplinary component models that integrate large amounts of data. A further disadvantage is that temporal developments cannot be easily represented. Guidelines for Bayesian Network modeling including a discussion on sensitivity of Bayesian Network output can be found in *Marcot et al.* [2006] and *Chen and Pollino* [2012]. *Kelly et al.* [2013] discuss advantages and disadvantages of the integrated modeling approaches system dynamics, Bayesian Networks, coupled component models, expert systems, and agent-based models.

Once a good system understanding has been achieved by all participants of a PRMP, joint development of qualitative scenarios is a very good means for knowledge integration and social learning, and for understanding how uncertain future developments might affect CC risk [e.g., *Carpenter et al.*, 2015; *Oteros-Rozas et al.*, 2015; *Düspohl and Döll*, 2016]. For CC risk assessment, participants develop exploratory scenarios that show the different plausible developments of future CC risks [*Maier et al.*, 2016], based on, e.g., a causal network and a derived joint perception graph, or some other sort of system analysis. A practical guideline for development of qualitative scenarios is provided by *Meinert* [2014], while *Cobb and Thompson* [2012] describe how the development of qualitative scenario based on future climate scenarios helps managers to better understand specific vulnerabilities and risks in National Parks.

Qualitative–quantitative scenarios are ideal for CC risk assessment but require the existence of quantitative models. The qualitative scenarios developed with stakeholders serve to derive consistent quantitative scenarios, e.g., by guiding the selection of values of input variables of the applied (integrated) models. In addition, they complement the quantitative scenarios with respect to variables that are not considered in the quantitative model [*Alcamo*, 2009]. Therefore, risk scenarios that combine quantitative with qualitative elements provide a richer description of risk than qualitative or quantitative scenarios alone.

For CC risk assessment, risk scenarios should be derived at least until 2100 as (1) risks can be expected to increase with time unless a strong emissions reduction takes place soon, (2) climate scenarios are available until that time, and (3) there are many human activities whose effects last that long (e.g., urban development and dam construction). If the time until mid-century is considered, a probabilistic approach to the characterization of CC hazards is appropriate as until then, CC depends more strongly on past than on unpredictable future emissions and uncertainty in translating emissions into CC is relatively high [*IPCC*, 2013]. Deep uncertainty of future vulnerability and exposure still requires a scenario approach even if only the near-term future is considered, unless the CC risk assessment is simplified by considering only current exposure and vulnerability (which is not recommended).

3.2.4. Phase 4: Risk Evaluation

The objective of this phase is to evaluate the CC risks assessed in the previous phase to identify the most important risks that should be considered when developing a risk management strategy in phase 5.

3.2.4.1. Uncertainties

Two main uncertainties can arise during risk evaluation: substantive epistemic uncertainty and ambiguity due to different and sometimes conflictive types of knowledge and values involved. Risk evaluation does not only rely on what is known or not known about CC risks but also on the knowledge gained by stakeholders through their experiences and practices.

3.2.4.2. Methods

The risk scenarios generated in the previous phase are analyzed and discussed with respect to (1) risk magnitudes, (2) temporal risk dynamics as caused by the temporal developments of hazards, exposure, and vulnerabilities, (3) which social groups are at major risk and who may benefit, and (4) their uncertainties. Then, risks are ranked according to their overall importance either individually or in small groups. The precautionary principle may lead participants to give risks with a high uncertainty but high potential damage a high rank. This is where deliberations on tolerable and intolerable risks are paramount. The stakeholders discuss their different rankings and different techniques are applied (e.g., dialogical learning) to agree on a ranking if possible. Otherwise, the different rankings should be documented.

3.2.5. Phase 5: Development of a Risk Management Strategy

The objective of this last phase is to develop a strategy for CC risk management by combining measures for adaptation to CC with measures for CC risk mitigation. Focusing on the most important risks identified in phase 4, this involves the identification of measures and assessment of their effects, consideration of costs, benefits, and trade-offs among risk management options, taking into account different social groups and ethical and political aspects. Given the high uncertainty of CC risks, CC risk management should be iterative and adaptive (see Section 2.1). While taking into account the long-term effects of risk management strategies, the PRMPs should consider that due to the uncertainties, strategies identified now need to be re-evaluated and adjusted in the light of new knowledge in, e.g., 10 years. This calls for flexible measures that can be easily abandoned, extended or adjusted and that constrain future options in a minimal way [*Maier et al.*, 2016]. If flexible approaches are not sufficient for CC adaptation, e.g., because infrastructure with large lifetimes is concerned, or because institutions and cultural norms are difficult to change, robust measures that perform satisfactorily under a large range of plausible futures (and not optimally under specific—unknown—future conditions) need to be identified. Adaptation strategies should aim at increasing the resilience of people and the social-ecological system to plausible future changes.

3.2.5.1. Uncertainties

There is substantive epistemic uncertainty in the effectiveness, fairness, cost, and acceptability of risk management measures [e.g., *Olmstead et al.*, 2016]. Table 4 lists the positions of such uncertainties. Ambiguity may be high in particular in case of negative impacts of adaptation measures and regarding their costs and benefits for particular groups. In multi-criteria decision analysis (MCDA) (Section 3.2.5.2), ambiguity affects the selected weights, while indicator choice including the choice of indicator states and drivers are positions of substantive epistemic uncertainty [e.g., *Hyde and Maier*, 2006]. Of all phases, this phase suffers most from PP-related epistemic uncertainty.

Table 4. Positions of Substantive Epistemic Uncertainty in Managing CC Risks by Identifying Suitable CC Adaptation and Mitigation Measures

Uncertain Knowledge About	Example Positions for Freshwater-Related CC Risks
Dynamics of hazard and risk, and their uncertainty	Future changes in flood and drought hazard
Goals of affected populations	Risk aversion regarding flood hazard
Effectiveness of different management instruments and their implications for stakeholders	Effect of financial incentives on water use Technical feasibility of potential new water infrastructure
Costs of mitigation or adaptation for different social groups	Costs of climate proofing water supply and storm water drainage; sources of revenue to cover these costs
Costs avoided by mitigation or adaptation for different social groups	Avoided flood damage
Functioning of governance	Complex water administration structure

CC, climate change.

3.2.5.2. Methods

To support the identification of risk management strategies, we propose to deepen the stakeholder network analysis done during the preparation phase (Section 3.1) by a visual and qualitative participatory network mapping exercise [see *Hauck et al.*, 2015]. Then potential risk management measures including adaptation and mitigation measures are identified. To this end, PRMP participants may develop qualitative normative scenarios in which they explore what measures can lead to an envisioned risk reduction under different scenarios of CC and other external drivers [*Düspohl and Döll*, 2016; *Maier et al.*, 2016]. Stakeholder knowledge about local risk governance including knowledge about the relevance of uncertainty in decision-making processes at various levels (personal, organizational) should be synthesized with knowledge from social sciences (Figure 2 and Table 4).

Then, the model developed for risk assessment is enhanced such that at least the effects of some risk management measures on the social-ecological system under consideration can be simulated. The development of adaptive risk management strategies is preferable. In such strategies, the set of measures 1 is appropriate before a certain turning point, while the set of measures 2 performs better once the turning point is reached [*Werners et al.*, 2013]. Such strategies can be developed with the risk assessment model following the Dynamic Adaptive Polity Pathways approach of *Haasnoot et al.* [2013].

Ideally, the effect of adaptation measures on greenhouse gas emissions and the effect of CC mitigation measures on risk is quantified, too. Non-quantifiable effects should be described in a qualitative manner. If any of the stakeholder groups is risk-averse, it may be suitable to consider only climate projections for a high emissions scenario for identifying plausible adaptation strategies.

To support strategy development, the net effects of risk management measures must be described quantitatively or qualitatively by indicators that allow for comparison of the performance of different measures. Comparison and selection are generally done by MCDA. We suggest applying a simple MCDA method as it is more transparent to stakeholders. *Munda* [2006] propose to perform a quantitative MCDA not to derive the final strategy directly from the quantitative MCDA result but only to support a holistic judgement of the best strategy. In this way, MCDA helps the stakeholders to shape or transform preferences and to make a decision in conformity with their goals. Strategy development in PPs can also be supported by scientific multi-criteria optimization studies, such as the study of *Beh et al.* [2015] who developed an adaptive optimal sequencing approach for urban water supply augmentation under deep uncertainty.

4. PRMP Evaluation

While CC risk management is urgent and requires the collaboration of a broad range of scientists and stakeholders, there is limited experience with participation in CC risk management. Therefore, it is very important to optimize the outcome of PRMPs by optimizing their design. This is best done by learning from PRMP experiences. Hence, evaluation of PRMPs, with publication of results and lessons learned, is necessary for improving CC risk management. Ideally, a set of PRMPs would be organized in such a way that they can be compared to each other, or learn from each other.

Obviously, a PRMP must be evaluated according to its goals. General goals are social learning and the development of a CC risk management strategy. The future outcome of the PRMP, e.g., its political effects, is beyond the scope of the evaluation. *Renn* [2008, his Table 8.3] lists normative, substantive and procedural evaluation criteria. For the evaluation, it is problematic that there is no widely accepted definition for social learning in the management of social-ecological systems [*Van der Wal et al.*, 2014]. An interpretation suitable for CC risk management can be found in *Pahl-Wostl and Hare* [2004, p. 195] who suggest seven capacities that stakeholders need to build up in order to be able to engage in social learning: (1) awareness of each other's sometimes different goals and perspectives; (2) shared problem identification; (3) understanding of the actors' interdependence; (4) understanding of the complexity of the management system; (5) learning to work together; (6) trust; and (7) the creation of informal as well as formal relationships. The first four aspects belong to the social-cognitive dimension, the others to the social-relational dimension of social learning. In the evaluation of a PRMP aiming at a comprehensive treatment of uncertainty, an eighth capacity would be added: understanding of uncertainties affecting risk management (social-cognitive). Convergence of perspectives (similar to capacity 2 above) can be evaluated by asking the participants the same questions before and after the PP, or by comparing perception graphs or concepts maps that were elicited before and after the PP [*Baird et al.*, 2014; *Van der Wal et al.*, 2014; *Düspohl and Döll*, 2016]. To support an improved design of PRMPs, it is important to not only evaluate the overall process but to evaluate the impacts of specific components such as the applied participatory modeling methods or the scenario development [*Düspohl and Döll*, 2016].

PRMP evaluation is discussed with the participants at the end of phase 1. After pointing out the importance of learning from the PRMP experience to improve future PRMPs, the PP experts set the two main PRMP goals to be evaluated, social learning (Table 1) and development of a CC risk management strategy. They suggest suitable evaluation criteria and methods and ask for feedback. PRMP evaluation is performed by the PP experts who share the evaluation results with the participants after the end of the PRMP (or selected evaluation results already during the PRMP).

5. Conclusions

Managing risks of CC is an inevitable but very complex task as CC risks are uncertain, pervasive, and delayed, as well as intertwined with many other risks to a sustainable development. The proposed roadmap encompasses the phase of CC risk management when CC risks are assessed and strategies for risk management are devised in a participatory manner through transdisciplinary knowledge integration among stakeholders and scientists. CC risk management means decision-making under uncertainty, or rather under a multitude of uncertainties; this is why the roadmap focuses on how uncertainties may be addressed in local and regional PPs for CC risk management.

Even with this roadmap, design and implementation of PRMPs will remain a challenge. To achieve a locally adapted and context-specific implementation, a good overall understanding of CC, its uncertain risks and risk management options must come together with an understanding of the local situation, in particular the institutional factors that shape options to address ambiguity [*Brugnach and Ingram*, 2012]. Awareness of the implementation challenges is key. Stakeholders and scientists hold different framings of the CC risk problem, and their interest in participating and collaborating needs to be fostered by creating a CC risk management space that supports collaboration. Research is required to better understand which of the participatory integrative risk modeling methods (Table 2) is suitable given local knowledge, data, and institutional conditions, and how these participatory modeling methods are best implemented within the PRMP, for example, without overloading participants given time constraints. Climate scientists and CC hazard modelers (e.g., hydrologists) need to work on characterizing and quantifying the uncertainty of hazards [see *Clark et al.*, 2016], while social scientists need to understand societal processes determining populations' vulnerability and diverse ways of framing risks. PRMPs should be evaluated with respect to the specific approaches and methods that were applied. Only by sharing experiences and mutual learning can PRMPs become more effective, which is what our societies need for their sustainable development.

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References

Agard, J., et al. (2014), *Annex II: Glossary, in Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* , pp. 1757–1776 , Cambridge Univ. Press, Cambridge, U. K.

Alcamo, J. (Ed) (2009), *Environmental Futures: The Practice of Environmental Scenario Analysis. Developments in Integrated Environmental Assessment*, vol. *2* , pp. 151–168 , Elsevier (ISBN-13:978–0444532930).

Ascough, J. C., II, H. R. Maier, J. K. Ravalico, and M. W. Strudley (2008), Future research challenges for incorporation of uncertainty in environmental and ecological decision-making, *Ecol. Model.*, *219*(3), 383–399, doi:10.1016/j.ecolmodel.2008.07.015.

Baird, J., R. Plummer, C. Haug, and D. Huitema (2014), Learning effects of interactive decision-making processes for climate change adaptation, *Glob. Environ. Change*, *27*, 51–63, doi:10.1016/j.gloenvcha.2014.04.019.

Bastin, L., D. Cornford, R. Jones, G. B. M. Heuvelink, E. Pebesma, C. Stasch, S. Nativi, P. Mazzetti, and M. Williams (2013), Managing uncertainty in integrated environmental modelling: The UncertWeb framework, *Environ. Model. Softw.*, *39*, 116–134, doi:10.1016/j.envsoft.2012.02.008.

Beebe, J., (1995), Basic concepts and techniques of rapid appraisal, *Human Organization*, *54*, 42–51.

Beers, P., B. van Mierlo, and A.-C. Hoes (2016), Toward an integrative perspective on social learning in system innovation Initiatives, *Ecol. Soc.*, *21*(1), 33, doi:10.5751/ES-08148-210133.

Beh, E. H. Y., H. R. Maier, and G. C. Dandy (2015), Adaptive, multiobjective optimal sequencing approach for urban water supply augmentation under deep uncertainty, *Water Resour. Res.*, *51*(3), 1529–1551, doi:10.1002/2014WR016254.

Bijlsma, R. M., P. W. G. Bots, H. A. Wolters, and A. Y. Hoekstra (2011), An empirical analysis of stakeholders' influence on policy development: The role of uncertainty handling, *Ecol. Soc.*, *16*, 1–51.

Blackstock, K. L., G. J. Kelly, and B. L. Horsey (2007), Developing and applying a framework to evaluate participatory research for sustainability, *Ecol. Econ.*, *60*(4), 726–742, doi:10.1016/j.ecolecon.2006.05.014.

Bots, P. (2007), Analysis of multi-actor policy contexts using perception graphs, in *2007 IEEE/WIC/ACM International Conference on Intelligent Agent Technology (IAT'07)*, pp. 160–167, IEEE, Computer Society, Los Alamitos, California. doi:10.1109/IAT.2007.31.

Brugnach, M., and H. Ingram (2012), Ambiguity: The challenge of knowing and deciding together, *Environ. Sci. Policy*, *15*(1), 60–71, doi:10.1016/j.envsci.2011.10.005.

Carpenter, S. R., et al. (2015), Plausible futures of a social-ecological system: Yahara watershed, Wisconsin, USA, *Ecol. Soc.*, *20*(2), 10, doi:10.5751/ES-07433-200210.

Carey, J. M., and M. A. Burgman (2008), Linguistic uncertainty in qualitative risk analysis and how to minimize it, *Annals of the New York Academy of Sciences*, *1128*, 13–17.

Catenacci, M., and C. Giupponi (2013), Integrated assessment of sea-level rise adaptation strategies using a Bayesian decision network approach, *Environ. Model. Softw.*, *44*, 87–100, doi:10.1016/j.envsoft.2012.10.010.

Chen, S. H., and C. A. Pollino (2012), Good practice in Bayesian Network modeling, *Environ. Model. Softw.*, *37*, 134–145, doi:10.1016/j.envsoft.2012.03.012.

Clark, M. P., R. L. Wilby, E. D. Gutmann, J. A. Vano, S. Gangopadhyay, A. W. Wood, H. J. Fowler, C. Prudhomme, J. R. Arnold, and L. D. Brekke (2016), Characterizing uncertainty of the hydrologic impacts of climate change, *Curr. Clim. Change Rep.*, *2*(2), 55–64, doi:10.1007/s40641-016-0034-x.

Cobb, A. N., and J. L. Thompson (2012), Climate change scenario planning: A model for the integration of science and management in environmental decision-making, *Environ. Model. Softw.*, *38*, 296–305, doi:10.1016/j.envsoft.2012.06.012.

Conference of the Swiss Scientific Academies/ProClim- (1997), Researchers Visions. Research on Sustainability and Global Change. Visions in Science Policy by Swiss Researchers. ProClim-, Forum für Klima und Global Change, Schweizerische Akademie der Naturwissenschaften SANW, Bern. [Available at http://proclimweb.scnat.ch/portal/ressources/1122.pdf.]

Crosbie, R. S., T. Pickett, F. S. Mpelasoka, G. Hodgson, S. P. Charles, and O. V. Barron (2013), An assessment of the climate change impacts on groundwater recharge at a continental scale using a probabilistic approach with an ensemble of GCMs, *Clim. Change*, *117*(1–2), 41–53, doi:10.1007/s10584-012-0558-6.

Dilling, L., M. E. Daly, W. R. Travis, O. V. Wilhelmi, and R. A. Klein (2015), The dynamics of vulnerability: Why adapting to climate variability will not always prepare us for climate change, *WIREs Clim. Change*, *6*(4), 413–425, doi:10.1002/wcc.341.

Döll, P. (2009), Vulnerability to the impact of climate change on renewable groundwater resources: A global-scale assessment, *Environ. Res. Lett.*, *4*, 036006 (12 pp.), doi:10.1088/1748-9326/4/3/035006.

Döll, P., and M. Krol (2002), Integrated scenarios of regional development in two semi-arid states of Northeastern Brazil, *Integr. Assess.*, *3*(4), 308–320, doi:10.1076/iaij.3.4.308.13588.

Döll, C., P. Döll, and P. Bots (2013), Semi-quantitative actor-based modeling as a tool to assess the drivers of change and physical variables in participatory integrated assessments, *Environ. Model. Softw.*, *46*, 21–32, doi:10.1016/j.envsoft.2013.01.016.

Döll, P., B. Jiménez-Cisneros, T. Oki, N. Arnell, C. Benito, G. Cogley, T. Jiang, Z. W. Kundzewicz, S. Mwakalila, and A. Nishijima (2015), Integrating risks of climate change into water management, *Hydrol. Sci. J.*, *60*(1), 3–14, doi:10.1080/02626667.2014.967250.

Dow, K., F. Berkhout, B. L. Preston, R. J. T. Klein, G. Midgley, and M. R. Shaw (2013), Limits to adaptation, *Nat. Clim. Chang*, *3*(4), 305–307, doi:10.1038/nclimate1847.

Düspohl, M., and P. Döll (2016), Causal networks and scenarios: Participatory strategy development for promoting renewable electricity generation, *J. Clean. Prod.*, *121*, 218–230, doi:10.1016/j.jclepro.2015.09.117.

Fatichi, S., V. Y. Ivanov, A. Paschalis, N. Peleg, P. Molnar, S. Rimkus, J. Kim, P. Burlando, and E. Caporali (2016), Uncertainty partition challenges the predictability of vital details of climate change, *Earth's Future*, *4*, 240–251, doi:10.1002/2015EF000336.

Grimble, R. (1998), *Stakeholder methodologies in natural resource management. Socioeconomic Methodologies. Best Practice Guidelines*, Natural Resources Institute, Chatham, U. K. [Available at http://www.nri.org/projects/publications/bpg/bpg02.pdf.].

Groves, D. G., J. R. Fischbach, N. Kalra, E. Molina-Perez, D. Yates, D. Purkey, A. Fencl, V. K. Mehta, B. Wright, and G. Pyke (2014), *Developing Robust Strategies for Climate Change and Other Risks: A Water Utility Framework*, RAND Corporation, Santa Monica, Calif. [Available at http://www.rand.org/pubs/research_reports/RR977.html.].

Haasnoot, M., J. H. Kwakkel, W. E. Walker, and J. ter Maat (2013), Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world, *Glob. Environ. Change*, *23*(2), 485–498, doi:10.1016/j.gloenvcha.2012.12.006.

Haasnoot, M., W. P. A. van Deursen, J. H. A. Guillaume, J. H. Kwakkel, E. van Beek, and H. Middelkoop (2014), Fit for purpose? Building and evaluating a fast, integrated model for exploring water policy pathways, *Environ. Model. Softw.*, *60*, 99–120, doi:10.1016/j.envsoft.2014.05.020.

Habermas, J. (1981), Theorie des kommunikativen Handelns, Band 1: Handlungsrationalität und gesellschaftliche Rationalisierung; Band 2: Zur Kritik der funktionalistischen Vernunft, Suhrkamp, Frankfurt am Main (ISBN 3-518-28775-3).

Hamilton, S. H., S. ElSawah, J. H. A. Guillaume, A. J. Jakeman, and S. A. Pierce (2015), Integrated assessment and modelling: Overview and synthesis of salient dimensions, *Environ. Model. Softw.*, *64*, 215–229, doi:10.1016/j.envsoft.2014.12.005.

Hauck, J., C. Stein, E. Schiffer, and M. Vandewalle (2015), Seeing the forest and the trees: Facilitating participatory network planning in environmental governance, *Glob. Environ. Change*, *35*, 400–410, doi:10.1016/j.gloenvcha.2015.09.022.

Hermans, L. M., and W. A. H. Thissen (2009), Actor analysis methods and their use for public policy analysts, *Eur. J. Oper. Res.*, *196*, 808–818, doi:10.1016/j.ejor.2008.03.040.

Holling, C. S. (Ed) (1978), *Adaptive Environmental Assessment and Management*, Wiley, Chichester, U. K. (ISBN: 0-471-99632-7).

Hyde, K. M., and H. R. Maier (2006), Distance-based and stochastic uncertainty analysis for multi-criteria decision analysis in Excel using visual basic for applications, *Environ. Model. Softw.*, *21*, 1695–1710, doi:10.1016/j.envsoft.2005.08.004.

Intergovernmental Panel on Climate Change (IPCC) (2013), Summary for policymakers, in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* , pp. 1–19, Cambridge Univ. Press, Cambridge, U. K. [Available at http://www.ipcc.ch/report/ar5/wg1/.].

Intergovernmental Panel on Climate Change (2014a), Summary for policymakers, in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* , pp. 1–32 , Cambridge Univ. Press, Cambridge, U. K. [Available at http://www.ipcc.ch/report/ar5/wg2/.].

Intergovernmental Panel on Climate Change (2014b), *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 1132 pp., Cambridge Univ. Press, Cambridge, U. K. [Available at http://www.ipcc.ch/report/ar5/wg2/.].

Intergovernmental Panel on Climate Change (2014c), *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 688 pp., Cambridge Univ. Press, Cambridge, U. K. [Available at http://www.ipcc.ch/report/ar5/wg2/.].

Jiménez Cisneros, B. E., T. Oki, N. W. Arnell, G. Benito, J. G. Cogley, P. Döll, T. Jiang, and S. S. Mwakalila (2014), Freshwater resources, in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, pp. 229–269, Cambridge Univ. Press, XXX.

Jones, R. N., A. Patwardhan, S. J. Cohen, S. Dessai, A. Lammel, R. J. Lempert, M. M. Q. Mirza, and H. von Storch (2014), Foundations for decision making, in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* , pp. 195–228 , Cambridge Univ. Press, Cambridge, U. K.

Kelly, R. A., et al. (2013), Selecting among five common modelling approaches for integrated environmental assessment and management, *Environ. Model. Softw.*, *47*, 159–181, doi:10.1016/j.envsoft.2013.05.005.

Klenk, N. L., and S. Wyatt (2015), The design and management of multi-stakeholder research networks to maximize knowledge mobilization and innovation opportunities in the forest sector, *For. Policy Econ.*, *61*, 77–86, doi:10.1016/j.forpol.2015.06.008.

Kwakkel, J. H., W. E. Walker, and V. A. W. J. Marchau (2010), Classifying and communicating uncertainties in model-based policy analysis, *Int. J. Technol. Policy Manage.*, *10*(4), 299–315, doi:10.1504/ijtpm.2010.036918.

Kwakkel, J. H., W. E. Walker, and M. Haasnot (2016), Coping with the wickedness of public policy problems: Approaches for decision making under deep uncertainty, *J. Water Resour. Plan. Manage.*, *142*, 01816001, doi:10.1061/(asce)wr.1943-5452.0000626.

Lang, D. J., A. Wiek, M. Bergmann, M. Stauffacher, P. Martens, P. Moll, M. Swilling, and C. J. Thomas (2012), Transdisciplinary research in sustainability science: Practice, principles, and challenges, *Sustain. Sci.*, *7*(1), 25–43, doi:10.1007/s11625-011-0149-x.

Maier, H. R., J. H. A. Guillaume, H. van Delden, G. A. Riddell, M. Hasnoot, and J. H. Kwakkel (2016), An uncertain future, deep uncertainty, scenarios, robustness and adaptation: How do they fit together? *Environ. Model. Softw.*, *81*, 154–164, doi:10.1016/j.envsoft.2016.03.014.

Marcot, B. G., J. D. Steventon, G. D. Sutherland, and R. K. McCann (2006), Guidelines for developing and updating Bayesian belief networks applied to ecological modeling and conservation, *Can. J. For. Res.*, *36*, 3063–3074, doi:10.1139/x06-135.

Mastrandrea, M., K. Mach, G.-K. Plattner, O. Edenhofer, T. Stocker, C. Field, K. Ebi, and P. Matschoss (2011), The IPCC AR5 guidance note on consistent treatment of uncertainties: A common approach across the working groups, *Clim. Change*, *108*(4), 675–691, doi:10.1007/s10584-011-0178-6.

Meinert, S. (2014), *Field Manual Scenario Building*, 32 pp, ETUI, Brussels, Belgium (ISBN 978-2-87452-314-4). [Available at https://www.etui.org/Publications2/Guides/Field-manual-Scenario-building.].

Milly, P. C. D., J. Betancourt, M. Falkenmark, R. M. Hirsch, Z. W. Kundzewicz, D. P. Lettenmeier., and R. J. Stouffer (2008), Stationarity is dead: Whither water management?, *Science*, *389*, 573–574, doi:10.1126/science.1151915.

Mimura, N., R. S. Pulwarty, D. M. Duc, I. Elshinnawy, M. H. Redsteer, H. Q. Huang, J. N. Nkem, and R. A. Sanchez Rodriguez (2014), Adaptation planning and implementation, in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* , pp. 869–898 , Cambridge Univ. Press, XXX.

Munda, G. (2006), Social multi-criteria evaluation for urban sustainability policies, *Land Use Policy*, *23*, 86–94, doi:10.1016/j.landusepol.2004.08.012.

Olmstead, S. M., K. A. Fisher-Vanden, and R. Rimsaite (2016), Climate change and water resources: Some adaptation tools and their limits, *J. Water Resour. Plan. Manage.*, *142*, 01816003, doi:10.1061/(asce)wr.1943-5452.0000642.

Oteros-Rozas, E., et al. (2015), Participatory scenario planning in place-based social-ecological research: Insights and experiences from 23 case studies, *Ecol. Soc.*, *20*(4), 32, doi:10.5751/es-07985-200432.

Pahl-Wostl, C., and M. Hare (2004), Processes of social learning in integrated resources management, *J. Commun. Appl. Soc. Psychol.*, *14*, 193–206, doi:10.1002/casp.774processes.

Pahl-Wostl, C., J. Sendzimir, P. Jeffrey, J. Aerts, G. Berkamp, and K. Cross (2007a), Managing change toward adaptive water management through social learning, *Ecol. Soc.*, *12*(2), 30.

Pahl-Wostl, C., M. Craps, A. Dewulf, E. Mostert, D. Tabara, and T. Taillieu (2007b), Social learning and water resources management, *Ecol. Soc.*, *12*(2), 5.

Reed, M. S., A. Graves, N. Dandy, H. Posthumus, K. Hubacek, J. Morris, C. Prell, C. H. Quinn, and L. C. Stringer (2009), Who's in and why? A typology of stakeholder analysis methods for natural resource management, *J. Environ. Manage.*, *90*, 1933–1949.

Regan, H. M., M. Colyvan, and M. A. Burgman (2002), A taxonomy and treatment of uncertainty for ecology and conservation biology, *Ecol. Conserv.*, *12*(2), 618–628.

Renn, O. (2008), *Risk Governance: Coping With Uncertainty in a Complex World*, 368 pp., Routledge, Earthscan Risk in Society.

Renn, O., A. Klinke, and M. van Asselt (2011), Coping with complexity, uncertainty and ambiguity in risk governance: A synthesis, *Ambio*, *40*(2), 231 – 246, doi:10.1007/s13280-010-0134-0.

Richards, R., M. Sanó, A. Roiko, R. W. Carter, M. Bussey, J. Matthews, and T. F. Smith (2013), Bayesian belief modeling of climate change impacts for informing regional adaptation options, *Environ. Model. Softw.*, *44*, 113 – 121, doi:10.1016/j.envsoft.2012.07.008.

Romero-Lankao, P., M. Borbor-Cordova, R. Abrutsky, G. Günthner, E. Behrentz, and L. Dawidowsky (2013), ADAPTE: A tale of diverse teams coming together to do issue-driven interdisciplinary research, *Environ. Sci. Policy*, *26*, 19 – 39, doi:10.1016/j.envsci.2011.12.003.

Romero-Lankao, P., and D. M. Gnatz (2014), Mexico city: A tale of water development, its values, and challenges, in *A History of Water, Series III, Volume 1*, edited by T. Tvedt and T. Oestigaard , pp. 629 – 648 , I. B. Tauris, London.

Romero-Lankao, P., J. B. Smith, D. J. Davidson, N. S. Diffenbaugh, P. L. Kinney, P. Kirshen, P. Kovacs, and L. Villers Ruiz (2014), North America, in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* , pp. 1439 – 1498 , Cambridge Univ. Press, Cambridge, U. K.

Rothman, D., P. Romero-Lankao, V. Schweizer, and B. Bee (2014), Challenges to adaptation: A fundamental concept for the shared socio-economic pathways and beyond, *Clim. Change*, *122*, 495 – 507, doi:10.1007/s10584-013-0907-0.

Rutledge, D. T., et al. (2008), Choosing regional futures: Challenges and choices in building integrated models to support longterm regional planning in New Zealand, *Reg. Sci. Policy Pract.*, *1*(1), 85 – 108, doi:10.1111/j.1757-7802.2008.00006.x.

Schewe *et al.* (2013).

Schewe, J., et al. (2014), Multimodel assessment of water scarcity under climate change, *Proc. Natl. Acad. Sci. U. S. A.*, *111*(9), 3245 – 3250, doi:10.1073/pnas.1222460110.

Scholz, R., and G. Steiner (2015), The real type and ideal type of transdisciplinary processes: Part II — what constraints and obstacles do we meet in practice? *Sustain. Sci.*, *10*(4), 653 – 671, doi:10.1007/s11625-015-0327-3.

Siew, T., and P. Döll (2012), Transdisciplinary research for supporting the integration of ecosystem services into land and water management in the Tarim River Basin, Xinjiang, China, *J. Arid. Land*, *4*(2), 196 – 210, doi:10.3724/sp.j.1227.2012.00196.

Stern, P. C., and V. Fineberg (Eds) (1996), *Understanding Risk: Informing Decisions in a Democratic Society, National Research Councel, Committee on Risk Characterization*, Natl. Acad. Press, Washington, D. C. [Available at http://www.precaution.org/lib/nas_understanding_risk.19960601.pdf.].

Stirling, A. (2010), Keep it complex, *Nature*, *486*, 1029 – 1031, doi:10.1038/4681029a.

Stokols, D. (2006), Toward a science of transdisciplinary action research, *Am. J. Commun. Psychol.*, *38*(1 – 2), 63 – 77.

Titz, A., and P. Döll (2009), Actor modelling and its contribution to the development of integrative strategies for management of pharmaceuticals in drinking water, *Soc. Sci. Med.*, *68*, 672 – 681, doi:10.1016/j.socscimed.2008.11.031.

United States Environmental Protection Agency/Science Advisory Board (Science Advisory Board) (2001), *Improved Science-Based Environmental Stakeholder Processes, EPA-SAB-EC-COM-01-006*, EPA Sci. Advisory Board, Washington, D. C.

Voinov, A., N. Kolagani, M. K. McCall, P. D. Glynn, M. E. Kragt, F. O. Ostermann, S. A. Pierce, and P. Ramu (2016), Modelling with stakeholders – Next generation, *Environ. Model. Softw.*, *77*, 196 – 220, doi:10.1016/j.envsoft.2015.11.016.

Van Asselt, M. B. A., and J. Rotmans (2002), Uncertainty in integrated assessment modelling: From positivism to pluralism, *Clim. Chang*, *54*, 75 – 105, doi:10.1023/a:1015783803445.

Van der Wal, M., J. de Kraker, A. Offermans, C. Kroeze, P. A. Kirschner, and M. van Ittersum (2014), Measuring social learning in participatory approaches to natural resource management, *Environ. Policy Govern.*, *24*(1), 1 – 15, doi:10.1002/eet.1627.

Werners, S. E., S. Pfenninger, E. van Slobbe, M. Haasnoot, J. H. Kwakkel, and R. J. Swart (2013), Thresholds, tipping and turning points for sustainability under climate change, *Curr. Opin. Environ. Sustain.*, *5*(3 – 4), 334 – 340, doi:10.1016/j.cosust.2013.06.005.

Wesselink, A., et al. (2015), Equipped to deal with uncertainty in climate and impacts predictions: Lessons from internal peer review, *Clim. Change*, *132*, 1 – 14, doi:10.1007/s10584-014-1213-1.