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The conceptual foundation of environmental decision support

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ABSTRACT

Environmental decision support intends to use the best available scientific knowledge to help decision makers find and evaluate management alternatives. The goal of this process is to achieve the best fulfillment of societal objectives. This requires a careful analysis of (i) how scientific knowledge can be represented and quantified, (ii) how societal preferences can be described and elicited, and (iii) how these concepts can best be used to support communication with authorities, politicians, and the public in environmental management. The goal of this paper is to discuss key requirements for a conceptual framework to address these issues and to suggest how these can best be met. We argue that a combination of probability theory and scenario planning with multi-attribute utility theory fulfills these requirements, and discuss adaptations and extensions of these theories to improve their application for supporting environmental decision making. With respect to (i) we suggest the use of intersubjective probabilities, if required extended to imprecise probabilities, to describe the current state of scientific knowledge. To address (ii), we emphasize the importance of value functions, in addition to utilities, to support decisions under risk. We discuss the need for testing "non-standard" value aggregation techniques, the usefulness of flexibility of value functions regarding attribute data availability, the elicitation of value functions for sub-objectives from experts, and the consideration of uncertainty in value and utility elicitation. With respect to (iii), we outline a well-structured procedure for transparent environmental decision support that is based on a clear separation of scientific prediction and societal valuation. We illustrate aspects of the suggested methodology by its application to river management in general and with a small, didactical case study on spatial river rehabilitation prioritization.

1. Introduction

Two main problems make decisions in environmental management difficult (McDaniels et al., 1999; Kiker et al., 2005; Clemen and Reilly, 2013). First, the society consists of individuals with a high diversity of perspectives, opinions, and interests. This makes it impossible to formulate "societal objectives" in any strict sense. Societal objectives may be defined as objectives with which a majority of people would agree. Still, such objectives may be conflicting and they are difficult to formulate and quantify. Second, environmental or coupled socio-environmental systems are complex. Therefore, it is difficult to reliably predict the consequences of decision alternatives. However, as the desirability of alternatives depends on the degree to which their consequences fulfill the objectives, it is very important to derive such predictions and consider their uncertainty in decision making.

To account for these difficulties, different decision support techniques have been suggested and applied in environmental management (Salminen et al., 1998; Lahdelma et al., 2000; Kiker et al., 2005; Mendoza and Martins, 2006; Mahmoud et al., 2009; Huang et al., 2011; Gregory et al., 2012; Linkov and Moberg, 2012). All of them structure the decision making process into procedural steps and assess the degree by which decision alternatives fulfill the objectives. Some techniques rely on qualitative assessments, while others quantify preferences and predictions and rank alternatives based on scores of the expected fulfillment of objectives.

Important elements contributing to the success of environmental decision support are: transparency of the procedure, a good representation of stakeholders, the willingness of stakeholders to participate constructively and make their objectives explicit, guidance by a good facilitator, and a good conceptual basis of the underlying methodology (Howard, 1988; Belton and Stewart, 2001;

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Hajkowicz, 2008; Eisenführ et al., 2010). This multiplicity of elements explains, why decision support in environmental management can be successful for different underlying approaches (Hajkowicz, 2008). An excellent facilitator, for instance, may compensate for a poorer conceptual basis, or uncooperative stakeholders may hinder the success even if a conceptually sound procedure is used.

Thus, a good conceptual basis of the decision support methodology is only one important element that contributes to success. It is particularly relevant to support the use of scientific knowledge in societal decision making that has to be justified to the public. This is a key element of environmental management. Important conceptual requirements of good environmental management decision support can thus be summarized as follows:

1. Use of a mathematical formalism to describe scientific knowledge that
   a) can deal with uncertainty (to consider poor predictability),
   b) is able to represent conditional knowledge (for given driving forces, future scenarios, or decision alternatives),
   c) can consistently describe a learning process based on new data (consistent means here that learning in two steps with partial data leads to the same result as learning in one step with all data).
2. Use of a mathematical description of preferences that
   a) imposes as few constraints as possible to allow large freedom for specifying individual preferences,
   b) considers risk attitudes to account for uncertainty in predictions in addition to describing preferences for certain outcomes,
   c) avoids unreasonable results, such as rank reversals of top scoring alternatives if inferior alternatives are added or removed.
3. Use of a structuring and quantification process that
   a) is relatively easy to understand and supports transparent communication of the reasons for a decision to the public,
   b) supports identifying causes of disagreement and separates scientific predictions from societal valuations,
   c) stimulates the generation of better alternatives and supports including them without re-elicitation of preferences.

As argued previously, procedures that violate some of these criteria can still lead to a successful decision support. However, we are convinced that a generally recommendable technique for bringing scientific knowledge into environmental management must be defendable against criticism. How can we convince stakeholders, if the chosen technique can lead to strange results that do not reflect common sense?

In the following, we first discuss which choices of methodologies these requirements imply. For each of these choices, we suggest modifications to established procedures to better adapt them for environmental management. In Sections 2 and 3, we do this for the mathematical representation of scientific knowledge and of societal preferences, respectively. Then, in Section 4, we discuss how these concepts can be applied in practice and explain key aspects of their use for river management. In Section 5, we illustrate the suggested procedure more concretely with a small, didactical case study on spatial prioritization for river rehabilitation. Finally, we summarize our conclusions in Section 6.

2. Representing and acquiring scientific knowledge

It is reasonable to base environmental management on the best available scientific knowledge. Scientific knowledge is always incomplete, dispersed in the scientific community, and it is difficult to identify the most relevant knowledge for a given decision. To support the transparent use of scientific knowledge, it is crucial to think about how to represent it mathematically, how to acquire it, and how to use it to get scientific predictions that optimally support environmental management (Reichert, 2012).

2.1. Representing scientific knowledge

2.1.1. Philosophical interpretations of probability

The history of scientific reasoning is closely related to the mathematical framework of probability. The correct interpretation of probabilities as a philosophical basis of (natural) science (see Hájek, 2012 and references therein) has been much more intensively discussed than any of the suggested alternative concepts. In our brief outline of different interpretations of probability we roughly follow Gillies (2000), particularly concerning the historic development (see Chalmers, 1999 for a broader coverage of the philosophy of science).

The most important distinction is between *objective* and *epistemic* interpretations of probability. Objective interpretations use probabilities to describe features of the material world that are independent of humans, whereas epistemic interpretations use probabilities to quantify human knowledge or belief.

Important objective interpretations are the *frequency* and *propensity* interpretations. The frequency interpretation (e.g. Von Mises, 1928) defines probability as the limit of relative frequencies of events in a repeatable experiment. It assumes underlying physical laws that guarantee that this limit exists. The propensity theory (Popper, 1959; see also Gillies, 2000) intends to make objective probabilities applicable to single events by emphasizing the circumstances or causes of a single event that could in principle make it repeatable.

In contrast, epistemic interpretations use the same mathematical construct of probability to describe degrees of belief of individuals. The *logical* theory (e.g. Keynes, 1921) assumes that different individuals will independently come to the same degree of belief given the same evidence. Doubts about the possibility to uniquely derive probability statements based on logical reasoning lead to the development of the *subjective* interpretation of probability (e.g. Ramsay, 1926; De Finetti, 1931). Here, probabilities describe degrees of belief of individuals. Such probabilities can be different for different individuals facing the same evidence.

In the subjective interpretation, probabilities are operationalized by lotteries about which an individual is indifferent. Assume a lottery provides a gain proportional to $(1 - p)$ for a statement to be true and a loss proportional to p otherwise. If an individual is indifferent between this lottery and the lottery with the reverse outcomes, then his or her belief that the statement is true is defined to be p. It can be shown that if an individual agrees to operationalize his or her beliefs in this sense and wants to avoid sure loss if someone makes a choice among lotteries the individual is indifferent, then these quantities, p, must be probabilities in the sense of fulfilling the axioms of probability theory (see Howson and Urbach, 1989 for a careful discussion and proof of this Ramsey–De Finetty theorem).

There are other, complementary arguments for using probabilities to describe subjective beliefs. Cox (1946) shows that conditional beliefs that fulfill minor requirements must follow the laws of probability theory. Lindley (1982) proves that any scoring rule to quantify uncertainty that fulfills some reasonable properties can be transformed to probabilities. The argument of Cox is particularly important for environmental management since we are often confronted with questions as “which are the expected consequences, given a management alternative or future scenario?” This requires specifying conditional beliefs. Interestingly, several,