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Assessment of Some Existing Water Quality Models

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ABSTRACT

One of the fundamental components of the environment which determine the existence of life on earth is the availability of freshwater for the use of humans and aquatic animals. However, increase in anthropogenic activities around the world have led to continuous degradation of ecosystems, which resulted into eutrophication of water bodies. Consequently, the quality of freshwater is being declined and the available water resources are getting depleted. Water quality models (WQM) are important tools used to maintain and monitor the quality of freshwater in various water bodies. This paper reviews some of the major water quality models used for different water bodies, which include AQUATOX, QUAL2E, WASP, CEQUALRIV1, MIKE11, SWAT and SIMCAT. The WQMs in the review are described based on their development, intended use, model strength, application and limitations. The selection of appropriate model and application to a specific water body is a critical task for water quality researchers and policy makers. This would ensure the availability of portable water for use. Hence, the review will help to choose appropriate water quality modelling tools for the different water quality problems.

INTRODUCTION

Streams are essential areas of the environment that serve as a source of water for human consumption and abode for aquatic animals. Industrialization, urbanization and agricultural practices discharge enormous quantity of organic and inorganic pollutants into water bodies. These result in the scarcity of quality water for the proper functioning of ecosystems (Yang et al. 2013, Kumarasamy 2015). The pollution of various water bodies is increasing due to the discharge of different pollutants, which can be grouped into conservative and non-conservative by their nature. On account of these various pollutants entering the water bodies with an increase in concentration, it is essential to make the streams safe from any form of pollutants. The increase in the rate of nutrient pollutants discharge into water bodies has resulted in eutrophication process which led to growth of algae and reduction of the dissolved oxygen (DO) (Yang et al. 2008, Conley et al. 2009). Stream water deterioration has been one of the most serious ecological threats faced by our environment. The decrease in the concentration of dissolved oxygen in the water column has resulted in major damage to the freshwater quality and reduction in the population of the aquatic animals in water bodies (Cox 2003, Seibel 2011).

Streams act as a carrier of discharged pollutants and disperse within the water bodies due to combined effects of diffusion and advection process (Jaiswal et al. 2011). Adequate assessment of dissolved oxygen and nutrients in the stream is essential for preserving the ecosystem's integrity and regulating the pollutants disposed into the streams. To maintain a healthy aquatic ecosystem, it is important to monitor and keep appropriate nutrient levels sufficient for the survival of aquatic animals and humans. Sharma & Kansal (2013), illustrated that development of water quality models is important for predicting pollutants in surface water. Water quality models (WQM) are decision support tools for simulating the fate of pollutants in water columns and assessing their associated risks (Chapra 2008, Wang et al. 2013). Estimation of pollutants through monitoring is a difficult task that requires a continuous update of existing models and development of new WQM for accurate measurement of solute transport in the water bodies. The first major research on water quality modelling was done by Streeter & Phelps in 1925 for simulating BOD and DO in the river system (Cox 2003, Chapra 2008, Gotovtsev 2014). WQM can be classified as simulation model and optimization model (Chapra 2008, Sharma & Kansal 2013). The simulation model describes all models which represent changes in water quality in some mathematical form. It includes all types of mechanistic models which are deterministic in nature. In addition, optimization models are generally used to find the least number of alternative data before carrying out simulation model. Moreover, it is best to implement simple models in simulating solute transport in water bodies prior to complex models because they are more complicated. The magnitude and quality of input data available determine the complexity of the model to be used in simulating water quality parameters. The fundamental principle governing model formulation is the law of conservation of mass, momentum and conservation of energy (Chapra 2008). Therefore, to develop water quality model, there are different formulations, which must be followed and each formulation depends on the different type of parameters to be modelled. Advection, dispersion and molecular diffusion are the primary processes that cause changes in pollutant concentration along the water bodies (Jirka & Weitbrecht 2005, Chapra 2008, Wang et al. 2012). Pollutant decay and kinetic reactions can be incorporated in the water quality models to give a clear understanding of the pollutants' impact and ecosystem response.

The rapid development in computer technology and mathematic techniques has brought improvement to water quality management, which has ensued in the development of different modelling tools. In determining that which models are the most useful, it is necessary to evaluate the existing WQM. Different water quality models are widely used, which have their advantages and limitations. The paper reviews seven major public domain water quality models: AQUATOX, QUAL2E, WASP, CEUALRIV1, MIKE11, SWAT and SIMCAT, which are currently available for different water bodies and are mostly mechanistic models. In addition, the review describes their capabilities and applications to different water bodies. The review would help to select a suitable model for different water quality problems. Furthermore, the limitations associated with the existing WQM have prompted the advancement of new models to simulate pollutant transport under various environmental conditions.

AQUATOX

The model was developed by USEPA to predict the fate of different contaminants and their effects on the aquatic environment (Park et al. 2008, Sharma & Kansal 2013). It is a mechanistic ecological model with the aim of predicting ecological stressors and their effects on the ecosystem. It simulates various water quality parameters which include nutrients, sediment and toxic chemicals. In addition, their impacts on the aquatic animals and plants are also simulated by the model (Park & Clough 2004, Bingli et al. 2008). Sharma & Kansal (2013) stated that the model integrates its algorithms from the clean model which is used for the biological aquatic ecosystem model. In addition, it simulates close to twenty parameters within the aquatic habitat simultaneously, which makes the model one of the best WQM. Moreover, the public can access the model freely online and can be combined with some watershed models which makes it better than some water quality models.

Model system: AQUATOX model is quite sophisticated and suitable WQM to predict various pollutants in a well-mixed ecosystem. The model is designed as a mechanistic model with spatial and temporal resolutions to determine the fate of pollutants in aquatic habitat (Sharma & Kansal 2013). It assumes the river to be comprised of different well-mixed segments with each time step and used average flow data for its operation. Moreover, the model equation was solved using the principle of fourth and fifth order Runge-Kutta integration techniques. The fifth-order differential equation solution was used to correct the error observed with the fourth-order solution. Consequently, the model can be used to understand the impact of various water quality parameters on aquatic habitats.

Model application: AQUATOX can be used to identify the different environmental stressors that cause ecological impairment and predict impacts of pollutants on the ecosystem. The model has been used to simulate the effect of different environmental stressors such as nutrients, sediments, organic waste, toxic substances, temperature, periphyton, phytoplankton and macrophytes in the water bodies. It has been applied to numerous water bodies by different researchers to predict the effect of pollutants on aquatic habitats. Blancher (2010) used the model to predict the effect of eutrophication within the Braden river reservoir, Bradenton Florida and it was observed that high concentration of nutrients in the water body affect the quality of the river. Shu et al. (2012) used the model to predict the concentration of nutrients in Lake Nansi, China. It was discovered that the quality of Lake Nansi has a moderate eutrophication condition. It was also used to simulate some nutrient parameters in Vimtim stream, Nigeria (Anyadike et al. 2013). Their results indicate that the predicted values have a clear trend with the observed values. Akkoyunlu & Karaaslan (2015) used the model to simulate the nutrients and sediments concentration in Morgan Lake, Turkey and it was discovered that the sources of nutrient pollutants in the lake were linked to pesticides and sediments. In addition, the lake has been exposed to intensive organic pollution. It was observed from the study that Aquatox model is a valuable tool for decision makers in the management of river quality. It could be used to simulate pollutants in different water columns which include ponds, rivers, streams and vertically stratified lakes (Shoemaker et al. 2005).

Model limitation: The model cannot model metals and cannot be linked with hydrodynamic models. In addition, the internal nutrients are not represented in algal bioenergetics. Moreover, it assumed a unit volume of water when simulating the change in nutrients, chemicals and sediment concentrations in the water body.

QUAL2E

QUAL2E is a steady state model for predicting contaminants in stretching rivers and well-mixed lakes (Brown & Barnwell 1987), and was developed by the United States Environmental Protection Agency (USEPA) (Cox 2003). It assumed the river to be a one-dimensional model which predicts the significant responses of nutrient cycles, sediment, algae formation, environmental damages and their effects on the concentration of DO in the water body (Birgand 2004). It is used to predict the spatial and temporal variations of some parameters such as temperature, nutrients, BOD and DO concentrations within the water column (Kannel et al. 2011). Furthermore, it can be used to know the effect of different sources of pollutants discharged into water bodies and how they affect the water quality. Furthermore, the effect of algal growth and death rate on dissolved oxygen in the water system can be predicted using the model.

Model system: The mathematical scheme which describes the model is a one-dimensional advection-dispersion equation which was solved by a mass balance method. The water body to be simulated will be discretized into different reaches and assumed to have the same length. However, the geometric properties and pollutant kinetics may change between the reaches. The reaches will be chosen based on either there is massive change in pressure within the water system and parameters to be simulated in the water body. The separation of every reach will be controlled by utilizing a GPS alongside topographic maps. The differential equation of QUAL2E model is presented below and was numerically solved with implicit finite difference method. In addition, an empirical method was used to estimate the longitudinal dispersion coefficient of the river.

$$\frac{\partial C}{\partial t} = \frac{\partial\left(A_X D_L \frac{\partial c}{\partial x}\right)}{A_X \partial x} - \frac{\partial\left(A_X UC\right)}{A_X \partial x} + \frac{dC}{dt} + \Delta S \qquad ...(1)$$

Where, C = concentration (mg/L), x = distance (m), t = time (min), Ax = area of the river reach (m^2), D_L = dispersion coefficient (m^2/min), u = average flow velocity (m/min), S = the sink or source of pollutants (mg/L).

The QUAL2E model simulates the real components and constituents that relate to the dissolved oxygen concentration. The significant sinks or source included in the equation are biochemical oxygen demand, algal reactions, and nutrient reactions. Also, QUAL2E can show the reaeration that happens when water is spilling over dams.

Model applications: The QUAL2E model is developed to simulate different water quality parameters such as dissolved oxygen, nutrients and conservative pollutants in water bodies (Cox 2003). Few applications of QUAL2E models can be found in Ning et al. (2001), where the model was used to predict the concentrations of BOD and DO along Kao-Ping River Basin, Taiwan. Park & Lee (2002) used the model to simulate nutrients concentration of the Nakdong River, Korea and it was observed from the result that the model represents the field data very well. In addition, it was applied to Yangtze River to simulate some water quality parameters and was discovered that the predicted values agreed well with the measured data (Zhang et al. 2006). Purandara et al. (2012) applied the model to assess the effect of point and non-point sources pollution of Ghataprabha River, Karnataka, India, where the result indicated that the quality of water within the river is highly acceptable. In addition, it was observed that increase in river flow leads to a reduction in dissolved oxygen.

Model limitation: A QUAL2E model cannot be applied to a river that experiences temporal variation in its flow. It models organic nitrogen, ammonia, nitrates and nitrites but neglect macrophytes, suspended sediment movement and denitrification processes. It cannot model variable flow condition due to its steady state assumption. QUAL2E has certain dimensional limitations which have been imposed during program development which includes; the reaches should not be more than 25, the computational element should not be more than 20 per reach or a total of 250. Furthermore, the headwater and junction elements should have a maximum value of 7.

WASP

The model was developed by the United States Environmental Protection Agency to simulate pollutants transport in water bodies (Connolly & Winfield 1984, Yang et al. 2007). The model can be applied in one, two or three - dimensional. It could be used to predict various parameters which include conservative and non-conservative pollutants within the water column (Wool et al. 2006). WASP is a dynamic model program, which follows a box modelling approach and can be used in solving different flow conditions along the aquatic habitat (Ambrose et al. 1993). It consists of seven versions ranging from WASP to WASP7 which has two sub-models used to simulate eutrophication and toxic processes within the water system. The model can be applied to different water bodies which include rivers, streams, lakes and ponds.

Model system: The WASP water quality model consists of DYNHYD and WASP stand-alone computer programs that could be used independently or combined with each other. The flow of water across the reach within the river system is simulated using the DYNHYD which is a hydrodynamics program. Moreover, to simulate the pollutant transport within the water column, the WASP program will be applied. There are two sub programs within the model system which are EUTRO and TOXI, respectively. The EUTRO model enables modelling of the conventional pollution which is related to water eutrophication, while the TOXI model is used to simulate toxic pollutants in waterways. The model uses conservation of mass and mass balance equations to solve the model equation. The model requires some input data to solve the mass balance equation. The input data include, initial and boundary concentrations, the source of pollutants, kinetic parameters coefficient, the flow characteristics and geometry of the river is also important in solving the mass balance equation. The model's mass balance equation is presented below:

$$\frac{\partial(AC)}{\partial t} = \frac{\partial}{\partial x}\left(-U_x AC + E_x A \frac{\partial C}{\partial x} \right) + A\left(S_l + S_b\right) + AS_k \qquad ...(2)$$

Where, C is the concentration of the pollutant (mg/L), A is the river area (m^2), U_x is the advective velocity (m/day), E_x is longitudinal dispersion coefficients (m^2/day), S_b is the boundary loading rate (g/m^3- day) and S_K is the total kinetic transformation rate (g/m^3- day).

Model application: It can simulate some water quality parameters which include; temperature, nitrogen, phosphorus, BOD, coliform bacteria, silica, DO, conservative pollutants, and synthetic organic compounds. The model was successfully used to estimate the level of DO concentration in the Altamaha River estuary, Georgia (Kaufman 2011). WASP model was applied by Ernst & Owens (2009) to a large Texas reservoir to simulate and predict eutrophication of the reservoir. Lai et al. (2013) used the model to determine the effect of NPS and ammonia pollutants on Kaoping River Basin, Taiwan and it was observed that high flow rate during rainy season caused high discharged of NPS into its upper section.

Model limitations: The complexity of the model requires extensive training for its user to effectively use the model for decision making. The calibration of the model and applying it to simulate some water quality parameters require extensive time for its user. Furthermore, the model cannot simulate periphyton and microalgae.

CE-QUAL-RIV1

The water quality model is a one-dimensional hydrodynamic model developed by the U.S. Army Engineers Waterways Experiment Station (WES) which was released in 1991 for simulating water quality parameters associated with streams, rivers and estuaries (Dortch et al. 1990, Martin et al. 2002, Sharma & Kansal 2013). A new version of the model was released in the year 1995. The model simulates highly unsteady flow condition of a river system because most models in existence were developed for steady flow conditions (Martin et al. 2002). CE-QUAL-RIV1 consists of two codes which include a water quality program code (RIV1Q) and a hydrodynamic program code (RIV1H) (Zemiñska-Stolarska & Skrzypski 2010). The RIV1H code is first applied to the water column to calculate the river hydraulics using the geometric properties of the river and boundary conditions. The output from RIV1H will be used by RIV1Q code for its water quality simulation. The RIV1H code uses the four-point's implicit solution method of the St. Venant equation to estimate the flow rates, depths, velocities and widths of the river. Fortran 77 program language code was used for the model and is available for MS-DOS based microcomputers. The nature of the river flow will determine if the model can be applied in simulating parameters into the water body.

Model system: The model equation is solved using St. Venant equations which comprise of continuity and momentum equation. Fourth-order explicit scheme and implicit scheme were used to solve the ADE equation. More parameters have been added to the governing equation which includes flood plains and cross-section storage flows. The equation presented below described the equation governing the water quality model.

The continuity equation

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial t} = q \qquad ...(3)$$

The momentum equation

$$\frac{\partial Q}{\partial t} + U\frac{\partial Q}{\partial x} + gA\frac{\partial h}{\partial x} = gA\left(S_o - S_f - \frac{h_e}{\Delta x} \right) + qU_q \qquad ...(4)$$

The one-dimensional advection and dispersion equation coupled with the sink and source is shown below:

$$\frac{\partial \alpha}{\partial t} + U\frac{\partial \alpha}{\partial x} = D\frac{\partial^2 \alpha}{\delta x^2} + \frac{q}{A}\left(K - a\right) - K_s \alpha + \sin\, ks \qquad ...(5)$$

Where, Q = flow rate, (m^3/s); U = average velocity, (m/min); A = area of the channel, (m^2); h = depth, (m); g is the gravitational acceleration; S_o and S_f are the bottom and friction slope respectively; x = length (m); t = time; α = parameters; q is the lateral flow rate (m^3/s); D = dispersion coefficient (m^2/min).

The equation was solved numerically because it was a nonlinear, hyperbolic, and partial differential function. The water quality module, RIV1Q, uses a fourth-order, explicit, finite difference scheme developed by Holly Jr & Preissmann (1977) to solve the constituent mass balance equation. The data required in the water quality model include the river geometry, initial flow condition of the water system and inflow water quality concentrations and meteorological data.

Model application: CE-QUAL-RIV1 can be applied to simulate the chemical, biological and physical processes in rivers. It can be used to predict the response of lakes and estuaries to pollutant loading. It could be used to predict a branched river with numerous hydraulic structures like dams and estimate the hydraulic and geometric properties of the water body. Furthermore, it can be used to simulate some water quality parameters which include the thermal stratification, growth of algae and macrophytes.

Model limitation: The model cannot be used to simulate sediment transport processes within the river system. The one-dimensional assumption of the model is also one limitation of the model. It contains limited eutrophication kinetics in its process and required extensive training by its user for them to use the model effectively.

MIKE-11

The model is a deterministic computer program that simulates unsteady flow in a water system, which was developed by Danish Hydraulic Institute, Nederland. It is used to calculate flow and water level in the river system. Also, it can be used as a hydrodynamic model to simulate tidal sections of a water system, and it could be used as a water quality model (Tsakiris & Alexakis 2012). The model can simulate more complex water quality problems such as DO, BOD, sediment exchange reactions, the balance of nitrate and ammonium without denitrification, and coliform bacteria (Tsakiris & Alexakis 2012).

Model system: The hydrodynamic model depends on the formulation of the Saint-Venant equations which was solved by implicit finite difference method. It can be applied to one and two-dimensional unsteady flow in water columns. The model can use kinematic, diffusive dynamic, vertically integrated mass and momentum equations for its simulation. The hydrodynamic module is solved using the continuity and momentum equation to determine the water level and the rate of flow. The other modules of the model depend on the hydrodynamic module in order to perform their functions. Iterations method was applied to solve the mathematical equations, by using the result of the first iteration to solve the second time step. The following assumptions were used to solve the 'Saint Venant' equations; water is incompressible and homogeneous, the wavelengths are large compared with the water depth, the bottom slope is small, and the flow is subcritical. The advection-dispersion equation was solved coupled with the pollutants first order decays and a dynamic solution is provided. The model uses the following equations:

The continuity equation

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial t} = q \qquad ...(6)$$

The momentum equation

$$\frac{\partial Q}{\partial t} + \frac{\partial\left(\alpha \frac{Q^2}{A}\right)}{\partial x} + gA\frac{\partial h}{\partial x} + \frac{gQ}{C^2 AR} = 0 \qquad ...(7)$$

Where, Q is the flow rate (m^3/s), α is the momentum coefficient, h is the height (m), q is the lateral inflow (m^2/s), C is the Chezy coefficient ($m^{1/2}/s$), R is the hydraulic radius (m), and A is the area of channel (m^2).

Model application: The model has been extensively applied by different researchers to study water parameters of different water bodies. It is an ecological model which can simulate BOD, DO, ammonia, nitrate and heavy metals. Kazmi & Hansen (1997) applied the model for the evaluation of the water quality conditions and effect of wastewater discharged on Yamuna River, Northern India. The result showed that the quality of the river is greatly affected by high eutrophication level discharged into the river system. MIKE11 was used to simulate DO and BOD in river Dender in Belgium (Radwan et al. 2003). It was also used to investigate the dissolved oxygen level and some water quality parameters in River Buriganga (Kamal et al. 1999). It uses the geographical information systems (GIS) to import and export water quality data.

Model limitation: The model can simulate complex water quality scenarios at first order decay and other factors such as temperature, but does not consider denitrification process in its development. The model is difficult to set up without the help of an expert. During the operation of the model, there is a requirement for a lot of information/data without which it will be difficult to simulate some parameters if the information is lacking.

SWAT

It is a hydrological and river basin scale model for water resource management which was developed by USDA Agricultural-based Research Service (USDA-ARS) (Neitsch et al. 2002, Tolson & Shoemaker 2007). The model is used to measure the influence of land management practices in a watershed and is free to access by the public (Gassman et al. 2007, Neitsch et al. 2011). It can simulate groundwater flow, nutrients, and water transportation from channel and reservoirs. In addition, it can be used to estimate the impacts of nutrients, chemical and sediment adsorption on watershed management.

Model system: The model requires accurate information for its operation which includes topography, weather, vegetation, soil properties and type of water body. It uses daily time step for its operation and performs its simulation by dividing the watershed into a large number of compartments. The compartments are connected in series and further divided into Hydrologic Response Unit (HRU). The simulation of water and pollutants from each Hydrologic Response Unit is routed through the stream network to the watershed exit. It can be used to solve various management problems of large river basin cost efficiently and used to study special processes of pollutants transport.

Model application: The model has been broadly utilized by researchers and applied extensively in various applications worldwide. Abbaspour et al. (2009) described the impact of future climate in Iran on its water assets using the model and it was discovered that wet region of the country will have more precipitation than dry region. The model was also applied to Cannonsvill reservoir, New York to calibrate and validate the prediction of flow, nutrients and sediment transport in the area. It was observed that the model adequately predicted the monthly phosphorus and sediment loading in the reservoir (Tolson & Shoemaker 2004). This model has been applied to determine the concentration of pesticides at a designated location. SWAT has been applied to predict the influence of rural and agricultural management practices on aquatic habitat.

Model limitation: SWAT model uses a relatively simple equation for sediment routing because it does not consider significant sediment transport process such as bottom shear stress in its formulation (Benaman et al. 2001). The model uses a daily time step for its operation, however, if a more flexible time increment is used it would be a significant development in the model. It does not accurately evaluate the extreme daily flow occurrence and simulation of runoff yield.

SIMCAT

Simulation catchment (SIMCAT) is one of the available models for simulating water quality parameters such as dissolved oxygen along water bodies. The model is a deterministic model used to predict river quality parameters and flow dynamics along the water column (Cox 2003). The model was developed by Anglian water (Warn 1987) in the United Kingdom and it has been applied to predict conservative and non-conservative pollutants in the river. It is a stochastic model which utilizes the Monte Carlo simulation approach for its operation and can be used to assess the influence of pollutants discharge on water bodies (Warn 2007).

Model system: The model used the concept of mass balance for its operation and represents the river reaches as continually stirred tank reactors in series (CSTRS) with a steady flow condition. The model can simulate pollutants in freshwater which do not rely on sediment interactions. The flow velocity is obtained from the velocity flow relationship and it is used to calculate the residence time for each reach. It assumes that pollutant is well mixed throughout each reach of the river (Cox 2003). The equation presented below described the mass balance for a reach of the river system:

$$C_o = \frac{C_i Q_i + C_t Q_t + C_e Q_e}{Q_r + Q_t + Q_e} \qquad ...(8)$$

Where, Q = flow, (m^3/min); C = pollutant concentration, (mg/L); o = outflow; i = upstream input; t = tributary input; e = effluent discharged, and a = abstractions.

$$v = aQ^b \qquad ...(9)$$

$$t = \frac{L}{v} \qquad ...(10)$$

Where, v = flow velocity, Q = flow rate; a, b are constants, t is the residence time and L = length of the reach.

The solute concentration is subjected to first-order decays which will be used to calculate the concentration of pollutants entering the next reach of the river.

Model application: The model required limited data for its application and it is readily applied at a catchment scale. Jacobs (2007) applied the model to River Dee, Wales to evaluate the potential of water quality influences on the proposed road drainage around the river and its tributaries. In addition, the model was used to calculate the pollution level of the area for both the annual average and ninety-five percentile concentration levels for each of the designed drains in the area. It was also used by Crabtree et al. (2010) to monitor water quality of the River Ribble catchment, UK by identifying the source of pollution either PS or NPS and predict their impacts on the river quality. The model has been described as a good water quality management tool.

Model limitation: The model is a simple and flexible model that does not simulate some parameters related to dissolved oxygen concentration. In addition, its application to simulation of respiration, photosynthesis, sediment oxygen demand, and reaeration rate is limited in its process.

GENERAL DISCUSSION

In the changing environmental situation, the water quality models are significant in describing the ecological state of different water bodies and to predict the change in the receiving water when certain boundary or initial conditions are altered. Such changes may be due to morphological

Table 1: Comparison of water quality models.

Model	AQUATOX	QUAL2E	WASP	CEQUALRIV1	MIKE II	SWAT	SIMCAT
Model type/Level of complexity	1-D, Dynamic state	1-D, Steady state/Dynamic	1,2,3- D, Dynamic	1-D/ Dynamic	2-D, Steady state, Dynamic	1-D, Quasi - Dynamic	1-D, Steady state
Receiving Water Type	River, Lake, Reservoir	River	River, Lake, Reservoir, Estuary	River	River, Reservoir	River, Lake, Reservoir	River
Modelling approach	Differential equations using 4th and 5th order, Runge-Kutta integration routines	The advection-dispersion-reaction equations, equal river reaches	The advection-dispersion-reaction equations	Continuity equation, Momentum equation, and Constituent fate and transport equation	Implicit finite difference Scheme to solve saint – Venant equation	Mass balance Equation	CSTRS
Model capabilities	DO, CBOD, NH_3, NO_3, OP, PO_4, Temperature, Sediment	DO, BOD, NH_3, NO_3, NO_2, OP, PO_4, Temperature, Coliform Bacteria	DO, CBOD, NH_3, NO_3, NO_2, OP, PO_4, Temperature, Sediment, Metals, Toxics	DO, BOD, NH_3, NO_3, NO_2, OP, PO_4, Temperature, Bacteria, Metals	DO, BOD, temperature, NO_3, NH_3, sediments, coliform bacteria	DO, BOD, NH_3, NO_3, NO_2, OP, PO_4, Temperature, sediment, Toxics, Metal	DO, CBOD, NH_3, PO_4
Special water quality features	Algae, phytoplankton, Periphyton, Planktonic, Benthic algae, Fish	Algae, phytoplankton, Periphyton, Planktonic, Benthic algae	Algae, phytoplankton, Periphyton, Planktonic, pesticides	NIL	phytoplankton, Periphyton, Planktonic, Benthic algae	Surface and groundwater interaction	NIL
Application Considerations	Limited Training/ Public Domain	Limited Training/ Public Domain	Substantial training/ Public Domain	Substantial training/ Limited Distribution	Substantial training/ Significant Cost	Moderate training/ Public Domain	Limited Training/ Public Domain

CBOD: Carbonaceous biochemical oxygen demand, DO: Dissolved oxygen, NH_3: Ammonia, NO_3: Nitrate, NO_2: Nitrite, BOD: biochemical oxygen demand, OP: Organic phosphorus, PO_4: Phosphate, CSTRS: Continually stirred tank reactors in series.

modifications to the water body, changes in the source of pollutants and location of pollutant loading into the system, and changing trends in climate condition. Thus, the degree of complexity in describing the ecological state varies in different water quality modelling tools. To choose the type of WQM to be used for different water bodies, it is necessary to investigate the type of pollutant problem affecting the water system; in addition, the cause of the water pollution should be determined and identify the best management solutions. Seven currently available WQM were evaluated for their capabilities and application to different water bodies. The important criteria in choosing water quality model were the easy accessibility of the program code source and existence of good documentation of the model. Evaluation table was developed to provide more detailed information on the capabilities of each model as presented in Table 1. The level of complexity in the receiving water was evaluated by categorizing AQUATOX, QUAL2E, CEQUALRIV1, SWAT and SIMCAT as a one-dimensional model, where SIMCAT is a simplistic model and has a limitation when simulating photosynthesis, respiration and sediment oxygen demand. In the application of the models to different water bodies, AQUATOX, WASP, MIKE 11 and SWAT could be used; however, each model should be calibrated and validated for a good result and conclusion. Furthermore, in comparing AQUATOX to other WQM, the prediction of the model appears to be accurately reflecting currently accepted ecological process and behaviour. All the models have been widely tested in relation to simulating nutrients in different water bodies. However, for MIKE 11 and QUAL2E do not consider denitrification process during its operation. In addition, QUAL2E and SIMCAT do not model variable flow conditions because the flow rate is assumed to be a steady state. The choice of the type of model, suitable for nutrient simulation in receiving water will be subjected to availability of data, model complexity, type of water body, and the water quality simulation capabilities as presented in Table 1. All the models reviewed apart from

SWAT have the capability of simulating in-stream fate and transport of a wide variety of pollutants. However, SWAT model can be linked with an in-stream model to give a better result and prediction. The complexity of water quality issue globally should open ways on how to combine different WQMs to simulate some water quality parameters in water bodies, which could solve the problem associated with a single model. WQM should be flexible and allow for further future improvements and updates based on newly conducted studies and water quality parameters. The water quality model should be chosen according to the basis of the available data to support the model processes. Moreover, the magnitude and quality of the available data determine the complexity of the model to be used.

CONCLUSION

Globally, prediction of changes in pollutant concentration for environmental management and decision making has been done through the development of surface water quality models. The paper described some of the more frequently used water quality models and their applications to different water bodies. The review has addressed aspects of water quality problems which include; water quality parameters, sediment transport, and hydrodynamics. It also provides the model type which is categorized as steady state, Quasi-dynamic and dynamic model. The level of complexity of the model in receiving water such as one, two, three dimensions and the governing equation was also discussed. It is important to identify the project goal when developing a water quality modelling tool through discussions with stakeholders, regulating agencies and technical personnel involved in the development. Simulation of water quality parameters in water bodies provides water management guidelines for water sustenance. In addition, to choose the best model for the water body, it is important that the user selects a water quality modelling tool subjected to the modelling objectives and available resources. To choose the type of modelling tool, a list of questions about the water column to be modelled should be adequately addressed with suitable selection criteria. The selected model must be able to simulate different water quality parameters within the water body. Moreover, the user must understand the assumptions used by the model and ensure that these assumptions reflect the appearance of the water system to be simulated. There are always uncertainties associated with different models, and these must be figured out to ascertain if the aims and the objective of the model will be met. Water quality models should be flexible and allow for further improvements in the future and updates based on new studies and water quality parameters. In general, it is best to choose the simplest model that satisfies the project goals.

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