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Research papers

Optimal spatio-temporal design of water quality monitoring networks for reservoirs: Application of the concept of value of information

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ABSTRACT

This paper presents a new methodology for optimizing Water Quality Monitoring (WQM) networks of reservoirs and lakes using the concept of the value of information (VOI) and utilizing results of a calibrated numerical water quality simulation model. With reference to the value of information theory, water quality of every checkpoint with a specific prior probability differs in time. After analyzing water quality samples taken from potential monitoring points, the posterior probabilities are updated using the Baye's theorem, and VOI of the samples is calculated. In the next step, the stations with maximum VOI is selected as optimal stations. This process is repeated for each sampling interval to obtain optimal monitoring network locations for each interval. The results of the proposed VOI-based methodology is compared with those obtained using an entropy theoretic approach. As the results of the two methodologies would be partially different, in the next step, the results are combined using a weighting method. Finally, the optimal sampling interval and location of WQM stations are chosen using the Evidential Reasoning (ER) decision making method. The efficiency and applicability of the methodology are evaluated using available water quantity and quality data of the Karkheh Reservoir in the southwestern part of Iran.

1. Introduction

Over the last decades, many dams have been constructed to address human needs such as supplying drinking, industrial and irrigation water demands. Fulfilling these goals and supplying water with moderately good quality necessitate water quality monitoring of reservoirs. The main issue in this type of monitoring is financial burden of sampling and analysis of water samples. To tackle this issue and provide comprehensive information about the spatial and temporal variations of water quality in these important water bodies, Water Quality Monitoring (WQM) networks for reservoirs should be optimally designed. Because of three-dimensional variations of water quality in reservoirs, monitoring of water quality in such systems is different from other water resources.

There are many statistical studies on river, polder, groundwater and rainfall monitoring network design. Many of these studies are entropy-based (e.g. Krstanovic and Singh, 1992a,b; Harmancioglu and Alpaslan, 1992; Mogheir et al., 2006; Alfonso et al., 2010a,b; Mishra and Coulibaly, 2010; Stosic et al., 2017; Hosseini and Kerachian, 2017; Alizadeh and Mahjouri, 2017) and some of them have utilized geostatistical-based methods (e.g. Bastin et al., 1984; Yfantis et al., 1987; Triki et al., 2013; Ran et al., 2015). Although there is a vast variety of literature on the optimization of monitoring networks of rivers, polders, and groundwater systems, previous works on the optimization of monitoring networks of reservoirs have been very limited.

According to UNEP/WHO (1996),[1] long-term WQM with one station next to the center or the deepest part of the lake is necessary for lakes with appropriate horizontal mixing. Also, the number of WQM stations must be more than one in stratified lakes. This number is recommended to estimate by $\log_{10}S$ (where S is the lake area in km^2), which can be utilized for great lakes with a vast variety of deep basins and a wide range of narrow bays (UNEP/WHO, 1996). Obviously, this guideline cannot be used for finding the location of WQM stations in thermally stratified reservoirs.

Jimenez et al. (2005) developed a methodology for the design of quasi-optimal monitoring networks for lakes and reservoirs. The main components of their methodology were a numerical model, which was used due to the lack of field data; a Kriging-based

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[1] United Nations Environment Programme (UNEP).

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module for spatial interpolation and getting estimates from the available monitoring networks and a genetic algorithm-based optimization model to generate the set of non-dominated optimal (accuracy vs costs) monitoring networks.

Beveridge et al. (2012) utilized a geostatistical method to determine optimal WQM stations of the Great Winnipeg Lake by clustering the lake and omitting stations with redundant information. They combined the Kriging method, which suggested redundant stations considering all existing stations, and the Local Moran's I values, which determined redundant stations of each cluster. Kovacs et al. (2014) developed a method on the basis of Combined Cluster and Discriminant Analysis (CCDA) to classify sampling sites into homogeneous groups. They declared that their technique is applicable to reduce the number of WQM stations in lakes. Yenilmez et al. (2014) proposed a model for determining the optimal location of WQM stations to measure dissolved oxygen (DO) in Porsuk reservoir by the combination of kernel density estimation (KDE) and ordinary kriging methods. The KDE method was utilized to decrease congestion of WQM stations, which resulted in the reduction of number of stations from 65 to 10, and the introduction of 5 locations for new stations. Lee et al. (2014) proposed an approach based on information theory to optimize the location of WQM stations in a specific depth in a reservoir. The results revealed that average water quality at optimal sampling stations was similar to this average in all potential WQM points. Nikoo et al. (2016) developed a multi-objective optimization model based on the Non-dominated Sorting Genetic Algorithms (NSGA-II) optimization model, entropy theory, a calibrated numerical model based on CE-QUAL-W2 and bargaining theory to optimize the location of WQM stations in Karkheh Reservoir considering utility function of main stakeholders. In this study, only spatial optimization of WQM network was considered. Recently, Aboutalebi et al. (2017) optimized the location of WQM stations in a reservoir based on NSGA-II optimization model with the objects of minimizing prediction error of Methyl Tertiary Butyl Ether (MTBE) and the average time of MTBE detection.

The concept of VOI was first used by decision makers to figure out whether it would be economic to invest in obtaining further stochastic information or not (Alfonso and Price, 2012). Previous applications of VOI theory are mainly rooted in two studies: (1) Hirshleifer and Riley (1979) who introduced the VOI theory in order to address some decision making problems under uncertainty; and (2) Alfonso and Price (2012) who optimized the location of hydrometric monitoring stations by applying hydrodynamic models associated with the VOI concept. They searched the location of some hydrometric monitoring stations along a polder system in the Netherlands to minimize flood damage.

Typically, the existing approaches for the optimization of reservoir WQM stations specify the optimal location of WQM stations in only one dimension, and none of them provides optimal sampling interval. In addition, in previous works, the VOI theory has been used to optimize the location of WQM stations in some water bodies such as polders, not reservoirs. In this paper, a new methodology is developed to spatially and temporally optimize a reservoir WQM network. In this regard, water quality in the reservoir is estimated based on the results of a calibrated numerical simulation model. The WQM network is optimized using the concept of value of information and entropy theory, and the results are compared. If the results of two methods are different, they might be combined using a weighting method, and the spatio-temporal optimization of the monitoring network is done using a hybrid VOI-entropy method. In the final step, the optimal WQM stations and sampling interval are specified using the Evidential Reasoning method. The Karkheh Reservoir in Iran is taken into account as a case study in order to evaluate the efficiency and applicability of the proposed methodology.

2. Methodologies

A flowchart of the proposed methodology for spatio-temporal optimization of reservoir WQM networks is presented in Fig. 1. Different steps of this flowchart are explained in the following sections:

2.1. Data collection

The collected information includes necessary data for the calibration and validation of the reservoir water quality simulation model (i.e. CE-QUAL-W2). The physical characteristics of reservoir evaporation rate, relative moisture, wind speed, weather temperature, reservoir operating rules and time series of inflow quantity and quality are the main inputs of the simulation model. The simulation model is calibrated and verified using observed data obtained from existing monitoring networks. To evaluate the spatial and temporal variations of water quality in the reservoir, a suitable water quality index (WQI) should be used.

2.2. Value of information (VOI)

Generally, water quality in a monitoring station with a specific prior probability varies in time. By obtaining new data, the posterior probability and the *VOI* of the new data can be estimated using the Baye's theorem. A combination of monitoring stations with maximum *VOI* can be selected as optimal WQM configuration. This process is repeated for each sampling interval to obtain optimal monitoring network characteristics for each water quality sampling interval. In the following sections, more details about the proposed methodology for estimating *VOI* of monitoring stations are presented.

2.2.1. Calculation of VOI for various sets of potential WQM locations

At first, a decision maker has an opinion about states of water quality in various part of the reservoir based on previous observations or simulations. After receiving new information (messages), his or her viewpoint will be updated, which may contribute to taking actions. If messages assist the decision maker to do the right thing, they are valuable, otherwise, they cause damages. Hence, according to the VOI concept, messages are evaluated and quantified based on the right or wrong outlook given to decision maker (Alfonso and Price, 2012). The steps of calculating VOI of each station in order to estimate the states of other points are given in the supplementary material.

2.2.2. Determination of the maximum number of required WQM stations

Actually, Points C and D in the supplementary material can be any of potential WQM locations. In this step, the *VOI* of potential WQM station C (point 5[2] in Figs. 2 and 3) for determining states of other potential WQM locations is calculated (Fig. 2), and a curve is fitted to these *VOI* values (Fig. 3). In Figs. 2 and 3, it is assumed that a reservoir is simulated in one dimension and point 5 is a WQM station located in 5 km from an origin (e.g. from the dam) in an arbitrary reservoir that determines states of other potential WQM locations in the same depth. It should also be noted that if the reservoir is simulated in two dimensions, the *VOI* diagram would be a three-dimensional surface. As presented in Fig. 3, the maximum *VOI* occurs at point 5. It means that if a decision maker wants to know just the state of point 5, he should put a new WQM station

[2] It is assumed that Point 5 is located in 5 km distance from an origin in an arbitrary one dimension reservoir.