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Research article

Sustainability assessments of regional water supply interventions – Combining cost-benefit and multi-criteria decision analyses



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ABSTRACT

To cope with present and future challenges, a growing number of water utilities in Sweden, Europe and elsewhere initiate various forms of inter-municipal cooperations creating a new regional level of drinking water governance. In order to reach viable decisions of alternative ways forward, there is an international consensus that sustainability needs to be addressed in water supply planning, design and decision-making. There are, however, few decision aids focusing on assessing the sustainability of inter-municipal cooperations and the inter-municipal policies and interventions that regional decision-makers are faced with. This paper presents a decision support model based on a combination of cost-benefit analysis and multi-criteria decision analysis for assessing the sustainability of regional water supply interventions, including formations of inter-municipal cooperations. The proposed decision support model integrates quantitative and semi-quantitative information on sustainability criteria. It provides a novel way of presenting monetized benefits and costs, capturing utilitarian aspects of alternative interventions, with non-monetized social and environmental effects, capturing aspects based in the deontological theories of moral ethics. The model is based on a probabilistic approach where uncertainties are defined by statistical probability distributions. A case study is used to exemplify and evaluate model application in decision situations regarding regionalization, (de)centralization, source water quality and redundancy. All evaluated alternatives were expected to contribute to a slightly improved social sustainability, whereas the results were more varying in the economic and environmental domains. A structured and transparent treatment of uncertainties facilitates a better understanding of the results as well as communication between decision-makers, stakeholders and the community.

1. Introduction

The main obligation of water utilities is to provide its customers with a continuous supply of safe drinking water. To fulfill this obligation, water utilities need to manage a variety of highly complex issues and future uncertainties. Climate variability, urbanization, ageing infrastructure and economic constraint add to other, ever present, challenges of water supply management. In Sweden, the responsibility for providing water supply to residents and society lies on each individual municipality. The 290 municipalities are characterized by a wide variety in land area and number of inhabitants. And as in many other countries, the Swedish municipalities' abilities to handle the above challenges vary significantly. To meet demands, a growing number of water utilities in Sweden, Europe and elsewhere initiate various forms of regional, inter-municipal, cooperations ranging from simple bilateral

agreements to formations of regional alliances and companies (Frone, 2008; Kurki et al., 2016; Stenroos and Katko, 2011).

The motives for these cooperations can vary, but financial, human, and technological resource gains are often central arguments. Other motives include the possibilities of joint source water use, balancing of socio-economic and spatial differences as well as enhanced professional capacity (AWWA, 2015; Frone, 2008). However, there are also challenges associated with these cooperations that may pose new or increased risks, such as decreased transparency due to increased autonomy, loss of local knowledge and subsidiarity, and increased vulnerability due to dependency of fewer facilities and source waters (Kurki et al., 2016; Lieberherr, 2011, 2016; SOU, 2016). So, taking these strengths and drawbacks into account, how do we make sure that decisions on inter-municipal cooperations and regional interventions are well-informed and sustainable? And what aspects determine water

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supply sustainability on a regional level?

Due to the generally high complexity of regional systems, the main planning challenge is to understand *which* interventions to implement in order to improve and prepare the systems to future challenges (Arena et al., 2014). To be able to choose the most sustainable alternative, the interventions need to be properly evaluated regarding their economic, social and environmental effects. Evaluation methods such as multi-criteria decision analysis (MCDA) (Godskesen et al., 2017), cost-benefit analysis (CBA) (Hunter et al., 2009), life cycle assessments (Schulz et al., 2012) and optimization techniques (Lim et al., 2010) have all been proposed for assessments of water supply interventions.

However, the literature lacks generic decision-support frameworks, adapted to the inter-municipal level, that can assess economic profitability and environmental and social aspects of alternative interventions while allowing for a structured handling of uncertainties. This is needed to aid in complex regional decision situations to ensure a sound prioritization of society's limited resources.

Hence, this paper aims to present and apply a decision support model for assessing the sustainability of regional water supply interventions, including formations of inter-municipal cooperations, by combining CBA with MCDA. Specific objectives are to: (1) present a generic decision support model that incorporates uncertainties and that enables to combine fully monetized costs and benefits with criteria in the social and environmental sustainability domains; (2) identify key criteria as a basis for regional assessments; and (3) evaluate the applicability of the model to aid in complex regional decision situations.

2. Model development

In this chapter, the basis for the presented model is introduced in terms of sustainability, multi-criteria decision analysis and cost-benefit analysis, and an overview of the key steps for developing the model is provided.

2.1. Sustainability

There is a wide range of definitions of sustainable development. One of the most widely used is that of the Brundtland Report, in which it is defined as a *development that meets the needs of the present without compromising the ability of future generations to meet their own needs* (WCED, 1987). In the proposed decision support model, each alternative intervention is assessed relative to a reference alternative. The model thus provides information on whether a specific alternative *leads towards* sustainable development or not, taking a reference alternative as a point of departure. Sustainability is defined based on a set of criteria within the economic, social and environmental sustainability domains.

The model recognizes whether alternatives lead towards strong or weak sustainability, i.e. whether there is compensation between sustainability criteria or sustainability domains. According to the view of weak sustainability (Pearce and Atkinson, 1993), sustainability is attained as long as the sum of natural and human-made capital does not decline. There is no difference in the value provided by natural capital, such as water resources, and human-made capital, such as production plants and infrastructure, and hence they can be substituted for one another. According to the view of strong sustainability, certain environmental functions cannot be substituted by human-made capital. Human and natural capitals are regarded as complements rather than substitutes (Ang and Van Passel, 2012). To achieve strong sustainable development, neither natural nor human-made capital may hence decline.

Furthermore, the model distinguishes between the ethical theories of utilitarianism (a form of consequentialism) and deontology in terms of interpretation of sustainable development. In utilitarianism, the rightness of an action or decision is judged on the basis of its contribution to overall utility (well-being) (Sidgwick, 1981). The concept

of sustainable development as put forward in the Brundtland Report has for example an anthropocentric utilitarian perspective which focuses on achieving and maintaining human well-being now and in the future (Farley and Smith, 2014). In deontological ethics, on the other hand, it is our duties to universal moral principles like justice and equity rather than fulfillment of well-being that guide our actions and decisions (Howarth, 1995). Hence, it is our duty, if not our preference, to leave an unharmed world to future generations (Laslett and Fishkin, 1993). The economic sustainability domain in the proposed model is assessed on the basis of welfare economics theory by means of CBA (Pearce et al., 2006), which means the evaluation is based on changes on human well-being. Thus, the economic domain of the model captures the anthropocentric utilitarian aspects of the alternative interventions. This is then balanced with the social and environmental domains which capture effects based in the deontological theories of moral ethics, such as final values of the environment, and local effects on equity and health (Söderqvist et al., 2015).

2.2. Multi-criteria decision analysis

The decision support model is based on the widely used decision support approach MCDA (Figueira et al., 2005) to support decisions of operational and strategic character. MCDA is often used for solving complex decision problems with large amounts of information and where several, possibly contradicting, criteria need to be considered in a structured and coherent way. Criteria are assessable objectives serving as performance measures in MCDA. Criteria can be quantitative, e.g. net present values based on monetized costs and benefits; semi-quantitative, e.g. scorings of social equity; or qualitative, e.g. value statements from public participation (Lindhe et al., 2013; Rosén et al., 2015). In the proposed model, we have used quantitative and semi-quantitative sustainability criteria.

The model makes use of the most common MCDA method to evaluate alternative interventions, i.e. the linear additive model (DCLG, 2009). Each sustainability criterion is assigned a weight reflecting its relative importance to the other criteria. Each alternative is scored, by e.g. expert judgement or data measure, based on how well that alternative performs in relation to a specific criterion on a predetermined performance scale. In the linear additive model, the total importance of an alternative is calculated as the weighted sum of scores on all criteria, allowing for compensation between criteria.

Several previous studies have proposed MCDA for evaluating sustainability of alternative water supply interventions, see for example Lai et al. (2008) and Scholten et al. (2015). There is however a lack of inclusion of cost externalities in existing evaluation criteria (Rathnayaka et al., 2016). To account for a more comprehensive economic analysis, the economic criterion in the proposed MCDA model is based on economic profitability including the impact of externalities and is evaluated by means of CBA.

2.3. Cost-benefit analysis

CBA is a systematic approach for estimating and comparing positive and negative economic consequences, i.e. benefits and costs, of alternative interventions and policies in relation to a reference alternative (Johansson and Krström, 2016). The results can be used to determine whether an alternative is economically profitable, i.e. if its benefits for society are larger than its costs for society, and hence provide decision support. Benefits and costs are as far as possible expressed in monetary units, in which benefits are defined as increases in human well-being and costs are defined as reductions in human well-being. (Pearce et al., 2006). Individuals' well-being depends on market goods and services as well as non-market ones, such as health and environmental quality (Freeman et al., 2014). By using CBA to assess the economic domain, evaluation of effects on well-being at society level is made possible in addition to assessment on overall sustainability.

2.4. Literature survey

A generic set of sustainability criteria for assessments of regional water supply interventions was developed in collaboration with stakeholders and experts in an iterative process of testing and evaluating their applicability. First, a list of possible criteria was compiled based on a literature review (Sjöstrand, 2017) on sustainability criteria proposed and used in the water sector. The search for relevant literature included search strings as sustainability, sustainability criteria, evaluation criteria, multi-criteria decision analysis, indicators, drinking water, urban water system, water supply, water supply governance, cost-benefit analysis, economic valuations, ecosystem services, regionalization, and inter-municipal cooperation.

The criteria were categorized in the three sustainability domains, economic, social and environmental sustainability and evaluated for relevance in assessments of large scale regional interventions, as well as for preference independence and risk for double counting. A reduced criteria list was then created.

2.5. Stakeholder workshops

The reduced criteria list was presented and discussed in two half-day stakeholder workshops. The workshop participants were representatives of the following stakeholders (number participating in first/second workshop): water utility managers (14/11), water authorities (4/0), community planners (2/1), environmental professionals (2/4), water supply researchers (2/4), water resource organizations (2/2), fishing organizations (0/2), local politicians (3/4), and the agriculture (2/1), transport (1/3) and hydropower sectors (1/1); in total 33 participants at each workshop.

The stakeholder representatives were divided into six groups with as large representation from the different stakeholder sectors as possible in each group. The first workshop focused on the economic domain and a prioritization of which generic consequences (costs and benefits) to be included in the economic criterion *Economic profitability*. The stakeholders were presented with a gross list of possible consequences, including both private costs/benefits and externalities. Each stakeholder group was then asked to discuss the relevance of them on a regional level and to reach an agreement on costs and benefits to add and/or remove from the list. The second workshop was set up in a similar way but focused on the social and environmental criteria. The criteria list was then modified as a result of the workshops.

2.6. Model application

A model application, further described in chapter 4, was used to test, evaluate and illustrate the use of the proposed decision support model in a real-world situation. The model application was set up to demonstrate decision situations regarding regionalization, (de)centralization, source water quality and redundancy, and to study effects on social welfare and on sustainability of such regional decisions.

3. Model description

A schematic description of the main components in the decision support model is presented in Fig. 1.

Sustainability is evaluated using the generic set of criteria developed for the model, encompassing the three sustainability domains social, economic and environmental sustainability. The economic domain is evaluated by means of CBA, whereas the environmental and social domains are evaluated through the MCDA procedures of scoring and weighting.

The generation of alternatives to solve water supply challenges on a regional scale can in itself be a major task. However, the focus in this paper is on assessments of already suggested alternatives, i.e. the sustainability assessment part of the model.

3.1. Sustainability criteria

The first part of the sustainability assessment involves a selection of evaluation criteria. Since assessment of criteria values can be both time consuming and expensive, a prioritization should be made for each analysis of which criteria to include. The generic list of sustainability criteria developed for the model is presented in Table 1 and the list of costs and benefits is presented in Table 2 (Rathnayaka et al., 2016; Sjöstrand, 2017; Young and Loomis, 2014).

3.2. Economic analysis

The economic domain in the model is evaluated by means of CBA (Johansson and Kriström, 2016). Identified costs and benefits are valued and monetized through available valuation techniques, e.g. non-market valuations, expert elicitations, benefit transfer or meta-analyses of past literature (Freeman et al., 2014; Johnston et al., 2015). Uncertainties about the monetized values are represented by lognormal distributions, see further in chapter 3.5.

Future costs and benefits are expressed in present values using specified discount rates. Discounting has a theoretical justification in the welfare economics of CBA. It has however consequences that some find morally and ethically questionable, e.g. the appeared inconsistency of that discounting makes future costs and benefits seem trivial with the concept of intergenerational equity (Pearce et al., 2006). As it is beyond the scope of this paper to go into detail on choice of discount rates, we refer to the extensive literature on that subject, see e.g. Gollier (2010), Newell and Pizer (2003) and Stern (2006).

The key decision metric of the CBA is the net present value (NPV), which is an estimate of an alternative's aggregated economic consequences, i.e. its economic profitability, relative a reference alternative. The NPV is calculated as:

$$NPV_a = \sum_{t=0}^T \frac{1}{(1+r_t)^t} [B_{a,t}] - \sum_{t=0}^T \frac{1}{(1+r_t)^t} [C_{a,t}] \quad (1)$$

where a is the alternative intervention, t is the time when benefit or cost occur, T is the time horizon, r_t is the discount rate at time t , and C and B are here costs and benefits from Table 2.

3.3. Social and environmental analyses

The social and environmental effects of the alternative interventions are also assessed relative to a reference alternative, through the MCDA procedures of scoring and weighting. The assessment principles are based on stakeholders' involvement and value judgements followed by an aggregation of preferences across the criteria.

First the decision-making team, together with key stakeholders, assigns each criterion a weight, which reflects that criterion's relative importance to the decision (in percent) against the other criteria of the same domain. The sum of all weights in each domain must hence add up to 100%.

The performance of each alternative intervention on each criterion is then scored by direct rating using expert and stakeholder value judgements. The experts estimate minimum, most likely (mode), and maximum values for each criterion on a scale from -10 to 10 based on the alternative interventions' performance in relation to a reference alternative. These estimates are then input parameters in Beta PERT probability distributions (Malcolm et al., 1959) to represent the uncertainties of the scores, see further in chapter 3.5. Time-differentiated effects are taken into account by letting the most likely, minimum and maximum values represent the total effects over the time horizon and the uncertainties surrounding this assessment. It is important that the scoring is consistent, hence a scoring aid was developed for each criterion in accordance with recommendations and examples provided in DCLG (2009) and Rosén et al. (2015), see example of scoring aid in Table 3.

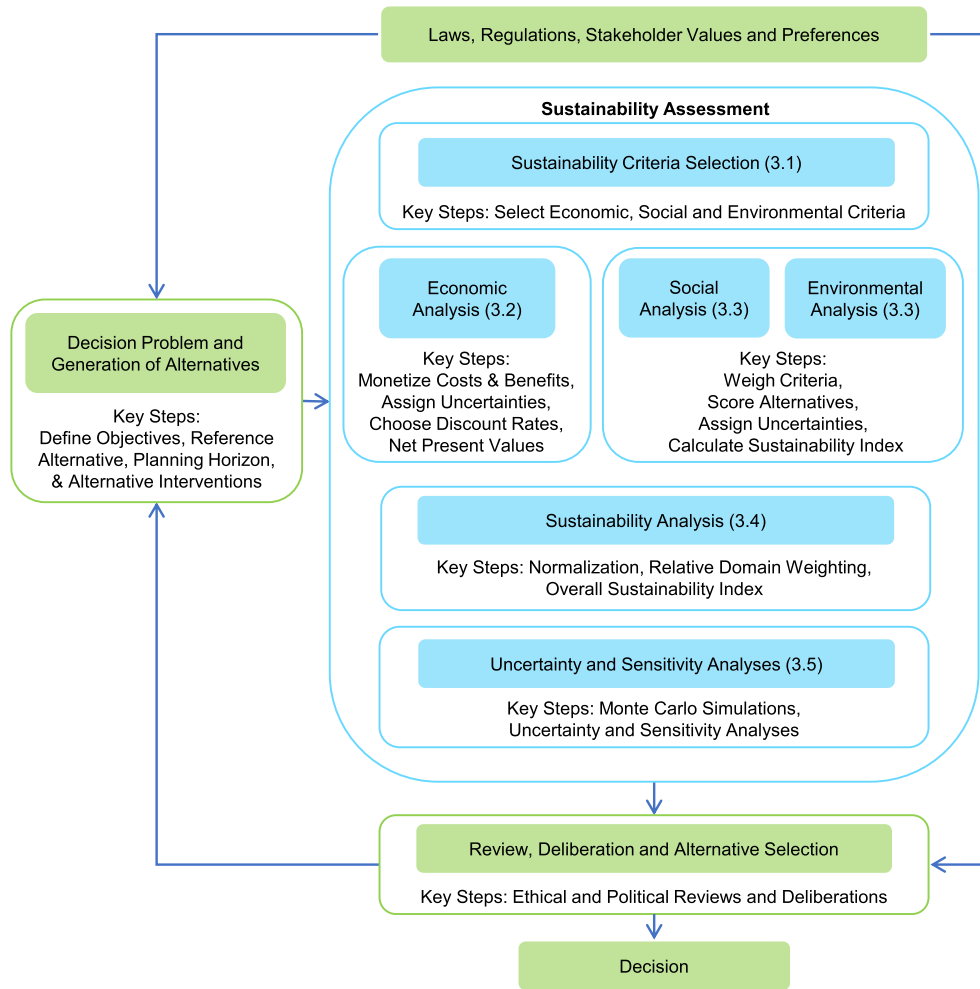


Fig. 1. Schematic description of decision support model for sustainability assessments of regional water supply interventions. The chapters explaining the model are included in brackets.

Table 1
Generic set of sustainability criteria.

Domains	Criteria	Description
Social	Equity	Effects on equity regarding if some consumers and/or municipalities are made worse off by the alternative.
	Health	Effects on human health due to insufficient source water quality, quantity, water treatment, distribution and/or emergency preparedness.
	Consumers' trust	Effects on consumers' trust in the water providers.
Environmental	Access and participation	Effects with regard to public access and participation in water supply planning and decision-making.
	Energy use at construction	Total energy use at construction.
	Energy use at production and distribution	Total energy use at production and distribution.
	Water use	Effects on water use in production and distribution, e.g. water reuse, alternative water use and leakage.
	Materials for construction	Use of non-renewable materials for construction.
	Chemical use	Effects on total chemical use in water production.
	Non-recyclable waste	Production of non-recyclable waste.
Economic	Aquatic ecosystems	Effects on aquatic ecosystem viability due to quality and/or quantity changes in water resources.
	Terrestrial ecosystems	Effects on terrestrial ecosystem viability due to e.g. land use changes.
	Economic profitability	Economic profitability assessed by means of CBA.

By using a linear additive model, a sustainability index S_{Env} and S_{Soc} for each alternative (a) is calculated as the weighted sum of the scores on all criteria (k) of that domain (d), given by:

$$S_{d,a} = \sum_{k=1}^K W_k Z_{a,k} \tag{2}$$

where w is the weight for each criterion and z is the score.

3.4. Sustainability analysis

The alternatives can now be ranked for each sustainability domain, by the sustainability index in the environmental and social domains and by the NPVs in the economic domain. Since all domains are assessed relative to a reference alternative, the alternatives performing worse than the reference alternative in a specific domain will have a negative sustainability index/NPV and alternatives performing better than the

Table 2
Potential cost and benefit items due to regional water supply interventions.

Criteria	Cost and benefit items	Description
Economic profitability	Water utility costs and benefits	Investments Operation and maintenance costs Other costs and benefits for water utilities
	Effects of water supply reliability	Lost value added in economic sectors Losses for residential consumers
	Water related health effects	Costs for healthcare Lost production Discomfort and loss of life
	Effects on ecosystem services	Drinking water Irrigation Hydropower Industrial water use Recreational activities Flood and erosion risk reduction Retention of contaminants Other ecosystem services
	Effects on agriculture, forestry and industry due to water protection restrictions	Agricultural, forestry and industrial production Other effects on agriculture, forestry and industry due to water protection restrictions

reference alternative will have a positive index/*NPV*.

To identify a single sustainability ranking order which takes all domains into account, as well as an optional relative ranking of the domains, an overall sustainability index (*S*) is calculated for each alternative, see Equation (3). However, this requires that the domains are comparable and assessed on a common scale.

The economic costs and benefits are being measured on a ratio scale, i.e. in monetary units. The environmental and social criteria, on the other hand, are scored on an ordinal, global scale (Monat, 2009; Pollesch and Dale, 2015), i.e. the best (worst) score possible according to decision-makers' and experts' experience and judgement is here set to 10 (−10). In order to calculate an overall sustainability index in which all three domains are aggregated, the *NPVs* of the economic domain are normalized onto a similar unit-less scale as the social and environmental domains, i.e. ranging from −10 to 10.

When normalizing ratio scale values, it is important to maintain the non-normalized order, distance meaning, and unique zero point. Hence, a valid method for normalizing ratio scale values is in the form of $x \rightarrow rx$; where $r > 0$ (Pollesch and Dale, 2015). We have chosen ratio normalization and scalar multiplication by a factor 10 to transform the economic domain.

Ratio normalization is a so called internal normalization in which the extreme value of the data set is used to normalize a single value (Pollesch and Dale, 2016). However, by using this form of ratio normalization the non-normalized extreme *NPV* value would always be transformed to the global scale extremes, i.e. transforming the best (worst) alternative's value, rather than the best (worst) possible value to 10 (−10). By utilizing that we have more information about the *NPVs*, in the form of uncertainty distributions, we can make a more informed choice of scaling factor. We consider the 5th and 95th percentile *NPV* values at hand to be a reasonable representation of the best and worst possible values we can encounter over a large number of interventions. The economic domain is hence normalized by the absolute maximum value of the 5th and 95th percentiles of all *NPVs*, Equation (4).

Similar to the social and environmental sustainability indexes, the overall sustainability index *S*, Equation (3), is calculated using a linear additive model for each alternative *a* by:

$$S_a = W_{Env} S_{Env,a} + W_{Soc} S_{Soc,a} + W_{Eco} S_{Eco,a} \tag{3}$$

where *W* is the relative weight of each domain, *S_{Env}* and *S_{Soc}* are the environmental and social sustainability index, and *S_{Eco}* is the normalized *NPV* for the economic domain given by:

Table 3
Scoring aid developed for each criterion, here exemplified by the social criteria Access and participation.

Question for scoring	Very negative effect −6 to −10	Negative effect −5 to −1	No effect 0	Positive effect 1 to 5	Very positive effect 6 to 10
To what extent does the alternative affect public access and participation regarding water supply planning and decision-making?	The public's access and participation in water supply planning and decision making are considerably reduced	The public's access and participation in water supply planning and decision making are reduced	The public's access and participation in water supply planning and decision making are not affected	The public's access and participation in water supply planning and decision making are increased	The public's access and participation in water supply planning and decision making are considerably increased

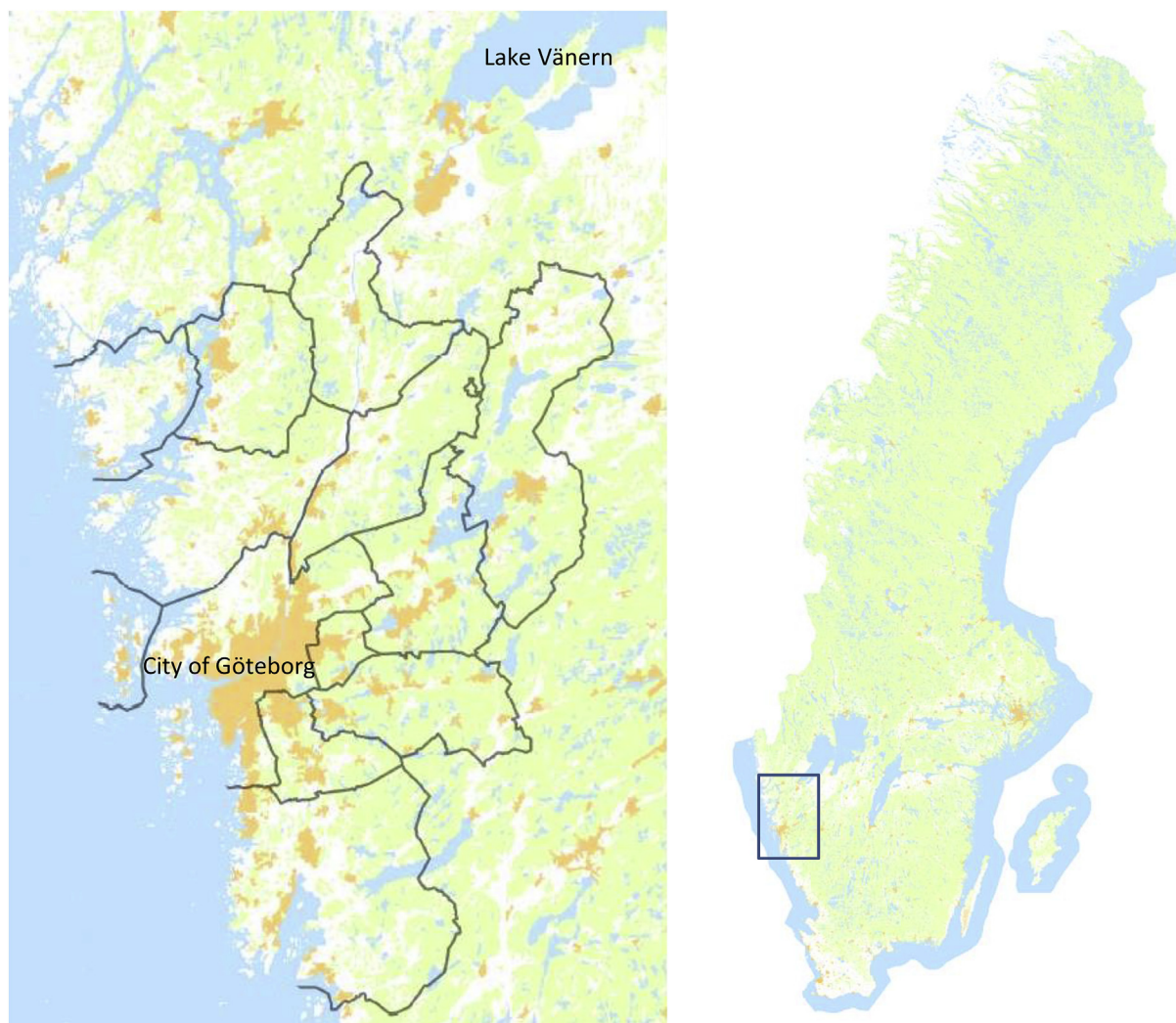


Fig. 2. The 13 municipalities of the Göteborg region (left) and their position in Sweden (right), © Lantmäteriet.

$$S_{Eco}, a = 10 \frac{NPV_a}{\text{Max}(|P05(NPV)|, |P95(NPV)|)} \tag{4}$$

The relative weights of the sustainability domains are scaled and calculated in the same way as the criteria weights.

3.5. Uncertainty and sensitivity analyses

Evaluations of alternative interventions' effects on society and environment, and on the water utilities themselves, will always comprise uncertainties. Uncertainties can for example derive from lack of available data or knowledge to estimate certain effects, bias and subjectivity of experts and stakeholders, and natural random variability.

Uncertainties in the economic domain are represented by lognormal probability distribution functions. The lognormal distribution is widely used in economics and cost analysis (Garvey et al., 2016). It is closely related to the normal distribution but positively skewed and always nonnegative. The parameters defining the distribution are the mean value and standard deviation of the specific cost or benefit, assessed in the monetization process. Alternatively, the log-normal distribution can be defined by two percentiles, e.g. the 5th and 95th percentiles, which may be very useful in practical applications.

Uncertainties about environmental and social scores are represented by Beta PERT probability distributions (referred to as PERT throughout the paper), which are able to capture high skewness and provides a flexible way of encoding expert judgements (Malcolm et al., 1959). The

PERT distribution is a transformation of the Beta distribution with the assumption that the expected value is a weighted average of the minimum, most likely (mode) and maximum values. The PERT distribution is similar to the triangular distribution, but with the smoother form of subjective estimates. The most likely value is given four times the weight compared to the minimum and maximum values. This means that the most likely value is a more “trusted” estimate than the minimum and maximum values, which is beneficial in expert elicitations since we are generally more capable to estimate mode values than extremes (Salling, 2011). The mean μ and standard deviation σ of the PERT distribution can be determined by:

$$\mu = \frac{\alpha + 4*m + \beta}{6}, \tag{5}$$

$$\sigma = \frac{\beta - \alpha}{6} \tag{6}$$

where α is the minimum, m is the most likely and β the maximum values. One benefit of the PERT distribution is that all three input parameters (min, mode, max) are easy to understand also for laymen assigning uncertainties.

Monte Carlo simulations are then used to model uncertainties in input data and results, here using Palisade's risk analysis software @ RISK (7.0.0.). Decision-makers can, thus, find out e.g. the probability of an alternative being economically profitable or which alternative is associated with the most uncertainties concerning e.g. the NPV values.

The Monte Carlo simulation facilitates sensitivity analyses by e.g. measuring the contribution of variance from each input variable to the total variance of the output variable and by calculating correlations between input and output variables. The variables can be ranked by order of impact on outcome uncertainty and thereby help decision-makers prioritize which variables to be aware of and which needs more data gathering to reduce uncertainties.

Additional sensitivity analysis, by varying specific baseline conditions, is used to study the impact of different discount rates, time horizons, and relative domain weights. These parameters are not assigned uncertainties but, by means of sensitivity analysis, provide important information on how the results may change. The same type of sensitivity analysis is also used to study the impact of uncertainties of future conditions such as demand and supply predictions, effects of climate change and demographic alterations.

4. Model application

A full sustainability assessment, incorporating risks and uncertainties and including the combination of cost-benefit and social and environmental analyses, was conducted for five alternative water supply interventions for the Göteborg region in Sweden (Fig. 2). By applying the decision support model to alternatives focusing on establishing inter-municipal organizations, (de)centralization of water production, source water quality, and redundancy aspects, the model was tested for evaluating some common decision situations in the water supply sector. The application in the Göteborg region was a way to further develop the model and evaluate its feasibility. The application is presented here with a focus on methodological aspects.

4.1. The Göteborg region

The Göteborg region, with its 13 municipalities and one million inhabitants, has 30 water treatment plants, of which 12 are supplied by surface water, 15 by groundwater and 3 by artificial groundwater. Four of the municipalities are fully or partly dependent on water produced in the City of Göteborg, which contributes to making the region's production to 75% dependent on source water from the river Göta älv. Göta älv, which flows from Lake Vänern to the City of Göteborg, has a varying water quality and is considered particularly exposed to effects of climate changes, e.g. increased risks of flooding, landslides, erosion, increased sea levels and varying storm water quality, making the region's main source water vulnerable. The ability of being able to replace the main source water with alternative source waters varies between the municipalities but is overall insufficient in the region (GR, 2014).

To be able to uphold the region's vision of a safe and long-term sustainable water supply, all 13 municipalities have agreed on implementing a Regional Water Supply Plan comprising nine targets: 1) Access to good quality source water; 2) Safe and redundant production and distribution; 3) Sustainable rate of infrastructure renewal; 4) Safe drinking water; 5) Maintain consumers' trust and confidence; 6) Resource effective solutions; 7) Water supply integrated in urban planning; 8) Readiness to address climate change; and 9) Access to the right skills (GR, 2014).

4.2. Evaluation of alternative interventions

The five alternative interventions analyzed in this paper were designed to meet the nine regional targets and to illustrate decision situations regarding regionalization, (de)centralization, source water quality and redundancy, see Table 4. In order to adequately account for the lifespan of water supply infrastructure, as well as effects that may occur well into the future, the alternatives were evaluated for the time horizons 30 and 70 years respectively, enabling sensitivity analyses of choosing a shorter versus longer time horizon. The alternatives were evaluated in relation to a reference alternative, i.e. the current water

supply system described above. Treatment and distribution capacities were increased in all alternatives, including the reference alternative, to handle expected population growths within the time horizons.

The prioritization, calculation, weighting and scoring of criteria for the Göteborg region was an iterative process performed parallel to the generic criteria development, and involved literature reviews, economic valuation techniques, stakeholder workshops and expert discussions. The two stakeholder workshops used to develop the generic sets of sustainability criteria and economic costs and benefits were also used in the application of the model for the Göteborg region.

For the Göteborg region application, the first workshop focused on prioritizing which costs and benefits to be monetized in the CBA. The stakeholder groups were asked to make a first general assessment of the alternative interventions from a gross list of possible consequences, i.e. they were to assess if the interventions could result in large, small or nonexistent costs and benefits. The gross list included both private costs and benefits and externalities. They were also asked to add costs and benefits to the list if they missed any, and to make a general assessment of the likelihood that they would occur (large, moderate, small, or nonexistent). The costs and benefits which were assessed to be small or nonexistent, and at the same time assessed to have a low or nonexistent likelihood to occur, were not included in the CBA.

The second workshop focused on weighting social and environmental criteria. The stakeholders in each group were instructed to assign higher weights to criteria they considered more important to the decision problem and lesser weights to criteria that were not that important, with the constraint that the weights in each domain should add up to 100%. Each group was asked to discuss the importance of the criteria until they had made an agreement on weights for that group. The final weights were calculated as the mean values from the different stakeholder groups. The scoring of the criteria was later made in a process where different experts and stakeholders, as well as team members of this research study, were asked to assess minimum, maximum and most likely values of the criteria for the different alternatives in relation to the reference alternative. The developed scoring aid, exemplified in Table 3, was used to provide consistency in the scoring assessments.

The costs and benefits were evaluated using two different discount rates, i.e. 1.4% and 3.5%. The discount rates were selected as 1.4% reflects the average discount rate used in the Stern Review on Climate Change (Stern, 2006), whereas 3.5% reflects the suggested current best-practice of the Swedish Transportation Administration Guidelines (ASEK, 2018). Details of the cost-benefit analysis performed for the Göteborg region is reported in (Sjöstrand et al., 2018).

5. Results

The outcome of the CBA for the time horizons 30 and 70 years and the discount rates 1.4% and 3.5% is presented as net present values in million SEK (1 MSEK \approx \$125,000) in Fig. 3. Since uncertainties are considered, the results are presented using the 5th, 50th (median) and 95th percentiles (P05, P50 and P95). The calculations of criteria and net present values were performed using Monte Carlo simulations, consisting of 10,000 iterations.

For the Göteborg region it was found that the alternatives A1 and A2, comprising a regionalized water utility and a centralized production, had the poorest performance in the economic sustainability domain. One reason for the poor economic outcome was the major investments in treatment and distribution capacities for the centralized systems. A3, which comprises a regionalized governance and maintained semi-decentralized production, was associated with the least degree of uncertainty and entailed the highest probability of having a positive NPV independent of applied discount rate and time horizon. One reason for the positive outcome for A3 was that the formation of a regional organization led to assumed decreases of operation and maintenance (O&M) costs. However, the model used to project new O&

Table 4
Description of alternative interventions evaluated for the Göteborg region.

Alternative interventions	Description
A1: Regionalized governance & centralized production from lake Vänern	Sweden's largest lake, Vänern, is the main source water for the entire region. Water is led in a tunnel from Vänern, which is located outside the region, to the City of Göteborg where it is treated and then distributed throughout the region. One single drinking water organization operates the production. Water protection areas and restrictions for prior source waters ceases to exist.
A2: Regionalized governance & centralized production from the river Göta älv	The river Göta älv is the main source water for the entire region. The water is treated in the City of Göteborg from which it is distributed throughout the region. One single drinking water organization operates the production. Water protection areas and restrictions for prior source waters ceases to exist.
A3: Regionalized governance & maintained semi decentralized production	Current water treatment plants, source waters and water protection areas are maintained. One single drinking water organization operates the production within the different municipalities.
A4: Maintained governance & decentralized groundwater dependent production	Current water treatment plants, water protection areas and source waters, except Göta älv, are maintained. The source waters are supplemented with increased/new withdrawals from several groundwater resources as well as some lakes. New water protection areas and restrictions are established for the new source waters.
A5: Maintained governance, with additional source waters and treatment plants	Current water treatment plants, source waters and water protection areas are maintained. The current system is expanded with two new water treatment plants and an increased proportional use of the region's largest lakes.

M costs (Sjöstrand et al., 2018) may provide over-estimated benefits for regional utilities without centralized production systems and hence benefited A3 over other alternatives in the analysis. A4, comprising maintained governance and decentralized production, showed similar but slightly more negative economic results as A5, with a maintained governance and expanded number of source waters and treatment plants. Overall, it can be noted that the economic benefits, of e.g. reduced risks of negative health effects and delivery failure, had a more positive impact on the net present values the longer the time horizon and the lower the discount rate.

The probabilistic outcomes from the social and environmental analyses are shown in Fig. 4 as P05, P50 and P95 values. All alternatives were expected to contribute to a slightly higher social sustainability, whereas the results were more varying in the environmental domain. In the social domain, the centralized alternatives' negative scores on access and participation were compensated with positive scores on consumers' trust. The negative scores on access and

participation are in accordance with research performed by Kurki et al. (2016) and Lieberherr (2011) indicating a negative relationship between public access and the degree of organizational autonomy. The positive scores on consumers' trust relate to assessment of changes in the organizations' professionalism, partly due to an increased possibility in larger organizations to employ and retain highly skilled personnel. The health criterion was considered highly important by the stakeholders, receiving a weight of 36%. The alternatives' assessed performances on health, however, varied only slightly. Equity was not considered to change in any of the alternatives.

In the environmental domain, the A4 alternative with a groundwater dependent production showed the highest sustainability index, mostly due to positive effects on chemical use and aquatic ecosystems. The positive scores on aquatic ecosystems were due to an increased amount of water protection areas in this alternative. The centralized alternatives, A1 and A2, had the lowest environmental sustainability index. Both the centralized alternatives were assessed to have

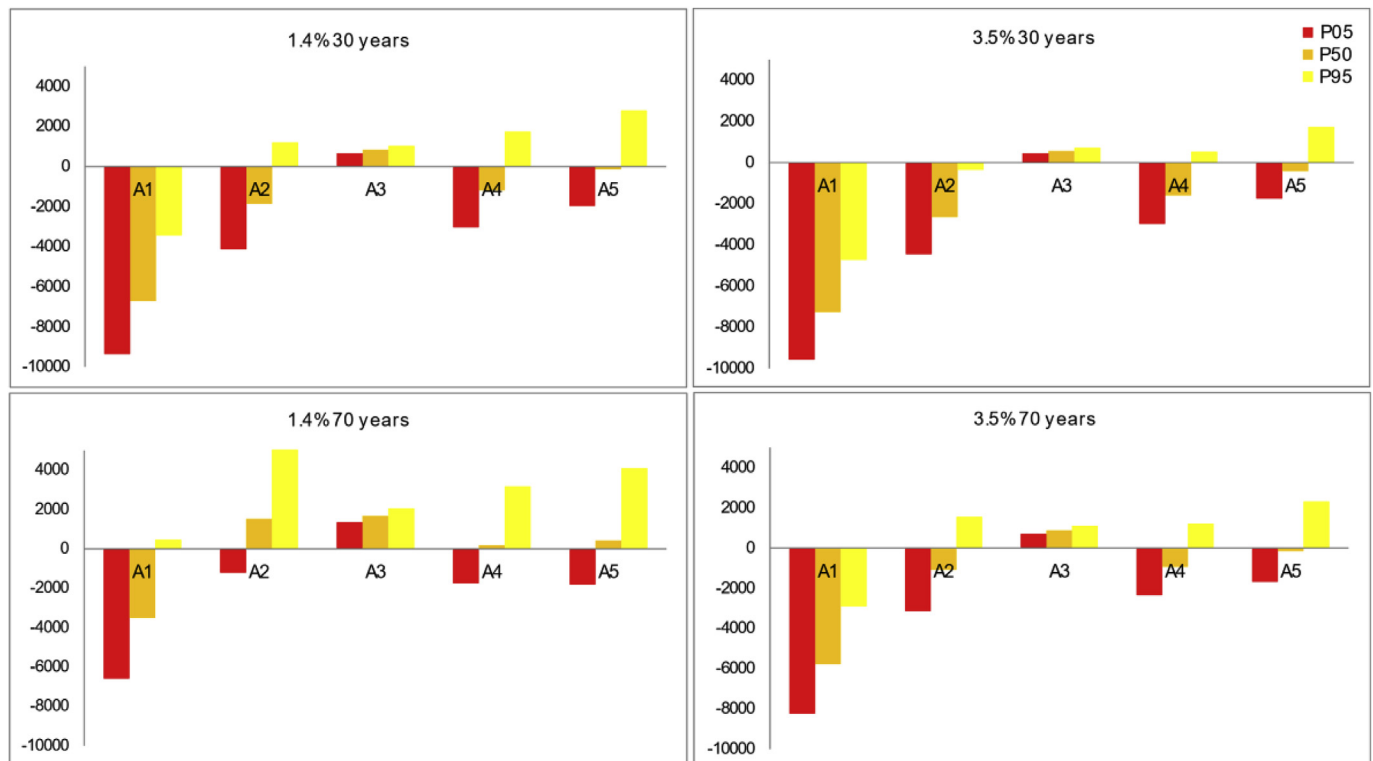


Fig. 3. Net present values (percentile P05, P50 and P95) of the five alternatives evaluated for the discount rates 1.4% and 3.5%, and the time horizons 30 years and 70 years (MSEK).

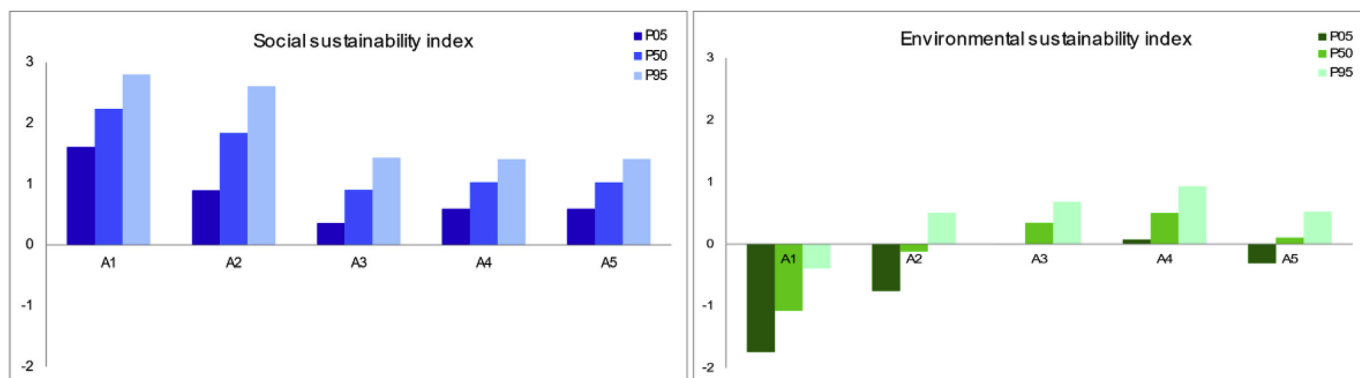


Fig. 4. P05, P50 and P95 of social (left) and environmental (right) sustainability indexes for the five alternatives.

somewhat negative effects on aquatic ecosystems due to decreased water protection areas in the region. In addition, A1 also received negative scores on terrestrial ecosystems, and energy and material use at construction, mostly due to effects assumed to arise during construction of a source water tunnel.

The probabilities of each alternative having the best sustainability index/NPV are shown in Fig. 5. A1 had the highest probability of being the most socially sustainable solution, whereas A4 and A3 had the highest probability of being the most environmentally and economically sustainable solutions, respectively.

Results from calculations of the overall sustainability index encompassing all domains show that A1 and A2 are the least sustainable solutions, see Fig. 6. A3 was associated with the least degree of uncertainty and A5 had a somewhat higher overall sustainability index than A4. On a domain level, A3 was assumed to lead towards strong sustainability with exclusively positive sustainability indexes/NPV. On a criteria level, on the other hand, there is compensation in both the social and environmental domains. The domains were here equally weighted and the NPVs were normalized according to Equation (4).

A3 and A5 were associated with the highest probabilities of having the best overall sustainability index given that the sustainability domains were weighted equally, see the left-hand side of Fig. 7. A3 still came out best when emphasizing the environmental and social sustainability domains over the economic, see the right-hand side of Fig. 7. A2, A4 and A5, however, received similar overall sustainability index when applying the unequal weights of 0.5, 0.3 and 0.2 for the environmental, social and economic domain respectively.

Fig. 8 shows an example of sensitivity analysis performed for A3, the alternative which showed the highest probability of having the best overall sustainability index. The environmental, social and economic variables are presented together, showing that the variable *Consumers'*

trust contributed most to the outcome uncertainty. This kind of sensitivity analysis can be performed for each sustainability domain and alternative, and can be particularly valuable when comparing two very similar alternatives. In this way, it is possible to study the effect of each individual variable more closely. It is also an important basis for prioritizing further studies to reduce uncertainties.

6. Discussion

The main purpose of the paper was to present and apply a decision support model for assessing the sustainability of regional water supply interventions, including formations of inter-municipal cooperations. The proposed model can support decision-makers in making informed and coherent choices on balancing the economic, social and environmental impacts of alternative interventions. The model allows for aggregation of gains and losses across the sustainability domains after which the overall sustainability as well as the specific sustainability criteria and domains can be compared and evaluated. Most aggregation functions are compensatory (Pollesch and Dale, 2015), and the large majority of sustainability assessment deliberations are based on net effect judgements, i.e. whether the overall gains exceed the overall losses (Gibson et al., 2005). Though, it should be noted that the use of a compensatory aggregation MCDA technique, which allows for offset between bad and good criteria performance, can only be used to enforce weak sustainability (De Mare et al., 2015; Munda, 2005). The proposed model can however identify whether certain alternatives lead towards strong or weak sustainability, i.e. whether there is an actual compensation between sustainability criteria or sustainability domains.

As many large-scale water supply interventions result in impacts occurring over several years and even decades, there is a need to address the time-differentiated effects in the strategic decision-making. In the economic domain, future costs and benefits are discounted to present values using specific discount rates. There is, however, no collectively used method for incorporating time dependency and long term consequences for MCDA criteria, and the topic is fairly under-published (DCLG, 2009; Montibeller and Franco, 2011). Methods used in the literature include e.g. applying discounting in a similar way as in cost-benefit analysis and use of several different MCDA models at a time, each method comprehending its own difficulties and limitations (Montibeller and Franco, 2011). In the proposed model, time-differentiated environmental and social effects are incorporated in the analysis by letting the minimum, most likely and maximum scores be representative values for the entire time period and the uncertainties surrounding this overall assessment.

To provide a single overall sustainability index, the three sustainability domains needed to be measured on similar scales, i.e. some sort of normalization needed to take place. One way of doing that could have been to treat all domains similar by normalizing all three domains. However, all normalization schemes have limitations. Thus, the non-

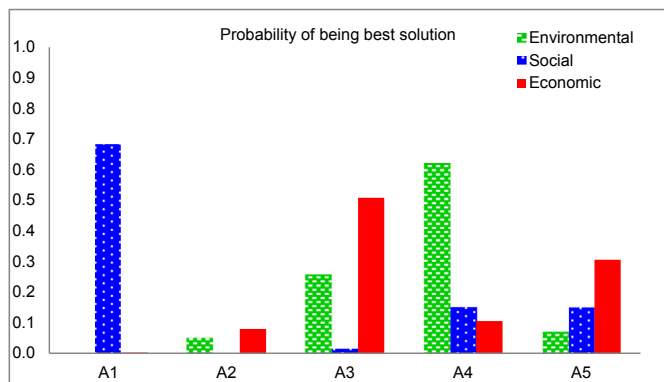


Fig. 5. Histogram showing the probabilities of each alternative having the best sustainability index/NPV. The economic domain is here evaluated for a 3.5% discount rate and a 70-year time horizon.

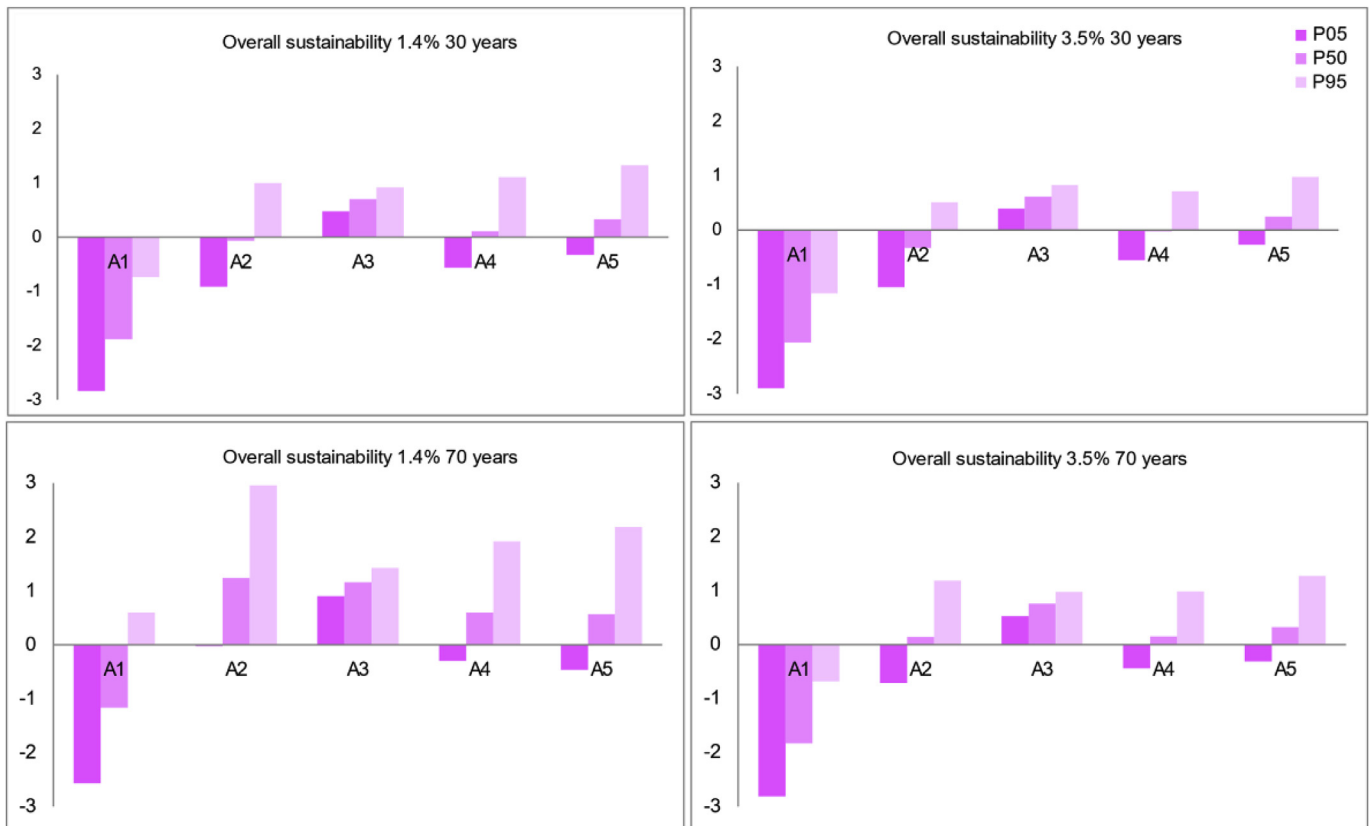


Fig. 6. Overall sustainability index with equal weights between sustainability domains and normalized NPVs.

normalized environmental and social scores were rather kept as is, representing an assessment on the global scale. Ideally, the economic domain should have been normalized by the best (worst) possible value to be fully representative on a global scale. Since these values are not obtainable, the choice of percentile becomes somewhat arbitrary when selecting a scaling factor based on distribution. We have selected the 5th and 95th percentiles, which are ubiquitous in statistical literature. The ratio normalization scheme however, makes the normalized values' significance determined by their relation to the extreme value, hence making the normalized NPV values and the aggregated overall sustainability index sensitive to changes in NPV extreme values (Pollesch and Dale, 2016).

This paper does not discuss the work procedure of generating alternative interventions to solve a certain problem. However, the outcome of the sustainability assessment may well show the potentials of

creating a new alternative not considered in the first place, e.g. by comparing the socially and environmentally most beneficial alternative with the least costly one.

The model was developed to make decisions on regional water supply interventions more informed, structured and inclusive. Uncertainties about costs, benefits and other sustainability criteria are handled by uncertainty distributions and integrated in a clear and transparent way. However, impacts of uncertainties about future conditions, such as population growth, regulatory restrictions, and climate change effects on for example source water quality and availability, have not been discussed thoroughly in this paper. The model will be further developed and tested in order to address missing topics, and one future research task will thus be to further explore the integration of multiple possible futures in the model.

The use of MCDA as a basis for the model enables analyses and

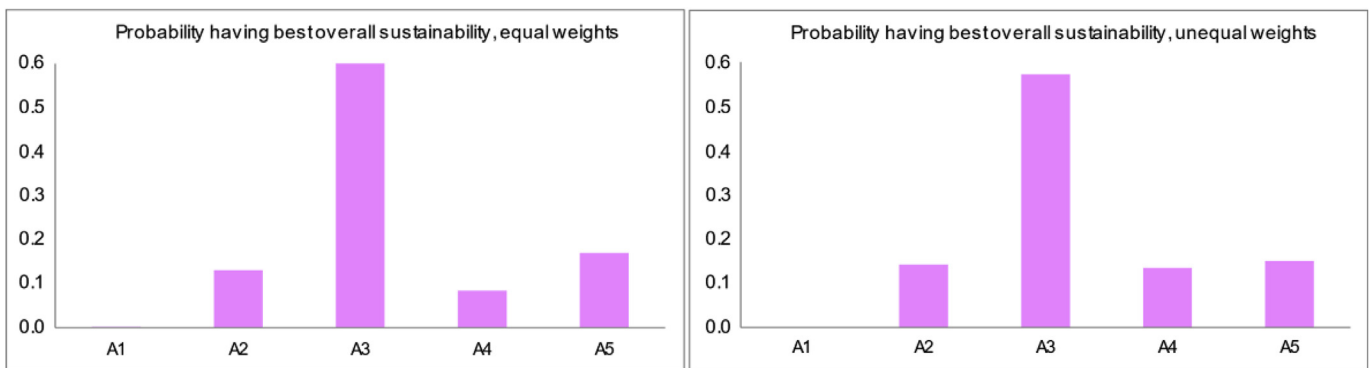


Fig. 7. Histogram showing the probabilities of each alternative having the best overall sustainability index, with equal weights between sustainability domains (left) and unequal weights of 0.5, 0.3 and 0.2 for the environmental, social and economic domains (right). The economic domain is here evaluated for a 3.5% discount rate and a 70-year time horizon.

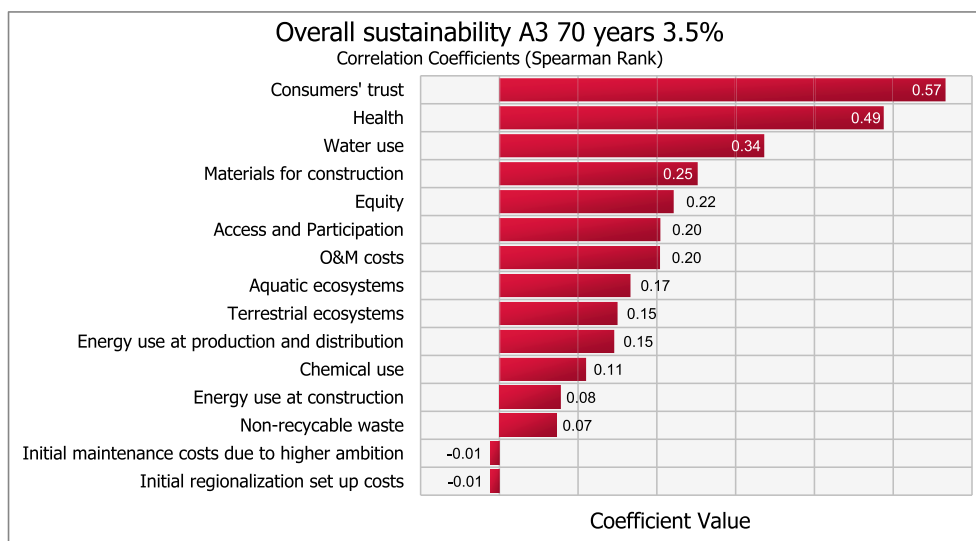


Fig. 8. Sensitivity analysis for A3 showing how uncertainties in input variables affect the overall sustainability.

comparisons of multiple criteria, which in turn help decision-makers develop coherent preferences and understand which gains are vital and which losses are unacceptable. This approach also allows for a high degree of stakeholder involvement, which is acknowledged to improve the quality and implementation of decision-making (UNECE, 1998). However, the assessment result does not disclose the final decision. The presented model is based on the view that decision support is to guide, inform and support rather than replace managerial judgement. As displayed in Fig. 1, ethical and political reviews and deliberations on issues such as risks and uncertainties and on non-prioritized criteria are still needed to ensure a fair evaluation in terms of stakeholder values and preferences. Furthermore, the applied set of criteria must be adjusted to the specific application. Human judgement is hence central in making a final decision (Ashley et al., 2004; Aven, 2012).

When managing our future water supply, decision-makers are often faced with complex decision situations involving conflicting environmental, social and economic requirements. This paper presents a decision support model with generic sustainability criteria specifically developed to deal with inter-municipal, regional water supply interventions. The application of the model demonstrates its possibilities as decision support for coherent comparisons of alternative interventions. The model enables analysis of performance within each sustainability domain and for each specific criterion. The model also facilitates analysis of uncertainties associated with each alternative in a systematic and transparent way. The combination of cost-benefit and multi-criteria decision analyses provides a structured approach for decision-makers to improve their ability of making well-informed and transparent decisions, a basis to ensure the society a safe and reliable water supply for generations to come.

7. Conclusions

The main conclusions of this paper are:

- The model presented here can be used by decision-makers to develop coherent preferences within economic, environmental and social sustainability so that decisions on regional water supply interventions can be taken with a higher degree of confidence.
- The decision support model integrates quantitative and semi-quantitative information on sustainability criteria in a structured and transparent way.
- The provision of a generic gross set of sustainability criteria with clear performance scales minimizes double counting effects and

other limitations previously observed in sustainability assessments.

- The probabilistic approach enables a structured handling of uncertainties in all three sustainability domains, and facilitates calculations of e.g. probabilities that alternatives exceed certain cost limitations or environmental threshold values.
- Stakeholders are integrated in the assessment process in an inclusive way, enabling viable and accepted decisions.
- The results can be used to rank alternative interventions from the most preferred to the least preferred within each sustainability domain and with regards to all domains.
- Communication with decision-makers, stakeholders and the community is facilitated by an organized and transparent treatment of uncertainties.
- The decision support model provides a novel way of presenting monetized benefits and costs, capturing utilitarian aspects of alternative interventions, with non-monetized social and environmental effects, capturing aspects based in the deontological theories of moral ethics.

Declarations of interest

None.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <https://doi.org/10.1016/j.jenvman.2018.07.077>.

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