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Interpreting drinking water quality in the distribution system using Dempster–Shafer theory of evidence

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Abstract

Interpreting water quality data routinely generated for control and monitoring purposes in water distribution systems is a complicated task for utility managers. In fact, data for diverse water quality indicators (physico-chemical and microbiological) are generated at different times and at different locations in the distribution system. To simplify and improve the understanding and the interpretation of water quality, methodologies for aggregation and fusion of data must be developed. In this paper, the Dempster–Shafer theory also called theory of evidence is introduced as a potential methodology for interpreting water quality data. The conceptual basis of this methodology and the process for its implementation are presented by two applications. The first application deals with the interpretation of spatial water quality data fusion, while the second application deals with the development of water quality index based on key monitored indicators. Based on the obtained results, the authors discuss the potential contribution of theory of evidence as a decision-making tool for water quality management.

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1. Introduction

Monitoring and inspection of a system or a process may use more than one type of measurements and/or observations to describe the overall *Condition State*. The credibility of measurements to assess overall *Condition State* is important to be quantified for reliable decision-making. The data fusion is useful for an objective aggregation that can be reproducible and interpretable. Many infrastructure engineering problems, e.g., condition assessment of assets, production process quality control, and water quality monitoring require more than one performance indicator to define the *Condition State*. In addition, the aggregation of spatial or temporal observations of one (or more) performance indicator(s) is generally performed for reliable predictions.

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The data fusion refers to the scientific aggregation of the observations and measurements. In some cases, different data sets (e.g., measured by different types of sensors and probes, various water quality indicators) give information on various aspects of the system or a process by complementing each other. Therefore, the motivation is to collect more information for accurate prediction of *Condition State*. It is also possible that the information collected by various data sets can also be redundant if it deals with the same aspect of the problem, but it improves the reliability as one measurement/observation is confirmed by the other. Complementing information and redundancy of data sets are the basis of data fusion applications in condition assessment of assets and water quality monitoring.

Regular monitoring of raw water quality, treatment processes and water quality in the distribution systems are integral parts of *total drinking water quality management* for the implementation of a *multi-barrier approach* for maintaining high-quality tap water for consumers. Water distribution systems are subjected to adverse reactions and events that can change the high-quality water to unpalatable and unsafe for human consumption by the time it arrives at the tap of the consumer (LeChevallier et al., 1996). As water quality can change significantly in the distribution system, regular monitoring is even more essential to ensure that high-quality drinking water reaches the consumer.

To monitor the quality of water in the distribution system, physical, chemical, and biological indicators are recorded from routine grab sampling, followed by an analysis in the laboratory or using portable kits in the field (APHA, AWWA, WPCF, 1995). Sensor technology exists that enables capturing some indicators through online monitoring rather than grab samples. This technology is continually evolving to encompass more types of water quality indicators. Some common water quality indicators used for water distribution are turbidity, residual disinfectant, pH, nitrates, phosphates, organic compounds, total/fecal coliforms, and heterotrophic bacteria (HPC) (Clark, 1994; Hunsinger and Zioglio, 2002; Coulibaly and Rodriguez, 2003).

Water uses generate a large amount of water quality data by routine sampling to control and maintain the acceptable *Condition State* of water quality in the system. Information is gathered on diverse water quality indicators using different techniques (manual sampling or auto-samplers and subsequent laboratory analysis, or online monitoring with automatic analyzer equipment). To better understand and interpret the water quality data, the use of novel techniques that favour the fusion and the aggregation of data is required to be explored.

In this paper, the application of Dempster–Shafer (D–S) theory or theory of evidence for interpretation of water quality in the distribution system is demonstrated with the help of two examples. The first example discusses the application of theory of evidence for water quality data fusion for the case of water samples collected at different locations in the distribution system at a given time (interpreting spatial information), which is equally valid for fusion of temporal data or combining both. The second example briefly discusses the application of D–S theory for developing water quality index (WQI) that helps in aggregating and interpreting water quality linguistically, but in a rational manner.

2. Dempster–Shafer theory for interpreting water quality monitoring data

There are numerous techniques available for conducting data and knowledge and information fusion, and most common among them are Bayesian inference, Dempster–Shafer rule of combination, fuzzy rule-based inference, and neural networks (Roemer et al., 2001). The idea of evidence integration and accumulation of beliefs are commonly used in Bayesian inference, which implies that $p(A) + p(\neg A) = 1$, i.e., the belief in a hypothesis A can be used to derive the belief in its complement (Alim, 1988). But "NOT A" is the missing evidence (lack of knowledge) that is dealt as equal non-informative priors (*Principle of Insufficient Reason*) in Bayesian inference instead of ignorance. Alim (1988) argued that "No evidence" is different from having the same degree of confidence in all hypotheses, which is the basic motivation behind D–S theory.

Dempster–Shafer theory is a theory of evidence, which is based on classic work by Dempster (1968) and Shafer (1976). The D–S theory can be interpreted as a generalization of probability theory where probabilities are assigned to *subsets* as opposed to mutually exclusive *singletons*. The probability theory can associate evidence to only one possible event, whereas D–S theory determines the evidence to sets of events, i.e., if the evidence is sufficient enough to permit the assignment of probabilities to single event (singleton), the D–S theory inference reduces to the probabilistic formulation (Sentz and Ferson, 2002).

The D–S theory applications in civil and environmental engineering vary from slope stability (Binaghi et al., 1998), environmental decision-making (Chang and Wright, 1996; Attoh-Okine and Gibbons, 2001), seismic analysis (Alim, 1988), failure detection (Tanaka and Klir, 1999), biological surveillance of river water quality (Boyd et al., 1993), and remote sensing (Wang and Civco, 1994) to climate change (Luo and Caselton, 1997). Many more applications of D–S theory can be seen in detailed bibliography reported by Sentz and

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