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Assessment of water quality management with a systematic qualitative uncertainty analysis

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Abstract

Uncertainty is an inevitable source of noise in water quality management and will weaken the adequacy of decisions. Uncertainty is derived from imperfect information, natural variability, and knowledge-based inconsistency. To make better decisions, it is necessary to reduce uncertainty. Conventional uncertainty analyses have focused on quantifying the uncertainty of parameters and variables in a probabilistic framework. However, the foundational properties and basic constraints might influence the entire system more than the quantifiable elements and have to be considered in initial analysis steps. According to binary classification, uncertainty includes quantitative uncertainty and non-quantitative uncertainty, which is also called qualitative uncertainty. Qualitative uncertainty originates from human subjective and biased beliefs. This study provides an understanding of qualitative uncertainty in terms of its conceptual definitions and practical applications. A systematic process of qualitative uncertainty analysis is developed for assisting complete uncertainty analysis, in which a qualitative network could then be built with qualitative relationship and quantifiable functions. In the proposed framework, a knowledge elicitation procedure is required to identify influential factors and their interrelationship. To limit biased information, a checklist is helpful to construct the qualitative network. The checklist helps one to ponder arbitrary assumptions that have often been taken for granted and may yield an incomplete or inappropriate decision analysis. The total maximum daily loads (TMDL) program is used as a surrogate for water quality management in this study. 15 uncertainty causes of TMDL programs are elicited by reviewing an influence diagram, and a checklist is formed with tabular interrogations corresponding to each uncertainty cause. The checklist enables decision makers to gain insight on the uncertainty level of the system at early steps as a convenient tool to review the adequacy of a TMDL program. Following the instruction of the checklist, an appropriate algorithm in a form of probability, possibility, or belief may then be assigned for the network. Consequently, the risk or evidence of the success of outcomes will be obtained. The incorporation of the systematic consideration of qualitative uncertainty into water quality management is expected to refine the decision-making process.

Keywords: Water quality management; Total maximum daily loads (TMDLs); Uncertainty analysis; Qualitative uncertainty; Checklist

1. Introduction

Uncertainty is inevitable in any system and is likely to cause confusion in decision-making. It mainly stems from gaps in human knowledge due to the limited information available. To understand the unknown “real

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world," people seek reasonable explanations and develop rules according to their observations and experiences from the known world. However, even from observations, measurement uncertainties are associated with the precision of sampling and analysis methods (Lee and Ramsey, 2001).

Many documents have summarized the types of uncertainty. For example, the USEPA (1997) reported two kinds of uncertainty: variability and uncertainty. Variability refers to inherent difference, and uncertainty is normally derived from limited information and can be reduced if more information is given. In addition, Stewart (2000) illustrated aleatory uncertainty and epistemic uncertainty, and Morgan and Henrion (1990) proposed frequency uncertainty and subjective uncertainty. Young (2001) categorized uncertainty into hard uncertainty and soft uncertainty according to the quality of information. The definitions and causes of uncertainty summarized by Zimmermann (2000) are explicit. He defined uncertainty as one's inability to predict or prescribe a system, behaviors, or characteristics deterministically and numerically when the quantitative and qualitative information is not appropriate, and the existence of uncertainty is caused by lack of information, complexity, conflicting evidence, ambiguity, and belief. In the literature, qualitative uncertainty is acknowledged, but most research in water quality management has focused on quantitative uncertainty analysis, such as model parameter uncertainty (Scavia et al., 1981), model uncertainty (Reckhow, 1979), and natural randomness. Few studies have discussed qualitative uncertainty. One example is the fuzzy set theorem, which was used for linguistic vagueness (Mujumdar and Sasikumar, 2002). Among these studies, the discussions of qualitative uncertainty are limited. However, consideration of qualitative uncertainty is important to aid in estimation of the interior states of a system and to promote careful decision-making (Cerquides and de Mantaras, 1998; Doyle and Thomason, 1999). To foster complete understanding and to reduce uncertainty, both quantitative and qualitative uncertainties need to be estimated concurrently. Unfortunately, qualitative uncertainty has been neglected in most cases.

Unlike quantitative uncertainty, which is expressed conventionally as probability, qualitative uncertainty cannot be addressed as an estimated value and is always treated as "particular assumptions" without further analysis. For example, the choice of a feasible water quality model is important because the decision will be made according to the model predictions. However, the model selection might be determined without objective comparisons but rather be based simply on the modeler assumption that the behavior of hydrological and pollution transport is the same in different watersheds. This is a biased assumption. One point to be emphasized is that such subjective uncertainty can be found in any decision and has significant influences on subsequent decisions. In response to decisions being made based not on numerical probability but instead on subjective human preference, researchers began to address qualitative analysis and develop analysis methods, e.g., the qualitative relationship (Parsons, 1995), qualitative decision theory (Doyle and Thomason, 1999; Dubois et al., 2003), and the qualitative probability networks (Wellman, 1990). Qualitative uncertainty analysis aims to eliminate system vagueness and clarify the causality of factors in systems, facilitating more reliable decision-making.

Although the importance of qualitative uncertainty is recognized, it is hard to be verified by the current approaches due to the lack of explicit identification and clear analytic process for assessing qualitative uncertainty. Two purposes are addressed in this study. One is to clarify qualitative uncertainty by a comparison with quantitative one, and to develop a systematic analytic process as a tool for assisting more sound decision-making. The other is reviewing and identifying previously ignored qualitative factors in TMDL programs, which serves as a surrogate of water quality management. We here clarify the qualitative uncertain conditions in TMDL programs. A checklist with interrogations corresponding to each qualitative uncertainty replacing implicit and abstract concepts is generated. The checklist comprises possible uncertainty causes in TMDL programs and provides valuable information for building the qualitative network that depicts the relationship between uncertain factors.

Detailed explanations of qualitative uncertainty are addressed in Section 2, including an overview of the causes of uncertainty in water quality management and the TMDL. Section 3 illustrates the transformation of the conceptual understanding to a practical checklist. A TMDL program in Taiwan is used as a case study to illustrate the application of the qualitative uncertainty analysis collaborated with the checklist in Section 4. Finally, a discussion of the integration of qualitative uncertainty into water quality management is included in Section 5.

2. Uncertainty

2.1. Qualitative uncertainty

Qualitative uncertainty analyses (QUA) deal with various kind of knowledge-based issues. Since knowledge-