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Incorporation of uncertainty in decision support to improve water quality

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Abstract: Decisions in environmental management can be challenging, amongst other things, due to two major sources of uncertainty. Predictions of consequences of different management alternatives can be very uncertain. Furthermore, uncertainty exists regarding the subjective preferences of decision makers and stakeholders. For a transparent decision process it is important to disentangle these different elements and the related sources of uncertainty by separating the prediction of consequences from their valuation. Predictions of consequences should be estimated as objectively as possible based on the current state of knowledge; the preference functions which are used to valuate these consequences must be elicited carefully to reflect the subjective preferences of each stakeholder.
We incorporate uncertainty in decision support by applying the multi-attribute value and utility theory. We propagate uncertainty in the prediction of consequences to the valuation (numerically implemented by Monte Carlo simulation) and incorporate the risk attitude of the stakeholders to discriminate between uncertain alternatives. Furthermore, we address uncertainties inherent in the model of the subjective preference structure by sensitivity analysis to evaluate the robustness of model results against a variation in parameters of the preference model. We illustrate this procedure with a case study on the improvement of water quality in a river catchment of the Swiss Plateau. Different management options to reduce point and non-point sources will be evaluated in this study. For deriving predictions of outcomes, expert knowledge as well as mathematical models can be used. The case study is integrated in a framework for multi-criteria water management (MCWM), which allows us to use existing assessment procedures to evaluate the ecological status of aquatic ecosystems.

Keywords*:* multi-criteria decision support; water quality, risk attitude, river management

1 Introduction

The multi-attribute value and utility theory (MAVT/MAUT) provides an attractive framework for decision support in environmental management for the following reasons (Keeney & Raiffa 1993; Eisenführ et al. 2010; Schuwirth et al. 2012):

- Multiple (conflicting) objectives can be considered.
- The views of different stakeholders can be reflected by eliciting their subjective preferences.
- The number of management alternatives does not increase the effort to elicit preferences.
- Subjective preferences for different consequences are formally separated from objective predictions of the consequences of different management alternatives.
- Uncertainty of predictions can be quantified by probability distributions and propagated to evaluation results.
- The risk attitudes of the stakeholders can be taken into account which might influence the final ranking of management alternatives, if differences in the uncertainty of consequences are large.

- Focussing on objectives rather than on alternatives facilitates a constructive discussion between stakeholders to find consensus-solutions.

Therefore, this theory is applied in our framework for multi-criteria water management (MCWM) (Reichert et al. 2011). This framework can be used to support decisions on integrative as well as sectoral management of surface waters.

An important challenge for applying this decision support methodology for environmental management lies in the elicitation of preferences. Usually, the preferences are elicited from the decision makers and important stakeholders and reflect their subjective views. However, there are cases, where the fulfilment of objectives characterized by measureable attributes is difficult to evaluate without specific expert knowledge. If this cannot be avoided by choosing simpler attributes, the preference functions of these objectives have to be elicited from experts with the appropriate knowledge. In the special case of river assessment, existing assessment procedures can be used and translated into preference functions to evaluate the ecological status (Langhans & Reichert, 2011, Langhans et al., submitted). Note, however, that the trade-offs between achieving a good ecological status and other sub-objectives at this hierarchical level, such as low costs, have to be elicited from the stakeholders. In the following sections we will introduce the MCWM and illustrate the decision support procedure with a case study on river water quality management in a catchment of the Swiss Plateau. The predicted chemical status resulting from hypothetical alternatives to improve stream water quality will be evaluated to illustrate how uncertainty in predictions as well as uncertainty in preference functions can be taken into account.

2 Important steps for decision support to improve river water quality

The MCWM consists of different steps, which are described in the following sections (Reichert et al. 2011; Schuwirth et al. 2012).

A. Definition of the decision context

In the first step of a decision support process, the decision context has to be defined. This step is important as the whole process can become useless if in a later phase the scope of the decision context is either restricted or extended. It has to be decided what the main objective of the decision is, which temporal and spatial scale should be considered, and which range and context of alternatives should be considered to achieve the objective.

In our case study, it was decided to focus on the catchment of the Mönchaltorfer Aa. The main objective is to improve the water quality of the streams in this catchment. The management alternatives that will be considered affect point sources and non-point sources.

B. Stakeholder analysis

The stakeholders who can be involved in the decision making process are individuals who make the decision, persons who are affected by the decision, or representatives of institutions/organizations that influence the decision or represent public or private interests. In our case study, particularly important stakeholders are representatives of the cantonal and municipal authorities responsible for the water quality management of this catchment. However, other groups that represent societal values, such as NGOs, farmer and recreational organizations, etc. could be included as well.

C. Formulate and structure objectives, select attributes

To facilitate the process of making the objectives more concrete, the main objective has to be broken down into sub-objectives that describe all important aspects of the main objective. Repeating this step at different levels of objectives results in a hierarchical structure that clarifies the meaning of the overall objective and simplifies the quantitative preference elicitation procedure (see step F below). Ideally, we would try to combine all sub-objectives of all stakeholders into a single objectives hierarchy. This is usually possible as stakeholders can assign weights of zero to branches that are irrelevant to them when quantifying the preferences in step F.

Objectives for a good river management strategy include the good ecological status of the whole river network, good ecosystem services, low costs, conformity with regulation and a robust design (Reichert et al. 2011). To limit the complexity of the decision process to improve river water quality, we concentrate on the objectives shown in Fig. 1.

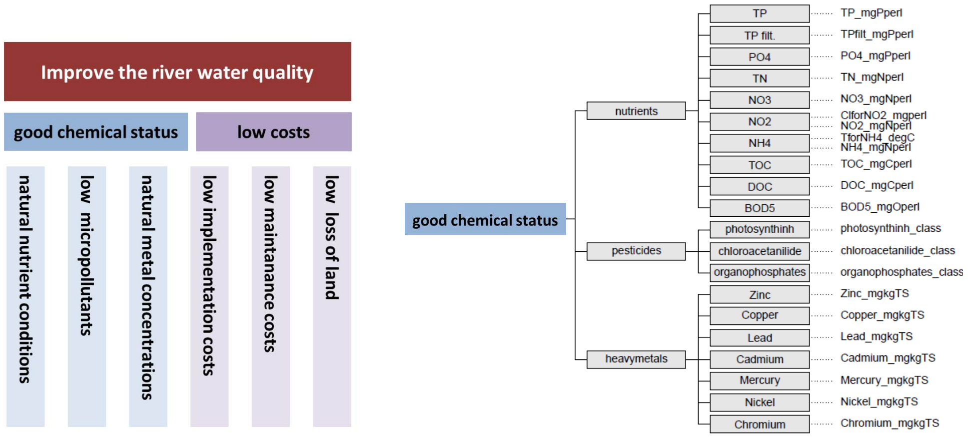

Fig. 1: Objectives hierarchy: main objectives (left), sub-objectives for "good chemical status" with attributes (right)

D. Create alternatives

To create the set of alternatives it can be useful to think about current deficits, to imagine how an ideal solution would look like, and to evaluate what happens if the context is broadened. We find it important to choose a decision analysis method which allows for an inclusion of new alternatives at every stage of the decision support procedure with a minimum of additional effort. This requirement is fulfilled by MAVT/MAUT. Alternatives that are considered in our case study include the upgrade of waste water treatment plants (WWTP) regarding the elimination of nutrients and micropollutants, alternatives regarding the waste water infrastructure, and the reduction of pesticide loss from agriculture and urban areas.

E. Predict outcomes

In this step, the consequences of the different alternatives regarding all attributes must be predicted. Since these predictions are uncertain, this step involves the quantification of the prediction uncertainty with probability distributions. Prediction of outcomes can be derived by extrapolation of simple phenomenological models, with the help of mechanistic cause-effect models, or by eliciting expert judgment, depending on the available knowledge and its degree of formalization.

F. Elicit (inter-)subjective preferences

The subjective preferences of the stakeholders (or intersubjective preferences of stakeholder groups) are elicited and represented quantitatively by a multiattribute utility function as described e.g. by Keeney and Raiffa (1993) and Eisenführ et al. (2010). The hierarchical structuring of the objectives significantly facilitates the construction of this function. In a first step, value or utility functions are constructed for the lowest level sub-objectives of the hierarchy. Therefore, values or utilities can be formulated as a function of a small number of attributes, usually even as single-attribute value or utility functions. A value function describes the strength of preference for different outcomes of the attribute(s). It assigns values of a common unit between 0 and 1 to the levels of the attribute(s) in its (their) original units. Examples are given in Fig. 2. Utility functions combine strength of preference with the risk attitude of the stakeholder (see below).

In a second step, these value or utility functions are aggregated to values or utilities at higher hierarchical levels. Methods of aggregation include the weighted arithmetic mean (=additive), which is most often used, the weighted geometric mean (=Cobb-Douglas), worst case aggregation (=minimum) or a mixtures of these. Criteria for the choice of an aggregation method are given in Tab. 1.

$$v_{\text{add}} = \sum_{i=1}^{n} w_i v_i \qquad \text{(additive = weighted arithmetic mean)}$$

$$v_{\min} = \min(v_i) \qquad \text{(minimum = worst case aggregations)}$$

$$v_{\mathrm{CD}} = \prod_{i=1}^{n} v_i^{w_i} \qquad \text{(Cobb-Douglas = weighted geometric mean)}$$

$$v_{\mathrm{mix}} = \alpha_{\mathrm{add}} \sum_{i=1}^{n} w_i v_i + \alpha_{\mathrm{min}} \min(v_i) + \alpha_{\mathrm{CD}} \prod_{i=1}^{n} v_i^{w_i} \quad \text{(mixed aggregation)}$$

v: value; v_i: value of sub-objective i, w_i: weighting factor of sub-objective i, sum of w_i = 1, n: no of sub-objectives; α =weighting factors between additive, min. and Cobb-Douglas aggregation, sum of α_i=1.

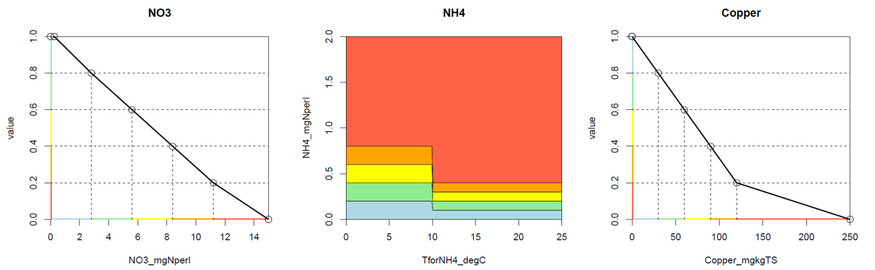

Fig. 2: Value functions for lowest level sub-objectives

Table 1: Relevant features for choosing the aggregation method

Features:	**Additive**	**Minimum**	**C-D**	**mixed**
sub-objectives have the same value: aggregated value = value of sub-objectives	+	+	+	+
different weighting of sub-objectives is possible	+	-	+	+
aggr. value **not** always 0 if value of one sub-objective is 0	+	-	-	+
increase of aggr. value **not** only possible by increasing the value of the worst sub-objective	+	-	+	+
low value of one sub-objective can be compensated by high value of another sub-objective	+	-	(+)	(+)
balanced alternatives are higher valued than extreme ones	-	+	+	+

To rank uncertain alternatives, the MAUT can be applied. This requires the transformation of elicited value functions that characterize preferences for certain outcomes into utility functions that also consider risk attitudes. The construction of a utility function from a value function is illustrated in Fig. 3. One method to elicit utility functions is the certainty equivalent method (e.g. Eisenführ et al., 2010): We imagine an uncertain alternative A with a 50/50 chance the value will be 0 or 1. The expected utility *EU* of such an alternative is *EU*(A) = 0.5*0 + 0.5*1 = 0.5. We now search for an alternative CE (=certainty equivalent) with a certain but unknown value *v*(CE) so that we are indifferent between A and CE (*EU*(CE) = *EU*(A) = 0.5). Let us assume this value *v*(CE) is 0.3. We have now three points of the utility function and can construct more points by applying a similar procedure.

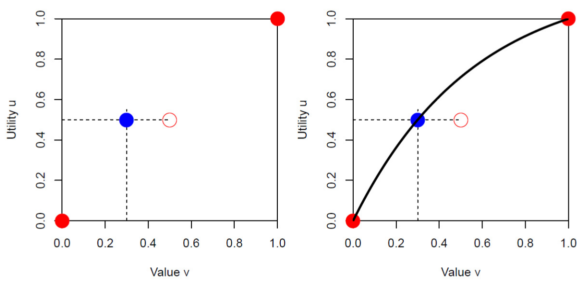

Fig 3: Construction of a utility function (solid line)
Red dots: Alternative **A** with a 50/50 chance that the *v*(**A**) is 0 or 1, *EU*(**A**)=0.5*0+0.5*1=0.5, blue dot: certainty equivalent with *EU*(**CE**) = *EU*(**A**)=0.5, *v*(**CE**)=0.3 in this example

Values on the x-axis of diagrams like Fig. 3 should be illustrated by corresponding levels of attributes to facilitate the assessment (if the value is based on a multi-attribute value function, there are different equivalent corresponding attribute levels).Since the evaluation of a good chemical status of the river depends on attributes that are difficult to evaluate for a non-expert, we use a translation of existing stream assessment procedures. For the sub-objectives of natural nutrient conditions we use value functions from Langhans et al. (2011) which are based on the Swiss Modular Concept for stream assessment (Bundi 2000; http://www.modul-stufen-konzept.ch) depending on the attributes shown in Tab. 2. To evaluate micropollutants (i.e. pesticides) and heavy metals, we use the assessment methods applied by the cantonal authorities (AWEL 2006) based on Chèvre et al. (2006) and LAWA (URL: www.umweltbundesamt.de/wasser/themen/fluesse-und-seen/fluesse/bewertung/ow_s2_2.htm). The value function for pesticides is based on a comparison of monthly grab samples with acute and chronic quality standards for substances that are grouped according to their mode of action. We show only resulting quality classes in Tab. 2. For the branch "low costs", the value function will be elicited from the stakeholders, as well as the trade-off between costs and the chemical status.

G. Rank alternatives, analyze results

Once the prediction of outcomes and the elicitation of preferences are completed, the values and/or expected utilities of all alternatives are calculated and a ranking according to values or utilities can be derived. The robustness of the results can be evaluated by sensitivity analysis with respect to predictions (or their probability distributions) and with respect to parameters of the value or utility functions. Alternatives that perform badly have to be analysed in detail to elucidate the underlying reasons.

H. Discuss results with stakeholders, search for consensus alternatives

In this stage of the procedure we want to find out 1) if stakeholders agree with the results of their preference model and if not, what are the reasons for potential disagreement, 2) the consensus potential between the different stakeholders, and in case of large deviations between the highest-ranked alternatives of different stakeholders the underlying reasons leading to this conflicting outcome, 3) how particular alternatives could be modified to get a better or more homogeneous evaluation by different stakeholders, 4) whether new alternatives can be generated with a higher consensus potential. This task can be facilitated by graphical representation of the result as shown in the next section.

It is important to point out the explicit separation of step (E) regarding objective predictions about expected outcomes for the different alternatives and step (F) which describes the (inter)subjective valuation of the stakeholder (groups). This is important to make the process transparent and to focus the discussions on differences in values rather than directly on the evaluation of alternatives.

3 Illustrative example

To illustrate this procedure, we use measured data from a site in the Mönchaltorfer Aa which is 300 m downstream of a WWTP and has a fraction of treated wastewater of about 40%. We evaluate the status quo and four hypothetical management alternatives: an upgrade of the WWTP to improve the removal of nutrients or micropollutants, respectively, a transition from conventional to organic farming, and the combination of the latter. Table 2 shows the attribute levels for the chemical status of the five alternatives. These estimates were derived from simple mass flow calculations based on measured data below and upstream the WWTP and expert judgement on substance specific relative inputs from agriculture and urban sources upstream of the WWTP. Fig. 4 (top) shows the resulting values for the objective "good chemical status" of the status quo using the mean of the attribute levels and different aggregation methods (additive, minimum, Cobb-Douglas and a mix of additive and Cobb-Douglas with equal weights). The minimum aggregation leads to the worst valuation (v_{min}=0.16) since it propagates the worst value of the sub-objectives to the higher objectives. The other three aggregation methods lead to values of the chemical status between 0.55 (Cobb-Douglas) and 0.70 (additive). Note that if one of the sub-objectives had a value of zero, the aggregated value of the Cobb-Douglas aggregation would be zero as well, irrespective of the values of the other sub-objectives. Fig. 4 (bottom) shows the values of the five alternatives using mixed aggregation with equal weights. The upgrade of the WWTP to remove micropollutants alone or in combination with a transition to organic farming would be ranked highest, followed by the upgrade of the WWTP to better remove nutrients, and organic farming alone and the status quo. In this example, organic farming alone does not lead to a visible improvement of the water quality because urban sources contribute substantially to pesticide pollution. For other micropollutants like pharmaceuticals no measurements and no value functions were available so far. However, these substances must be included in future analyses to evaluate the management alternatives properly. Note that the example is only intended for illustrative purposes, results are not transferable to other situations.

Table 2: Attributes of different alternatives

Attributes	Units	Status quo	Upgrade WWTP nutrients	Upgrade WWTP micropoll	organic farming	Upgrade WWTP micropoll + org. farming
nutrients	*distribution:*	*lognormal*	*lognormal*	*lognormal*	*lognormal*	*lognormal*
ammonia	mg N/L	0.07 ± 0.0035	0.06 ± 0.003	0.06 ± 0.003	0.07 ± 0.0035	0.06 ± 0.003
nitrate	mg N/L	11.9 ± 0.6	4 ± 1.5	4 ± 1.5	11.9 ± 0.6	4 ± 1.5
nitrite	mg N/L	0.008 ± 0.0004	0.008 ± 0.04	0.008 ± 0.04	0.008 ± 0.0004	0.008 ± 0.04
phosphate	mg P/L	0.05 ± 0.0025	0.009 ± 0.0045	0.009 ± 0.0045	0.05 ± 0.0025	0.009 ± 0.0045
total P	mg P/L	0.13 ± 0.0065	0.02 ± 0.008	0.02 ± 0.008	0.13 ± 0.0065	0.02 ± 0.008
DOC	mg C/L	4.3 ± 0.22	2 ± 1	2 ± 1	4.3 ± 0.22	2 ± 1
pesticides	*distribution:*	*discrete*	*discrete*	*discrete*	*discrete*	*discrete*
photosynthesis inhibitors	class	very good: 5% good: 90% moderate: 5%	very good: 5% good: 90% moderate: 5%	very good: 80% good: 20%	very good: 30% good: 70%	very good: 90% good: 10%
chloroacetanilides	class	very good: 75% good: 25%	very good: 75% good: 25%	very good: 75% good: 25%	very good: 95% good: 5%	very good: 96% good: 4%
organophosphates	class	moderate: 5% poor: 75% bad: 20%	moderate: 5% poor: 75% bad: 20%	moderate: 5% poor: 90% bad: 5%	moderate: 5% poor: 90% bad: 5%	moderate: 7% poor: 92% bad: 1%
metals	*distribution:*	normal	normal	normal	normal	normal
Cadmium	mg/kg DM	0.65 ± 0.16	0.65 ± 0.16	0.65 ± 0.16	0.65 ± 0.16	0.65 ± 0.16
Chromium	mg/kg DM	49.5 ± 12.4	49.5 ± 12.4	49.5 ± 12.4	49.5 ± 12.4	49.5 ± 12.4
Copper	mg/kg DM	88 ± 22	88 ± 22	88 ± 22	88 ± 22	88 ± 22
Mercury	mg/kg DM	0.28 ± 0.07	0.28 ± 0.07	0.28 ± 0.07	0.28 ± 0.07	0.28 ± 0.07
Nickel	mg/kg DM	33.6 ± 8.4	33.6 ± 8.4	33.6 ± 8.4	33.6 ± 8.4	33.6 ± 8.4
Lead	mg/kg DM	77 ± 19	77 ± 19	77 ± 19	77 ± 19	77 ± 19
Zinc	mg/kg DM	333 ± 83	333 ± 83	333 ± 83	333 ± 83	333 ± 83

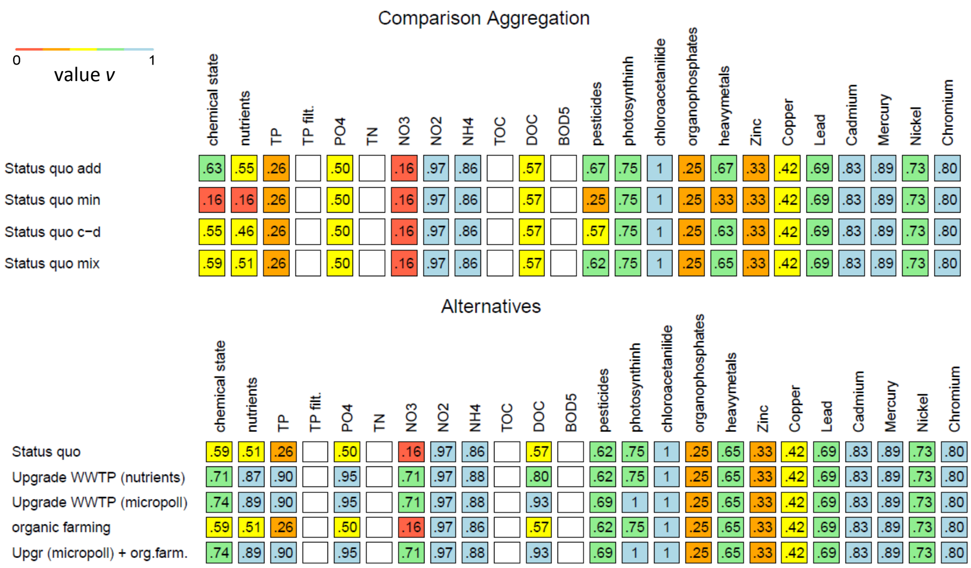

Fig. 4: Evaluation of the objective "good chemical status" and its sub-objectives (=values *v* between 0 and 1). Top: status quo with four different aggregation methods and equal weights for all sub-objectives of one objective. Bottom: five alternatives with mixed aggregation and equal weights. See legend for colours in the top left corner.

Dealing with uncertain predictions
Fig. 5 shows the results of two alternatives considering prediction uncertainty using mixed aggregation. It shows how the uncertainty in the predictions of attributes (Tab. 2) propagates to the uncertainty of values of the corresponding sub-objectives as well as to the higher objectives. Mean values (mean(*v*)) and standard deviation of values (std(*v*)) for the chemical state are given in Tab. 3.

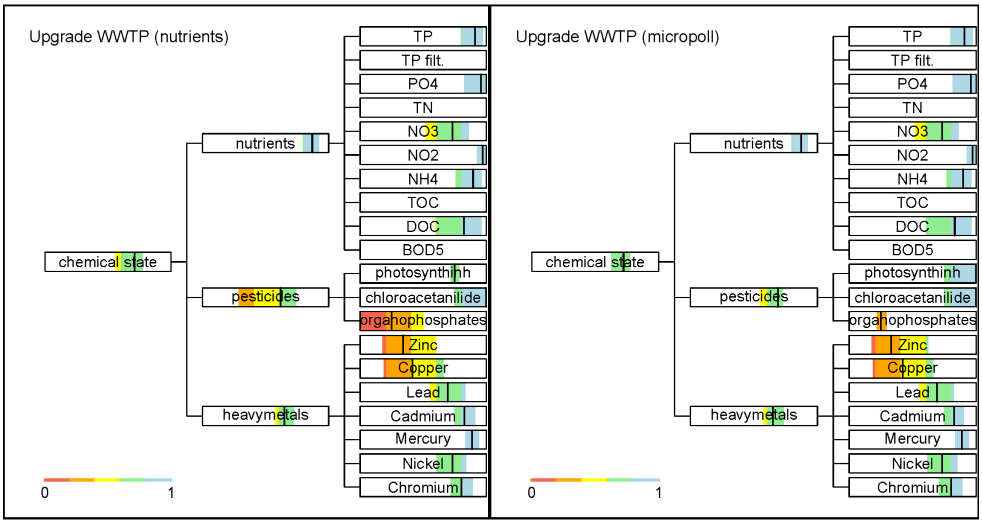

Fig. 5: Results of two uncertain alternatives with the 5 to 95% quantile ranges coloured (see legend bottom left) and a black line indicating the median.

Sensitivity analysis regarding risk attitude
To evaluate the influence of the intrinsic risk attitude on the final ranking of the alternatives we perform a sensitivity analysis by assuming four different risk attitudes: risk-neutrality, and three levels of risk-aversion (Arrow/Pratt measure of 1, 4 and 10, respectively, see Fig. 6, Tab. 3). In this case, the ranking does not change with risk-attitude because the mean values of the three different alternatives are significantly different and the uncertainty of the alternative with the highest mean value is smaller than the uncertainty of the other alternatives. This would be different for alternatives with similar mean value but large differences in the uncertainty (=std of values).

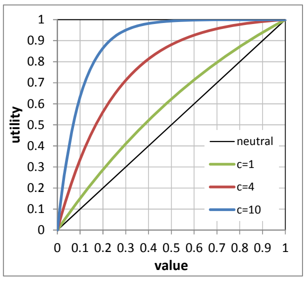

Fig. 6: Illustration of four different risk attitudes

An important next step to facilitate the decision process between these alternatives is the elicitation of values for costs and the trade-off between costs and the good chemical status shown in the objectives hierarchy in Fig. 1.

Table 3: Mean values and standard deviation of values as well as the ranking according to expected utility for four different risk attitudes for five alternatives.

alternatives	mean(*v*) ± std(*v*)	ranking with neutral risk attitude	ranking with risk aversion (c=1)	ranking with risk aversion (c=4)	ranking with risk aversion (c=10)
Status quo	0.58 ± 0.05	5	5	5	5
WWTP (nutrients)	0.70 ± 0.06	3	3	3	3
WWTP (micropoll)	0.72 ± 0.04	2	2	2	2
organic farming	0.60 ± 0.03	4	4	4	4
WWTP (microp.) + org farming	0.73 ± 0.03	1	1	1	1

Conclusions and Recommendations

The example shows how we can consider uncertainty in predictions of consequences as well as with uncertainty in preference functions for environmental decision support and communicate this uncertainty to stakeholders. The latter was illustrated by a sensitivity analysis regarding different aggregation methods and different risk attitudes. A first step to evaluate the uncertainty in predictions on the evaluation of alternatives is to propagate uncertainty of attributes to the uncertainty in values. This can reveal whether a discrimination between the alternatives is possible without evaluating the risk attitude of the stakeholder. However, to come up with a final ranking of uncertain alternatives, the application of MAUT is necessary. This means that the risk attitude of the decision maker has to be included in the analysis by using utility functions to quantify preferences. Nevertheless, it can be advantageous to first derive a multi-attribute value function instead of an utility function. The elicitation of value functions is much easier than the elicitation of utility functions since one has to compare only different certain outcomes and not lotteries of outcomes. Secondly, the elicitation of utility functions mixes up two different aspects: the strength of preference and the intrinsic risk attitude. To learn from the analysis about the preferences for different alternatives, the information about the strength of preference is of interest on its own. For decisions in environmental management, this learning effect might be more important than the derivation of a final ranking. Furthermore, it may be advantageous to elicit values of outcomes for some branches of the objectives hierarchy from experts instead of stakeholders or even use existing assessment procedures, as shown in the example. In such cases, the personal risk attitudes of the experts are not relevant. The risk attitudes and trade-offs to other branches of the objectives hierarchy can be added later by eliciting utilities from stakeholders at higher hierarchical levels (Keeney and Raiffa, 1993). Anyhow, the risk attitude might only be influential on the ranking of alternatives, if alternatives have similar values but large differences in the uncertainty of the value. This can be assessed by sensitivity analysis (see example above and Schuwirth et al, 2012).

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