Overview of water quality modeling

Mamuye Tebebal Ejigu

Abstract: Due to population growth, urbanization, and industrialization, water demands have increased, and the quality of water is degraded. Water quality modeling is a significant tool that aids managers and policymakers in multiscale integrated water resources and environmental management. However, water quality modeling is challenging due to several constraints. The modern application of modeling is essentially utilized by the need to comply with rules and regulations. In view of this, water quality modeling requires the standardization of models, identification of common features of models, the hotspots of pollution, and the current state of policy-relevant models. This review presents an overview of water quality modeling and major models frequently applied for water quality assessment at the catchment and at waterbody scales. This review is intended to highlight the applicability of certain water quality models, and the state of water quality modeling, model classification, and uncertainties. Water quality models are described and selected based on their applicability, strengths, weaknesses, and intended use. Some models are applicable for the specific waterbodies, simulate selected water quality parameters, have uncertainties, are not commercially available, require skilled model users, and have huge data requirements. When selecting suitable models, it is recommended to consider the availability of data, model complexity, and type of waterbody, and intended objectives to be modeled.

ABOUT THE AUTHOR

Mr. Mamuye Tebebal is a lecturer at Addis Ababa Science and Technology University, Ethiopia. He has published five research articles in International reputable Journals. His research interest is more focused on the area of hydrodynamics, morphodynamics, groundwater modeling, irrigation, water supply network, sediment, and water quality modeling.

PUBLIC INTEREST STATEMENT

Water quality modeling helps decision and policy makers to decide the best and practically resilient solutions for water quality management. Tangible results from water quality modeling are significant to make successful decisions and directions with the root causes of the environment and waterbody. Some scholars have been done on water quality modeling; however, some water quality models are improved, new models are developed and the gap of the model is identified. Hence, as the need for recent water quality model characteristics knowledge, this review on water quality modeling is essential. The principles, application, gaps, advantages, and types of water quality models have been reviewed. The review will contribute to the selection of an appropriate model for varied water quality problems and different waterbodies, illustrates available models and model uncertainties.
1. Introduction

Water is one of the key elements of the environment that determines the survival of life and restricts the socio-economic growth of the people (Stolarska & Skrzypski, 2012). Overseas and inland surface and sub-surface water systems play an incredible role in everyday life activities mainly for drinking, agricultural, industrial, recreational, and other public uses. Our everyday lives depend on the availability and quality of water. Accessibility of suitable water quality for different purposes (EPA (Environmental Protection Agency), 2003; FAO, 1975; FAO, 1979a and Jonnalagadda et al., 1991) is becoming difficult due to rapid population growth and expansion of agro-industries. Some industrial, agricultural, and human activities have a serious effect on ecological diversity. In addition, surface water quality depends on natural phenomena; the quality of water in lakes and dams is suffering from incessant degradation due to natural processes resulting from eutrophication and anthropogenic causes (Stolarska & Skrzypski, 2012).

Water resources in the world are under pressure; particularly eutrophication is a major environmental problem. Eutrophication is caused by high loading of dissolved and particulate organic matter and inorganic nutrients (Goshu & Aynalem, 2017) due to lack of proper soil and water conservation practices in the watershed (Teshale et al., 2002; Yitaferu, 2007), inappropriate wastewater disposal, and the lack of wastewater treatment technologies. The continuous urbanization and industrialization with increased human activities have a negative impact on water quality and adversely affect the aquatic ecosystem. Human activities are one of the major factors of pollution in environments (EIC (Environmental International Consultant), 2009). Urbanization, industrialization, and agricultural practices have a substantial contribution to water pollution, and they discharge a huge quantity of organic and inorganic pollutants into the waterbodies. Most of the industries mainly in developing countries like Ethiopia discharge the wastewater into the environment without proper treatment. Mainly the cities have the highest pollution rate with inadequate waste management systems that have resulted in excessive pollution of receiving waterbodies. Sedimentation is also a big problem for the lakes, rivers, dams, and coastal areas. According to EEPA (Ethiopia Environmental Protection Agency (2003), some industries located in Addis Ababa have discharged 90 percent of their waste into the nearby waterbodies and open spaces without treatment. The discharges from agricultural inputs (fertilizers and pesticides), domestic and industrial wastes pollute freshwater systems and endanger the socio-economic and ecological values.

Contaminations of ecosystems commonly are organic (pesticides and hydrocarbons) and inorganic (phosphates, nitrates, and metals). The increased concentrations of nutrients cause eutrophication that is a manner of increased algae growth and growth of other forms of plants in the aquatic system (Hussein et al., 2015). Eutrophication can result in the reduction of the dissolved oxygen in the waterbody (X.E. Yang et al., 2008; Conley et al., 2009). Watercourses are essential areas of the ecosystem, and are a source of water for human activities and provide habitat for aquatic animals. However, the discharge of pollutants from different sources results in the scarcity of reliable water quality for the definite functioning of ecosystems (L. Yang et al., 2013; Kumarasamy, 2015). For most of the rivers and lakes in urban areas of developing countries, the wastewater effluents at the downstream section are discharged from industries. Industrial sectors are liable for dumping 300–400 million tons of heavy metals, solvents, toxic sludge, and other waste into water sources globally each year (UNEP (United Nations Environment Programme), 2012). The highest ecological pressure in the environment is the one due to river water pollution. For instance, in Lake Tana, Ethiopia, the quality of water has extensively deteriorated over the
years. Recent studies have shown a serious decline in fish stocks due to the spread of aquatic weed, water hyacinth around fish spawning grounds in Lake Tana (Solomon, 2017).

The forgoing problems mainly arise from imbalances of development interventions and environmental protection activities (Teshale et al., 2002). Major indicators of this imbalance include: accumulation of persistent pollutants in fish species located in reservoirs, decreased fish production, and extended reservoir eutrophication periods, growth of water hyacinths on the reservoir surface, increased costs of operating water treatment plants, increased reservoir sedimentation, and irrigation water quality reduction. Accordingly, the effects of the development of projects and other linked activities on the environment have to be considered before implementation in order to achieve the successful management of the environment and reducing the effects of wastes on the ecosystem.

Water resources and environmental management require continual monitoring in terms of quality and quantity. Proper assessment of the degree of water pollution is used as the benchmark for management and well-adjusted utilization of water resources. One of the basic approaches, which are required to solve the water pollution problem is the modeling of water quality changes. In the past years, the development of mathematical modeling has been rapid (Stolarska & Skrzypski, 2012) and many models have been utilized to date so far. Mathematical models have been applied to assess water quality changes as a result of wastewater discharge vagaries (World Bank Group, 1998). Various mathematical water quality models have been developed and applied by some researchers to study the quality of water in many countries, for example, in Poland (Stolarska & Skrzypski, 2012), the USA in the Shenandoah River watershed (Mboundingo et al., 2019), and Florida Bay (Carl et al., 2000), and South Korea in Ara artificial canal (Zhenhao & Dongil, 2013). Water quality models have been applied for water quality assessment in various waterbodies, one-dimensional (1D) and two-dimensional (2D) coupled hydrodynamic and water quality models were used in the Ca Mau Peninsula (Tri et al., 2018), development of surface water model (Q. Wang et al., 2013; Kayode & Muthukrishna, 2018), mathematical models have been applied for reservoirs (Stolarska & Skrzypski, 2012), the Rio Chone estuary (Stram et al., 2005), the East Johor and Singapore Straits (Sundarambal & Pavel, 2014) and Kas bay (Kagan & Lale, 2015). These studies are important for the planning and management of waterbodies. A summary review of water quality models has also been done (Bai et al., 2011; Q. G. Wang et al., 2009). One of the purposes of a water quality study is to determine its suitability for the intended use. For water quality modeling, the primary and secondary water level and water quality data have been used (Tri et al., 2018).

Investigative water quality models are both mathematical expressions and expert scientific judgment, which comprise process-based (mechanistic) and data-based (statistical) models. They are effective resources for assessing and predicting pollutant transport (Q. G. Wang et al., 2009; Bai et al., 2011; Huang et al., 2012), identifying pollution, fate, and behavior of pollutants (Q. G. Wang et al., 2009), simulating and forecasting complex processes in water ecosystems (Liu, 2018), recognizing the spatial and temporal distribution of pollutants in the water, and intensifying decisions regarding how water quality will be altered (Q. Wang et al., 2013). Water quality models are also needed for investigating the environmental situation of different waterbodies, evaluating the variation in water quality when initial or boundary conditions are changed (Kayode & Muthukrishna, 2018), predicting long-term surface water quality, and performing environmental impact assessment with different pollution scenarios (Q. Wang et al., 2013). The models play on an important role in reducing the cost of labor, materials, and time for a large number of pollution mitigation scenario experiments to some degree (Q. Wang et al., 2013), for watershed and watercourses in the ecosystem. Many types of water quality models have been used to simulate the quality of water in several sorts of water systems comprising rivers, streams, lakes, reservoirs, estuaries, coastal waters, and oceans (Loucks & Van Beek, 2017). Since then, several water quality models have been established with different model algorithms (Liou et al., 2003; Q. Wang et al., 2013) by various organizations and researchers. However, due to different theories and algorithms
used in the models, the modeling outputs of different models have big differences, as a result, the use of different models may provide different environmental management decisions when the outputs cannot be referenced to or associated with each other (Obropta et al., 2008). Assessment of pollutants through monitoring is a challenging task, which requires a continuous update of existing models and the development of new water quality models. The first study on water quality modeling for simulating BOD and DO in a river system was done by Streeter and Phelps in 1925 (Cox, 2003 and Chapra, 2008).

Water quality modeling applies in the estimation and prediction of water pollution using mathematical simulation techniques. An illustrative water quality model consists of a collection of formulations, representing physical mechanisms that determine the position and movement of pollutants in a waterbody (Victoria, 2012). Mathematical water quality modeling is considered as one of the best approaches to estimate the existing pollutant load, pollutant transfer, and upcoming cause–effect relation between pollutant sources and water quality (Nair & Bhatia, 2017). Water quality modeling allows decision and policy makers to choose better, more technically strong solutions among alternative possibilities for water quality management. The models are required to determine better alternatives for solving sustainable water quality problems in the long term. In addition, models are essential to provide a basis for economic analysis, and then decision-makers can use the output to assess the environmental implications of a project and the cost–benefit ratio. The quality of water has been evaluated and modeled with its physical, chemical, and biological characteristics. The relations between the processes related to these characteristics are necessarily multifaceted, and water system managers must pursue to develop a worthy understanding of the main factors and processes that affect the water quality of each local water resource they are responsible for if they are to make correct or improved management decisions (Liu, 2018). The concentrations and distribution of contaminants are influenced by the inactivation of contaminants and some dynamic processes, including diffusion, dispersion, and advection. These processes are closely related to the water flow characteristics, influent and effluent entering and leaving, respectively, the waterbody, wind stress, and temperature stratification (Liu, 2018). Hence, for a better understanding of how the environment and water systems are polluted and to make fruitful decisions and directions, concrete knowledge derived from water quality modeling is significant.

Integrated water quality assessment such as physical observation, and model-based simulation can be used by agencies, resource managers, planners, scientists, engineers, project implementers helping for achieving basin-wide and at large and small-scale level load reduction goals. The water system normally is studied with various approaches including theoretical analyses, mathematical modeling, laboratory tests, and field observations. Laboratory analysis and field observations are the most reliable ways to acquire tangible information for a specific system, which will provide a reliable basis for analysis and modeling. Meanwhile, observed or measured data are typically rare and not sufficient to indicate or predict a complete picture of the real scenario in the large and complex waterbody. Moreover, the available data may not necessarily be very reliable and low-quality data with high errors that might lead researchers to compose a wrong or misleading idea of what is actually happening. Thus, mathematical water quality modeling coupled with observations for verification and calibration is essential in such cases. Integrated models such as hydrodynamic and water quality models have been extensively developed and used (Liu, 2018) for assessing lakes, rivers, reservoirs, ponds, estuaries, and coastal water in many aspects.

Due to the need of water quality models, several authors have rewritten review papers on water quality modeling (Beck, 1987; Tsakiris & Alexakis, 2012; Loucks & Van Beek, 2017; Rauch et al., 1998), developed models (Ambrose et al., 2009) and modeled with different water quality models (Q. Wang et al., 2013; Sundarambal & Pavel, 2014; Whitehead, 2016; Yuceer & Coskun, 2016). Therefore, in the view of up-to-date modeling concepts, improved model development, simulation, and prediction of water quality in a changing environment, it is essential to review water quality
modeling regarding the principles, application, analysis, and development of water quality models by various scholars and organizations. The current review will support the selection of a suitable model for diverse water quality problems (Kayode & Muthukrishna, 2018) and different water-bodies highlight available models and model uncertainties.

2. Significance of water quality modeling
Water quality management is an essential component of overall integrated water resources management (UNESCO, 2005). The output of the model for different pollution scenarios with water quality models is an imperative component of environmental impact assessment (Q. Wang et al., 2013). Sound water quality is very limited in the world and more care to water quality modeling is inevitable (Davies & Simonovic, 2011). Water quality models have been utilized to study and determine existing circumstances for assessing potential impacts because of human activities (Hicks & Peacock, 2005). Water quality models are decision support tools for simulating the fate of pollutants in water and assessing their related hazards (Chapra, 2008; Q. Wang et al., 2013). Water quality modeling is essential to develop a perfect conceptual model based on the existing information, understand the transport regime of pollutants, test hypotheses, quantify the dominant controlling processes, and certify with governing principles and observations. Also, Water quality modeling is vital to understand the history of pollutant transport and to determine time ranges in which a pollution incident might have started or contaminants have reached a targeted concentration in areas of concern (Zheng and Gordon, 1995).

The purpose of modeling is to solve problems of surface water pollution and to track water quality changes (Chapra, 1997; Holnicki et al., 2000; Stolarska & Skrzypski, 2012). Water quality models are applicable to analyze the existing phenomena, predict and compute effects of changes in the aquatic environment, set limits for pollutant discharge or load, identify the location of sources of pollution and causes of water quality deterioration on a given segment of the stream, and selecting an optimal approach for sustainable development (Holnicki et al., 2000; Chapra, 1997). Various water quality modeling methods with diverse commercial software packages have been used in different studies; for instance, QUAL2K and HEC-RAS were used for the Keelung River in Taiwan (Fan et al., 2009) and QUAL2EU was used in the Yamuna River, India (Hussein et al., 2015) to evaluate the quality of water.

3. Water quality modeling problems and model standardization
Water quality modeling is challenging due to some constraints including lack of experience of a model user (Shanahan et al., 1998), sufficient representative site selection and sample gaps, and lack of calibration, errors in data reporting (Chapman, 1996). In some cases, a number of models are location and parameter specific; they depend on waterbody type, do not conform to certain dimensional analysis, and may not have the ability to model point and nonpoint source pollution together. The uncertainty in water quality modeling commonly comes from numerous sources of errors: measurements of input and response uncertainty (Rode & Suhr, 2007), parametric uncertainty, and structural error due to the incapability of a specified model structure to reproduce the physical mechanisms (Montanari, 2004). In most developing countries, a uniform model standardization system has not been recognized (J. Q. Wang et al., 2004; Cao & Zhang, 2006) that limits extensive utilization of those models for ecological and water management as a result of the lack of benchmarks and comparisons between different modeling outcomes (Q. Wang et al., 2013). Several serious problems in catchment-scale water quality modeling have spatial variability, which commonly takes over the catchment behavior, proper selection of representative sites, and integration of nonlinear biogeochemistry (Rode et al., 2010). On the other hand, the model complexity, lack of data, and poor data quality are other limiting factors for water quality modeling.

To fruitfully apply respectable model system regulation, it is very essential for most developing countries to develop their model standardization. Model standardization favors a sound understanding of the accessibility, accuracies, methods of computation, calibration, and development of
various water quality models (Cao & Zhang, 2006; Politano et al., 2008). The modeling outputs are important and variable, and thus water quality models have to be more standardized, accessible, and consistent when they are applied to support programs to meet water quality standards and legal documents (Q. Wang et al., 2013). Water quality models could be structured and standardized through procedures described in recognized published research articles, workshops, or by setting up a resident workgroup, the formation of national model assessment indicators, and an authentication system (EPA (Environmental Protection Agency), 2003). Some developing countries need to standardize some widely utilized water quality models for effective environmental impact assessment. Standardization of water quality models will support environmental management agencies’ guarantee in the uniform application of water quality models for regulatory uses (Q. Wang et al., 2013).

4. Model classification and selection
Numerous commercial and open-source models have been applied to simulate complex water quality processes in diverse environmental conditions. Some of these models including MIKE21 (Chapman, 1996), HEC-RAS RAS (US Army Corps of Engineers, 2014, 1998), QUAL2K (Fang et al., 2008), WASP 6 (Artioli et al., 2005), QUASAR (Lees & Sincock, 2002; Whitehead et al., 1997), and SWAT (Grizzetti et al., 2003). Because of data, the existence of captures the core of the problem, the simplest reliable model is always chosen over complex models. An excessively complex model will have increases the computational time, cost, and leads to extra uncertainties if detailed data are not available (Zheng and Gordon, 1995). Kayode and Muthukrishna (2018) have assessed the AQUATOX, QUAL2E, WASP, CEQUAL-RIV1, MIKE11, SWAT, and SIMCAT models and have defined their capabilities and applications for different waterbodies. MIKE 11 and QUAL2E do not consider the denitrification process for the period of its operation. Besides, QUAL2E and SIMCAT cannot model variable flow conditions since the flow rate is expected to be steady state. SWAT has the capacity of simulating in-stream fate and transport of a wide variety of pollutants, and it can be coupled with an in-stream model to provide a good outcome.

4.1. Model selection
Water quality models can be selected based on different criteria such as model complexity, availability of data, type of waterbody, water quality simulation capabilities, easy accessibility of the program code source, and the existence of good certification of the model (Kayode & Muthukrishna, 2018). Also, the model applicability, cost, familiarity, and support are criteria used for selecting suitable water quality models. Many water quality models are not widely used and are no longer being updated to comprise the latest developments. For deciding the most suitable models, it is essential to assess the existing water quality models (Smith Warner International, 2005). Different water quality models are widely used around the world, which has advantages and limitations. Nevertheless, the model must be calibrated and validated for an acceptable outcome. The U.S. Environmental protection Agency (Grimsrud et al., 1976) has described the model selection process and criteria with four levels of selection phases for models. The selection process is intended to provide users guidance to select some levels of features they might require for the problem to be solved. The phases of the model selection processes are Phase I (model applicability test), Phase II (cost constraint test), Phase III (performance index rating; simplified), and Phase IV (performance index rating; advanced). The first two phases are the elimination of unsuitable models and the last two phases are the ranking of the remaining models. The exclusion of available models in phase I is essential to condense the assessment of models in the next phase.

In the first phase, the elimination of models is done based on the suitability of the model to the problem at hand (the type of waterbody, time variability, discretization, special features, constituents modeled, model input data, driving forces, and boundary factors). As per the constraints, those candidate models that do not meet the users’ requirements can be rejected. However, if the assessment shows that the model is possibly applicable, it might be preserved for further consideration in the next phase. If all the available nominated models are excluded in the first phase,
then the user must search either for a new model; reexamine the applicability constraints, or unrestraint effort requirements to use a water quality model for the design requirements. Phase II also is an eliminatory phase, in which the model is selected based on cost (data acquisition, mechanism model and workers costs, acquisition, and equipment requirements). The third phase (Phase III) is required to rank models based on weights related to the criteria from phases II and I. Phase IV is the last phase of the model selection process, and it needed for advanced ranking of models based on relevant processes including accuracy (numerical stability, model representation, and dispersion), the competence of available model certification, ease of modification, data input design, and output form and content (Grimsrud et al., 1976). Similarly, models can be selected with simple approaches (Marios et al., 2018). In general, before performing water quality simulation, suitable models should be selected. In order to select the type of water quality models required for different waterbodies, various factors should be considered, in particular inspecting the type of pollutant problem affecting the water system, determining the cause of water pollution, identify the best management practice solutions, the modeling objectives, and the available resources are essential. Also, identifying the project goal is essential when developing a water quality modeling tool through discussions with the stakeholders, regulating agencies, and technical personnel involved in the development (Kayode & Muthukrishna, 2018).

4.2. Model classification
Water quality models can be classified as physical (laboratory) and mathematical (analytical) models (Holniki et al., 2000; UNESCO, 2005). Besides, they can be categorized according to the complexity of computer simulation (1D, 2D, and 3D models), data requirements (extensive databases and minimum data requirements models), type of approach (physically based, conceptual and empirical), pollutant type (nutrients, sediment, and salts, etc.), area of application (catchment, groundwater, river system, lake, coastal waters, integrated), nature (deterministic or Stochastic), state analyzed (steady state or dynamic simulation), and spatial analysis (lumped, distributed) (Tsakiiris & Alexakis, 2012). The advantages, disadvantages, applicability, and assumptions for 1D, 2D, and 3D models are summarized in Table 1. On the other hand, based on the extent and spatial scales, some models are considered as operational, tactical, strategic, and directional models (Stolarska & Skrzypski, 2012). The SKM (2011) classification scheme has described categories for three types of water quality models such as catchment models (derive flows from the rainfall-runoff process and simulate related pollutant loads), in-stream models (simulate hydrodynamic behavior of flows and in-stream water quality processes), and ecological response models (simulate the ecosystem response to stressors, such as flow and water quality). Water quality models have been classified as steady state models (planning models: intended for long-term trends and routine monitoring), dynamic stochastic models (design: short-term dynamics continuous and long-term trends and routine monitoring tasks), and dynamic models (operational: which is required for short-term dynamics and continuous monitoring for operational management) (Whitehead, 2016). Water quality models can also be classified as a simulation model and optimization model (Chapra, 2008; Sharma & Kansal, 2013). The simulation model defines and represents changes in water quality in some mathematical form. However, optimization models are commonly applied to find the smallest number of alternative data before doing the model simulation. The models are typically classified with respect to model complexity, type of receiving water, and water quality parameters to which the model can be predicted. When the model is more complex, it is highly difficult and expensive for application to a given condition because of the data requirements (World Bank Group, 1998).

The major principle governing model preparation is the law of conservation of energy, momentum, and conservation of mass (Chapra, 2008). There are different formulas that can be followed to develop a water quality model and each application depends on the different types of parameters to be modeled (Kayode & Muthukrishna, 2018). Several water quality models (i.e. Agricultural Non-Point Source, AGWA, ANSWERS-2000, APEX, AQUATOX, BASINS, EFDC, EPD-RIV1, GLEAMS/CREAMS, HSPF, KINEROS2, LSPC, MIKE SHE, NLEAP, PRMS, QUAL2E, QUAL2K, SWAT, SWMM, WAM, WARMF, WASP7, WCS, and AquaChem) have been used to analyze water quality around the
Table 1. Features of 1D, 2D, and 3D water quality models (Balcerzak, 2000)

| Model                  | Advantages                                                                 | Limitations                                                                 | Applicability & assumptions                                                                                     |
|-----------------------|-----------------------------------------------------------------------------|----------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------|
| One-dimensional (1D) models | • Used quickly for lake and reservoir water without pre-calibration and with a small available database of measurements  
• The simplest and most commonly used models in the analysis of river water quality. | • Do not describe the complex chemical, physical and biological reactions in water  
• Are not designed to estimate the variation of concentration with time. | • Assume significant changes in determining the water quality parameters arising only along with the longitudinal profile of the watercourse.  
• Valid in long creeks, rivers, streams, and narrow channels (Lubo, 2018).  
• Typically applicable to rivers, and for estuaries and lakes with large length-width ratios. |
| Two-dimensional (2D) models | • Can be significant to examine water quality at various depths,  
• The study of individual parameters can be made at different time intervals (hour, day, week, month, and year). | • The models need more data and more skilled analytical users than one-dimensional models,  
• Requires careful calibration and is sensitive to changes in many parameters of water quality. | • Assumes significant changes in water quality occur both in along and the longitudinal profile of the watercourse  
• Applicable to simulate water quality mostly in reservoirs, deep rivers, and lakes. |
| Three-dimensional (3D) models | • Required to estimate the spatial distribution of concentrations of simulated water quality parameters | • Need vast amounts of data and more skilled analytical experts  
• Due to the high complexity of the examined issues, the models are rarely used. | • Applicable to examine changes in water quality in reservoirs, dams, deep rivers, lakes, estuaries, and sea bays. |

... world. Also, TOMCAT, SisBaHIA, SIMCAT, QUAL2KW, MOHID water system (MARETEC (Marine and Environmental Technology Research Center), 2018), MIKE HYDRO River/MIKE2016 (DHI (Danish Hydraulic Institute), 2016), and CE-QUAL-W2 version 4.1 (US Army Corps of Engineers, 2018) have been applied in various countries to simulate water quality in various waterbodies.

5. Parameters and data for water quality modeling

Water quality modeling needs information and data to predict existing and future water quality situations in the ecosystem as a function of the baseline conditions and pollutant loads (Grimsrud et al., 1976). To model water quality, several parameters and data are required as input (Table 2). The input data needed to investigate water quality characteristics can be found from the literature, organizations, measured directly in the field, or determined through model calibration (Liu, 2018). The availability and accuracy of data is a great concern in the development and use of models for water quality analysis and management (Loucks & Van Beek, 2017). The amount and quality of available input data will govern the complexity of the model to be applied for simulating water quality parameters (Kayode & Muthukrishna, 2018). The necessities of data for water quality models intensify with model complexity and range of applications (Rode et al., 2010). Existing input data and information that would be relevant for water quality modeling include initial and boundary concentrations, source of pollutants, baseline conditions, flow characteristics, the geometry of the modeled waterbodies (river, lake, coastal, ponds, reservoirs, etc.). Moreover, the initial
Table 2. Characteristics of commonly applied water quality models

| Models | Type | Application and Components | Weakness |
|--------|------|-----------------------------|----------|
| BASINS |      | • Applicable for water quality simulation in the watershed level (Q. Wang et al., 2013 and USEPA (U. S. Environmental Protection Agency), 2019)  
        |      | • It is a multiuse environmental analysis system  
        |      | • Simulates the effects of integrated point and non-point source pollution (Q. Wang et al., 2013). | • The models require large amounts of input data |
| MIKE   | 1D, 2D, and 3D models | • Applicable to rivers, tidal wetlands, and estuaries (Q. Wang et al., 2013).  
        |      | • MIKE-3: helps to model water quality in any surface water system including flow, transport and metabolism of nutrients, heavy metals, the phenomenon of drying troughs, floods, and the processes occurring in bottom sediment (Chapman, 1996, Stolarska & Skrzypski, 2012).  
        |      | • MIKE 11: Suitable for simulating water quality, flows and sediment transport in rivers, estuaries, irrigation systems, and other waterbodies, analyses the influence of water on the environment, flood phenomena, and runoff rainwater estimation (DHI (Danish Hydraulic Institute), 1993 and Stolarska & Skrzypski, 2012). | • It is challenging to set up without the support of an expert.  
        |      | • Requires much information/data for model operation and calibration (Kayode & Muthukrishna, 2018).  
        |      | • Assumes channel bed slope is negligible  
        |      | • Does not consider wind effects (Razdar et al., 2011).  
        |      | • The 2D effects (i.e. cross-channel momentum) are not considered  
        |      | • Does not account for urban drainage (World Bank, 2016). | Note: All limitations are for the MIKE 11 2D model |

(Continued)
| Models          | Type                          | Application and Components                                                                                     | Weakness                                                                                                                                                                                                 |
|-----------------|-------------------------------|----------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Streeter-Phelps | 1D steady state models        | • Emphasizes on oxygen balance, and first-order decay of BOD (Q. Wang et al., 2013).                           | • The model is based on the assumptions that a single BOD input is distributed evenly at a cross-section of a stream/river and it moves as plug flow without mixing in the river (Lin & Lee, 2001),   |
|                 |                               | • One DO sink (carbonaceous BOD, CBOD) and one DO source (reaeration) only are considered in the standard (Schnoor, 1986). These overviews will increase errors in the model. |
| QUAL            | 1D steady state/dynamic model. | • Applicable to dendritic rivers and non-point source pollution (Q. Wang et al., 2013).                        | • Because of its steady-state assumption, it is not capable to simulate a river, for which temporal flow variation affects key water quality conditions.                                                 |
|                 |                               | • QUAL2E: Flexible, accurate, and usually applied to track the fate and transport of pollutants in medium-sized rivers (Ning et al., 2000; Pelletier et al., 2006; Zhu et al., 2015). Suitable to simulate contaminants in well-mixed streams and rivers (Brown & Barmwell, 1987). Usually applied to analyze the effect of point source discharge changes on water quality, including the impacts of nutrients on algal concentration and DO (World Bank Group, 1998). Vital to the analysis of the spatial and temporal variations of nutrients, T, BOD and DO concentrations in the water column (Kannel et al., 2011). |
|                 |                               | • Not considered suspended sediment movement, macrophytes, and denitrification processes.                     | • In model development, the reaches and computational elements must not be more than 25 and 20 per reach or a total of 250, respectively.                                                                  |
|                 |                               | • The headwater and junction elements would have a maximum value of seven (Kayode & Muthukrishna, 2018).        |                                                                                                                                                                                                         |

(Continued)
| Models      | Type                  | Application and Components                                                                                                                                                                                                 | Weakness                                                                                                                                                 |
|------------|-----------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------|
| AQUATOX    | Ecosystem model       | • Suited to foresee the fate of nutrients, sediment, and organic chemicals in waterbodies,                                                                                                                                   | • Is not capable to model metals and impossible to couple with hydrodynamic models,                                                                       |
|            |                       | • Applicable to characterize a range of aquatic ecosystems comprising vertically stratified lakes, reservoirs, and ponds, estuaries, streams, and rivers (Shoemaker et al., 2005 and Stolarska & Skrzypski, 2012). | • While simulating the change in nutrients, chemicals, and sediment concentrations, it supposed a unit volume of water in the waterbody,               |
|            |                       | • Forecast the direct and indirect effects on the resident organisms,                                                                                                                                                       | • The internal nutrients are not represented in algal bioenergetics (Kayode & Muthukrishna, 2018).                                                            |
|            |                       | • Analyze the transfer of biomass and chemicals from one section of the ecosystem to another.                                                                                                                               |                                                                                                                                                          |
|            |                       | • Aids to recognize the cause and effect dealings between the chemical water quality, physical environment, and aquatic life.                                                                                                 |                                                                                                                                                          |
|            |                       | • Examines multiple environmental stressors and their impacts on aquatic animals and plants (macrophyte, invertebrate, algae, and fish groups) (Park & Clough, 2004, Bingli et al., 2008, Stolarska & Skrzypski, 2012). |                                                                                                                                                          |
| Models       | Type      | Application and Components                                                                                                                                                                                                 | Weakness                                                                                                                                                                                                 |
|--------------|-----------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| CE-QUAL-RIV1 | 1D model  | • Comprises hydrodynamic (RIV1H) & water quality code (RIV1Q).  
• Used to simulate 1D hydraulic and water quality variations in streams and rivers with highly unsteady flows and steady flow conditions.  
• Suitable where lateral and vertical variations are small  
• Determines longitudinal variations in hydraulic and quality characteristics.  
• RIV1Q simulates the effects of macrophytes and analyzes the variations of constituents (i.e. CBOD, temperature, organic nitrogen, ammonia nitrogen, nitrate (V) + nitrate (III) nitrogen, dissolved oxygen, organic phosphorus, dissolved phosphates, algae, dissolved iron, dissolved manganese, and coliform bacteria) (Stolarska & Skrzypski, 2012). | • Less commonly applied than WQAM, QUAL2E, and WASP (World Bank Group, 2012).  
• Not suited for two and three-dimensional model  
• Has inadequate eutrophication kinetics in its processes and requires extensive experiment by users.  
• Not suitable to simulate sediment transport processes in the river (Kayode & Muthukrishna, 2018). |
| Models    | Type   | Application and Components                                                                                       | Weakness                                                                                                                                                                                                 |
|-----------|--------|---------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| CE-QUAL-W2| 2D model | • Commonly suitable in stratified surface water systems (i.e. rivers, reservoirs, lakes, and estuaries).       | • The equations are written in the conservative form via Boussinesq and hydrostatic estimates.                                                                                                             |
|           |        | • Is both a hydrodynamic and water quality model in 2D (longitudinal-vertical).                                | • Vertical momentum is not considered and might give rise to imprecise outcomes, where substantial acceleration is present.                                                                                   |
|           |        | • Simulates horizontal and vertical velocities, water levels, temperature, and 21 other water quality parameters (Stolarska & Skrzypski, 2012). | • Its application is a complex and time-consuming task (Cole & Wells, 2013).                                                                                                                              |
|           |        | • Well-mixed in the lateral direction and hydrostatic hypothesis for the vertical momentum equation             | • Well-mixed in the lateral direction and hydrostatic hypothesis for the vertical momentum equation                                                                                                        |
|           |        | • The main equations are laterally and layer averaged,                                                        | • Due to the complications of the model, data to drive the model can be a prime restraint,                                                                                                                 |
|           |        | • Due to the complications of the model, data to drive the model can be a prime restraint,                     | • Computational and storage burden on a computer when making continuing simulations,                                                                                                                     |
|           |        | • Accessibility of input data is the limiting issue for the application or misuse of the model (Cole & Wells, 2018). | • Accessibility of input data is the limiting issue for the application or misuse of the model (Cole & Wells, 2018).                                                                                         |
| Models | Type | Application and Components | Weakness |
|--------|------|----------------------------|----------|
| DUFLOW | 1D unsteady state model | • Applicable to simulate 1D unsteady flow and water quality in open water systems <br>• Analysis of both water flow and quality <br>• Applicable for modeling the transport of substances through the free movement of surface flow (Stolarska & Skrzypski, 2012). | • Data inputs and outputs are only in metric units <br>• Limited to simulate about 250 channel sections and structures <br>• Dimensional inputs are restricted to ±0.01 m and ±0.01 m³/s <br>• Time steps are limited to one minute increments. <br>• The number of boundary conditions multiplied by the number of time steps may not above 50,000 <br>• Cross-sections might be defined up to 15 depth-width pairs (Clemmens et al., 1993). |
| HSPF | | • Applicable for natural and artificial systems to simulate hydrology and water quality for pervious and impervious land surfaces, streams, and well-mixed impoundments <br>• It helps to estimate the movement of pollutants through watersheds with mathematical models (Stolarska & Skrzypski, 2012). | • The model is not sensitive to spatial variation <br>• Restricted to well-mixed rivers, reservoirs, and one-dimensional flow <br>• Difficult for solving complex situations <br>• Needs a high level of skills for application <br>• Numerous physical processes are based on empirical relations, not mechanisms <br>• A large number of elements are needed and challenging to assure their accuracy, thus, extensive calibration is required <br>• The model accuracy is dependent on meteorological factors (LJZ, C. Liu & Li, 2012). |
Table 2. (Continued)

| Models | Type | Application and Components | Weakness |
|--------|------|-----------------------------|----------|
| TELEMAC | 2D and 3D model | • Suitable to analyze 2D and 3D flow, water quality, and transport of contaminants  
• The model is widely used for water quality modeling and commercially accessible (Stolarska & Skrzypski, 2012)  
• Applied widely in the world, free tools for pre- and post-processing (World Bank, 2016). | • TELEMAC 2D: Challenging to determine the friction factor  
• Use command lines to run software  
• Cannot account for groundwater or coupling with urban drainage flood systems  
• Needs at least three programs to generate results (World Bank, 2016). |
| WASP | 1D, 2D and 3D model | • Suitable to simulate 1D, 2D, and 3D water quality of rivers, lakes, estuaries, streams, ponds, coastal water, and reservoirs (Stolarska & Skrzypski, 2012; Q. Wang et al., 2013).  
• Supports to decision-makers for allowing better pollution management solutions with interpreting and predicting water quality responses to artificial and natural phenomena (USEPA, U.S. Environmental Protection Agency), 2019).  
• Flexible and requires high levels of data and expertise (World Bank Group, 1998).  
• Can universally to model the transport and contaminant fate in surface waterbodies.  
• Vital to the analysis of some water quality characteristics including conventional pollutants (N, P, bacterial contamination, T, BOD, sediment oxygen demand), nutrients, metals, and toxic chemical movement (Stolarska & Skrzypski, 2012). | • Model calibration and application to predict water quality parameters necessitate is time-consuming for the user.  
• Needs far-reaching training for users due to its complexity.  
• Cannot analyze periphyton and microalgae (Kayode & Muthukrishna, 2018).  
• Cannot predict the results of control structure (Nasser et al., 2017).  
• Cannot run in batch mode,  
• Does not handle variable processes (i.e. mixing zone processes, non-aqueous phase liquids, segment drying, and metals speciation),  
• Large external hydrodynamic file (USEPA, 2005).  
• Requires a large amount of data for calibration and verification,  
• Does not handle mixing zones or near field effects, sinkable/floatable materials,  
• Cannot successfully simulate suspended solids loading in the river (Kannel et al., 2011). |
| Models | Type | Application and Components | Weakness |
|--------|------|----------------------------|----------|
| HEC-5Q | 1D model | • Mostly applicable to analyze water quality and flow in reservoirs and related downstream river reaches.  
• Executes reservoir operation simulations (i.e., regulating outflows in gates and turbines) and vertical temperature gradients (World Bank Group, 2012). | • Only simulate one dimensional and cannot solve for the velocity field in a stratified reservoir system.  
• Any point source inputs to the reservoir section are spread over the entire longitudinal distribution of the reservoir (US Army Corps of Engineers, 1986). |
| EFDC  | 1D, 2D and 3D model | • Applicable to analysis of water quality in lakes, estuaries, rivers, wetlands, and reservoirs.  
• Provides high accuracy for numerical simulation (Q. Wang et al., 2013, USEPA (U. S. Environmental Protection Agency), 1997, and USEPA (United State Environmental Protection Agency), 1999).  
• Required for recognizing the degree of salinity intrusion effects at varied river flow rates (Liangliang & Daoliang, 2014). | • Cannot predict internal waves (Liu et al., 2009). |
flow condition of the water system, inflow water quality concentrations, waterbody type, time, kinetic parameters, calibration, bathymetric, meteorological and flow data (Smith Warner Cole & Wells, 2018; International, 2005; Kayode & Muthukrishna, 2018), the water level at sampling, major aquifer type, aquifer map, flow duration statistics, lake and piezometric levels between sampling are required (Chapman, 1996). Nevertheless, the required input data used for water quality modeling depends on the expected objectives, waterbodies to be investigated, models applied for simulation, and data availability and quality.

The water quality of lakes, rivers, estuarine, streams, ponds, reservoirs, etc. can be characterized by various physical, chemical, and biological parameters including temperature, PH, the concentration of dissolved minerals, turbidity, salinity, total dissolved solids (TDS), Na, Ca, Mg, K, bicarbonates, suspended solids, nitrate, BOD, DO, chloride, the concentration of nutrients, bacteria/coliforms, suspended sediment, nutrients, algae concentration, sulfates, heavy metals, CBOD and other constituents. These constituents can be analyzed with models; however, according to Liu (2018), the modeling outcomes of several parameter values shall be compared with the observed data. The model parameter values that realize the best match between measured and predicted constituents concentrations can be selected for advanced modeling runs.

6. Conclusions
Water pollution is one of the worldwide challenges facing both developed and developing countries. The cities mainly have the highest pollution rates because of inadequate waste management systems and urban runoff pollution. Water pollution problems are usually due to economic growth and have an impact on both the environment and human health. The causes of water contamination include soil erosion, deforestation, habitat destruction, improper waste management, overgrazing, lack of awareness in management, shortage of decision support tools, and an inadequate organized database system. In the current situation, the ecosystems require a sustainable management solution for improved socioeconomic development. For a better understanding of how the environment and water systems are polluted and to make fruitful decisions and directions, concrete knowledge of water quality modeling is needed. This review described an overview of water quality modeling emphasizing modeling application, commonly used water quality models, and model selection, application, and limitations for different waterbodies. Water quality modeling is a significant tool that helps to water managers and policymakers applying for unified water and environmental management. Scholars, policymakers, and designers through rules and regulations significantly require the practice and application of water quality modeling. Models have been applied to simulate various water quality characteristics and evaluate water quality changes as a result of wastewater discharge to the ecosystem. Various water quality models have been developed and applied in some countries to study the quality of water in various waterbodies with 1D, 2D, and 3D simulations. Different types of water quality models including some extensions of model software have been developed for predicting in different topography, waterbodies, and pollutants at different space and time scales. Water quality model studies are very important for providing solutions and directions towards sustainable planning and management of waterbodies.

One of the requirements for water quality modeling is to determine its suitability for the intended use. However, water quality modeling has several limitations. Some models are applicable for specific waterbodies, simulate selected water quality parameters, have uncertainties, require skilled model users, are not commercially available, and require a huge amount of data. On the other hand, various water quality models can be integrated with other hydrodynamic and hydrological models. Every model has its particular sole purpose and simulation features. Many countries are working to develop guidelines on water and environmental quality investigation and management, providing regulated models for water quality prediction. Consequently, it is advisable to standardize water quality models for all countries. When developing water quality modeling and selecting suitable models for a waterbody, it is vital to make the selection through discussions with stakeholders, based on modeling objectives, time, and available resources (data, cost, etc.).
However, to meet the accuracy of the study objectives, the user should know the assumptions and model uncertainties.

**Funding**

The author received no direct funding for this research.

**Author details**

Mamuye Tebebal Ejigu1

E-mail: bic.ma12@gmail.com

ORCID ID: http://orcid.org/0000-0002-5793-6913

1 College of Architecture and Civil Engineering, Addis Ababa Science and Technology University, Addis Ababa, Ethiopia.

**Citation information**

Cite this article as: Overview of water quality modeling, Mamuye Tebebal Ejigu, Cogent Engineering (2021), 8: 1891711.

**References**

Ambroso, R. B., Wool, T. A. J., & Barnwell, T. O., Jr. (2009). Development of water quality modeling in the United States. Environmental Engineering Research, 14(4), 200–210. https://doi.org/10.4491/eer.2009.14.4.200

Artioli, Y., Bendoricchio, G., & Palmeri, L. (2005). Defining and modeling the coastal zone affected by the Po River. Ecological Modeling, 184(1), 55–68. Retrieved September 14, 2019, from https://doi.org/10.1016/j.ecolmodel.2004.11.008

Bai, J. H., Cui, B. S., & Chen, B. (2011). Spatial distribution and ecological risk assessment of heavy metals in surface sediments from a typical plateau lake wetland, China. Ecological Modelling, 222(2), 301–306. https://doi.org/10.1016/j.ecolmodel.2009.12.002

Balcerekz, W. (2000). Application of selected mathematic models to evaluate changes in water quality. International Conference on Water Supply, Water Quality, and Protection. Krakow.

Beck, M. B. (1987). Water quality modeling: A review of the analysis of uncertainty. IAASA research report, IIASA, Laxenburg, Austria: RR-88-003. Reprinted from Water Resources Research, 23(8).

Bingli, L., Huang, S., Min, Q., Tianyun, L., & Zijian, W. (2008). Prediction of the environmental fate and aquatic ecological impact of nitrobenzene in the Songhua River using the modified AQUATOX model. Journal of Environmental Sciences, 20(7), 769–777. https://doi.org/10.1016/S1001-0742(08)62125-7

Brown, L. C., & Barnwell, T. O. (1987). The enhanced stream water quality models QUAL2E and QUAL2E-UNCAS: Documentation and user manual, US environmental protection agency. Office of Research and Development, Environmental Research Laboratory.

Cao, X. J., & Zhang, H. (2006). Commentary on a study of surface water quality model. Journal of Water Resources and Architectural Engineering, 4(1), 18–21.

Carl, F. C., Barry, W. B., Allen, M. T., & Mark, S. D. (2000). Water quality model of Florida bay. 277.

Chapman, D. V. (Ed.). (1996). Water quality assessments: A guide to the use of biota, sediments, and water in environmental monitoring-second edition. CRC Press. Retrieved September 02, 2019, from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC10010742/08/62125-7

Chapra, S. C. (1997). Surface water quality modeling. McGraw-Hill Companies, Inc.

Chapra, S. C. (2008). Surface water quality modeling. McGraw-Hill Companies, Inc.

Clemmons, A. J., Holly, F. M., Jr, & Schuurmans, W., & . (1993). Description and evaluation of program: DUFLOW. Journal of Irrigation and Drainage Engineering, 119(6), 724. https://doi.org/10.1061/(ASCE)0733-9437(1993)119:6(724)

Cole, T. M., & Wells, S. A. (2013). CE-QUAL-W2: A two-dimensional laterally averaged, hydrodynamic and water quality model, version 4.1 user manual. Portland State University, Portland, OR. Retrieved September 14, 2019, from http://www.ce.pdx.edu/w2/w2manual41_rev8.pdf.

Cole, T. M., & Wells, S. A. (2018). CE-QUAL-W2: A two-dimensional laterally averaged, hydrodynamic and water quality model, version 4.1 user manual. Portland State University.

Conley, D. J., Paerl, H. W., Howarth, R. W., Boesch, D. F., Seitzinger, S. P., Havens, K. E., Lancelot, C., & Likens, G. E. (2009). Controlling eutrophication: Nitrogen and phosphorus. Science, 324(5917), 1014–1015. https://doi.org/10.1126/science.1167755

Cox, B. (2003). A review of currently available in-stream water quality models and their applicability for simulating dissolved oxygen in lowland rivers. Science of the Total Environment, 314, 335–377. https://doi.org/10.1016/S0048-9697(03)00063-9

Davies, E. G. R., & Simonovic, S. P. (2011). Global water resources modeling with an integrated model of the social-economic-environmental system. Advances in Water Resources, 34(6), 684–700. https://doi.org/10.1016/j.adwat.2011.02.010

DHI (Danish Hydraulic Institute). (1993). MIKE11, user guide & reference manual, Danish Hydraulics Institute. Danish Hydraulic Institute.

DHI (Danish Hydraulic Institute). (1996). MIKE 3 eutrophication module, user guide and reference manual, release 2. 7. Danish Hydraulic Institute.

DHI (Danish Hydraulic Institute). (1996). MIKE21: User guide and reference manual.

DHI (Danish Hydraulic Institute). (2016). MIKE HYDRO River/MIKE 2016. Danish Hydraulic Institute. Retrieved August 16, 2019, from https://www.mikepoweredbydhi.com/products/mike-hydro-river.

EEPA (Ethiopia Environmental Protection Agency). (2003). Brewery effluent standards. Addis Ababa.

EIC (Environmental International Consultant). (2009). Environmental impact assessment for Jabel Ali power & desalination station. Retrieved August 14, 2019, from http://www.ogportal.de/pdf/nachhaltigkeit/ea/jabel_dubai_kraftwerk.pdf.

EPA (Environmental Protection Agency). (2003). Manual of industrial water supply systems. Supper intendent of Documents, US. Government Printing Office. 155 EPA (Environmental Protection Agency). (2003). Revision to the guideline on air quality models. Adoption of a Preferred Long-Range Transport Model and Other Revisions. 87 (3), 1840–1842. Retrieved 06, 2019, from https://www.govinfo.gov/content/pkg/FR-2003-04-15/pdf/03-8542.pdf

Fan, C., Ko, C., & Wang, W. S. (2009). An innovative modeling approach using Qual2k and HEC-RAS integration to assess the impact of the tidal effect on river water quality simulation. Journal of Environmental Management, 90(5), 1824–1832. https://doi.org/10.1016/j.jenvman.2008.11.011

Fang, X., Zhang, J., Chen, Y., & Xu, X. (2008). QUAL2K model used in the water quality assessment of Qiantang River, China. Water Environment Research, 80(11), 2125–2133.

FAO. (1973). Organic materials as fertilizers. FAO Bulletin No 27.

Page 18 of 21
and rivers using a genetic algorithm for calibration. Environmental Modelling and Software, 21(3), 419–425. https://doi.org/10.1016/j.envsoft.2005.07.002

Polito, M., Haque, M. M., & Weber, L. J. (2008). A numerical study of the temperature dynamics at McNary Dam. Ecological Modelling, 212(3–4), 408–421. https://doi.org/10.1016/j.ecolmodel.2007.10.040

Rouah, W., Henze, M., Koncsos, L., Reichert, P., Shanahan, P., Somlyody, L., & Vanrolleghem, P. (1998). River water quality modeling. I: State of the art. IAQW Biennial International Conference, Vancouver, British Columbia, Canada.

Razdar, B., Mohammadi, K., Samanic, J. M. V., & Pirooz, B. (2011). Determining the best water quality model for the reservoir in North of Iran, Case study in Pakistan River. Computational Methods in Civil Engineering, 2 (1), 105–111. Retrieved September 10, 2019, from https://journals.guilan.ac.ir/article_888_70e9f4e6156db66e5a0234538dbb3.pdf

Rode, M., Arhonditis, G., Balin, D., Kebede, T., Krysanova, V., Van Grien, A., & Van Der Zee, S. E. (2010). New challenges in integrated water quality modelling. Hydrological Processes, 24(24), 3447–3461. https://doi.org/10.1002/hyp.7766

Rode, M., & Suhr, U. (2007). Uncertainties in selected river water quality data. Hydrology and Earth System Sciences, 11(2), 863–874. https://doi.org/10.5194/hess-11-863-2007

Schnoor, J. (1986). Environmental modeling, fate, and transport of pollutants in water, air, and soil. Wiley Interscience.

Shanahan, P., Henze, M., Koncsos, L., Rouah, W., Reichert, P., Somlyody, L., & Vanrolleghem, P. (1998). River water quality modeling: II. Problems of the Art. IAQW Biennial International Conference, Vancouver, British Columbia, Canada.

Sharmar, D., & Kansal, A. (2013). Assessment of river water quality models: A review. Reviews in Environmental Science and Biotechnology, 12(3), 285–311. https://doi.org/10.1007/s11157-012-9285-8

Shoemaker, L., Dai, T., Koenig, J., & Huntsh, M. (2005). TMOD model evaluation and research needs. National Risk Management Research Laboratory, US Environmental Protection Agency.

SKM, (2013). Development of water quality modeling framework for the MDB Phase 1 Scoping Study. Sinclair Knight Merz, report prepared for Murray-Darling Basin Authority.

Solomon, K. (2017). Ethiopia’s Lake Tana is losing the fight to water hyacinth. The University of California.

Stolarska, A. Z., & Skrzypski, J. (2011). Review of mathematical modeling of water quality. Ecol Chem Eng S, 19 (2). https://doi.org/10.2478/v10216-011-0015-x

Stram, D. L., Kincaid, C., & Campbell, D. E. (2005). Water quality modeling in the Rio Chone Estuary. Journal of Coastal Research, 21(4), 797–810. https://doi.org/10.2112/011-NIS.1

Sundarambal, P., & Pavel, T. (2014). Water quality modeling in the East Johor and Singapore Straits. Open Journal of Water Pollution and Treatment, 15.

Teshaole, B., Lee, C., & Girma, Z. (2002). Development initiatives and challenges for sustainable resource management and livelihood in the Lake Tana Region of Northern Ethiopia. Journal of Technology Management Sustainable Develop, 1(2), 111–124.

Tri, D. Q., Linh, N. T. M., Thai, T. H., & Kandasamy, J. (2018). Application of 1D-2D coupled modeling in water quality assessment: A case study in Ca Mau Peninsula, Vietnam. Physics and Chemistry of the Earth, Parts A/B/C.

Tsakiris, G., & Alexakis, D. (2012). Water quality models: An overview. European Water, 37, 33–46.

UNEP (United Nations Environment Programme). (2012). Fresh Water for the future; a synopsis of UNEP activities in water. UNEP.

UNESCO. (2005). Water resources systems planning and management. Retrieved August 5, 2019, from https://ecommons.cornell.edu/bitstream/handle/1813/2804/12_chapter12.pdf?sequence=8&isAllowed=y

US Army Corps of Engineers. (1986). HEC-5 simulation of flood control and conservation systems, CPD-SQ. Hydrologic Engineering Center.

US Army Corps of Engineers. (1998). HEC-RAS; River analysis system hydraulic reference manual. Hydrologic Engineering Center.

US Army Corps of Engineers. (2014). Hydrologic engineering centers river analysis system (HEC-RAS). Retrieved August 28, 2019, from http://www.hec.usace.army.mil/software/hec-ras.

US Army Corps of Engineers. (2018). CE-QUAL-W2 version 4.1. Portland State University. Retrieved August 28, 2019, from https://www.ce.pdx.edu/w2.

USEPA (U. S. Environmental Protection Agency). (1997). Compendium of tools for watershed assessment and TMDL development. Technical Report, EPA 841-B-97-006, U.S. U.S.EPA, Washington, DC, USA.

USEPA (U. S. Environmental Protection Agency). (2019). BASINS 4.5 modeling framework. National Exposure Research Laboratory, RTP. Retrieved August 26, 2019, from https://www.epa.gov/ceam/water-quality-analysis-simulation-program-wasp.

Victoria, (2019). Water quality modeling. IWA Publishing. Retrieved August 06, 2019, from https://www.environmental-expert.com/articles/water-quality-modelling-288501.

Wang, J. Q., Zhong, Z., & Wu, J. (2004). Steam water quality models and its development trend. Journal of Anhui Normal University (Natural Science), 27(3), 243–247.

Wang, Q., Li, S., Jia, P., Qi, C., & Ding, F. (2013). A review of surface water quality models. The Scientific World Journal, 231768. Retrieved August 14, 2019, from https://doi.org/10.1155/2013/231768

Wang, Q. G., Dai, W. N., Zhao, X. H., Ding, F., Li, S. B., & Zhao, Y. (2009). Numerical model of thermal discharge from Laoibin power plant based on Mike 21. Research of Environmental Sciences, 22(3), 332–336.

Whitehead, P. G. (2016). Water Quality Modeling. Wiley StatsRef. Statistics Reference Online, Retrieved August 22, 2019, from 1–21.

Whitehead, P. G., Williams, R. J., & Lewis, D. R. (1997). Quality simulation along river systems (QUASAR): Model theory and development. Science of the Total Environment, 194–195, 194–195, 447–456. https://doi.org/10.1016/S0048-9697(96)05382-X
World Bank (2016) Review of water resource models. Retrieved August 22, 2019, from http://www.appследigital.com/ModelPrimer/index.html.

World Bank Group. (1999) Water quality models, pollution prevention, and abatement handbook. Retrieved August 5, 2019, from http://web.worldbank.org/archive/webworldbank/21st-century/WorldBankGroup-WaterQualityModels.pdf.

World Bank Group. (2012). Water quality models. World Bank.

Yong, L., Mei, K., Liu, X., Wu, L., Zhang, M., Xu, J., & Wang, F. (2013). Spatial distribution and source apportionment of water pollution in different administrative zones of Wen-Rui-Tang (WRT) river watershed, China. Environmental Science and Pollution Research, 20(8), 5341-5352. https://doi.org/10.1007/s11356-013-1536-x

Yong, X. E., Wu, X., Hao, H. L., & He, Z. L. (2008). Mechanisms and assessment of water eutrophication. Journal of Zhejiang University Science B, 9(3), 197–209. https://doi.org/10.1631/jzus. B0710626

Yitaferu, B. (2007). Land degradation and options for sustainable land management in the Lake Tana Basin (LTB), Amhara Region, Ethiopia. Ph.D. thesis, University of Bern.

Yuceer, M., & Coskun, M. A. (2016). Modeling water quality in rivers: A case study of Beylerdhesi River in Turkey. Applied Ecology and Environmental Research, 14 (1), 383-395. Retrieved August 14, 2019, from http://www.aloki.hu.

Zheng, C., & Gordon, B. (1995). Applied contaminant transport modelling. Van Nostrand Reinhold, New York.

Zhenhao, Y., & Dongli, S. (2013). Water quality modeling of the Ara canal, using EFDC-WASP model in Series. Journal of Korean Society of Environmental Engineers, 35(2), 101-108. https://doi.org/10.4491/KSEE.2013.35.2.101

Zhu, W., Niu, Q., Zhang, Y., Ye, R., Qian, X., & Qian, Y. (2015). Application of QUAL2K model to assess ecological purification technology for a polluted river. The International Journal of Environmental Research and Public Health, 12(2), 2215–2229. https://doi.org/10.3390/ijerph12022215

© 2021 The Author(s). This open access article is distributed under a Creative Commons Attribution (CC-BY) 4.0 license.

You are free to:
Share — copy and redistribute the material in any medium or format.
Adapt — remix, transform, and build upon the material for any purpose, even commercially.

The licensor cannot revoke these freedoms as long as you follow the license terms.

Under the following terms:
Attribution — You must give appropriate credit, provide a link to the license, and indicate if changes were made.
No additional restrictions

Submit your manuscript to a Cogent OA journal at www.CogentOA.com