

MS-E2177 Seminar on Case Studies in Operations Research 2017

AN APPROACH AND A TOOL FOR WATER RISK ASSESSMENT

Client: Finnish Environment Institute, SYKE

Final report

May 26, 2017

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1. Introduction

“A water-secure world is one where every person has enough safe, affordable, clean water to lead a healthy and productive life and where communities are protected from floods, droughts, and water-borne diseases. Water security (WS) promotes environmental protection and social justice by addressing the conflicts and disputes that arise over shared water resources” [1].

Key to WS is water resources management, which is a cross-sectoral activity seeking to ensure secure water for people, food, ecosystems. However, we cannot manage what we cannot measure. By measuring, we mean assessing the present state of WS. In keeping with van Beek & Arriens (2014)[1], WS assessment includes (i) identifying the key dimensions of WS (social WS, environmental WS, economic WS etc.), (ii) identifying the risks that threaten the key dimensions (drought, pollution, structural failures etc.), (iii) measuring the impact of the risks on the key dimensions and (iv) comparing the impact against an acceptable level. If the impact is deemed unacceptable, water-management actions are needed to achieve the acceptable level [1].

The selection of indicators used for water security assessment requires sound principles and targets, in addition the indicators should reflect the current knowledge and aspirational values. The information needs to be aggregated to dimensionless or normalized indicators [2]. Dickson et al. [3] found in a review study 179 different indicators used in the water security assessment. An example of the indices used is the approach developed by the Asian Development Bank [4].

In addition to the impact of the risks, the assessment of WS can also take into account the *resilience* of the system. In a system of high resilience (be it in the form of inherent recovery ability or of a learning process over time), indeed, impacts may be a lot smaller or risks may never occur [5]. Nevertheless, the evaluation can be quite challenging due to the amount of additional information required. Therefore, a two-stage approach can be adopted in which (i) first WS is assessed by only considering the risks and their impact (as we do in this project) and, subsequently, (ii) evaluations about resilience are made to examine how the impacts (but also the likelihoods) of the risks can decrease.

Once WS has been assessed, the choice of water-management actions can be informed by the prioritization of the risks, as recommended by recent theories on the best way to manage national WS [1][6][7]. Nevertheless, many of these theories still remain rather theoretical and lack practical approaches and tools [1][6].

The overall objective of the project is to develop an approach and a tool for the water security risk assessment. This objective is pursued through more specific objectives. One is to evaluate and compare the water related risks in terms of their impacts and likelihood of occurrence, while taking into account interactions (synergies and causal dependences) between these

risks. Another objective is to evaluate WS in terms of the single key dimensions as well. The tool is also meant to present the results in an illustrative and understandable way. Thus, the results of the assessment could be used for supporting decisions on WS risk management options. Among the objectives, there is also the evaluation of the benefits and challenges of the tool, and of its potential for use in the overall water security assessment of Finland.

2. Methodological structure of the tool

We have developed a tool for evaluating water security in the domain of interest (municipality, region, country...) under the threat of multiple water-related risks, e.g. *Drought*, *Dam break*, *Chemical release* etc. These risks give rise to many different scenarios, whereby each scenario specifies the magnitudes with which the risks occur. On the grounds of the information entered by the user, the tool evaluates likelihoods and impacts of all scenarios. These quantities are then aggregated into an overall Water-Security Index (WSI), which is a percentage quantifying water security in the domain of interest for the evaluated risks.

The methodological structure of the tool comprises two parts, namely a Bayesian network (BN) of risks and a Multi-criteria Decision Analysis (MCDA) hierarchy. The BN serves to evaluate the likelihoods of the scenarios, whereas the MCDA hierarchy helps evaluate the impacts of the scenarios. In what follows, we describe the BN of risks (Section 2.1) and the MCDA hierarchy (Section 2.2).

2.1. Bayesian network of risks

A BN represents a system and the causal dependences within the system, both graphically and mathematically [8]. Graphically, a BN is a set of nodes which represent the system components, and of directed arcs which represent the causal dependences between the nodes. Each arc starts from a node, called the *predecessor*, and points to another node, called the *child*, thus indicating the causal dependence of the child on the predecessor. Mathematically, nodes are modeled as stochastic variables and arcs as conditional probabilities, i.e., the probability that the child assumes a given state is conditioned on the state of the predecessor. In the tool, a BN is constructed in which the risks correspond to the nodes and the causal dependences between the risks correspond to the arcs.

In the remainder of this section, we define risks (Section 2.1.1) and describe the two-stage procedure for determining the conditional probabilities for modeling the causal dependences between the risks (sections 2.1.2 e 2.1.3). Furthermore, we describe how the likelihoods of the scenarios are obtained (Section 2.1.4).

2.1.1. Risks

Each of the n_R risks¹ is associated with a stochastic variable $X_i, i = 1, \dots, n_R$, describing the physical quantity that characterizes the magnitude with which the risk can occur. Specifically, the stochastic variable X_i can assume three discrete states representing *negligible* (n), *medium* (m) and *large* (l) magnitudes of occurrence, respectively.

If a continuous range is more appropriate than a discrete one for characterizing the magnitude of occurrence of a risk, the discrete states of X_i are to be interpreted as labels of the intervals derived from discretization of the continuous range. For instance, *Chemical release* can be measured in kilograms of released substance, whereby the interval $[0, 1\text{kg}]$ of *negligible* releases can be represented by the state 1 kg, the interval $(1\text{kg}, 1,000\text{kg}]$ of *medium* releases can be represented by the state 1,000 kg, and the interval $(1,000\text{kg}, 66,000\text{kg}]$ of *large* releases² can be represented by the state 66,000 kg (Figure 1). The reason for using quantitative states as interval labels is to gain clarity on what is meant by *negligible*, *medium* or *large*.

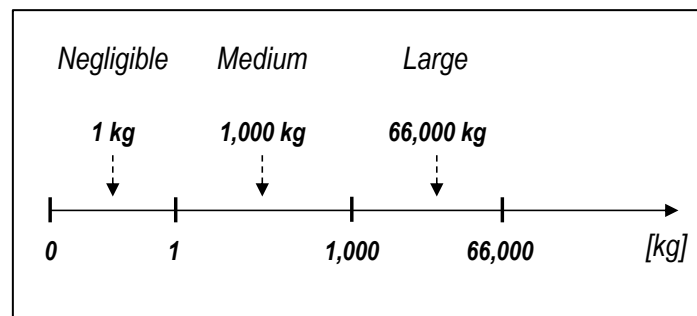


Figure 1. Discretization of the continuous scale measuring the magnitude of occurrence of the risk *Chemical release* in kilograms (66,000 kg is the largest possible release). The three intervals are labelled through the states *Negligible*, *Medium* and *Large*, and through the quantitative states 1kg, 1,000 kg and 66,000 kg.

Operatively, the user enters the risks for the analysis (e.g. *Drought*, *Dam break*, *Chemical release*...), along with their respective units of measurement. For each risk, the quantitative states representing *negligible*, *medium* and *large* are also required from the user. Figure 2 shows an illustrative table from the tool, in which the user has entered the information on the risks.

¹ In the current release of the tool, the number n_R of risks is equal to five.

² 66,000 kg could be, for example, the total inventory at a facility, so that it effectively represent a ceiling to the release.

Risk	units of measurement	Magnitude of occurrence		
Drought	[months]	1	6	24
Dam break	[10 ⁶ m ³]	0.01	5	50
Chemical release	[kg]	1	1000	66000
Water pipeline deterioration	[%]	0.1	0.1	0.5
Terror attack	type	None	Small	Severe

Figure 2. Illustrative table from the tool, in which the user has specified the risks along with their units of measurement and the states representing negligible (third column), medium (fourth) and large (fifth) magnitude of occurrence.

2.1.2. Prior probabilities

The conditional probabilities for modeling the causal dependences between the risks are constructed in a two-stage procedure. The first stage is the construction of the *prior* probabilities of the magnitudes of occurrence of each risk, in the assumption that the magnitude of occurrence of all other risks is *negligible*. The second stage is the specification of coefficients for quantifying the causal dependences between pairs of risks. In this section, we describe the elicitation of the prior probabilities, whereas that of the causal-dependence coefficients is described in Section 2.1.3.

Here, a *prior* probability mass distribution is to be constructed over the magnitudes of occurrence of each risk. By prior, we mean the probabilities of the magnitudes of occurrence of risk i in the assumption that all other risks k occur *negligible* magnitudes, i.e. $p_n^i = P(X_i = n | X_k = n)$, $p_m^i = P(X_i = m | X_k = n)$ and $p_l^i = P(X_i = l | X_k = n)$, $\forall k$. If the users wishes, it is possible to directly enter the values of the prior probabilities. Otherwise, for risk i , the user can construct the prior probability mass distribution stepwise by:

1. Ranking the magnitudes of occurrence from the most (1) to the least (3) likely, through the integers $R_j^i = 1, 2, 3$, $j = n, m, l$
2. Selects the preferred function to turn the ranking into probabilities. The available rank-to-probability functions are (R_j^i and p_j^i are the rank and the probability of the state $j = n, m, l$ for risk i , respectively):

- Rank sum
$$p_j^i = \frac{4 - R_j^i}{6}$$

- Rank reciprocal $p_j^i = \frac{6}{11 \cdot R_j^i}$
- Rank exponent (2) $p_j^i = \frac{(4 - R_j^i)^2}{14}$
- Rank exponent (3) $p_j^i = \frac{(4 - R_j^i)^3}{36}$
- Logarithmic (1) $p_j^i = \frac{10^{-R_j^i}}{0.111}$
- Logarithmic (1.5) $p_j^i = \frac{10^{-(R_j^i)^{1.5}}}{0.1014908}$
- Logarithmic (2) $p_j^i = \frac{10^{-(R_j^i)^2}}{0.1001}$

As it can be verified, each function ensures that $p_n^i + p_m^i + p_l^i = 1$. Then, the user can evaluate whether the distribution reflects his or her qualitative beliefs. Figure 3 shows the prior probability mass distribution over the magnitudes of occurrence of *Chemical release* obtained by ranking plus the *Rank exponent (3)* function.

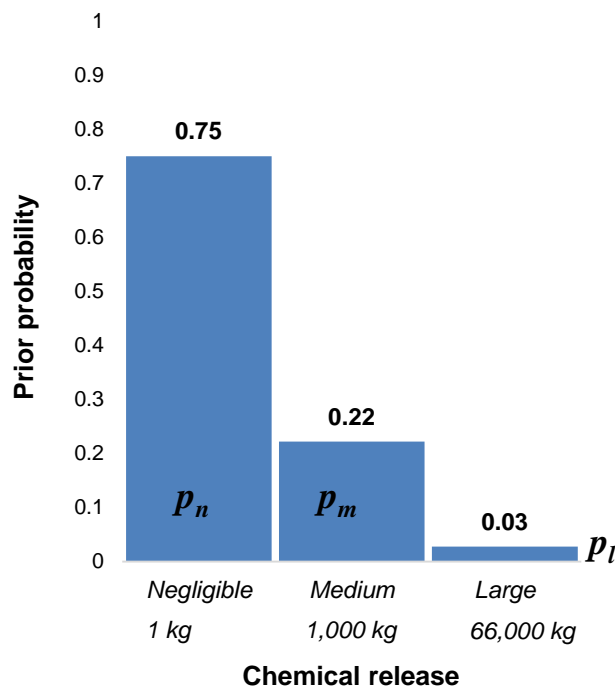


Figure 3. Prior probability mass distribution over the magnitudes of occurrence of *Chemical release*.

When constructing the probability distributions, it is important that the user keeps in mind that the quantitative states such as 1 kg, 1,000 kg and 66,000 kg for *Chemical release* represent

intervals of magnitudes of occurrence, and do not have meaning as specific point values. Therefore, continuing with the example of *Chemical release*, if 100 kg is used instead of 1,000 kg for representing releases of *medium* magnitude, the probability estimates should not be influenced.

2.1.3. Causal dependences

Causal dependences between the risks mean that the occurrence of one risk with non-*negligible* magnitudes can influence the probability distribution over the magnitudes of occurrence of another risk. In keeping with the terminology of BNs [8], we say that the *child* risk is influenced by the *predecessor* risk. Here, coefficients are specified for quantifying the causal dependences between pairs of risks.

Specifically, the user fills in a special cross-impact matrix [9] whose generic element $c_{ki} \in [-5, 5]$, $\forall k, i, k \neq i$ indicates the causal dependence of risk i on risk k . The principle is that positive (or negative) values of c_{ki} imply that the occurrence of the predecessor risk with non-*negligible* magnitudes increases (or decreases) the probabilities of non-*negligible* magnitudes of occurrence of the child risk, whereas zero indicates independence. The coefficients c_{ki} are used to obtain the *conditional* probabilities of the magnitudes of occurrence of risk i in the assumption that its predecessor risk k occurs with non-*negligible* magnitudes, i.e. $p_n^i = P(X_i = n | X_k > n)$, $p_m^i = P(X_i = m | X_k > n)$ and $p_l^i = P(X_i = l | X_k > n)$, as follows. If c_{ki} is positive, the occurrence of the predecessor risk k non-*negligible* magnitudes causes a shift of the prior probability mass distribution for the dependent risk i towards larger magnitudes. Specifically, the ratio $\alpha_{ki} = c_{ki}/5$ determines the share of probability mass which is transferred from the state *negligible* to the *medium* and *large* ones. Hence (see also Figure 4):

- the conditional probability p_n^i of *negligible* magnitude of occurrence, if the predecessor risk occurs with non-*negligible* magnitudes reads $p_n^i = (1 - \alpha_{ki})p_n^i$;
- the probability mass $\alpha_{ki}p_n^i$ is shared between the *medium* and *large* magnitudes proportionally to the prior probabilities of these magnitudes, i.e. $p_m^i = p_m^i + \alpha_{ki}(p_m^i / (p_m^i + p_l^i))p_n^i$ and $p_l^i = p_l^i + \alpha_{ki}(p_l^i / (p_m^i + p_l^i))p_n^i$.

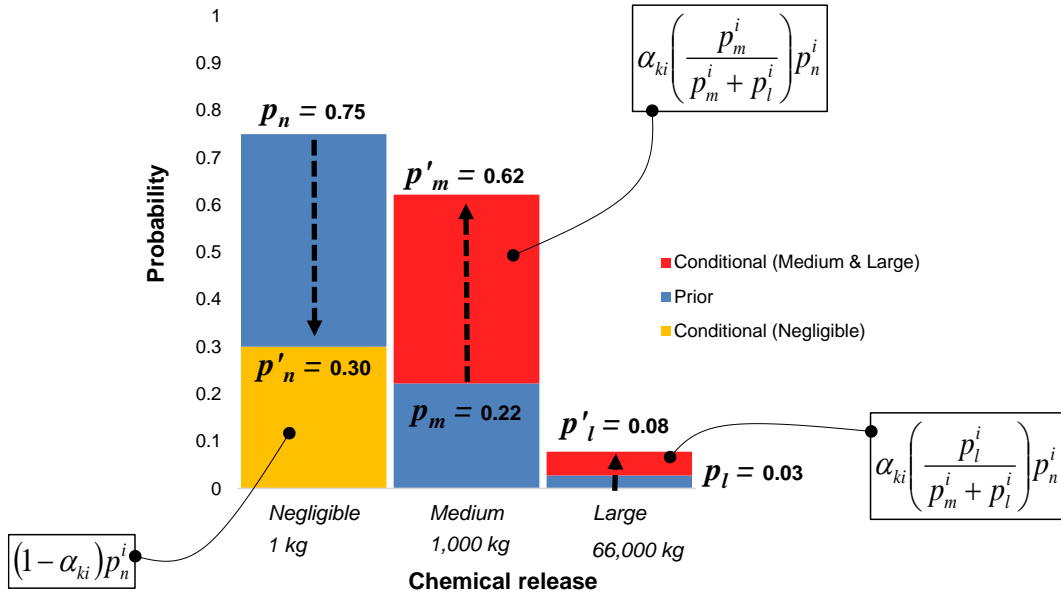


Figure 4. Use of $\alpha_{ki} = c_{ki}/5$, $c_{ki} \geq 0$ to obtain the conditional probability mass distribution p_n^i, p_m^i, p_l^i over the magnitudes of occurrence of risk i if the predecessor risk k occurs with non-negligible magnitudes, by updating the prior conditional probability mass distribution p_n^i, p_m^i, p_l^i of Figure 3.

If c_{ik} is negative, the conditional probabilities are calculated analogously, except that the probability mass is transferred from the *large* magnitude of occurrence to the *negligible* and *medium* ones.

For ease of presentation, we have thus far assumed that risk i has only one predecessor risk k . In general, a risk can have multiple predecessors, say a number N_{PRED} . For taking into account multiple predecessors, not all of which necessarily occur with non-negligible magnitudes, the coefficient α_i is to be used instead of α_{ki} :

$$\alpha_i = \frac{\sum_{k=1}^{N_{\text{PRED}}} c_{ki} \cdot \delta_k^{\text{occur}}}{5 \cdot N_{\text{PRED}}},$$

where δ_k^{occur} is equal to one if the predecessor risk k occurs with non-negligible magnitudes, zero otherwise. Then, the direction of the probability mass transfer is determined by $\sum_{k=1}^{N_{\text{PRED}}} c_{ki} \cdot \delta_k^{\text{occur}}$ being positive or negative. It follows that, if the magnitude of occurrence of all predecessors of risk i is *negligible*, then the conditional probability related to risk i is still the prior.

From the perspective of the BN, entering a value of c_{ki} different from zero is equivalent to drawing a directed arc between risk k and risk i . Against this background, the user should fill

in the matrix of causal dependences without forming feedback loops between the risks. For the probability mass balance to be respected, indeed, the BN needs to be a *directed acyclic graph* [8]. Figure 5 shows an illustrative matrix of causal dependences that accommodates a loop between *Dam break*, *Water-pipeline deterioration* and *Chemical release*.

		Child risks				
→		Drought	Dam break	Chemical release	Water pipeline deterioration	Terror attack
Predecessor risks	Drought		0	0	0	0
	Dam break	0		0	4	0
	Chemical release	0	2		0	0
	Water pipeline deterioration	0	0	3		0
	Terror attack	0	0	0	0	

Figure 5. Illustrative matrix of causal dependences from the tool, in which a feedback loop has been formed: *Dam break* influences *Water-pipeline deterioration*, which influences *Chemical release*, which influences back *Dam break*.

2.1.4. Scenario likelihoods

Each scenario specifies the magnitudes with which the risks occur. More precisely, a scenario is a n_R -sized array in which the magnitude of occurrence of each risk is specified. Here, we wish to examine the complete collection of scenarios in the BN. Specifically, because each risk can occur with three different magnitudes, the set S of all scenarios contains 3^{n_R} scenarios, ranging from the scenario in which the magnitude of occurrence of all risks is *negligible* to the scenario in which all risks occur with *large* magnitude.

Based on the theory of BNs [8], the probability of a scenario is the product of the individual probabilities that the risks occur with the magnitudes specified in the scenario. Suppose risk i occurs with magnitude $j = \{n, m, l\}$ in the scenario under consideration: if risk i has no predecessor, then it appears in this product with its prior probability p_j^i ; if risk i has some predecessors, then it appears in this product with a conditional probability which is obtained by modifying the prior probability of risk i based on the coefficient α_i calculated as in Section 2.1.3.

Therefore, each scenario s is associated with a probability L_s , to which we refer as the *likelihood*. Better than the term “probability”, indeed, the term “likelihood” reflects the fact that

L_s may derive from qualitative or semi-quantitative beliefs of the user (i.e. the ranking and the rank-to-probability functions in Section 2.1.2, and the causal-dependence coefficients in Section 2.1.3). Of course, the likelihoods of the scenarios are such that $\sum_{s \in S} L_s = 1$.

2.2. Multi-Criteria Decision Analysis hierarchy

In view of evaluating the impact of each scenario, a MCDA [10] hierarchy is built in which (Figure 6): the highest layer corresponds to the overall impact; the second layer corresponds to the Key dimensions (KDs) *Environment*, *Society* and *Economy* (i.e. a shortlist of the KDs considered by the Asian Development Bank [11]); the third layer corresponds to the underlying criteria of each KD, e.g. *Surface waters* and *Groundwater* for the *Environment*; the bottom layer is constituted by the quantitative indicators through which each criterion is characterized, e.g. *Fatalities* and *Injuries* for the criterion *Human health* in the KD *Society*.

The rationale of the MCDA hierarchy is that the risks (occurring with magnitudes specified in the scenario under consideration) impact on the indicators by worsening their levels. Then, for each indicator, the new level is turned into a zero-to-one impact value. Subsequently, the impact values are propagated through the hierarchy until obtaining a zero-to-one value for the overall impact, which represents the impact of the scenario under consideration.

In the remainder of this section, we define the indicators (Section 2.2.1), describe the procedure for evaluating the impact of the risks on the indicators (Section 2.2.2) including considerations on synergies (Section 2.2.3) and timing (Section 2.2.4) of the impacts. We also describe the propagation of the impact through the MDCA hierarchy (Section 2.2.5) and how the overall impacts of the scenarios are obtained (Section 2.2.6).

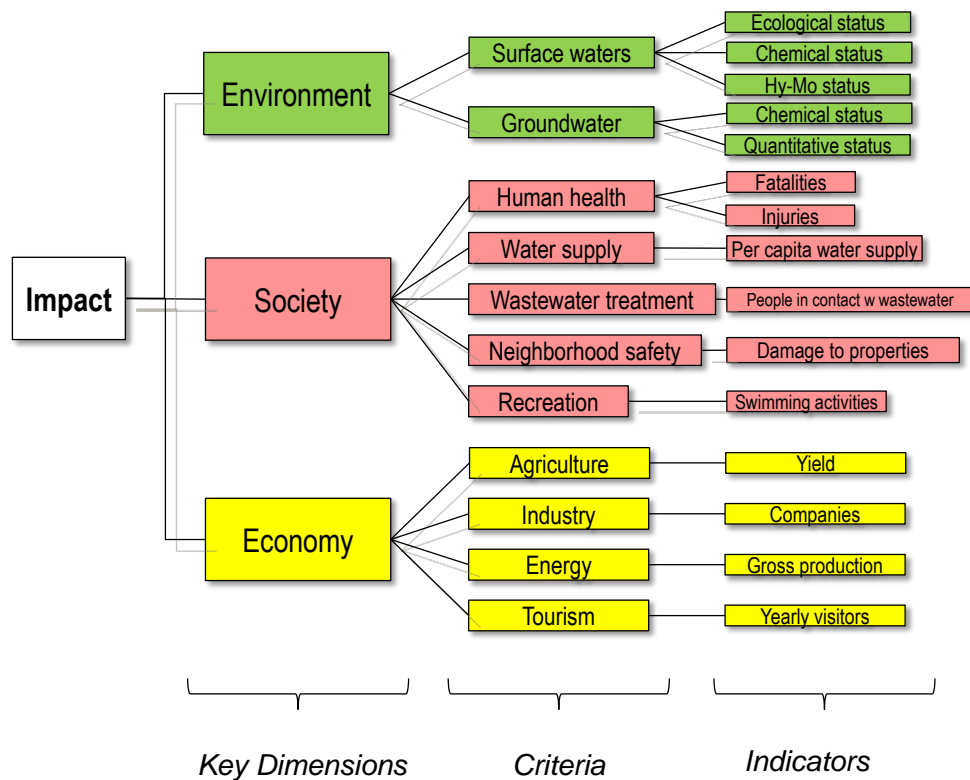


Figure 6. Multi-criteria Decision Analysis hierarchy for evaluating the overall impact (top) of the risk scenarios. The hierarchy then comprises, in order of decreasing abstraction, the Key Dimensions, the Criteria and the Indicators.

2.2.1. Indicators

The indicators are physical quantities defined over scales with suitable units of measurement. For each indicator, the minimum and maximum possible levels l_{\min} and l_{\max} are specified with respect to the domain of interest (municipality, region, country...). Depending on the indicator, one extreme corresponds to the worst level for water security, while the other extreme can be some physical limit: for instance, the worst level of such indicators as *Fatalities* is l_{\max} , whereas zero is the obvious l_{\min} ; for such indicators as *Yield*, the worst level is l_{\min} , while l_{\max} can be some reasonably attainable yield. Furthermore, the current situation in the domain of interest is represented by the level l_{curr} of each indicator.

In view of propagation through the MCDA hierarchy, the levels of the indicators are turned into impact values $\text{imp}(l) \in [0,1]$ by means of impact functions. All the impact functions available in the tool imply an impact equal to one for the worst level of the indicator and equal to zero for the other extreme, but with different shapes. The *neutral* function varies linearly over the interval $[l_{\min}, l_{\max}]$. The *conservative* function has a concave quadratic polynomial shape, so that for the resulting impact is always larger than that of the *neutral* impact function. The *impact-tolerant* function has a convex quadratic polynomial shape, so that the resulting impact

is always smaller than that of the *neutral* impact function. The expressions and the shapes of the impact functions are illustrated in Table I and in Figure 7, respectively, where we differentiate the cases in which the worst level of the indicator is the minimum or the maximum.

Table I. Expressions of the impact-tolerant, neutral and conservative impact functions, depending on whether the worst level of the indicator is the minimum or the maximum.

Worst level	Impact-tolerant	Neutral	Conservative
min	$imp(l) = \left(\frac{l - l_{MAX}}{l_{min} - l_{MAX}} \right)^2$	$imp(l) = 1 - \frac{l - l_{min}}{l_{MAX} - l_{min}}$	$imp(l) = 1 - \left(\frac{l - l_{min}}{l_{MAX} - l_{min}} \right)^2$
MAX	$imp(l) = \left(\frac{l - l_{min}}{l_{MAX} - l_{min}} \right)^2$	$imp(l) = \frac{l - l_{min}}{l_{MAX} - l_{min}}$	$imp(l) = 1 - \left(\frac{l - l_{MAX}}{l_{min} - l_{MAX}} \right)^2$

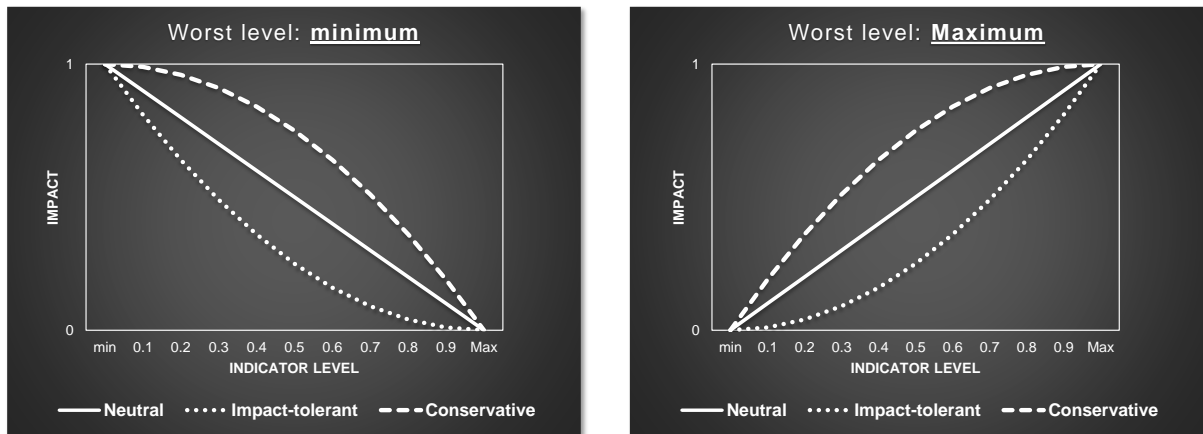


Figure 7. Shapes of the impact-tolerant, neutral and conservative impact functions, depending on whether the worst level of the indicator is the minimum or the maximum.

Operatively, the user specifies the units of measurements of the indicators, along with the minimum and maximum possible levels l_{min} and l_{MAX} and the current level l_{curr} in the domain of interest. Additionally, for each indicator, the user specifies whether the worst level to water security is the minimum or the maximum one, and selects the preferred impact function.

2.2.2. Prior impacts

Analogously to the construction of the conditional probabilities in the BN, the impact of the risks on the indicators is determined in two stages. First, the *prior* impact of each risk on each indicator is specified, in the assumption that the magnitude of occurrence of all other risks is *negligible*. Second, coefficients are specified for quantifying synergies between the risks. In this section, we describe the elicitation of the prior impacts, whereas that of the synergies is described in Section 2.2.3.

Here, the user fills in a table whose generic element $\gamma_{i,j}^h \in [0, 5]$ indicates the impact of risk i occurring with magnitude $j = \{m, l\}$ on indicator h . Such an impact is prior because it is specified while assuming that the magnitude of all other risks is *negligible*. Then, the coefficient $\gamma_{i,j}^h$ serves to change the current level l_{curr} of indicator h into the “impacted” level l_{imp} when risk i occurs with magnitude $j = \{m, l\}$, as follows.

If the worst level of the indicator is l_{MAX} , the current level becomes:

$$\begin{cases} l_{imp} = l_{curr} + \Delta \\ \Delta = \min \left[\frac{\gamma_{i,j}^h}{5} \cdot (l_{MAX} - l_{min}); (l_{MAX} - l_{curr}) \right], \end{cases}$$

whereas if the worst level of the indicator is l_{min} , the current level becomes:

$$\begin{cases} l_{imp} = l_{curr} - \Delta \\ \Delta = \min \left[\frac{\gamma_{i,j}^h}{5} \cdot (l_{MAX} - l_{min}); (l_{curr} - l_{min}) \right]. \end{cases}$$

2.2.3. Synergies

Synergies between the risks mean that when two risks occur with non-*negligible* magnitudes they can cause larger changes in the indicator levels than the sum of the changes they would cause individually. Here, coefficients are specified for quantifying the synergies between pairs of risks. Specifically, the user fills in a matrix whose generic element $\theta_{ik} \in [0, 5]$, $i, k = 1, \dots, nR, i \neq k$ indicates the synergy between risk i and risk k . Because $\theta_{ik} = \theta_{ki}$, the user needs to fill in only the part of the matrix above the diagonal. The coefficients θ_{ik} are used as follows to obtain the impact $\gamma_{i,j}^h$ on indicator h of risk i occurring with magnitude $j = \{m, l\}$ if there are synergies with other risks [12]:

$$\gamma_{i,j}^h = \left(1 + \sum_{k=1, k \neq i}^{nR} \frac{\theta_{ik} \cdot \delta_k^{occur}}{5} \right) \cdot \gamma_{i,j}^h.$$

2.2.4. Time of impacts

We intend to include time considerations in evaluating the impacts of the risks on the indicators. Therefore, the user (i) specifies the time horizon T_{HOR} of interest (in years) and (ii) fills in a matrix whose generic element t_{hi} indicates the time of impact (in years) of risk i occurring with non-*negligible* magnitude on indicator h . By time of impact we mean the time lapse between

the occurrence of the risk and the realization of the impact on the indicator. Here, the rationale is that impacts farther in time can be considered less important.

Against this background, a function of the time of impact can be used to discount the $\gamma_{i,j}^h$ taking T_{HOR} into account. To this aim, the tool involves a step function such that the coefficient $\gamma_{i,j}^h$ is set to zero if $t_{hi} > T_{HOR}$. Arguably, some sigmoid function that implies a smoother discount of $\gamma_{i,j}^h$ can guarantee more balanced evaluations of the impacts, but the step function was chosen in the current version of the tool for ease of implementation. The step function of the tool (and an illustrative sigmoid function that could be implemented in future releases) is shown in Figure 8.

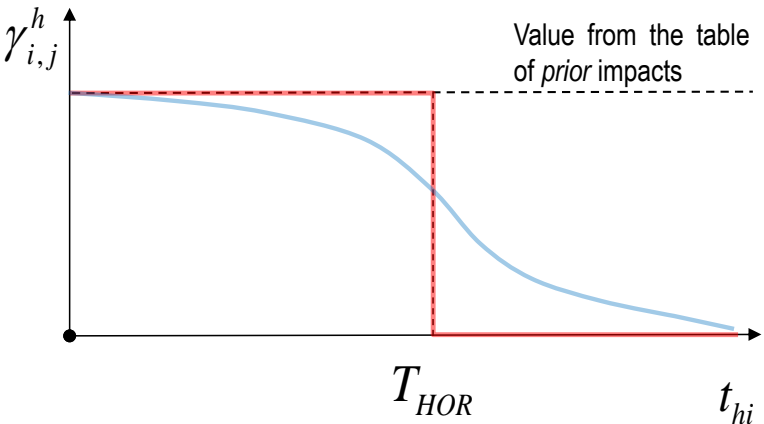


Figure 8. Step function for discounting $\gamma_{i,j}^h$ depending on t_{hi} and T_{HOR} (red), and an illustrative sigmoid function (blue) to be considered in future releases of the tool.

When applying the step function, it is assumed that, if the risk occurs with non-negligible magnitude (thus triggering its impact on the indicators), it does at the time of the analysis, so that t_{hi} can be directly compared to T_{HOR} . More realistically, the risk could occur at any time, thus making it necessary to take the time of occurrence into account. This is another feature to appear in future releases of the tool. At any rate, even though the current assumption is not fully realistic, it is conservative.

2.2.5. Weights

Thus far we have described how to obtain impact values $imp(l)$ on each indicator, in response to risks occurring with non-negligible magnitudes. Then, these zero-to-one impacts have to be propagated through the MCDA hierarchy, until obtaining an overall impact at the top of the hierarchy. The impacts are propagated from the indicators layer to the top of the hierarchy by

weighted aggregation, where the weights should reflect the user's preferences between items in the same layer of the hierarchy.

The adopted weighting mode is *hierarchical*: weights are specified at each layer of the hierarchy, and separately for each branch. Specifically: first, weights are specified for the indicators, and separately for each group of indicators branching from one criterion; then, weights are specified for the criteria, and separately for each group of criteria branching from one key dimension; finally, weights are specified for the key dimensions, which all branch from the overall impact at the top of the hierarchy. In what follows, we describe the specification of the weights at each layer of the hierarchy.

First, the impact values on the indicators have to be aggregated to obtain the impact values on the criteria. If a criterion is characterized by only one indicator (as it is often the case in Figure 6), weighting is not necessary and the aggregation is straightforward: the impact value of the criterion is the same as that of the indicator. If a criterion is characterized by multiple indicators, then these indicators need to be weighted. Here, weighting is done through the specification of l_{\min} and l_{\max} for the indicators. Let us consider, for instance, the indicators *Fatalities* and *Injured/ill*. For both it holds that $imp(l_{\max}) = 1$, so that the specific values of l_{\max} entered by the user for these indicators represent impacts between which the user is indifferent. Then, the impact values of multiple indicators are aggregated by simple averaging. Second, the impact values on the criteria have to be aggregated to obtain the impact values on the key dimensions. Towards this end, the weights of the criteria underlying each key dimension are specified by trade-off weighting. Specifically, the user states the impact change on a criterion that would be equally undesirable to the maximum impact (i.e. from zero to one) on another criterion. Figure 9 shows the questions for the criteria *Agriculture*, *Industry*, *Energy* and *Tourism* underlying the Key Dimension *Economy*. If there are n criteria, these questions correspond $n-1$ equations which, in addition to the constraint that the weights sum up to one, enable the solution of the system that provides the user with the weights of the criteria. If the criterion in the second part of the question is more important than that in the first part, the answer should be a number larger than one, which can be counterintuitive for the user because $imp(l) \in [0,1]$. Hence, the user has to rank the criteria before the questions are shown, so that the criterion in the second part of each question is always more important than that in first part, and the answer is a number between zero and one (a warning message appears if it is not so, see Figure 10).

Question:	Answer:
Imagine an impact change from 0 to 1 on Tourism. What would be an equally undesirable impact change on Agriculture?	0.3
Imagine an impact change from 0 to 1 on Agriculture. What would be an equally undesirable impact change on Industry?	0.9
Imagine an impact change from 0 to 1 on Industry. What would be an equally undesirable impact change on Energy?	0.9

Figure 9. Trade-off questions from the tool, for weighting the criteria underlying the key dimension Economy.

Question:	Answer:
Imagine an impact change from 0 to 1 on Tourism. What would be an equally undesirable impact change on Energy?	1.2
Imagine an impact change from 0 to 1 on Energy. What would be an equally undesirable impact change on Industry?	
Imagine an impact change from 0 to 1 on Industry. What would be an equally undesirable impact change on Agriculture?	

Warning

For consistency with the preferred ranking, this value should lie between 0 and 1.

Continue?

Yes No Cancel Help

[Was this information helpful?](#)

Figure 10. Warning message from the tool if the user answers with a value larger than one to the trade-off between a less (Tourism) and a more (Energy) important criterion, according to the user's ranking.

Finally, weights are to be specified for the key dimensions, what is done in the same way as for the criteria. Figure 11 shows the questions as they would appear after the user ranks Society, Environment and Economy in descending order of importance.

Question:	Answer:
Imagine an impact change from 0 to 1 on Economy. What would be an equally undesirable impact change on Environment?	0.7
Imagine an impact change from 0 to 1 on Environment. What would be an equally undesirable impact change on Society?	0.8

Figure 11. Trade-off questions from the tool, for weighting the key dimensions.

2.2.6. Scenario impacts

In Section 2.1.4 a scenario has been defined as an array in which the magnitude of occurrence of each risk is specified. Building on this definition, the impact of each scenario on each indicator *h* can be obtained by superimposing the impacts of each risk *i* occurring with the

magnitude $j = \{n, m, l\}$ specified in the scenario³. More specifically, the coefficients $\gamma_{i,j}^h$ are summed and the current level l_{curr} of indicator h is changed into the “impacted” level l_{imp} on the basis of this sum. Subsequently, the impact values $imp(l_{imp})$ of all the indicators are propagated through the MCDA hierarchy, thus obtaining the overall impact I_s of each scenario s .

3. Illustrative results

The main result of the tool is the WSI, which is a percentage quantifying water security in the domain of interest. The WSI is obtained by aggregating likelihoods and impacts of the scenario from the BN and the MCDA as follows:

$$WSI = 1 - \sum_{s=1}^{3^{nR}} L_s \cdot I_s.$$

Although the WSI does not have a proper physical meaning, it can still support risk-informed decision making in that it synthesizes the knowledge and preferences of the user in a single value, obtained through a methodological structure. Figure 12 reports a graph from the tool in which the WSI is compared to a reference scenario selected by the user, e.g. the scenario in which the magnitude of all risks is *negligible*.

Another graph provided by the tool is a scatter plot in which each dot represents one of the 3^{nR} scenarios with its likelihood (horizontal) and impact (vertical axis). One possible use of this graph (not yet covered in the current version of the tool) is for risk-management applications. Specifically, clusters of scenarios can be identified based L_s and I_s so that risk-reduction strategies can address particular clusters of scenarios. For instance, Figure 13 shows an illustrative graph in which a cluster of scenarios in the top-right region represents high-likelihood and high-impact scenarios. Then, by looking at the risk occurrences that recur in this cluster, insights are gained on how to tailor risk-reduction strategies to these risk occurrences.

If it is necessary to understand individual items of the MCDA hierarchy, the overall WSI can be disaggregated e.g. by key dimension (Figure 14). Such disaggregation is performed by (i) stopping the propagation of the impacts at the key-dimension layer of the MCDA and (ii) using the key-dimension-wise impacts of the scenarios rather than the I_s in the equation of the WSI. By so doing, the user can notice that, while the overall WSI was mostly determined by *Society* because of the larger weight of this key dimension, the WSI for the sole key dimension

³ It is recalled that a risk does not have any impact if it occurs with *negligible* magnitude (n).

Economy is even lower. Thus, if resources are available, these can be allocated to the risk-management of *Economy*, even if this key dimension was not on top of the user's preferences. Besides disaggregation by key dimension, also disaggregation by risk can be useful for risk-management applications. This notwithstanding, disaggregation by risk is hampered by the interactions between the risks, that is, causal dependences and synergies. These interactions, indeed, imply that likelihoods and impacts are determined by the joint rather than by the individual occurrence of the risks. In the current version of the tool, a simplified disaggregation by risk is done by looking at the impact (not yet at the WSI) of scenarios in which only one risk at a time occurs. The result is shown in Figure 15, which illustrates the impact (still disaggregated by key dimension) of each risk, occurring with *medium* or *large* magnitude. The disaggregation is important that the decision maker and user see and understand how the WSI is composed and is not merely a number from black box. Otherwise risk mitigation measures can have even an opposite impact on WS on some other dimension.

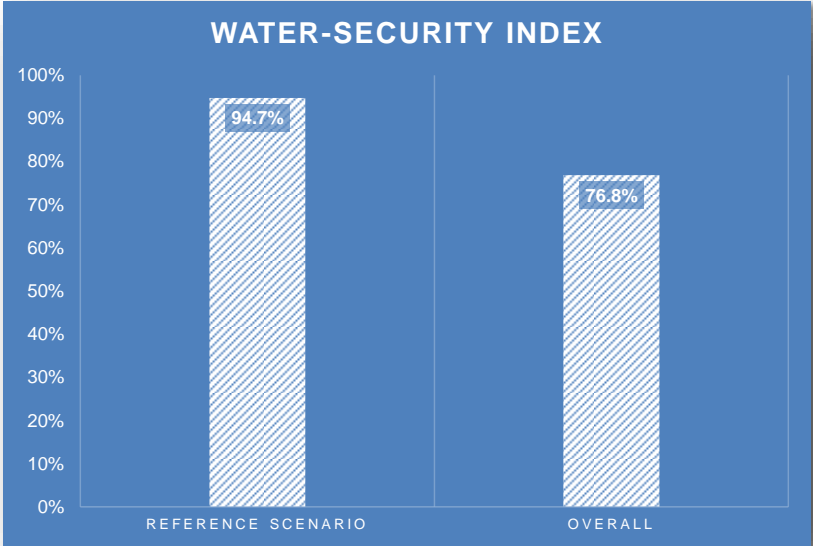


Figure 12. Graph from the tool, showing the WSI obtained from the analysis (right) and compared to a reference scenario (left).

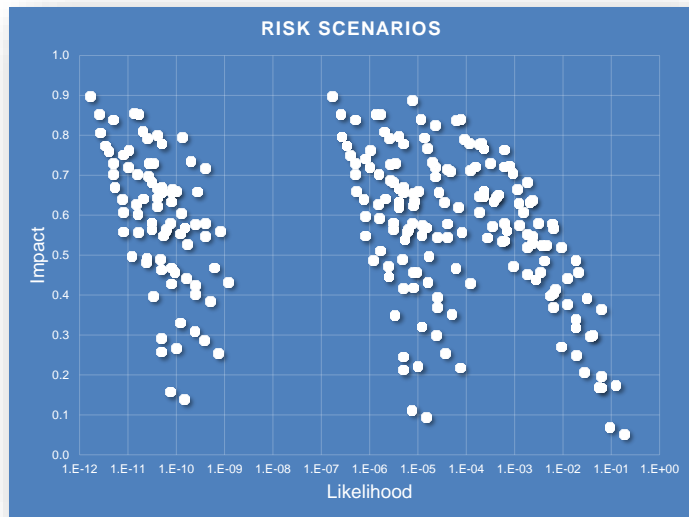


Figure 13. Scatter plot from the tool, in which each dot represents one of the 3^{nR} scenarios with its likelihood (horizontal) and impact (vertical axis).

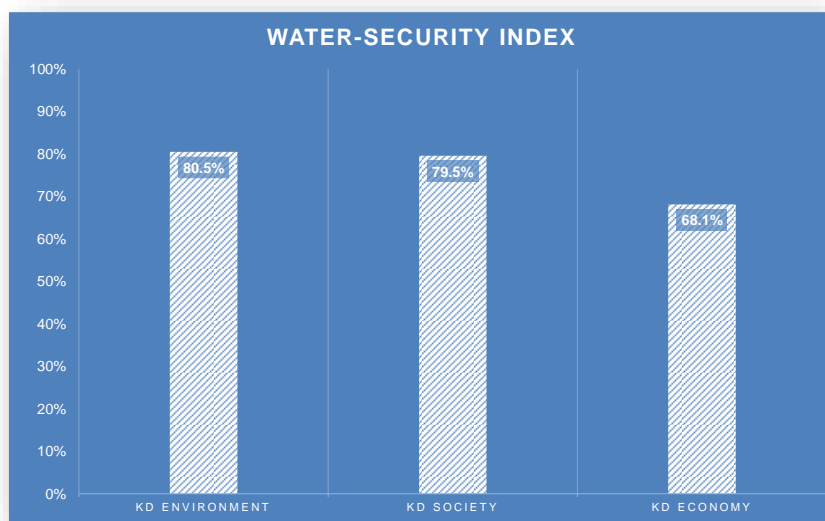


Figure 14. Graph from the tool, showing the WSI disaggregated by key dimension.

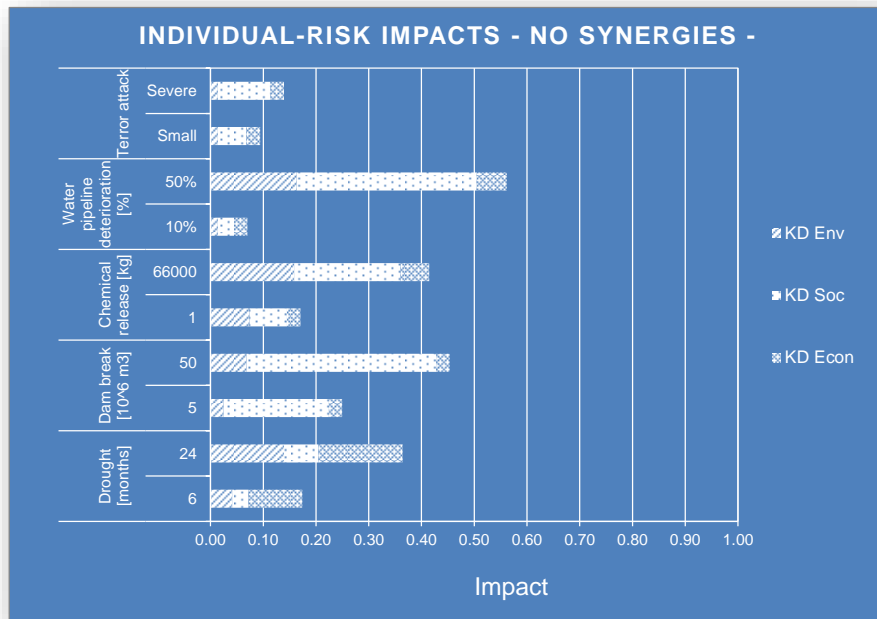


Figure 15. Graph from the tool, showing the Impact (horizontal axis) disaggregated by risk and magnitude of occurrence (vertical axis), and by key dimension (different colors in the bars).

4. Sensitivity analysis

Among the main tasks of this project is the testing of the tool, including (i) model verification and (ii) sensitivity analysis. Model verification consists of checking that the results are coherent with the theory behind the methodological structure of the tool: probabilities are between zero and one, the likelihoods of the scenarios sum up to one etc. Model verification has been performed successfully, but its results are not shown here for the sake of brevity. Sensitivity analysis evaluates the influence of the individual assumptions and variables of the tool on the final results. In this section, we show the main results from sensitivity analysis of the tool.

Here, we carry out a simplified sensitivity analysis to examine the influence of the following elements of the tool: (i) the rank-to-probability functions for turning the ranks assigned to the magnitudes of impact of each risk into a probability mass distribution, (ii) the interactions, i.e. the causal dependences in the BN and the synergies in MCDA, and (iii) the impact functions for turning the level of each indicator into an impact value between zero and one. Specifically, we take inspiration from the nominal-range sensitivity analysis approach [13], and look at the change in the WSI as each individual element is changed from one extreme setting to the other, while the other elements stay fixed to their nominal setting. For clarity, Table II shows, for each of the three investigated elements, the nominal (third column) and the extreme settings (second and fourth columns) considered in sensitivity analysis.

Table II. Elements of the tool investigated in sensitivity analysis (first column), and their “lower” (second), nominal (third) and “upper” (fourth) settings for the nominal-range sensitivity analysis.

Element of the tool	“Lower” extreme setting	Nominal setting	“Upper” extreme setting
Rank-to-probability functions	<i>Rank sum</i> for all risks ⁴	<i>Rank exponent (3)</i> for all risks	<i>Logarithmic (2)</i> for all risks
Interactions (causal dependences and synergies)	All causal dependences <u>above the diagonal</u> ⁵ set to -5 All synergies set to 5	All causal dependences and synergies set to zero $c_{ki} = 0, \forall k, i$ $\theta_{ik} = 0, \forall i, k$	All causal dependences <u>above the diagonal</u> set to +5 All synergies set to 5
Impact functions	<i>Impact-tolerant</i> for all indicators	<i>Neutral</i> for all indicators	<i>Conservative</i> for all indicators

The rationale for choosing the extreme settings reported in Table II is the following. For the rank-to-probability functions, *Rank sum* implies the most even probability mass distribution, whereas *Logarithmic (2)* implies the most unbalanced one. For the interactions, causal dependences of -5 imply that large risk magnitudes of the dependent risks are prevented if their predecessor risks occur, whereas +5 implies that the dependent risks are bound to occur with non-negligible magnitudes if their predecessor risks occur (synergies are set to 5 in both cases, as there is no other extreme value for them). For the impact functions, *Impact-tolerant* leads to a lower evaluation of the impact than the *Neutral*, whereas the opposite happens with the *Conservative* one. Conversely, the nominal settings are chosen to represent balanced settings between the extreme ones.

Operatively, the WSI is first computed in correspondence of the nominal settings for all elements⁶. This value of WSI, is used as benchmark in each of the charts showing the change in the WSI as each individual element is changed from one extreme setting to the other, while the other elements stay fixed to their nominal setting. The sensitivity to the Rank-to-probability functions is shown in Figure 16, the sensitivity to the interactions is shown in Figure 17, and the sensitivity to the impact functions is shown in Figure 18.

⁴ The negligible and the large magnitudes of occurrence are ranked as the most and the least likely, respectively, for all risks.

⁵ Recall that the causal dependences must be entered without forming feedback loops in the BN, see Figure 5.

⁶ The other elements of the tool, not submitted to sensitivity analysis, are also set to nominal settings to reduce their influence on the computed WSI: current levels of the indicators all set to the best level; equal weights in all sets of criteria and key dimensions; prior impacts all set to one; time of impacts all set to zero.

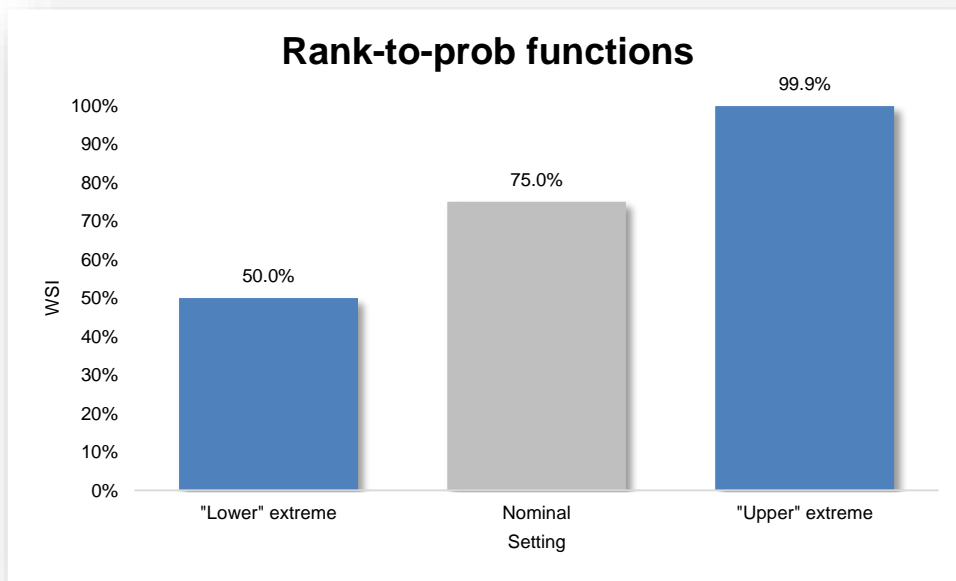


Figure 16. Nominal-range sensitivity analysis of WSI to the Rank-to-probability functions. The nominal settings corresponds to Rank exponent (3), whereas the "lower" extreme corresponds to Rank sum, and the "upper" extreme corresponds to Logarithmic (2), for all risks.

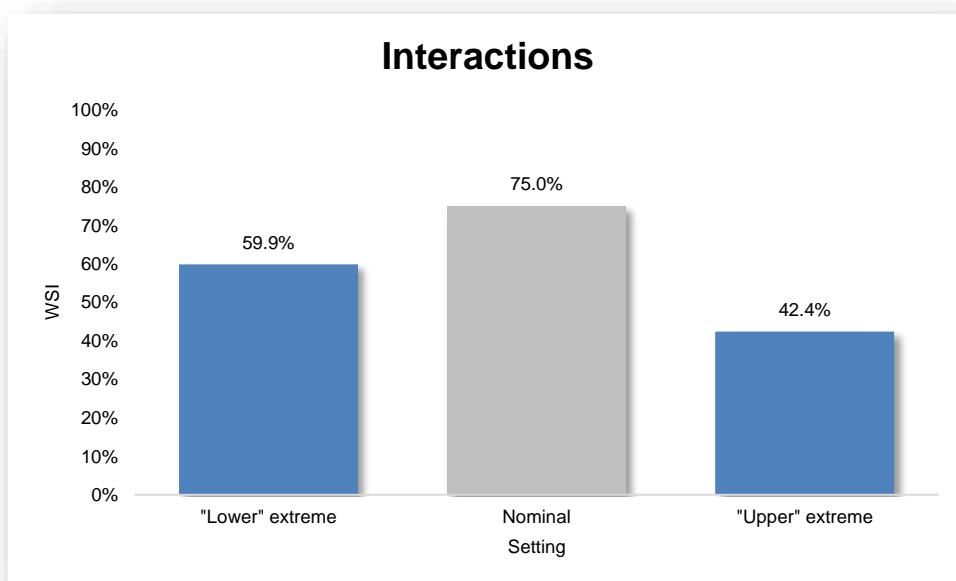


Figure 17. Nominal-range sensitivity analysis of WSI to the Interactions in the BN (causal dependences) and in MCDA (synergies). The nominal settings corresponds to causal dependences and synergies set to zero, whereas the "lower" extreme corresponds to causal dependences set to -5, and the "upper" extreme corresponds to causal dependences set to +5 (synergies are all set to +5 in both extreme settings).

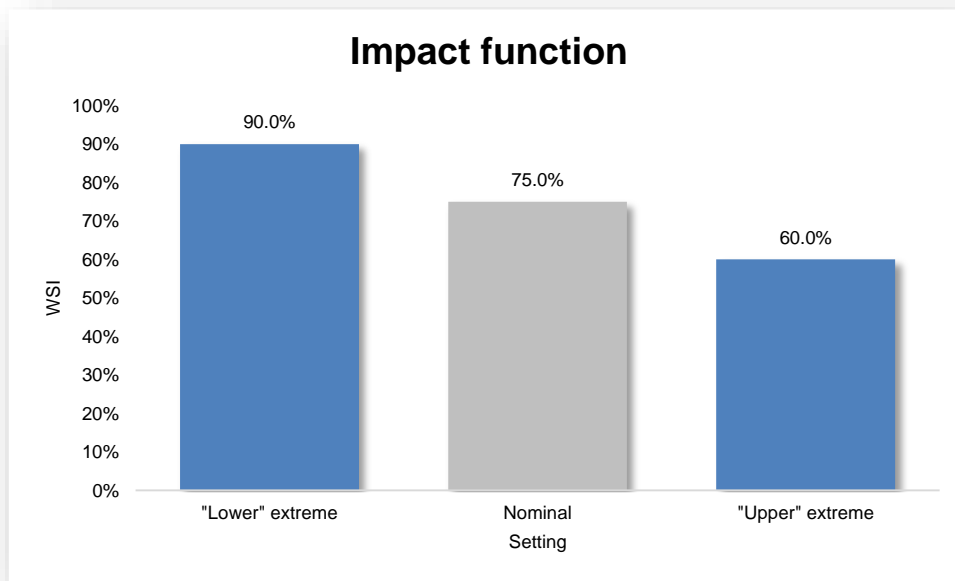


Figure 18. Nominal-range sensitivity analysis of WSI to the impact functions. The nominal settings corresponds to Neutral, whereas the "lower" extreme corresponds to Impact-tolerant, and the "upper" extreme corresponds to Conservative, for all indicators.

Because the sensitivity analysis carried out here is not fully systematic, detailed comments on e.g. which element is more influential to the WSI than the others, or on the linear or non-linear dependence of WSI on each individual element, cannot be provided. Still, we can note that changes in the elements of the tool can cause considerable changes in the resulting WSI, i.e. in the range of 10-30%. On one hand, this means that the tool offers a variety of options to evidently represent different beliefs (Rank-to-probability functions and interactions) and preferences (impact functions). On the other hand this implies that the user shall pay attention to enter information that properly reflects his or her beliefs and preferences, because changes can have a great impact on the results.

5. Expert workshop for collaborative use of the tool

Bakker [14] identified the need for interdisciplinary and collaborative research as a requirement for successful socio-environmental analysis and science-informed policy in water security. Therefore we propose organizing a multidisciplinary expert workshop for using the tool.

The tool needs different inputs from different fields of experts to give viable and balanced results. The workshop can be done in various ways, but discussion between experts usually gives even more information and increase the knowledge around the risks. So the workshops and the approach itself increase knowledge of the risk even without the tool. The tool and facilitated workshop give structure and documentation platform for the discussion. It also visualizes the results, accounts for interactions and makes the comparison of risks easier for

the experts and decision makers. Depending on the domain of interest and level of detail the workshop can take from half a day to two days. The workshop requires a lot of preparation and background work from the user who is doing the WS assessment. The workshop has to be closely facilitated that the experts understand the assumptions of the tool and the impacts of their opinions. Getting the right stakeholders to the workshop is very important not only to the assessment phase, but possibly also to the risk mitigation phase later on.

6. Discussion

The objective of the project was to develop an approach and a tool for water security risk assessment. The selected approach combines Bayesian networks (BNs) and a Multi-criteria Decision Analysis (MCDA) hierarchy. Traditionally risk assessment is about the probability and impact of the risks. The BN part of the tool is designed for changing beliefs of an expert (or group of experts) in to probabilities of unlikely events (risk) occurring. The model takes into account the conditional probabilities of multiple risks happening at the same time. The MCDA part is designed to compare the risks based on their expected impact on economy, environment and the society. A weight elicitation procedure has been implemented into the tool, in order to capture the preferences of decision makers, e.g. to give more weight for losses of human lives over economic losses.

The tool can be used to assess water security in the domain of interest (municipality, region, country...) based on the likelihood and impact of the risks assessed, and compared to the selected baseline scenario. In addition the tool can be used to illustrate and compare the impacts of individual risks, and their impact on different key dimensions of water security. This can be very useful for identifying the risks to be mitigated, and to see if the risks affect to all dimensions of water security or just to a certain aspect of water security. The tool can be used as a part of a larger water security assessment or as a smaller case study to get better understanding to a specific set of risks.

The tool balances between usability and complexity of the assessment. Therefore some simplifications and assumptions have been made. For example in the tool some simplification are needed when describing the risks under assessment. E.g. drought is defined based on the duration of the drought period, but another important factor would be the deviation from average rainfall in millimeters. In the user's guide (a separate deliverable of the project) a recommendation for defining the risks as accurate as possible is made, in order to help the impact assessment.

In addition, the probabilities of risks can be given exactly, if available. The use of ranking in defining the probabilities should be explained to the users very carefully, as done by the user's

guide. Also a facilitator of an expert workshop should be aware of this and pay special attention to the probability assessment.

Another issue to be dealt with special attention is the scaling (0-1) of attributes using the impact functions. In the tool a global scale is defined based on the characteristics of the domain of interest (municipality, region, country...). Then the impact of different risks to the indicators is evaluated in respect to the scale. Whereas a more traditional MCDA approach would have been using a local scale, where the range would be defined using the risks at stake. To ensure the comparability of the impacts and additivity of the models the min and max values should be defined consistently. At the moment, for example, the scale for fatalities and injuries is the same (max = no. of inhabitants within the domain of interest) and these are weighted equally in sub-criteria human health. In the future, however, the tool should be developed so that the user can set weight at the indicator level. For example to make 10 deaths account for equal to 1000 injuries.

In current version of the tool, the weighting is based on the scaled (0-1) values of the impact. Instead it would be more intuitive for the user, if the weights were to be assessed based on the actual values of the indicators (e.g. change from Bad to High surface water quality). In addition, at the moment the weights set at the water security key dimension level are a bit abstract, (see Figure 11 in section 2.2.5). In order to make them more intuitive in the future, the weighting could be built by comparing the prioritized indicators within each key dimension against each other.

In addition to the above, for the tool to be used in actual WS risk assessment for example in Winland project, some further development is needed. The development needs were identified together with experts from Finnish Environment Institute. These include introduction of sensitivity analysis into the user interface of the tool. For now some sensitivity analysis has been only provided within this report (see Section 4). In addition the tool is now only capable of dealing with maximum of 5 risks. The possibility to add more risks is however only a question of coding exercise and would not affect the mathematical structure of the model. However, it should be kept in mind that adding more risks will also make the workshop more laborious. In addition, other features on the user interface could be improved using Visual Basic.

The ARVI approach

In the assignment the so called ARVI approach was suggested as a reference for the assessment. ARVI is a MCDA based tool for systematic impact significance assessment related to the Environmental Impact Assessment (EIA) made for a proposed development project [15]. The principle in ARVI approach is that for each impact the sensitivity of the receptor and the magnitude of change is assessed.

However, the ARVI approach did not, quite fit into the aims of this project, as the impacts to be considered related to water security are manifold. For example the key dimensions of water security were defined as environmental, social and economic water security. The criteria for these key dimensions include for example many of the sub criteria under the “sensitivity of the receptor” in the ARVI approach. In addition, the water security key dimensions fit very well into a traditional way of building a value tree, including the environment, society and economy, with possible trade-offs between the criteria.

7. Conclusions: self-assessment of the project

The objectives of the project were pursued through several tasks, some of which can be here given special emphasis. First, the meeting with the client served to set the scope of the project. On the basis of this meeting, the conceptual framework for the WS assessment was developed. The conceptual framework was then turned into a methodological structure (the combination of BN and MCDA) the implementation of which is the Excel tool. Finally, the tool was tested through model verification and sensitivity analysis. All tasks were shared evenly among the team members to ensure that each member had a sound understanding of the contents of each task. As Figure 19 shows, we carried out the tasks on schedule.

For evaluating the success (or less so) of the project, it is appropriate to evaluate whether the specific objectives of the project were achieved. Towards this end, we refer to Table III, which reports all specific objectives along with evaluations (blue bars, the lengths of which are purely illustrative) and short comments (third column) on the degree of achievement. The achievement of the objectives is discussed at more length in the following.

The tool enables the assessment of WS through the evaluation of likelihoods and impacts of all the scenarios originating from the risks occurring with different magnitudes. This evaluation takes interactions into account, in the form of causal dependences and synergies. In keeping with the scope stated with the client at the beginning of the project, the number of risks is restricted to five. The tool could be improved by allowing the user to include any number of risks.

We believe that the tool represents a satisfactory balance between complexity of the methodological structure and usability. Specifically, the tool enables the derivation of quantitative information from qualitative or semi-quantitative beliefs of the user. However, some of the structures through which quantitative information is derived (especially the -5 / +5 and 0 / +5 scales) could be revisited to enhance flexibility and realism of the tool.

The tool enables the definition of the spatial and temporal scale of interest. Specifically, the spatial domain of interest (country, region, municipality...) is defined through the values of risk magnitudes and indicator levels entered by the user: for example, the largest magnitude of

occurrence for *Chemical release* can correspond to the total inventory of a chemical at a specific facility in a specific town. The temporal scale is defined by the user through the time horizon of interest. Improvements about the definition of the spatial and temporal scale are that the former could be defined more explicitly, and the latter could be taken into account more realistically than it currently is in the tool.

In addition to providing the overall WSI, the tool disaggregates the WSI by Key dimension. Here, the avenue is to improve the determination of the weights in the MCDA hierarchy. Specifically, improvement could be sought by, (i) employing a non-hierarchical weighting in the place of the current hierarchical one (i.e. the weights could be elicited only at the indicator layer, and across all of them contextually, and then propagated to the upper layers by sum), and (ii) eliciting the weights of the indicators directly (e.g. by trade-off comparisons), rather than implicitly through the specification of the worst level of each indicator.

Arguably, the tool provides illustrative and understandable results, which are obtained from Excel sheet which are easy and quick to fill in by the user. Nevertheless, the actual extent to which the tool is illustrative, understandable, easy and quick may be verified more thoroughly by further test sessions with the client.

A similar consideration applies to the evaluation of the potential of the tool for use for the WS assessment on a large scale, for instance that of Finland. In this case, the client may be involved for identifying a suitable real case study on which to test the tool.

The objective of evaluating the resilience of the system was added when the project was ongoing. However, the resources required for this objective were fairly uncertain, so that the re-scoping (or even the removal) of this objective was seen as possible. For the time being, because the available resources proved not to be sufficient for an additional objective, the evaluation of resilience was not included in the tool.

Overall, the self-evaluation of the project is that the objectives have been achieved. Section 6 and the above paragraphs of this section highlight some avenues for improvement, but not with the intent of indicating what could have been done differently in hindsight. In fact, it is a natural process that of developing a model (in this case, the tool) and progressively improving it. In other words, it would not be so reasonable to expect the tool to have a non-improvable methodological structure at this stage (i.e. at the end of a four-month project). However, something that could have been better managed in the project is the following.

During the project, there were two meetings with the client, in which suggestions were given on how to improve the tool. These meetings could not be planned ahead of time, hence their absence from the schedule. The second meeting, which took place relatively late in the project, helped the team understanding that the weighting procedure in the MCDA hierarchy could be improved. More specifically, such an understanding was gained from combining the client's

comments on the use of global scales for the indicators (see Section 6) with the comments from the interim-presentation audience on the appropriateness of non-hierarchical rather than hierarchical weighting procedure. Therefore, in hindsight, there could have been a meeting with the client after the interim presentation to improve the weighting procedure.

Schedule: Finnish Environment Institute

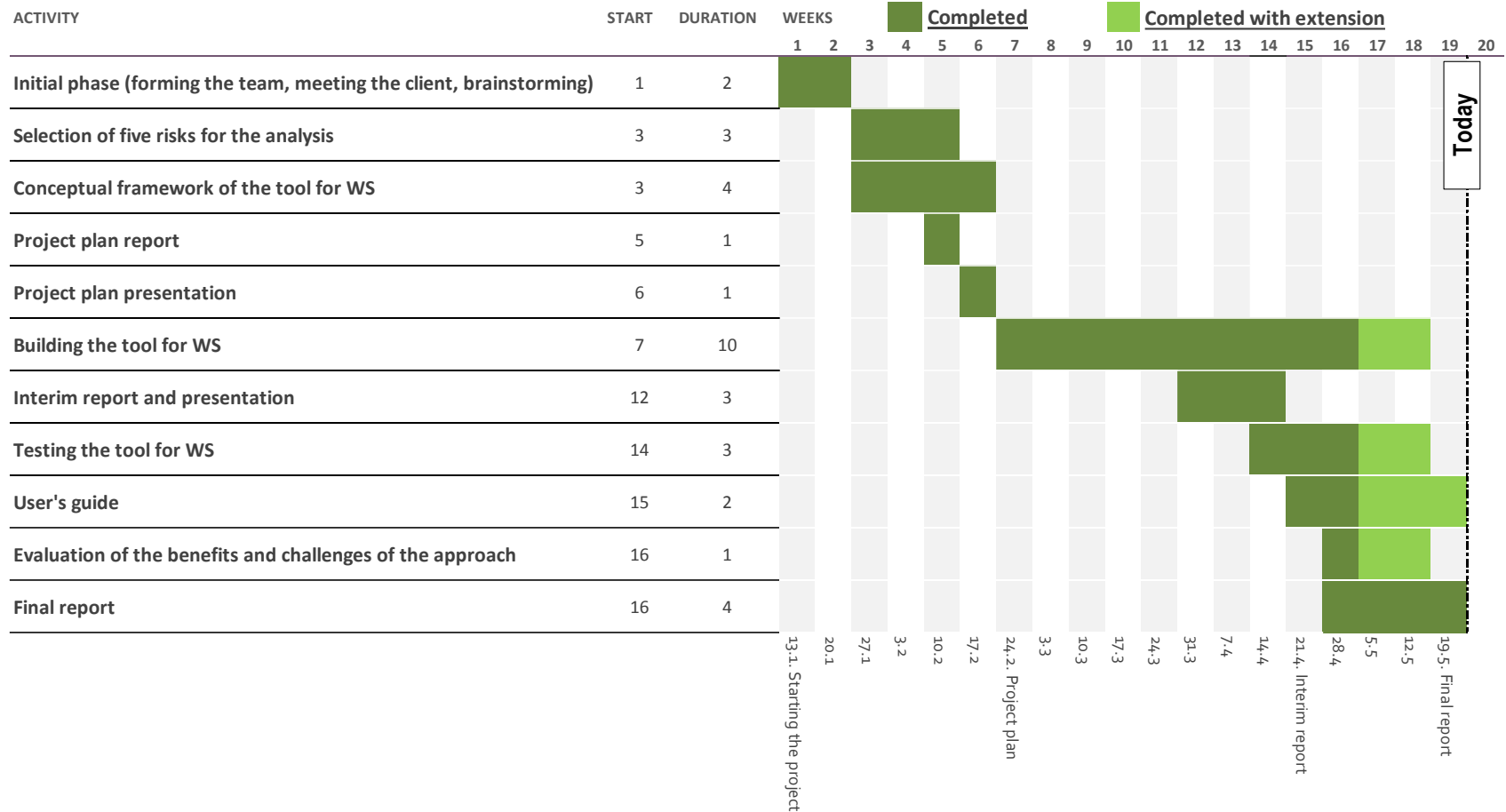










Figure 19. Gantt chart illustrating the updated project schedule. The green bars indicate completion as planned, while light green bars indicate completion with extension with respect to the initial schedule.

Table III. Specific objectives of the project, with degree of achievement (second column, the length of the bars is purely illustrative) and comments for improvement (third column).

Objective	Achieved	Comment
Evaluate and compare impacts and likelihoods of water-related risks, taking into account interactions (causal dependences and synergies) between these risks.		The selection of any number of risks could be enabled.
Design a tool for use by experts in water security. If data are not available, offer a structure to quickly derive quantitative data from qualitative or semi-quantitative experts' beliefs.		More flexible and realistic elicitation than -5 / +5 or 0 / +5 coefficients could be implemented.
Make it possible to assess water security at any spatial and temporal scale.		The spatial scale could be defined more explicitly than through the specific risk magnitudes and indicator levels. The temporal scale is defined explicitly, but not fully realistically.
Compare the impact on single key dimensions of water security.		A non-hierarchical weighting procedure in MCDA could provide more the weights of the KDs more thoroughly.
Present the results in an illustrative and understandable way.		The understandability of numerical results and graphs could be tested more thoroughly with the client.
Evaluate the benefits and challenges of the tool, and identify the potential of the tool to be used in the overall water-security assessment of Finland.		The potential of the tool could be tested on a real case study.
Provide a tool which is easy and quick to use.		The usability could be tested more thoroughly with the client.
Support the evaluation of resilience against water-related risks.		This objective was removed from the project for lack of time resources (as admitted by the schedule).

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