Review of reservoir water quality monitoring and modelling

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Abstract

Reservoir water quality assessment is important for decision makers to manage the water quality in the reservoir and downstream. Integration of reservoir water quality monitoring and modelling could provide better information for water quality assessment. The purpose of this study is to review the development of reservoir water quality models and monitoring network designs. Various mathematical models like CE-QUAL-W2, MIKE, WASP, and EFDC have been developed in the literature in order to simulate water quality in a reservoir. The capabilities and limitations of different models are presented and illustrated in this paper. Several studies may be found in the literature for selection of water quality variables, design of sampling locations to monitor reservoir water quality, and identification of sampling frequencies. Generally, the optimal design of monitoring networks would reduce the fiscal burden of long term stewardship and improve the understanding of reservoir operators on the water quality that is delivered to downstream, while allowing stakeholders to select, understand, and balance their design objectives. This research could aid the decision makers to directly select the reliable reservoir water quality models and appropriate approaches for optimal design of monitoring networks to save millions of dollars that are currently spent on sampling redundant data.

Keywords: Reservoir water quality, Monitoring network, Mathematical models, Stakeholder involvement.

1. INTRODUCTION

Designing a reservoir monitoring network is an important issue which plays a direct role in the monitoring network reliability and expenditure. Numerous aspects have to be considered in this problem such as sampling locations, sampling frequencies, and stakeholders' monitoring objectives.

Integration of reservoir water quality monitoring and modelling could provide better information for water quality assessments. Besides, modelling may be used in some situations where monitoring is not possible. Water quality modelling in reservoirs is more difficult compared to river and estuarine systems because of thermal stratification and wind mixing processes [1]. Various models have been developed to simulate the water quality in reservoirs. From the variety of mathematical models, only two and three-dimensional models which are widely used (CE-QUAL-W2, MIKE, WASP, and EFDC) are briefly discussed here. The capabilities and limitations of these models are presented and illustrated in this paper.

In order to find the best compromised monitoring plan, concerned stakeholders must be included in the decision-making process. It is an effective way to achieve a shared vision (a consensus) and lead to more sustainability for water resources system [1]. Participated stakeholders can input their expert knowledge during the design process of a reservoir monitoring network.

This study provides a review of the most challenging problems in reservoir water quality monitoring and modelling to identify the state-of-the-art in this field. The following sections condense an extensive literature on reservoir monitoring network design, reservoir water quality models, and stakeholder involvement in reservoir water quality modelling and monitoring.

2. RESERVOIR MONITORING NETWORK DESIGN

Designing a monitoring network is difficult because of complex aspects such as selecting water quality variables, identifying sampling locations and sampling frequencies as well as the duration and objectives of sampling [2].

Identifying optimal locations to monitor water quality at a reservoir reduces the cost of monitoring program considerably. Generally, the optimal locations reduce the number of trips to sample a reservoir and improve the understanding of reservoir operators on the water quality that is delivered at downstream. Lee and Kwon (2009) and Lee et al. (2011) tried to decrease redundant sampling locations in a reservoir with measuring their similarity using statistical techniques [3, 4]. Lee et al. (2014) applied entropy theory to optimize water quality monitoring stations in a reservoir and identified the relative importance of water quality variables including chemical oxygen demand, suspended solids, total nitrogen, and total phosphorus. They used the collected water quality data from nine sampling locations at depths between 5 and 6 m of Lake Yongdam in the Korean peninsula. They tested all possible combinations of the nine sampling locations to find the optimal locations and showed that the time series of each water quality variable averaged over all the nine sampling locations closely matched the time series averaged on the six optimal locations [5]. Yenilmez et al. (2015) minimized the number of monitoring stations in the Porsuk Dam Reservoir located in Turkey based on the spatial correlation structure in surface dissolved oxygen values. In their study, kernel density estimation and ordinary kriging was coupled to identify the representative monitoring stations in the reservoir [6]. Jabbari et al. (2016) obtained critical paths with maximum time variance in quality indices values for placement of monitoring stations in Karkheh Dam Reservoir using CE-QUAL-W2 model. They considered phosphate, nitrate, chlorophyll-a, and dissolved oxygen to control eutrophication in the reservoir [7]. Nikoo et al. (2017) presented a new methodology for multi-objective optimization of water quality monitoring stations of the ***Karkheh Dam Reservoir*** in Iran. Their proposed approach was based on NSGA-II (Non-dominating Sorting Genetic Algorithm-II), transinformation entropy and social choice methods to achieve a common option agreed upon by social stakeholders. They selected five water quality variables: phosphate (PO_4), nitrate-nitrite (NO_3-NO_2), electrical conductivity (EC), ammonium (NH_4), and dissolved oxygen saturation (DO_{sat}). In their study, water quality samples were taken at two stations (monthly) at 5 m depth intervals for 14 months. They simulated water quality over 40 years by a calibrated and verified CE-QUAL-W2 model. They selected 22 potential monitoring stations at different depths along the length of the reservoir. Their results showed that the number of optimized monitoring stations was 3 out of 22 potential stations across all seasons, however, the locations were different across seasons [8].

Identifying optimal sampling frequencies could decrease the corresponding expenditure. Varol et al. (2012) studied the spatial and temporal variations of water quality in Kralkızı, Dicle and Batman dam reservoirs in the Tigris River basin, in Turkey based on multivariate statistical techniques like cluster analysis, principal component analysis, factor analysis, and discriminant analysis. They showed that discriminant analysis resulted in more data reduction [9].

3. RESERVOIR WATER QUALITY MODELS

Water quality models are designed for simulation and assessment of water quality in water bodies, which may reduce the monitoring expenditure. Integration of reservoir water quality monitoring and modelling could provide better information for water quality assessment. Designing a water quality model is a difficult task because of highly non-linear and complex aspects, stochastic elements of natural systems, and limited knowledge of the events taking place in water bodies. Thus, many simplification and assumptions are considered in any model [10]. Various models have been developed to simulate the water quality in reservoirs like DYRESEM, HEC-5Q, WQRRS, CE-QUAL-W2, MIKE, WASP, and EFDC. Only two and three-dimensional models i.e. CE-QUAL-W2, MIKE, WASP, and EFDC are discussed in the following sub-sections. Capabilities and limitations of these models are presented in Table 1. The models are compared in Table 2.

3.1. CE-QUAL-W2

CE-QUAL-W2 model is a two-dimensional, hydrodynamic and water quality model, that was developed by the United States Army Corps of Engineers [11]. The CE-QUAL-W2 model has the ability to model 21 water quality state variables [12]. It is most appropriate for simulation of the water quality in narrow and deep reservoirs due to well mixing in the horizontal and lateral direction. The governing equations are the continuity, momentum and advection/diffusion equations. The hydraulic parameters and geometric, inflow/outflow and meteorological data are needed for model application [13].

A review of previous studies shows that CE-QUAL-W2 model is widely used for water quality modelling in reservoirs. Kuo et al. (2006) investigated the stratification and eutrophication problem in two reservoirs (Tseng-Wen and Te-Chi) in Taiwan using a CE-QUAL-W2 model. The simulated values of temperature, total phosphorus, ammonia, nitrite/nitrate, chlorophyll-a, and dissolved oxygen matched the field data well [14]. Ha and Lee (2007) applied a CE-QUAL-W2 model to study the eutrophication in Daecheong Dam Reservoir in South Korea. They monitored dissolved oxygen, biochemical oxygen demand, chemical oxygen demand, total suspended solids, and pH [15]. Debele et al. (2008) utilized the CE-QUAL-W2 model for water quality simulation in the Cedar Creek Reservoir (long and narrow), TX, USA [12]. Liu et al. (2009), Dai et al. (2012); Huang (2014); Chang et al. (2015), and Torres et al. (2016) applied this model for reservoir water quality modelling [16, 17, 18, 19, 20]. Noori et al. (2015), Jabbari et al. (2016), and Nikoo et al. (2017) used the CE-QUAL-W2 model for simulation of water quality in the ***Karkheh Dam Reservoir*** in Iran [21, 7, 8].

3.2. MIKE 11- RESERVOIR

MIKE 11 is a fully dynamic model that is designed by Denmark Hydrology Institute (DHI) in 1993 for simulation of flood, sediment transport, and water quality in rivers and channels [22]. The Reservoir Module (MIKE 11-Reservoir) is developed within MIKE 11 for water quality simulation in deeper water bodies like reservoirs. The water quality model of MIKE 11-Reservoir is a two-dimensional hydrodynamic model that solves Navier Stokes equation, combined with the equation for conservation of mass, salinity and temperature [23].

Kjelds and Storm (2001) presented a comprehensive integrated modelling system including MIKE 11, MIKE 11-Reservoir, MIKE BASIN, and MIKE SHE to assess and minimize the adverse environmental impact of Wielowies Klasztorna Reservoir in Poland [24]. Rzadar et al. (2011) compared the CE-QUAL-W2, WASP5 and MIKE11 models for simulation of the water quality of Pasikhan River in Iran. They showed that the CE-QUAL-W2 model was more reliable comparing with WASP5 and MIKE11 models. They also concluded that MIKE11 model did not consider the wind effects [25]. Xin et al. (2015) applied MIKE 21 to simulate the water quality in the Danjiangkou Reservoir [26]. The MIKE 21 model is suitable for simulation of water quality, eutrophication and sediment transport in two-dimensional horizontal free surface flows [27].

3.3. WATER QUALITY ANALYSIS SIMULATION PROGRAM (WASP)

Water Quality Analysis Simulation Program (WASP) was developed by the USEPA (Di Toro et al., 1983) for water quality simulation in one, two, or three-dimensional problems (rivers, lakes, estuaries, coastal wetlands, and reservoirs) [28]. The boundary conditions, loads, mass transfer rate, kinetic rates and concentrations of organic compounds, trace elements and phytoplankton are needed for model application. The output are variable concentrations [10]. The WASP model is a time-variable model that can be coupled with hydrodynamic and sediment transport models to calculate flows, velocities, temperature, salinity and sediment fluxes [29].

The WASP model has been used in many rivers, lakes, and reservoirs. Kuo et al. (1986) investigated the vertical water quality variations in the Te-Chi Reservoir using the WASP model [30]. Kuo et al. (1994) coupled the WASP model with a two dimensional laterally averaged hydrodynamic model (LARM2) to study the eutrophication problem in Te-Chi Reservoir [31]. Debele et al. (2008) claimed that using the CE-QUAL-W2 model has more advantages than the WASP model for simulation of water quality in Cedar Creek Reservoir. Also, the CE-QUAL-W2 is suitable for modeling the changes in water levels in the reservoir [12]. Ernst and Owens (2009) combined a WASP model with a SWAT model to control eutrophication in Cedar Creek Reservoir in Texas. The nutrient loads in their study came from various sources (watershed loading, wastewater treatment plans, atmospheric loading and internal NH_4 and OPO_4 sediment flux). They claimed that the WASP model has fewer degree of freedom and consequently is less affected by errors in comparison with CE-QUAL-W2 model [32]. Narasimhan et al. (2010) applied the WASP model in combination with the watershed model SWAT to develop a comprehensive modeling approach to simulate the algal growth (chlorophyll-a) in the Cedar Creek Reservoir in Texas. They concluded that the proposed modeling approach can lead us to find out the dynamics of nutrient loading from the watershed in large reservoirs [33].

3.4. ENVIRONMENTAL FLUID DYNAMICS CODE (EFDC)

Environmental Fluid Dynamics Code (EFDC) is a three-dimensional model which includes hydrodynamic, sediment and contaminant, and water quality modules. It was developed by Hamrick (1992), Virginia Institute of Marine Science [34]. The EFDC model solves the equations of motions, transport equations for turbulent kinetic energy, salinity and temperature and Eulerian transport-transformation equations for dissolved and suspended materials [35]. This model, as noted by the United States Environmental Protection Agency (USEPA), is a tool for water quality management [36].

Literature shows that this model has been used in many rivers, lakes, and reservoirs. Li et al. (2007) applied the EFDC model for water temperature simulation in Manwan Reservoir in China. Their results showed that the simulated values of water temperature data using the EFDC model matched the observed data well [37]. Çalışkan and Elçi (2009) used the EFDC model to study the effects of selective withdrawal on hydrodynamics of Tahtali Reservoir in Turkey. The numerical model results showed the same trends as the measurements. Their results also showed that EFDC had not the capability of simulating internal waves [38]. He et al. (2011) modeled eutrophication in Beijing Guanting Reservoir in China using EFDC model to manage the reservoir's water quality and reduce the external nutrients loading. The Beijing Guanting Reservoir was shallow and wide, and they selected the EFDC model to identify the nutrients concentration in the reservoir [39].

4. STAKEHOLDER INVOLVEMENT IN RESERVOIR WATER QUALITY MODELLING AND MONITORING

Involving stakeholders in decision-making, and a shared vision, can lead to more sustainability for water resources system [1]. Integrated water resources management is based on stakeholder engagement that include policy-makers, decision-makers, water conservation organizations, universities and the general public [40].

Participated stakeholders, which often have conflicting requirements, can input their expert knowledge during the design process of a reservoir monitoring network. As we mentioned earlier, stakeholder participation was proposed by Nikoo et al. (2017) in a multi-objective optimization of water quality monitoring stations of the ***Karkheh Dam Reservoir*** in Iran. In their study, the involvement of the stakeholders was performed using social choice methods [8]. Social choice methods can be used to find the best solution considering conflicting objectives and disputing stakeholders [41].

Table 1- Capabilities and limitations of Reservoir water quality models

Models	Capabilities	Limitations
CE-QUAL-W2	• Two-Dimensional (longitudinal/vertical) • Based on continuity, momentum and advection/diffusion equations • Using a fully explicit or an explicit/implicit finite difference solution technique • Predicting water surface elevations, velocities, and temperatures, in addition to water quality computation • Ability to model rivers, lakes, reservoirs, estuaries, and combinations thereof • Ability to model multiple water bodies in the same computational grid including multiple reservoirs, steeply sloping riverine sections between reservoirs, and estuaries • Any combination of constituents can be included/excluded from a simulation • Including time-varying data input subroutine • Adjusting the time step to ensure hydrodynamic stability • Allows the model user to set dynamic parameters for the water level control over time • Calculation of ice-cover • Having numerical algorithms for pipes, weir/ spillways, gates, and multiple pumps • Having a graphical pre/postprocessor, allowing the user considerable flexibility in the type and frequency of outputs • Having multiple turbulence closure schemes including $k-\varepsilon$ turbulence model • Selective withdrawal calculations and vertical port selection in a reservoir • Computation of topographic and vegetative shading • Estimating suspended solids re-suspension as a result of wind-wave action [13]	• Laterally averaged • Model application is a complicated and time-consuming task • The user must decide among several vertical turbulence schemes the one that is most appropriate for the type of water body being simulated • The equations are written in the conservative form using Boussinesq and hydrostatic approximations • Since vertical momentum is not included, the model may give inaccurate results where there is significant vertical acceleration [13].
MIKE 11-Reservoir	• Two-Dimensional (longitudinal/vertical) • Solves Navier Stokes equation, combined with the equation for conservation of mass, salinity and temperature • Ability to simulate flows, water quality and sediment transport • Selective withdrawal (outflows) and inflows calculations • Reservoir flushing and eutrophication • Vertical oxygen profiles, i.e. oxygen conditions, in the bottom waters • The model is equipped with advanced turbulence models (e.g. $k-\varepsilon$ model) • Including 12 state variables: phytoplankton (C, N, P, chlorophyll-a), zooplankton, detritus (C, N, P), inorganic nutrients (ammonia, nitrate and phosphate) and DO. • It is specifically designed to study impacts of catchment inflow and operational strategies on the physical and biological processes within the reservoir [23]	• Laterally integrated Navier Stokes equation assuming hydrostatic pressure distribution • Does not consider the wind effects [25]
WASP	• Three-dimensional • Ability to model rivers, lakes, estuaries, coastal wetlands, and reservoirs • A time-variable model • Predicting water quality responses to natural phenomena and man-made pollution • Including variables: DO, CBOD, ammonia, NO_3, organic nitrogen, orthophosphate, organic phosphorous, algae, benthic algae, detritus, sediment, and salinity • It can be linked with hydrodynamic and sediment transport models that can provide flows, depths velocities, temperature, salinity and sediment fluxes • Ability to bring data into the model as simple as cut and paste or queried from a database [10, 28, 29]	• Not capable of simulating control structures
EFDC	• Three-dimensional • Based on the equations of motions, transport equations for turbulent kinetic energy, salinity and temperature and Eulerian transport-transformation equations • Using a semi-implicit, conservative finite volume solution scheme • Ability to model rivers, lakes, reservoirs, estuaries, coastal regions and wetlands • Simulation of drying and wetting, representation of hydraulic control structures, vegetation resistance, wave-current boundary layers and wave induced currents • Allows the simulation of multiple size classes of cohesive and non-cohesive sediment • Can represent the transport and fate of an arbitrary number of contaminants, including metals and hydrophobic organics, sorbed to any of the sediment classes and dissolved and particulate organic carbon using a three-phase equilibrium partitioning formulation • Allows the representation of various degradation and transformation processes • Includes a variable configuration eutrophication component for simulation of aquatic carbon, nitrogen and phosphorous cycles • The full configuration of state variables based on the CE-QUAL-ICM model (The configuration can be readily reduced to WASP equivalent configurations) • Can create hydrodynamic transport files formatted for WASP and CE-QUAL-ICM • Support various graphics packages such as IDL, TECPLOT and MATLAB [34, 35, 36]	• Not capable of simulating internal waves [16]

Table 2. Comparison of Reservoir water quality models

		Models			
		CE-QUAL-W2	MIKE	WASP	EFDC
Dimension	1-D	✓	✓	✓	✓
	2-D (length-width)	-	-	✓	✓
	2-D (length-depth)	✓	✓	✓	✓
	3-D	-	-	✓	✓
Hydrodynamics	inlet	✓	✓	✓	✓
	control structure	✓	✓	-	✓
Water quality processes	TDS	✓	✓	✓	✓
	temperature	✓	✓	-	✓
	bacteria	✓	-	✓	✓
	DO-BOD	✓	✓	✓	✓
	nitrogen cycle	✓	✓	✓	✓
	phosphorus cycle	✓	✓	✓	✓
	phytoplankton	✓	✓	-	-
	zooplankton	✓	✓	✓	-
	algae	✓	-	✓	✓
	SOD* simulation	✓	-	✓	✓

*Sediment Oxygen Demand

5. CONCLUSIONS

This paper addresses the three most challenging issues that face reservoir monitoring network designers: (1) optimal design of monitoring networks; (2) reliable reservoir water quality models; (3) stakeholder engagement. Optimal design of monitoring networks reduces the cost of monitoring program considerably. Different approaches for optimization of reservoir water quality monitoring stations are presented in this paper. A comparative study of different models shows that there is no general model that can be appropriate for all situations. In wide reservoirs, like the Beijing Guanting Reservoir in China, the EFDC model is appropriate for simulation of the reservoir's water quality. However, the EFDC has not the capability of simulating internal waves. The CE-QUAL-W2 model is the most appropriate for simulation of the water quality in narrow and deep reservoirs. This model has more advantages than WASP model for simulation of water quality. Also, it is suitable for modeling the changes in water levels in the reservoirs. WASP model has fewer degree of freedom and consequently is less affected by errors in comparison with CE-QUAL-W2 model. CE-QUAL-W2 model is more reliable comparing with WASP and MIKE11 models. Furthermore, MIKE11 model does not consider the wind effects. Finally, in developing long-term monitoring plans, decision makers and stakeholders must be involved to discover, understand, and balance tradeoffs among a variety of performance objectives.

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