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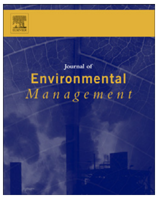

Research article

A scenario-based MCDA framework for wastewater infrastructure planning under uncertainty

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ABSTRACT

Wastewater infrastructure management is increasingly important because of urbanization, environmental pollutants, aging infrastructures, and climate change. We propose a scenario-based multi-criteria decision analysis (MCDA) framework to compare different infrastructure alternatives in terms of their sustainability. These range from the current centralized system to semi- and fully decentralized options. Various sources of uncertainty are considered, including external socio-economic uncertainty captured by future scenarios, uncertainty in predicting outcomes of alternatives, and incomplete preferences of stakeholders. Stochastic Multi-criteria Acceptability Analysis (SMAA) with Monte Carlo simulation is performed, and rank acceptability indices help identify robust alternatives. We propose step-wise local sensitivity analysis, which is useful for practitioners to effectively elicit preferences and identify major sources of uncertainty. The approach is demonstrated in a Swiss case study where ten stakeholders are involved throughout. Their preferences are quantitatively elicited by combining an online questionnaire with face-to-face interviews. The trade-off questions reveal a high concern about environmental and an unexpectedly low importance of economic criteria. This results in a surprisingly good ranking of high-tech decentralized wastewater alternatives using urine source separation for most stakeholders in all scenarios. Combining scenario planning and MCDA proves useful, as the performance of wastewater infrastructure systems is indeed sensitive to socio-economic boundary conditions and the other sources of uncertainty. The proposed sensitivity analysis suggests that a simplified elicitation procedure is sufficient in many cases. Elicitation of more information such as detailed marginal value functions should only follow if the sensitivity analysis finds this necessary. Moreover, the uncertainty of rankings can be considerably reduced by better predictions of the outcomes of alternatives. Although the results are case based, the proposed decision framework is generalizable to other decision contexts.

1. Introduction

The wastewater infrastructure system is of core importance for water pollution control and human health. The importance of infrastructure asset management has been increasingly recognized (Ashley et al., 2008; Cardoso et al., 2012; Ugarelli et al., 2009). The current wastewater infrastructure system in industrialized countries functions well, but is aging and expensive because of increasing rehabilitation needs (Maurer et al., 2005). Infrastructure performance is stressed by demographic changes, as well as by numerous environmental pollutants (EEA, 2012) and climate change (e.g. Milly et al., 2008).

It is challenging to decide which wastewater system best fulfills sustainability requirements. Traditional centralized wastewater systems perform well, but are also criticized for their high use of water for flushing toilets, low nutrient recovery, massive costs, inflexibility, etc. (Ashley et al., 2008). Novel, promising decentralized technologies such as urine separation, gray-water, or biogas systems are not yet widely spread (Larsen et al., 2013). They can potentially change the paradigm of wastewater handling, although the implementation is still a challenge due to the need of practice experience (Guest et al., 2009; Larsen et al., 2009, 2016).

Many planning tools have been used to compare different wastewater infrastructure alternatives, such as life-cycle assessment (Schiller and Dirlich, 2015), qualitative assessment (Dominguez et al., 2011), and performance indicators (Makropoulos and Butler, 2010). We aim at a more comprehensive representation

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of the ‘triple bottom line’ of sustainability, namely society, economy, and the environment (Ashley et al., 2008). However, there is still no consensus on the definition of sustainability (Ashley et al., 2008; Muga and Mihelcic, 2008). The choice of indictors and their aggregation remains unsolved (Rowley et al., 2012). Secondly, stakeholders should be actively involved in public decisions to embrace a diversity of values (Reed, 2008). Thirdly, uncertainty needs to be tackled. The consequences of wastewater infrastructure alternatives are uncertain by nature. Preferences of stakeholders are seldom precisely known, e.g. because they are vague or difficult to express in numbers (Gregory et al., 2012). Fourthly, long-term planning is required to address climate change and socio-demographic developments. Therefore, an improved decision support tool is clearly necessary.

Multi-Criteria Decision Analysis (MCDA) seems capable of addressing these challenges (Belton and Stewart, 2002; Eisenführ et al., 2010; Keeney and Raiffa, 1976). There are a variety of MCDA methods, including Multi-attribute value/utility theory (MAVT/MAUT) (Keeney and Raiffa, 1976), Analytic Hierarchy Process (AHP) (Saaty, 1980), Dominance-based rough set approach (Greco et al., 2001), outranking methods (Roy, 1996), etc.

MCDA has been applied to water resource management, including water policy, strategic planning, and infrastructure selection (Hajkowicz and Collins, 2007). Keeney and Wood (1977) illustrated the feasibility of MAVT for long-range water resource planning. Chung and Lee (2009) used AHP to estimate weights of criteria and ranked water management alternatives with ELECTRE II, Regime, and Evamix methods. Yang et al. (2011) prioritized the alternatives for watershed management under climate change and urbanization also using ELECTRE II. Ülengin et al. (2001) selected remedy for water-crossing problem with the PROMETHEE method. Kim et al. (2013) prioritized the best sites for treated wastewater instream use with Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (fuzzy TOPSIS) considering various uncertainties. For sustainable wastewater management, Guest et al. (2009) argued that the lack of a socio-technological planning and design methodology is the larger problem than the availability of technology, and encouraged using MCDA. Ashley et al. (2008) devised a multi-criteria assessment framework to support asset investment decisions for wastewater systems, which however, remains largely unused (Hurley et al., 2008). Molinos-Senante et al. (2014) developed a composite indicator embracing economic, environmental and social issues to assess the sustainability of wastewater treatment, and AHP was used to assign weights to each indicator.

Each MCDA method has strengths and weaknesses (Cinelli et al., 2014). Outranking methods are widely used in practice, and promoters of ELECTRE (Bernard and Denis, 1993; Figueira et al., 2013; Roy, 1996) and PROMETHEE-GAIA (e.g. Behzadian et al., 2010; Brans et al., 1986) have developed user-friendly software, based on pairwise comparisons and outranking relations. Pairwise comparisons are possibly easier for decision-makers because they mimic intuitive decision-making, but can result in a large number of questions and may be cognitively demanding (Macharis and Springael, 2004). AHP also uses pairwise comparisons and is extremely popular (Saaty, 1980), but has been heavily criticized (Smith and Von Winterfeldt, 2004). We chose MAVT/MAUT because of its solid axioms of rationality (Reichert et al., 2015). Moreover, we follow the spirit of value-focused thinking (Dyer, 2005; Keeney, 1996), which proposes that eliciting stakeholders’ preferences should be independent of the decision alternatives. This can be achieved in MAVT/MAUT, while rank reversals may occur e.g. in AHP when new alternatives are introduced or a lower ranked alternative is removed (Dyer, 1990). Moreover, MAUT is particularly suitable to manage random and probabilistic input criteria values (Reichert et al., 2015), which is relevant because many wastewater engineering models predict the performance of alternatives with uncertainty (Cinelli et al., 2014).

The application of MAUT is challenging especially when stakeholders' preferences are incorporated and several scenarios considered. Preference elicitation is cognitively demanding for respondents if difficult trade-offs have to be made (Gregory et al., 2012). Moreover, some common simplification such as the widely used additive model (see Section 2.4.2 for the definition) and linear marginal value functions do not always hold, especially for environmental decisions (Langhans and Lienert, 2016; Langhans et al., 2014). Finally, the elicitation of preferences regarding different scenarios remains unresolved (Stewart et al., 2013). A careful design of the MCDA process to incorporate stakeholders’ preference is vital for successful application.

This research is part of the ‘SWIP’-project (Sustainable Water Infrastructure Planning, www.eawag.ch/swip), conducted within the Swiss National Research Programme NRP 61 ‘Sustainable Water Management’ (www.nfp61.ch). Previously, we analyzed the roles of different actors in the decision (Lienert et al., 2013) and presented the structuring phase of the MCDA and the development of scenarios (Lienert et al., 2015). This paper furthers our previous research and aims at providing a practical tool to support wastewater infrastructure decisions. It deals with:

1. Eliciting stakeholders' preferences and incorporating them into MAUT;
2. Identifying robust wastewater infrastructure alternatives considering external uncertainties, and uncertainties of predictions and the stakeholders' preferences;
3. Using local sensitivity analysis to help practitioners verify the appropriateness of common simplifications, i.e. additive aggregation and linear marginal value functions; identifying which uncertainty source matters most;
4. Demonstrating the applicability of the framework in a real-world case study.

In Section 2 we describe the decision framework and its application to the case study. The MCDA elements in our previous work are briefly recalled. We then focus on the prediction of outcomes of alternatives, preference elicitation and modeling, identification of robust alternatives, and the step-wise sensitivity analysis. Section 3 provides the results of the predictions, the elicited preferences, and the evaluation of alternatives for all stakeholders and four future scenarios. Section 4 presents the sensitivity analysis results. In Section 5, we discuss interesting findings, lessons learnt, and recommendations for using the decision framework. We end with some conclusions.

2. Materials and methods

2.1. A structured decision analysis procedure

We followed a standard MCDA procedure (Belton and Stewart, 2002; Eisenführ et al., 2010; Keeney and Raiffa, 1976) (Fig. 1). Structuring the decision included clarifying the context, stakeholder selection, and problem formulation (define scenarios, alternatives, objectives hierarchy, and attributes). These steps for the case study are described in detail in (Lienert et al., 2013, 2015); we briefly recall the relevant results in Section 2.2. This paper focuses on the next steps, namely assessing the outcomes of alternatives, preference elicitation, MCDA evaluation, sensitivity analyses, and stakeholder feedback. We present details in the supplementary material (SM), which intends to help interested readers to understand and maybe use the procedure for their own decision.