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Research

Toward a Relational Concept of Uncertainty: about Knowing Too Little, Knowing Too Differently, and Accepting Not to Know

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ABSTRACT. Uncertainty of late has become an increasingly important and controversial topic in water resource management, and natural resources management in general. Diverse managing goals, changing environmental conditions, conflicting interests, and lack of predictability are some of the characteristics that decision makers have to face. This has resulted in the application and development of strategies such as adaptive management, which proposes flexibility and capability to adapt to unknown conditions as a way of dealing with uncertainties. However, this shift in ideas about managing has not always been accompanied by a general shift in the way uncertainties are understood and handled. To improve this situation, we believe it is necessary to recontextualize uncertainty in a broader way—relative to its role, meaning, and relationship with participants in decision making—because it is from this understanding that problems and solutions emerge. Under this view, solutions do not exclusively consist of eliminating or reducing uncertainty, but of reframing the problems as such so that they convey a different meaning. To this end, we propose a relational approach to uncertainty analysis. Here, we elaborate on this new conceptualization of uncertainty, and indicate some implications of this view for strategies for dealing with uncertainty in water management. We present an example as an illustration of these concepts.

Key Words: *adaptive management; ambiguity; frames; framing; knowledge relationship; multiple knowledge frames; natural resource management; negotiation; participation; social learning; uncertainty; water management*

INTRODUCTION

Uncertainty has become highly topical to natural resource management and environmental sciences over the past decade (Pahl-Wostl 2007a, van der Sluijs 2007). This has occurred for two main reasons: one, statistical and computational models can now accommodate more sophisticated approaches to data analysis, and two, the demand for resource management practitioners to address multiple spatial and temporal scales and numerous variables has intensified. As a result, given the levels of precision required for predicting complex system behavior, uncertainty and ways to deal with it have emerged as a subject of analysis in their own right. Furthermore, the perception of the role of uncertainty in resources management has changed. Instead of considering uncertainty as "something to get rid off" or to minimize, it has become accepted as an unavoidable fact of life, and definitional to the problem at hand.

This attitudinal shift has spawned the development of new concepts, such as adaptive management. Adaptive management practices intentionally acknowledge and embrace uncertainty by using scenario planning, employing experimental approaches, and developing flexible solutions that are able to adapt to changing conditions and unexpected developments (Walters 1986, Pahl-Wostl 2007b). At the same time, there has been a parallel conceptual rethinking of the role of social processes in natural resources management, both in terms of how and by whom decisions are made, and their influence in system functioning. Management frameworks reflect these concepts in the use of interactive and participatory approaches that aim at developing and sustaining the capacity for collective action (Walters 1986, Gunderson et al. 1995, Lee 1999, Pahl-Wostl 2007a).

Although all these changes have pressed for novel approaches of analyses, methods used to model

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uncertainty lag behind concept. For instance, conventional, deterministic characterizations have become increasingly unwieldy and experienced a concomitant drop in the ability to provide accurate representations of socio–technical–environmental systems. Furthermore, common approaches and applications of uncertainty analyses (e.g., Monte Carlo simulations used to propagate uncertainty in simulation models) rely on formal and quantitative methods that typically use statistical analyses (e.g., confidence intervals, empirical probability distributions, modeling results, etc.) to characterize different sorts of scientific uncertainties. Although this schema has produced successful results in many fields, such as probabilistic estimates of flood events used to inform the flood management activity (Toth et al. 2000, Krzysztofowicz 2001, Chen and Yu 2007), it fails to adequately function in cases where uncertainty cannot be captured by probabilistic approaches. This is the case when problems are not well defined, information is partial or not always quantifiable, and different sorts of uncertainty are not easily differentiated.

The probabilistic methods usually employed are also ill suited to current decision-making and knowledge-creation processes employed in participatory management. The involvement of multiple parties of diverse backgrounds means that a spectrum of opinions, experiences, expectations, values, and forms of knowledge must be accommodated. In such situations, there are often multiple equally valid ways of framing a problem (Dewulf et al. 2005), which may result in ambiguities and conflicting values about the problem domain and its solution. Therefore, any attempt to deal with uncertainty in natural resource management should also include the plurality of perspectives with respect to the issue at hand (Funtowicz and Ravetz 1990, Pahl-Wostl et al. 1998, Klinke and Renn 2002). Some authors claimed that this can only be achieved by combining analytical procedures with deliberative approaches, as together they can provide a synthesis of scientific expertise and value orientations (Stern and Fineberg 1996, Klinke and Renn 2002, Schusler et al. 2003). It is through the mechanism of deliberation that social learning can occur, enhancing the knowledge available by reflecting public values, purpose, and guidance for action (Schusler et al. 2003). Through learning, it is possible to share diverse perspectives and experiences, and develop a common framework of understanding as a basis for collective action. In this way, it is possible to create the opportunity to discover more innovative and more integrative actions than the ones that are usually considered within a single view on the problem (Duijn et al. 2003, Pahl-Wostl et al. 2007).

Even though there have been several developments in which quantitative and qualitative aspects of uncertainty are combined (e.g., Funtowicz and Ravetz 1990, Klinke and Renn 2002, van der Sluijs et al. 2005), an approach that explicitly integrates social processes and multiple perspectives into uncertainty analyses is, to our knowledge, still lacking. Here, we propose a relational concept of uncertainty analysis, where uncertainties are recontextualized in a broader way: relative to their role, meaning, and relationship with actors in decision making. To this end, we explicitly take into account, in addition to uncertainties associated with scientific information, those uncertainties that result from the multiple, and sometimes conflicting, framing of problems. Our purpose is not to provide a new uncertainty theory and prove it right or wrong, but to examine how a relational approach can provide better capacity to deal with uncertainty, opening up more possibilities for facilitating and intervening in socio–technical–environmental systems. This approach aims at structuring the identification and diagnosis of uncertainties and supporting the process of learning and change that may take place when dealing with natural resource management issues. We also elaborate on some of the implications of the relational approach on the strategies for dealing with uncertainty. An example is used to illustrate these concepts.

FRAMES AND FRAMING

The concepts of frames and framing have been extensively studied in the fields of environmental conflict (e.g., Lewicki et al. 2003), decision making (e.g., Tversky and Kahneman 1981), and negotiation (e.g., Putnam and Holmer 1992), and have lately gained great importance in natural resource management (Bouwen and Taillieu 2004, Dewulf et al. 2005, Pahl-Wostl et al. 2007). According to Pahl-Wostl et al. (2007) during the initial stages of dealing with a problem situation, the processes involved in framing and reframing a problem domain strongly influence the direction of the overall managing process. The framing of a resource management situation defines what is at stake, and who should be included and in what role.

Framing research has important roots in the work on cognitive biases and decision heuristics (Tversky and Kahneman 1981, De Martino et al. 2006). From this perspective, frames are representations of the external world, but these heuristic representations are biased when compared with accurate, decision-theoretical representations (cf. Tversky and Kahneman 1981). This view has been adopted in classical decision-making theory, and served as a basis to study inconsistencies underlying judgment and choice (e.g., Kahneman and Tversky's (1996) work on judgmental heuristics and limitations of intuitive choice). In this context, "framing effects" represent a violation of the standard economic account of human rationality. Having different formulations of what decision theory considers to be the same problem (in terms of expected utility) elicits different preferences: risk aversion can be encouraged by framing the situation in terms of gains, whereas risk seeking is encouraged by framing the situation in terms of losses (Tversky and Kahneman 1981). Although we do not share the assumption of the decision-heuristic approach that there is always a unique and correct decision-theoretical formulation of a decision problem, this research does demonstrate that formulating a problem in a different way may elicit distinct decision preferences (Tversky and Kahneman 1981), affecting the meaning of and the importance attributed to uncertain information, and pointing toward different actions.

We understand frames as sense-making devices (Weick 1995) that mediate the interpretation of reality by adding meaning to a situation. The same situation can thus be framed in multiple, equally valid ways. For example, a situation of water shortage can be framed as a problem of "insufficient water supply" by one actor and, one of "excessive water consumption" by another. When a problem is framed as insufficient water supply, the most relevant uncertainties will be those associated with the amount of water available, and technical solutions that help avoiding water shortage can be favored (e.g., adopt a more efficient irrigation technology, Koundouri et al. 2006). However, when the problem is framed as an excessive water consumption issue, other solutions can be considered, such as changing the way in which water is used and consumed (e.g., diversification of crops). In this case, uncertainties associated with how society will react to a change in land use, or policies that stimulate the change (e.g., Common Agricultural Policy) will be the most important. In this way, frames significantly affect how meaning is inferred and how a situation is understood, serving to define a problem relative to core values and assumptions and to determine how to respond to it (Nisbet and Mooney 2007).

There have been two main approaches to framing research, namely, a cognitive approach where frames are defined as "cognitive representations," and an interactional approach where frames are defined as "interactional co-constructions" (an in-depth comparison of both approaches can be found in Dewulf et al. (2008)). The cognitive approach has focused on frames as knowledge structures. It is based on the idea that frames are memory structures that help us organize and interpret incoming perceptual information by fitting it into pre-existing categories about reality (Minsky 1975). In contrast, the interactional approach focuses on how parties negotiate frame alignments in interactions. It considers frames as communicative devices, that is interactional alignments or co-constructions that are negotiated and produced in the ongoing interaction through "metacommunication" that indicates how a situation should be understood. From this perspective, frames are co-constructions of the meaning of the external world. This view has been adopted in multiparty collaborations and is exemplified in Dewulf et al. (2004) and Putnam and Holmer (1992).

Here, we adopt an interactional approach, where framing is defined as the process through which the meaning of a situation is negotiated among different actors (Putnam and Holmer 1992, Gray 2003a, Dewulf et al. 2004). Thus, framing is thought to be an interactive process where actors are engaged in developing an understanding of problems and alternative solutions. It is through the joint activities of framing, and reframing, that the actors can arrive at a joint problem definition. From this social experience, a common language and a new sense of community can emerge, opening up possibilities for further creativity and developments, and fostering learning and change (Bouwen 2001).

In our definition of uncertainty, we incorporate the concept of multiple frames, in order to capture the difference among multiple forms of knowledge. We consider each frame to represent a potentially valid view of a situation, reflecting the viewpoint of a particular community of practice (Bouwen 2001). Under the rationale of an interactional approach to framing research, we acknowledge the social processing of uncertain information and capture the interactions among actors during deliberative processes of framing and reframing. However, during these processes, encountering multiple frames that are incompatible is unavoidable, and results in ambiguity about the meaning and importance attributed to uncertain information. Next, we discuss and describe some of the implications of ambiguity in the conceptualization of uncertainty.

AMBIGUITY: UNCERTAINTY OF A THIRD KIND

Uncertainty has been defined differently in different domains and disciplines (see Walker et al. (2003) for a review). Amid the variety in definitions, one thing on which many authors agree is the distinction between the ontological and epistemic nature of uncertainty. This distinction is important because it suggests different ways of addressing uncertainty (Walker et al. 2003). Authors, such as Walker et al. (2003), Klauer and Brown (2004), and Refgaard et al. (2005) refer to epistemic uncertainty, as the imperfection of knowledge about a system, and to ontological uncertainty, as the inherent variability or unpredictability of the system. Similarly, van Asselt and Rotmans (2002), in their typology of sources of uncertainty, make the distinction between variability uncertainty and limited knowledge. In this paper, we incorporate a third dimension in the nature of uncertainty: the ambiguity that results from the simultaneous presence of multiple frames of reference about a certain phenomenon (Dewulf et al. 2005).

Weick (1995) defined ambiguity not as a lack of information, but as too many possible interpretations of a situation. Some authors make a clear distinction between the categories of uncertainty and ambiguity. Klinke and Renn (2002), for example, make the distinction between complexity, uncertainty, and ambiguity in risk management. They highlight the importance of ambiguity related to different equally valid interpretations of knowledge and different normative judgements on acceptable risks. van Asselt and Rotmans (2002) introduce a pluralistic approach and make an explicit link between the presence of multiple perspectives and the management of uncertainty. We also deem it crucial to take into account ambiguity resulting from multiple frames. However, we consider ambiguity as a third kind or nature of uncertainty, along with ontological and epistemic uncertainty, rather than just a source of uncertainty. For us, the relevant dimension for ambiguity is not the one from complete knowledge to complete ignorance, but something ranging from unanimous clarity to total confusion caused by too many people voicing different but still valid interpretations (Dewulf et al. 2005).

Considering ambiguity as a different “nature” of uncertainty can also help develop more useful strategies to deal with it. When confronted with multiple incompatible frames, there are other options than either trying to “correct” the frames or to single out the only right one (an epistemic strategy), or accepting these frame differences as an unchangeable fact (an ontological strategy). In this way, ambiguity brings into focus strategies that aim at integrating different frames, negotiating a mutually acceptable frame, or finding a workable relation between the different views and actors. The incorporation of ambiguity as another dimension in the conceptualization of uncertainty leads us to propose the following definition: “Uncertainty refers to the situation in which there is not a unique and complete understanding of the system to be managed.”

RECONSIDERING UNCERTAINTY AS A KNOWLEDGE RELATIONSHIP

In the above definition, uncertainty is viewed from the point of view of a decision maker who is somehow affected by this uncertainty, in understanding a problem and reacting to it; mediating the translation of uncertainty into an action choice (e.g., in making a model, in assessing a situation, or in making a water management decision; Pahl-Wostl 2002). However, the idea to integrate the human actors (e.g., decision maker, stakeholder) into the conceptualizations of uncertainty has already been the subject of a vast body of research. To this end, several theories, that are suitable for including human opinions and judgments, have been developed (e.g., Bayesian probability theory (Carlin and Louis 2000), possibility theory (Dubois and Prade 1988), evidence theory (Schafer 1976), fuzzy set theory (Zimmermann 1985), certainty theory (Kanal and Lemmer 1986)) and applied in the field of natural resource management (e.g., Bayesian decision analysis for environmental management, Pestes et al. (2007)). Here, however, we propose going beyond a subjective understanding of a decision situation, and focusing on the properties that define the relationship between a decision maker and the socio–technical–environmental system.

When a decision maker makes a decision about a particular issue, there is more to problem understanding and sense making than an individual (subjective) interpretation. Actors are not isolated, but are part of a social network and any problem definition or action choice influences and is influenced by other actors (Brock and Durlauf 2001). Hence, the social context in which the subject is embedded, or the communities of practice in which the actor takes part, shape the way in which a problem is understood and the meaning that is given to it (Wenger 1998). Dealing with natural resource issues requires the participation of multiple stakeholders: where experts, manager practitioners, politicians, and scientists are brought together to collaborate in finding feasible and acceptable solutions for a common problem. The inclusion of such a diversity of actors entails an exchange of knowledge from different backgrounds and disciplines, where different paradigms, experiences, and assumptions must be made compatible. This implies a shift in the way in which knowledge is conceived.

When considering the social context in which the decision maker is embedded, knowledge is influenced by the interaction among different actors and other elements of the system. Under this rationale, knowledge is understood to have both a content and a relational aspect (Bouwen 2001). The content refers to “what” is being understood. This includes formal and systematic knowledge, such as hard and quantifiable data (e.g., scientific knowledge). The relational aspect refers to “who” is being included or excluded from the problem understanding. Thus, knowledge becomes specific to a particular situation. This is different from a pure cognitive understanding of knowledge, a view that is deeply ingrained in the traditional way of management, where the focus is only on content, or substance, and knowledge is conceived as information units that are transferred from one individual to another (Bouwen and Taillieu 2004).

From a relational perspective, we consider uncertainty impinging on a decision situation has no meaning in itself, but acquires meaning through the relationships established between the decision maker and the socio–technical–environmental system. The decision maker operates at both the content and relational levels. In this way, the definition of a problem and what is uncertain about it depends not only on scientific or expert understanding, but on the knowledge, views, and preferences of the decision maker in relation to those of other actors with whom the decision maker interacts to make sense of the situation (Schusler et al. 2003). Uncertainty, then, becomes a property of how an individual in a social context relates to a system through certain practices and activities (e.g., managing water), involving knowledge of different kinds. Being explicit about the type of relationships established between an actor and the system is important because it reveals the assumptions that actors hold. By frame-breaking interactions, it is possible to uncover alternative relations that can change the meaning of the problem and open up opportunities for new solutions (Bouwen 2001).

Treating uncertainty as a relation involves three elements: (1.) an object of perception or knowledge (e.g., the socio–technical–environmental system); (2.) one or more knowing actors (e.g., a decision maker) for whom that knowledge is relevant; and (3.) different knowledge relationships that can be established among the actors and the objects of knowledge. Next, we describe the types of knowledge relationships that can be established and the objects of knowledge these relationships are based on.

TYPES OF UNCERTAIN KNOWLEDGE RELATIONSHIPS

Based on the distinction of uncertainty by its nature, we identify three types of knowledge relationships: unpredictability, incomplete knowledge, and multiple knowledge frames. Each of these relations differs in the nature of the involved uncertainty (ontological, epistemic, ambiguity) and thus, the kind of knowledge relationship between what and who are involved. Even though unpredictability and lack of knowledge have already been the subject of an extensive body of research, it is when considered together with multiple frames that they provide a comprehensive framework for analyzing uncertainties in natural resource management.

Unpredictability

The systems to be managed are complex systems, whose behavior is variable in space and time. These systems are constantly learning and adapting to new conditions. They express a non-linear and sometime chaotic behavior, and are very sensitive to initial or boundary conditions. These characteristics make them impossible to predict. With this kind of uncertainty, we accept the unpredictability of the system as something that will not change in the foreseeable future (ontological uncertainty, Walker et al. (2003)).

Incomplete Knowledge

This type of relationship refers to situations where we don't know enough about the system to be managed, or where our knowledge about it is incomplete (epistemic uncertainty, Walker et al. (2003)). This can be due to a lack of information or data, to the unreliability of the data that is available, to lack of theoretical understanding, or to ignorance. Uncertainty that comes from incomplete knowledge can, in some situations, be reduced with enough time and means. However, this must not necessarily imply an increase in predictability. Doing more research may even uncover other uncertainties. The knowledge relationship may, for example, shift from incomplete knowledge to unpredictability.

Multiple Knowledge Frames

This relationship refers to the situation where there are different, and sometimes conflicting, views about how to understand the system to be managed. It is important to note that these different views may all be plausible and legitimate. Ways of understanding the system can differ in where to put the boundaries of the system or what and whom to put as the focus of attention. Differences can also emerge from the way in which the information about the system is interpreted. Different decision makers can give different meanings to this information (e.g., about what the most urgent problems are).

OBJECTS OF KNOWLEDGE

The objects of knowledge (sensu van Asselt and Rotmans (2002)) considered are: the natural, the technical, and the social systems. Although we assume that these systems are closely interlinked in a complex socio–technical–environmental system, it is useful to determine which part of the system an uncertainty refers to. These objects constitute analytical categories to help decision makers organize their knowledge about the system, taking into consideration that the knowledge about each of these subsystems is of a different kind.

Natural System

The natural system includes, along with its aspects of climate impacts, water quantity, water quality, and ecosystem.

Technical System

The technical system includes the technical elements/artifacts that are deployed to intervene in the natural system, with infrastructure (e.g., dams) and technologies (e.g., sprinkler irrigation).

Social System

The social system includes economic, cultural, legal, political, administrative, and organizational aspects.

If we combine both dimensions, the three uncertainty relationships can be applied to the three subsystems of the water management regime. Each combination leads to specific uncertainty questions (Table 1).

IMPLICATIONS OF A RELATIONAL VIEW ON THE STRATEGIES FOR DEALING WITH UNCERTAINTY

Uncertain knowledge relationships express the specific understanding an actor has about a problem situation. Multiple relationships can be present simultaneously, implying different aspects of problem understanding. The identification of uncertain knowledge relationships is important because each relationship suggests a range of relevant strategies to deal with uncertainty while hindering others. When a decision maker understands uncertainty as inherent unpredictability, he or she "accepts not knowing" and will probably

Table 1. Examples of uncertainties identified in each of the three knowledge relationships and objects of knowledge

	Unpredictability (unpredictable system behavior)	Incomplete knowledge - lack of information - unreliable information - lack of theoretical understanding - ignorance	Multiple knowledge frames - different and/or conflicting ways of understanding the system - different values and beliefs - different judgement about the seriousness of the situation, growth potential of problems, priority of actions or interventions
Natural system - climate impacts - water quantity - water quality - ecosystem	Unpredictable behavior of the natural system, e.g., How will climate change affect weather extremes?	Incomplete knowledge about the natural system, e.g., What are reliable measurements of water levels?	Multiple knowledge frames about the natural system, e.g., Is the main problem in this basin the water quantity or ecosystem status?
Technical system - infrastructure - technologies - innovations	Unpredictable behavior of the technical system, e.g., What will be the side-effects of technology X?	Incomplete knowledge about the technical system, e.g., To what water level will this dike resist?	Multiple knowledge frames about the technical system, e.g., Should dikes be built or flood plains created?
Social system - organizational context - stakeholders - economic aspects - political aspects - legal aspects	Unpredictable behavior of the social system, e.g., How strong will stakeholders' reactions be at the next flood?	Incomplete knowledge about the social system, e.g., What are the economic impacts of a flood for the different stakeholders?	Multiple knowledge frames about the social system, e.g., Should water markets be introduced to deal with water scarcity or negotiation platforms?

not choose strategies that involve improving predictive models, but rather strategies that aim at managing the system with its irreducible uncertainties. When a decision maker understands uncertainty as incomplete knowledge or "knowing too little," efforts are probably going to be directed at remedying the deficiencies in the available knowledge by gathering more information, or doing or contracting more research. When a decision maker understands the uncertainty as multiple knowledge frames, strategies addressing the relation between these multiple frames and actors are likely to be adopted in order to deal with the situation of "knowing too differently." Here, we do not aim at identifying the supposedly best strategy, but rather the relevant range of strategies a decision maker might consider from within each of the aforementioned knowledge relationships.

Our approach can help make explicit all knowledge relationships, considering that ignoring certain kinds of relationships may impede finding a solution to a problem. For example, Gray (2004) illustrates this situation with a case in which a conflict about the establishment of a nature park and center for ecotourism could not be resolved because certain knowledge relationships were neglected. In this case, authorities and environmental groups defined the conflictive issue, and its major uncertainties, as the amount of compensation payments for the local farmers. However, the local population saw their identity, and the identity of the whole region, severely threatened by the way in which environmental groups and government conceived the problem. This lack of transparency, and failure to incorporate farmers' understanding, resulted in a polarization of viewpoints and the incapacity to create a joint basis of communication to find a solution.

Furthermore, we do not distinguish between different motives underlying the adoption of a knowledge relationship. A decision maker may have strategic reasons for adopting certain knowledge relationships, claiming for example that knowledge is incomplete in order to delay a decision. However, we assume that our approach can structure a dialog and make different knowledge relationships more obvious. Next, we outline some of the relevant strategies to approach uncertainty in the different knowledge relationships.

Strategies for Dealing with Unpredictability

Unpredictability implies accepting that it is not possible to make deterministic predictions about a phenomenon and that doing more research will not change this situation in the near future. Under these circumstances, control is one of the strategies that is commonly applied (Ackof 1983). The underlying rationale is that to overcome the lack of predictability, a system can be influenced by interventions that generate favorable conditions (e.g., when variations in the flow rate of a river cannot be predicted, it is possible to build a dam to artificially control the flow rate). Although control measures have been widely applied in natural resources management, they often include large-scale infrastructure and, therefore, present the drawbacks of large sunk costs and lack of flexibility to deal with emerging challenges. Furthermore, the failure of control generally entails substantial damage (e.g., collapse of a dike).

As suggested in the field of adaptive management, a more effective way of dealing with unpredictability is to avoid control by creating the capacity, through learning and adaptation, to respond flexibly and effectively to changing and unknown conditions. There are several relevant strategies for facing a (partially) unpredictable and (partially) uncontrollable phenomenon that has potential negative effects. They can be summarized as:

- To identify multiple possible future scenarios and to develop “robust solutions” that are useful under each of the different scenarios (Pahl-Wostl 2007b).
- To “diversify” the measures or solutions to ensure that one or more measures will be effective under each of the possible scenarios, even if some of the measures fail (e.g., using dikes and floodplains).
- To control damage, or to adapt to an unpredictable uncontrollable phenomenon by dealing with the consequences and not with the phenomenon itself (e.g., physical or financial damage control in the event of a flood).
- To combine multiple strategies to maximally control the negative effects in the chain of consequences (e.g., combining robust solutions with damage control).
- To apply temporary adaptation strategies: measures that are feasible within the timeframe of an unfolding event (e.g., a storm surge barrier that is closed only under extreme weather conditions).
- To improvise. This implies that the strategies are not planned beforehand but thought up and implemented in the time frame of the unfolding events. This strategy relies on good monitoring, communication, and coordination capacity in crisis situations.

Strategies for Dealing with Incomplete Knowledge

Incomplete knowledge implies that, in principle, uncertainty could be reduced or even eliminated by carrying on more research, or collecting more or better data, in order to improve the description and understanding of the situation. To this end, science and the scientific method, through an incremental process of theory construction and data gathering can gradually work toward increasing understanding and reducing uncertainties about a problem.

Relevant strategies can be summarized as follows:

- Range estimation (confidence intervals)
- More data gathering and scientific research to complete or improve the factual knowledge base
- Simulation models for evaluating implications of imperfect knowledge
- Uncertainty propagation in models
- Use of expert opinions

In this context, the use of computer models offers a general and flexible framework that can aid the process of problem analysis (Brugnach and Pahl-Wostl 2007). In cases of unpredictability or incomplete knowledge, strategies that allow evaluating and quantifying the effects of uncertainty, such as sensitivity, uncertainty, and scenario analyses, become important (Brugnach et al. 2007). Sensitivity analysis is a general approach to understand the behavior of simulation models that may be used to represent and analyze the dynamics of the system under consideration. Sensitivity analysis implies studying the relationship between information flowing in and out of the model (Haefner 1996, Saltelli 2000, Beck 2002). The analysis aims at measuring the sensitivity of an output to variations in input factors, like parameters or input data. Uncertainty analysis constitutes another commonly used approach of uncertainty evaluation. It measures the uncertainty of models' results. This class of analysis is concerned with estimating the overall uncertainty of model output given the uncertainty associated with parameters or input data (Campolongo et al. 2000). Scenario analysis is another approach to understand the effects of uncertainty. It aims at simulating different possible scenarios, each of which embeds different assumptions about the future.

Although these analytical approaches do not necessary complete knowledge, their usefulness resides in assessing how lack of knowledge affects the description and understanding of a situation. Used in combination, they can serve to identify where more research or better data are needed, or to devise or improve monitoring plans. However, it should also be noted that despite the need for more research, the cost, time, and urgency of a problem should be taken into consideration when choosing a strategic solution. As exemplified by Lauck et al. (1998) in fisheries management, accepting the inevitability of errors and planning cautious measures may be the most appropriate criteria. Further on, it should be noted that attempts to complete knowledge do not always yield the desired result: new uncertainties may be uncovered.

Strategies for Dealing with Multiple Knowledge Frames

Multiple or conflicting views about how to understand the system often represent different kinds of knowledge that are difficult to reconcile or integrate. The incompatibility in frames may result from different scientific backgrounds, from differences between context-specific experiential knowledge and general expert knowledge, from different societal positions or ideological backgrounds, and so forth. In relational terms, actor A has a certain knowledge relation to phenomenon X, and actor B has a different knowledge relation to the same phenomenon X. In this kind of situation, relevant strategies address the relationship between A and B for dealing with the frame differences.

Bouwen et al. (2006) outline relevant strategies for dealing with multiple knowledge frames based on deliberative approaches toward resolving conflicting views. A first approach, "persuasive communication," consists of trying to convince others of one's own frame of reference, not by imposing it but by presenting it as attractive and worthwhile (see, e.g., Bouwen and Fry (1991)). A second approach, the "dialogical learning" approach, aims at understanding one another's frames better through open dialog and by encouraging learning on all sides (see, e.g., Argyris and Schön (1978)). A third approach, the "negotiation approach" (see, e.g., Leeuwis (2000)), aims at reaching a mutually beneficial and integrative agreement that makes sense from multiple perspectives or frames. The negotiation can have a predominantly "integrative" quality when actors develop synergetic win–win outcomes. The negotiation can rather be "distributive" when the actors take a win–lose position, and distribute profits and gains in an antagonistic way. Finally, "oppositional modes of action" are also a way of dealing with multiple frames (see, e.g., Gray (2003b)). Cold conflict means that distancing and avoiding each other are the dominant mode of operating. Hot conflict refers to heated opposition and adversarial actions. Parties try to impose their frame of reference upon others by force.

EXAMPLE

This example illustrates how a relational view on uncertainty can be advantageously applied in a real-life situation. It is inspired by the problematic of the Upper Guadiana river basin (UGB, see Martinez-Santos (2007) for more information). The UGB is a semiarid region located in the southeastern part of Spain's Central Plateau. Groundwater is the most important water resource of the basin, and is mostly used for agricultural purposes. Due to the extensive use of water by farming activities, in addition to climatic-induced droughts that affected the region, water scarcity became a major problem in the basin, and it presently constitutes a priority issue for decision making.

Traditionally, agricultural activity was supported by surface-water irrigation and was restricted to areas where water was easily accessible. However, over recent decades, a series of agricultural policies (e.g., the Common Agricultural Policy) have encouraged crop production, which in combination with advances in groundwater-extraction technologies, has transformed the basin into a prosperous agricultural region supported almost solely by groundwater irrigation. These changes modified the way in which farmers behaved. Unlike surface water, groundwater can be extracted by individuals; on the one hand, this made it easy for farmers to acquire water, however, on the other hand, it resulted in an anarchic extraction of water that could not be controlled.

In addition, changes in the legal system also had a big impact on the way in which groundwater was used. In 1985, the Water Law established that water was no longer a private right, as it had been considered until then, but rather a public right. This law was rejected by many farmers who claimed that water was a right that could not be removed, and has resulted in a situation in which some farmers comply with the law whereas others break it through illegal extraction. At present, legal farmers have limited extraction regulated by a water quota, but law-breaking farmers are able to extract as much water as they need. Despite the socioeconomic benefits of this transformation, the intense agricultural practices had a negative environmental impact. Declining groundwater levels led to the loss of groundwater-dependent ecosystems (i.e., wetlands). In turn, this situation raised great concern among environmental groups regarding the conservation and preservation of the ecosystems in the region.

Identification of uncertainties: In the UGB, the government, at the regional and national levels, is in charge of managing the water resources in the region, but does not know how much water is available or how much can be extracted. From this point of view, the major uncertainties are associated with the lack of knowledge of water quantity. The amount of water is difficult to monitor because of the physical characteristic of the problem (groundwater), and the illegal water extraction. Table 2 indicates some of the major uncertainties a decision maker in the regional government may identify in this situation.

Under this view, having a better estimate of the amount of water would allow the basin to be managed more efficiently, as it would be possible to better determine how much water could be extracted. In this regard, modeling techniques combined with remote sensing can help decision makers reach this point. Another solution to the problem could be to ensure the supply of water by transferring water from another basin. However, these solutions present several drawbacks. First, to estimate the amount of groundwater is a challenging task, due to both the complexity associated with groundwater behavior and the illegal extraction. Second, even though these solutions could facilitate management in the short term, by allowing a better distribution of water, the problem of supply will persist if practices do not change. Third, the social unrest these solutions generate may counteract their benefits. By increasing the control over illegal extraction, not only do law-breaking farmers feel threatened, but more generally, it puts the responsibility for water scarcity completely on the farmers, who as the sole responsible party are pressured to change their behavior.

In the solutions presented above, the uncertainty discussion focuses on the knowledge relationships that represent unpredictability and lack of knowledge about the system. The underlying rationale is that knowing more about how much water is available allows better strategies to be set to deal with water scarcity. However, “more” is not always “better.” This is only a partial view of what the UGB problem is about, one that ignores the big differences in the perception of the nature of the problem. For example, for an ecologist, this can be a problem of “excessive water consumption,” for the government, of “illegal water extraction,” and for a farmer of “insufficient water supply.” By considering these multiple knowledge frames, as our relational approach to uncertainty indicates, different interpretations of the problem are revealed (Table 3) as well as different solutions.

A closer look at the uncertainty questions identified shows a conflict of interests among various stakeholders as well as a lack of coordination between the agricultural and water policies. For the purpose of illustration, a possible approach to deal

Table 2. Major uncertainties identified in the Upper Guadiana Basin

	Unpredictability (we don't know and we will not know ...)	Incomplete knowledge (we don't know but we could get to know ...)
Natural system	How do the complex dynamics of groundwater processes affect the day-to-day water level?	What are current piezometric levels?
Technical system	What are the side-effects of building the structure for water transfer?	How much water can be saved with new irrigation technologies?
Social system	What would the reaction of stakeholders be to stronger control of illegal extraction?	How much water is taken from the ecosystem by illegal water extraction? What are the economic impacts of reducing the amount of illegal extraction?

with this situation could be outlined as follows. The European Water Framework Directive, as an important contextual element, can be used to consider new actors and new criteria. It could be used as a starting point to reconsider the failing laws, and add new perspectives by bringing the relevant stakeholders together to reconsider the continuation of wealth creation in the valley by means of a series of search conferences. Action could be taken to bring the different governmental bodies in line by coordinating their policies, while also organizing discussions between the different actors where they can jointly consider their interests. Negotiations about how to sustain the wealth creation in the region could lead to a series of actions and measures that make the system more sustainable. This set of solutions would probably limit all parties to a certain degree, but would not make it impossible for any of them to satisfy their own interests (farming would not be eliminated, quotas could be assigned or bought, exceptional measures could be taken in dry seasons, etc.).

When uncertainty is considered as a relation, what is known about the river system becomes inseparable from the social context in which the system is embedded. In addition to factual information, the process of identification and diagnosis of uncertainties becomes informed by the type of relationship the different actors have with the river system: how the water resources are perceived, how water is used, what is expected in the short and long term, in which way a common resource is shared. By acknowledging the interrelationships among actors and the views each of them have on the system, win–win solutions can be generated. In the UGB, this means that farmers and conservation groups are not seen as competitors for water, but together learn how to share the water resources. To this end, more research or information about water levels may be of little help. Instead, a process of negotiation, where all parties can express their opinions and find a solution may be more appropriate. As adaptive management practices suggest, in this situation, problems have to be redefined based on a shared frame of the issues and stakeholders involved; and any choice of action has to be the result of an interactive process of learning and negotiation.

CONCLUSIONS

We have proposed a relational conceptualization of uncertainty. Under this view, we have illustrated how uncertainty cannot be understood in isolation,

Table 3. Uncertainties in the Upper Guadiana Basin when multiple knowledge frames are considered

	Unpredictability (we don't know and we will not know ...)	Incomplete knowledge (we don't know but we could get to know ...)	Multiple knowledge frames (different actors give different answers to the question ...)
Natural system	How do the complex dynamics of groundwater processes affect the day-to-day water level?	What are current piezometric levels?	Is this an area of valuable wetland ecosystems disturbed by farming, or of valuable agricultural activities that need water?
Technical system	What are the side-effects of building a structure for water transfer?	How much water can be saved with new irrigation technologies?	Is the water-transfer system a tool for optimal water distribution in the country or is it an expensive infrastructure that favors provinces with more voters?
Social system	What would stakeholders' reaction be to a stronger control of illegal extraction?	How much water is taken from the ecosystem by illegal water extraction? What are the economic impacts of reducing the amount of illegal extraction?	Is the main problem excessive water consumption, illegal water extraction, or insufficient water supply? Is the main problem lack of environmental awareness among famers or lack of law enforcement?

but only in the context of the socio–technical–environmental system in which it is identified. This relational approach considers a knowing subject, an object of knowledge, and knowledge relationships. This thesis is based on the insight that uncertainty derives its meaning from the relationship between an individual (decision maker or stakeholder) and the system of interest. By taking into account the relationship, the notion of uncertainty shifts from being an objective property of a system, to include in its definition the human experience. It is from this relationship that individuals give meaning to a situation and possible interventions (Bouwen 2004). In focusing on the relationship between decision makers and the natural environment, on the position of individuals in complex social networks, we explore the elements that shape the representation of a problem, the identification of its uncertainties, and subsequent actions. From this perspective, any comprehensive characterization of uncertainty needs to take into consideration the possibility of different but equally valid ways of interpreting a problem. This is central to the fields of conservation and environmental decision making, where problems and solutions need to consider multiple ways of knowing that include what it is that individuals value and believe to be important. Knowledge is, therefore, redefined relationally. This approach to knowledge development and sharing opens up possibilities for innovation, creativity, and learning.

We identified three kinds of knowledge relationships: multiple knowledge frames, unpredictability, and lack of knowledge. Although unpredictability and lack of knowledge have been the focus of most of the discussion in the uncertainty literature, here we incorporate multiple knowledge frames, as a different knowledge relationship, to capture the multiple ways of understanding or interpreting a system. Whereas frames can be seen as devices through which people make sense of reality, considering the ambiguity that results from having more than one valid view serves to put the problem and its analysis into perspective. In this way, how a problem is interpreted, what and who are included or excluded from its definition, and what aspects of the problem are the most relevant to consider become relative to the frame through which a problem is looked at. Hence, making transparent the assumptions people hold about a problem treats the views that prevail as only one of the many possible ways of interpreting and solving a problem.

Such understanding of uncertainty brings a significant perceptual shift. When uncertainty is conceptualized as something separated from us, the perceivers, it becomes something external and independent from the human experience. Solutions are, therefore, restricted to improving the description of reality to be able to better predict and control a system of which we are not a part. This constitutes a problem when dealing with water management issues because their complexity makes prediction, for the most part, an unattainable goal. However, when the properties that define relationships become the focus of attention, human actors, with their views and expectations, themselves now become included as part of the problem, offering an opportunity for new ways of intervention. Thus, handling uncertainties shifts from elimination toward exploring other options by reconsidering our relation to the water management situation and the other actors involved.

On a higher level of abstraction, a strategy to deal with uncertainty can also consist of changing the nature of the uncertain knowledge relationships themselves, and thus approaching the situation with qualitatively different strategies. For example, changing the relationship from incomplete knowledge or multiple knowledge frames to one of unpredictability means accepting that there are aspects of the problem that cannot be known, even though more research is done, or discussions are carried on. Changing from incomplete knowledge or unpredictability to multiple knowledge frames implies learning how to look at a situation from a different perspective, accepting that each perspective can only give a partial view of the problem. Finally, changing from a relationship of unpredictability or multiple knowledge frames to incomplete knowledge means that, by doing more research or building more models, new insight about a problem can be gained. From a strategic point of view, this way of understanding uncertainty opens up new possibilities for solutions. Hence, dealing with uncertainty is not confined to improving the factual information, but also encompasses changing the way in which we relate with the natural systems. By reframing a problem, it is possible to pass beyond current definitions and think toward a new vision of the problem and, in this way, allow different relations to emerge. This can be achieved through reflection, dialog, and negotiation.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/vol13/iss2/art30/responses/

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