

A review of hydrological/water-quality models

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Abstract Water quality models are important in predicting the changes in surface water quality for environmental management. A range of water quality models are widely used, but every model has its advantages and limitations for specific situations. The aim of this review is to provide a guide to researcher for selecting a suitable water quality model. Eight well known water quality models were selected for this review: SWAT, WASP, QUALs, MIKE 11, HSPF, CE-QUAL-W2, ELCOM-CAEDYM and EFDC. Each model is described according to its intended use, development, simulation elements, basic principles and applicability (e.g., for rivers, lakes, and reservoirs and estuaries). Currently, the most important trends for future model development are: (1) combination models—individual models cannot completely solve the complex situations so combined models are needed to obtain the most appropriate results, (2) application of artificial intelligence and mechanistic models combined with non-mechanistic models will provide more accurate results because of the realistic parameters derived from non-mechanistic models, and (3) integration with remote sensing, geographical information and global position systems (3S)—3S can solve problems requiring large amounts of data.

Keywords water quality models, applications, future trends

1 Introduction

Hydrologic/water quality models are commonly applied for management, planning and pollution control. Each of these requires a different level of confidence in the model output. With the influence of human economic activity, environmental degradation and activity zones (e.g., household water supply, agriculture, hydropower and fisheries), the water quality is threatened by point (PS) and non-point (NPS) source pollution. Thus, hydrologic/water quality

models are important tools for water quality decision analysis [1].

Since 1925, surface water quality models have undergone three important stages in development [2], the first stage being the primary stage (1925–1965). These applications mostly modified and further developed the Streeter–Phelps models (S-P models). They were focusing on interactions among different components of water quality in river systems, such as hydrodynamic transmission, sediment oxygen demand, and algal photosynthesis and respiration. The models of this time were one-dimensional, steady-state models and the BOD-DO model was successfully used in water quality prediction [3]. The second was an improvement stage (1965–1995) with rapid model development. Before 1975, researchers included not only dissolved oxygen (DO) but also other elements (such as the N and P cycling system, phytoplankton and zooplankton system, and the relationships between biologic growth rate and nutrients, sunlight and temperature) [4–6], and the one-dimensional models were expanded to two-dimensional models. After 1975, three-dimensional models were developed and sediments were an important element considered in the interaction processes of these models [7]. The third has been a broadening stage (1995 onwards). As a result of economic development, NPS pollution had an important effect on cities and countries. Pollution models were developed in this stage to help government control the pollution sources [8,9]. Also, during this stage, new methods were used in some models to simulate specific scenarios, such as fuzzy inference systems [10], genetic algorithm [11], neural network [12] and support vector machine [13]. Although being important developments, these models are not discussed in this review.

Water quality models are effective tools to simulate and predict the water environment. Therefore, they have been a focus of attention in recent years. Cox [14] and Kannel et al. [15] described some water quality models (such as SIMCAT, TOMCAT, QUAL2E and QUASAR) for simulating DO in rivers and streams. Yang and Wang [16] provided critical reviews of most popular and public-domain models for diffuse water modeling, with detailed

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sources and application potential. Those papers provide detailed information about the models and their capability. However, the description of the models was of limited scope (e.g., just DO). Therefore, in this review, we describe not only the capability of the models but also their application to particular situations.

In this paper, eight water quality models that are used widely around the world are described including intended use, development, simulation elements, basic principle, limitations, model strengths and their application to particular situations. The models, SWAT, WASP, QUALs (QUAL2E, QUAL2K, QUAL2Kw), MIKE 11, HSPF, CE-QUAL-W2, ELCOM-CAEDYM and EFDC are included. This review provides support for researchers to make informed decisions when choosing an appropriate model for their work.

2 A review of water quality models

The models selected for application here are mostly mechanistic models. Water quality models are developed to predict contaminant fate and transport in water-bodies such as rivers, reservoirs, lakes and estuaries. They can be helpful tools for water resource management. All these models can be useful in management and improvement of water quality.

2.1 SWAT

SWAT (Soil Water and Analysis Tools), a physical-based model, was developed by the United States Department of Agriculture (USDA) Agricultural Research Service (ARS) in the early 1990s for the prediction of the long-term impact of rural and agricultural management practices (such as detailed agricultural and planting, tillage, irrigation, fertilisation, grazing and harvesting procedures) on water, sediment and agricultural chemical yields in large, complex watersheds with varying soils, land use and management conditions [17]. The model is available without cost from <http://www.brc.tamus.edu/swat>. Several versions (SWAT98.1, SWAT99.2, SWAT2000, SWAT2005, SWAT2009 and WAT2012) are currently available. The model can perform daily simulation of groundwater flow, and nutrient and water transportation from channels and reservoirs and, in particular, the calculation of the parameters (algae, DO and carbonaceous BOD) that impact the quality of stream water.

There has been a range of applications of this model in different contexts. Abbaspour and Schuol [18] addressed some calibration and uncertainty issues using SWAT to model a 4 million km² area in West Africa. They found SWAT could be used for large-scale water quantity investigations and a 95% prediction uncertainty band was necessary to bracket 80% of the observed data, indicating that the uncertainty of the conceptual model was

quite large. They indicated that some processes (for instance large reservoirs regulating the runoff) in Niger might be important, however in the large Inner Niger Delta, delaying the runoff and evaporation losses were not included in the model. For the land phase nutrient cycle, SWAT was used to simulate the organic and mineral nitrogen and phosphorus fractions by separating each nutrient into component pools. Then, N and P could increase or decrease depending on their transformation and/or additions/losses occurring within each pool [18,19]. In addition, in NPS water quality for nutrients and sediments, Chen et al. [20] used the SWAT model to compare the effects of different kinds of watershed management measures on the transport of sediments and nutrients (ammonium and nitrate nitrogen) in one of the main tributaries of the Xiangjiang River, the Zhengshui River. These results showed a 10% and 30% increase compare to that of CSA plans for NO₃⁻ and NH₄⁺, so the model could facilitate the selection and implementation of more effective and reasonable measures to improve the water quality. Yi and Wu [21] used the SWAT model to investigate the influence of PS and NPS pollution on the water quality of the East River (Dongjiang in Chinese) in southern China. Their results also indicated that NPS pollution was the dominant contribution (>94%) to nutrient loads except for mineral phosphorus (50%).

However, SWAT has some limitations: (1) it does not simulate sub-daily events such as a single storm event and diurnal changes of DO in a water body, (2) it is difficult to manage and modify when there are hundreds of input files because the watershed is so large and divided into hundreds of hydrologic response units, (3) it does not simulate detailed events based flood and sediment routing, and (4) during the spring and winter months, it has difficulties in modeling floodplain erosion and snowmelt erosion [22–24].

2.2 WASP

WASP (Water Quality Analysis Simulation Program) is a surface water quality model developed by the US Environmental Protection Agency (EPA) for the water quality modeling [25,26]. WASP is a 1, 2 and 3 dimensional dynamic model. Currently it has seven versions (WASP1–7). It can be downloaded at no cost from <http://www.epa.gov/athens/wwqts/html/wasp.html>. In WASP, different interacting systems are developed comprising ammonia, nitrate, phosphate, phytoplankton, biochemical oxygen demand (BOD), DO, organic nitrogen and organic phosphorus [27,28]. It can be used to analyze a variety of water quality problems in such diverse water bodies as ponds, streams, lakes, reservoirs, rivers, estuaries and coastal waters. WASP can also be linked with hydrodynamic and sediment transport models that provide flows, depths, velocities, temperature, salinity and sediment fluxes. The latest version, WASP7, comes with two

general kinetic modules: TOXI for toxicants and EUTRO for conventional water quality to solve conventional pollution (involving DO, BOD, nutrients, and eutrophication) and toxic pollution (involving organic chemicals, metals and sediment). WASP employs the conservation of mass and momentum equations to determine the river hydraulic characteristics (e.g., depth, velocity, top width and flow rate) [29–32]. The continuity equation [Eq. (1)] and momentum equation [Eq. (2)] used in the WASP model are as follows:

$$\frac{\partial Q}{\partial t} + \frac{1}{B} \frac{\partial Q}{\partial x} = q_s \quad (1)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left(\frac{Q^W}{A} \right) + gA \left(\frac{\partial z}{\partial x} + \frac{Q|Q|}{K^2} \right) = 0 \quad (2)$$

where Z is the water surface elevation, Q is the flow rate, B is the wetted cross sectional width, A is the wetted cross sectional area, t is the time, x is the distance along the channel, K is the conveyance of the channel, g is the gravitational acceleration, and q is the side discharge per unit channel length [33].

This model helps users interpret and predict water quality responses to natural phenomena and manmade pollution for various pollution management decisions. Lai et al. [33] combined the Integrated Watershed Management Model (IWMM) and the Water Quality Analysis Simulation Program model. The IWMM model was applied to the Kaoping River Basin for the simulation of the potential water quality and NPS pollution loading conditions, and the WASP model was used to simulate water quality conditions in the down-gradient section of the Kaoping River, so that they could evaluate the NPS pollution loading and the Kaoping River water quality. However, WASP could not effectively simulate the suspended solid (SS) loading in the river. Lai et al. [33] developed a direct linkage between the River Pollution Index (RPI) calculation and WASP containing a SS equation to predict water column DO, SS, BOD, and $\text{NH}_3\text{-N}$ loading and evaluate their impacts on river water quality using the integrated modeling system. Lin et al. [34] used WASP to evaluate the pollution and toxicity level of sediments for water quality and develop pollution control and watershed management strategies for the Salt-water River.

Although WASP can be run with 1, 2 or 3 dimensions as desired, the model has limitations: (1) it does not handle mixing zones or near field effects, (2) it does not handle sinkable/floatable materials, and (3) it requires an extensive amount of data for calibration and verification [15].

2.3 MIKE 11

MIKE 11 is a powerful and popular hydrological modeling system, a one-dimensional modeling tool for the detailed

design, management, and operation of both simple and complex river and channel systems, developed by the Danish Hydraulic Institute (DHI) (<http://www.mikebydhi.com>). It is composed of several modules, including rainfall runoff (RR), hydrodynamic (HD) and advection dispersion (AD), which can be used in combination or as stand-alone simulators [35]. MIKE 11-NAM is a rainfall runoff model that is part of the MIKE 11 RR module. The MIKE 11 hydrodynamic (HD) is a one-dimensional modeling tool for computing unsteady flow, discharge and water level in rivers and channels that are based on formulation of the Saint-Venant equations and the formulation as follow:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q \quad (3)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left(\alpha \frac{Q^2}{A} \right) + gA \frac{\partial h}{\partial x} + \frac{n^2 g Q |Q|}{AR^3} = 0 \quad (4)$$

where Q and A are the discharge [$\text{m}^3 \cdot \text{s}^{-1}$] and the cross section (flow) area [m^2], respectively; q is the lateral inflow [$\text{m}^2 \cdot \text{s}^{-1}$]; h is the water level above a reference datum [m]; x is downstream direction [m]; t is time [s]; n is the Manning resistance coefficient [$\text{s} \cdot \text{m}^{-1/3}$]; R is the hydraulic or resistance radius [m]; g is the acceleration due to gravity [$\text{m}^2 \cdot \text{s}^{-1}$] and α is the momentum distribution coefficient [e] introduced to account for the non-uniform vertical distribution of velocity in a given section.

MIKE 11 has been widely used by researchers mainly for rivers and lakes. Christian and Refsgaard [36] used the MIKE 11-NAM coupled with MIKE SHE and WATBAL on three catchments in Zimbabwe for water resource decision making, and it worked well using at least one year's data for calibration. Thompson et al. [37] used a coupled MIKE SHE/MIKE 11-HD model for a lowland wet grassland in South-east England. The results showed that the system could make an accurate representation of the macropore flow associated with soil cracking and swelling, and the seasonal dynamics of groundwater and ditch water and were generally consistent with the observed data. In addition, Liu et al. [38] coupled a spatially distributed hydrological model for catchment hydrology and groundwater, implemented in the MIKE-SHE hydrological modeling software of DHI Water and Environment, with a MIKE 11 hydraulic model to simulate dynamic changes in groundwater within the study area for both flood and dry seasons. The results indicated that the proposed methodology is applicable for the management of water resources in arid regions. The modeling and hybrid fractal-wavelet method study allowed quantification of the processes affecting groundwater levels and provided an insight into their implications in exploring groundwater level management. Kamel [39] applied the MIKE 11 HD in the Euphrates River in Iraq to unsteady flow simulations along stream channel reach, and the results showed that MIKE 11 HD was better than the Uday

model that was used for the same river in simulating the flow according to a comparison between the estimated and observed stage hydrograph. Recently, Doulgeris et al. [40] used MIKE 11-HD to simulate the unsteady flow of the Strymonas River and Lake Kerkini and MIKE 11-NAM to simulate the rainfall runoff process. The research provided a strong case for improving the water resources management.

MIKE 11 model is an advanced model of flow and water-quality in stream and can simulate solute transport and transformation in complex river systems. However it has its limitations: (1) there is a need for a large amount of data and it is difficult to simulate some determinants well if the data are lacking, and (2) channel cross-sections are needed at reach boundaries which makes the calibration and evolution of the results a substantial task and requires a long computational times [14].

2.4 QUALs

The US Environmental Protection Agency (EPA) released a series of QUAL models such as QUAL2E, QUAL2E-UNCAS, QUAL2K and QUAL2Kw. The models allow the simulation of up to 15 parameters (DO, BOD, temperature, algae as chlorophyll *a*, organic nitrogen as N, ammonia as N, nitrite as N, nitrate as N, organic phosphorus as P, dissolved phosphorus as P, coliform bacteria, one arbitrary non-conservative constituent solute and three conservative constituent solutes) associated with water quality in any combination chosen by the user. For one-dimensional, steady-state models, these elements, hydrological balance, heat balance and material balance are influenced by flow, temperature and concentration. Also, QUALs are widely used on rivers. Both advective and dispersion modes of transport are considered in mass balance which can be expressed as:

$$V \frac{\partial c}{\partial t} = \frac{\partial(A_c E \partial c / \partial x)}{\partial x} dx - \frac{\partial(A_c U)}{\partial x} dx + V \frac{dc}{dt} + s \quad (5)$$

where V is the volume, c is the concentration of constituent, A_c is the element cross-sectional area, E is the longitudinal dispersion coefficient, x is the distance (in the direction of flow from point load), U is the average velocity, s is the external sources (positive) or sinks (negative) of the constituent [41].

QUAL2E is the latest version of QUAL-II and Soon and Park [42] used it to prove that autochthonous sources and denitrification played an important role in BOD and nitrogen dynamics. QUAL2E has been widely used in water quality prediction and pollution management. Palmieri et al. [43] predicted the water quality of the Corunbatai River, located in São Paulo State, Brazil using QUAL2E, and the results showed that the sensitivity analyses were more sensitive to the BOD decay coefficient. Ritu Paliwal et al. used QUAL2E to determine the

pollution loads in the Yamuna River. Four different pollution scenarios were used to examine the influence on river water quality. The results showed that it was suitable for water quality if the flow rate was more than $10 \text{ m}^3 \cdot \text{s}^{-1}$. In addition, the uncertainty analysis provided a useful method for prediction of model parameters, DO and BOD. Bailey et al. [44] used a coupled QUAL2E-OTIS model to investigate the factors that govern DO and NO_3 in space and time for the Lower Arkansas River Basin in south-eastern Colorado. The results showed that many processes (including algal growth and respiration, and chemical kinetic reactions) had a time-dependant influence due to seasonal changes in water temperature and solar radiation. Other processes (groundwater discharge and solute mass loading) were of moderate influence in the Arkansas River, but of very strong influence in its tributaries. Thus efficient remediation strategies may be taken in time. Also, Salvetti et al. [45] used two different models: QUAL2E (the simulation of the dry weather scenario) and BASINS-SWAT (the simulation of the wet weather scenario) to analyze the source apportionment of a river basin, the Dese-Zero river, located within the North-Eastern part of the Venice Lagoon Watershed (VLW), Italy. The results showed that about 30% surface runoff loads, about 15% point sources and about 55% of the total annual load were related to non-rain-driven diffuse sources.

QUAL2K is similar to QUAL2E in the following respects: (1) one dimensional and steady-state hydraulics, (2) diurnal heat budget, (3) diurnal water quality kinetics, and (4) heat and mass input. Point and non-point loads and abstractions are simulated. However, there are different features. The QUAL2K framework includes various new elements: (1) Excel is used as the graphical user interface with all interface operations programmed in the Microsoft Office macro language (Visual Basic for Applications), (2) the element size for QUAL2K can vary from reach to reach, and multiple loadings and withdrawals can be input to any element, (3) two forms of carbonaceous BOD (slow and fast) are used to represent organic carbon with the model accommodating anoxia by reducing oxidation reactions to zero at low oxygen levels, (4) denitrification is modeled as a first-order reaction that becomes pronounced at low oxygen concentrations, (5) oxygen and nutrient fluxes are simulated as a function of settling particulate organic matter, reactions within the sediments, and the concentrations of soluble forms in the overlying waters, and (6) the model explicitly simulates attached bottom algae. Light extinction, pH, and pathogens are also calculated. Zhang et al. [46] showed that QUAL2K was an effective tool for the comparative evaluation of potential water quality improvement programs through simulating the effects of a range of water quality improvement scenarios in the Hongqi River. Their results indicated that the optimal scenario comprised a bio-contact oxidation system upstream, followed by an ecological floating bed

and a vertical moveable eco-bed downstream. The reduction rates achieved by this scenario for BOD were 50%, ammonia nitrogen (NH₃-N) 33%, total nitrogen (TN) 36%, and total phosphorus (TP) 45%.

In QUAL2Kw [47], a genetic algorithm is included to determine the optimum values for the kinetic rate parameters, which maximize the goodness of fit of the model compared with measured data. However, it is to be noted that there is no relationship between QUAL2K and QUAL2Kw and QUAL2Kw obtains good results in conversion of algal death to carbonaceous BOD [48]. Hence, this model suits the situation where macrophyte (rooted aquatic plants) cause important interactions. It also has an automatic calibration system and Kannel et al. [49] used QUAL2Kw to simulate the DO concentrations on the Bagmati River in Kathmandu Valley, Nepal. The sensitivity analysis showed that the model was highly sensitive to water depth and moderately sensitive to point source flow, TN, carbonaceous BOD and nitrification rate. The model has the limitation that it cannot simulate branches of the river systems.

2.5 HSPF

HSPF (Hydrological Simulation Program-FORTRAN) was also developed by US Environmental Protection Agency (USEPA) to represent contributions of sediment, nutrients, pesticides, conservatives and fecal coliforms from agricultural areas, and to continuously simulate water quantity and quality processes on pervious and impervious land surfaces and in streams and well-mixed impoundments [50]. HSPF is based on the original Stanford Watershed Model IV [51] and combines three previously developed models: Agricultural Runoff Management Model, Non-point Source Runoff Model, and Hydrological Simulation Program (HSP) including HSP Quality. Details are available at <http://www.epa.gov/ceampubl/swater/hspf/index.htm>. It can simulate the water quality elements including temperature, fecal coliforms, DO, BOD, total suspended solids, nitrates, orthophosphates, and pH. Kim and Chung [52] developed an index-based robust decision making framework for watershed management dealing with water quantity and quality issues in a changing climate using HSPF to understand the watershed components and processes, producing an improved system for integrated water management (IWM). Fonseca et al. [53] used HSPF to predict the impact of PS and NPS pollution on the water quality of the Lena River. The model simulated detailed watershed temperatures and concentrations of various water constituents in the river.

The limitations of HSPF include: (1) many physical processes are based on empirical relationships not mechanisms, (2) accuracy of the model is susceptible to meteorological factors, (3) the model is limited to well-mixed rivers and reservoirs and one-dimensional flow and it has difficulty in solving complex situations, (4) a large

number of elements are needed and it is difficult to make sure their of their accuracy so extensive calibration is required, (5) it is not sensitive to spatial variation, and (6) it requires a high level of expertise for application [54].

2.6 CE-QUAL-W2

CE-QUAL-W2 model (W2), is a waterp quality and hydrodynamic model with two dimensions (longitudinal and vertical) for rivers, estuaries, lakes, reservoirs and river basin systems. It was developed by the US Army Corps of Engineers' Waterways Experiment Station [55]. It is available at no cost from www.ce.pdx.edu/w2. The model assumes lateral homogeneity, which is particularly suited for water systems with little lateral variations in the water quality constituents. The model can simulate DO, TOC, BOD, *Escherichia coli* and algae. Seventeen kinds of water quality variables of concentration change [Eq. (6)] [56].

$$\frac{\partial BC}{\partial t} + \frac{\partial UBC}{\partial x} + \frac{\partial WBC}{\partial z} - \frac{\partial \left(BD_x \frac{\partial C}{\partial x} \right)}{\partial x} - \frac{\partial \left(BD_z \frac{\partial C}{\partial z} \right)}{\partial z} = C_q B + SB \quad (6)$$

where B is the layer of time space change; C is the horizontal component of the average concentration; U and W are the lateral average velocities in x direction and y direction, respectively; D_x and D_z are the diffusion coefficients of temperature and composition, respectively; C_q is the components of input and output flow of material flow rate; and S is Sources and sinks.

W2 has been applied to many different water systems, including lakes, reservoirs and estuarine environments. Lung and Sen [57] used W2 in Patuxent estuary to address the impact of current and projected land-use changes (stress) on the water quality. The results showed reductions of nutrient loads would lead to improvement of anoxic conditions in the bottom waters of the lower Patuxent estuary. W2 was used to examine the distribution and survival of white sturgeon (*Acipenser transmontanus*) in a reservoir subject to large spatial and temporal variation in DO and temperature [58]. Soon et al. [59] used W2 to describe the influence of diffuse pollution on the temporal and spatial characteristics of natural organic matter in a stratified dam reservoir, the Daechong Dam. Recently, Deus et al. [60] used the W2 to validate about 5 years of field data for temperature, nitrate, ammonia, phosphorus, total suspended solids, DO and chlorophyll *a*. The model was able to reproduce horizontal and vertical gradients, and their temporal variability. The results also showed that chlorophyll *a* should be used as the key indicator to assess the trophic state of the system, and they also examined future scenarios by using the model. Yongeun Park et al.

[61] applied the W2 model to predict the pollutant load and to help in reservoir management.

2.7 EFDC

EFDC (Environmental Fluid Dynamics Code), developed by Hamrick [62], is a versatile surface water modeling system, which includes hydrodynamics, sediment transport, toxic contaminant transport and water quality-eutrophication components. EFDC has become one of the most widely used hydrodynamic models. EFDC has been applied to different water bodies including rivers, lakes, reservoirs, wetlands, estuaries, and coastal regions in environmental assessment and management [63–65]. Franceschini and Tsai [66] coupled two numerical models, the Environmental Fluid Dynamic Code (EFDC), for the hydrodynamic portion, and WASP, for the fate and transport of contaminants, using the data from May 1995 to March 1997 on Lake Eris, and achieved an improved comparison of model predictions and measured data. For algae growth prediction, Wu and Xu [67] used the EFDC model to describe and simulate the eutrophication process in the Daoxiang Lake, Beijing. The results showed that EFDC was effective at predicting the algal blooms through chlorophyll-a. To examine salinity spread, Xu et al. [68] used the model to calibrate and verify against water level variation, temperature and salinity variations during 2003 and 2001 in the Pamlico River Estuary. The results showed that salinity intruded further upstream under scenarios with low flow, down river local wind, and water level set-up conditions. Jeong et al. [69] used the model in the analysis of the salinity intrusion characteristics in the downstream sector of the Geum River. EFDC provided high accuracy for numerical simulation and could also be used as a basis for understanding the extent of salinity intrusion effects at different river flow rates. To examine the influence of waterway constructions on estuarine circulation, EFDC was calibrated with measured tidal current and salinity forces by observing freshwater discharge and tides on the Changjiang Estuary and adjacent coastal sea. The model helped improve the understanding of the response of the transport timescale under different dynamic conditions, and the impact of the waterway construction on the transport processes [70].

2.8 ELCOM-CAEDYM

ELCOM-CAEDYM (Estuary and Lake Computer Model-Computational Aquatic Ecosystem Dynamics Model), a three-dimensional hydrodynamic and ecological model, was developed by the Centre for Water Research at the University of Western Australia. ELCOM-CAEDYM has been widely used for lakes, reservoirs and estuaries [71–77]. ELCOM can solve the unsteady, hydrostatic, Boussinesq, Reynolds-averaged, Navier–Stoke equations, thermodynamic models and scalar transport equations to

simulate spatial and temporal water temperature and velocity distribution [78,79]. CAEDYM is an ecological model, and can simulate three dimensional biogeochemical processes [80]. CAEDYM can also simulate macrophytes, zooplankton, fish and benthic invertebrates [81]. Robson et al. [82] used the ELCOM-CAEDYM model to evaluate the likely outcomes of different management scenarios when there was a large, mono-specific bloom of the cyanobacterium, *Microcystis aeruginosa*, after rainfall in January 2000. The results showed that salinity and temperature were important in controlling the growth of *M. aeruginosa*, demonstrating the usefulness of the model as a predictive management tool.

Spillman et al. [73] applied the coupled model, first validated against available field and satellite data, and subsequently used it to resolve the influence of river inflows, basin-scale circulation patterns and stratification patterns on the spatial distributions of nutrients and phytoplankton. They indicated a close coupling of physical and biologic processes over a range of space and time scales through the model simulation results and mass balance calculations. Recently, in response to algal blooms, Yajima et al. [77] applied the model to the Urayama Reservoir in order to examine the effect of an inflow bypass on the water quality in the reservoir through simulating water temperature, DO, turbidity, nutrients and four groups of phytoplankton (cyanobacteria, diatoms, chlorophytes and cryptophytes). The results indicated the operation of the bypass system was useful in decreasing inflow nutrient loads and decreasing the transport of the algal biomass from upstream to the dam wall.

3 Discussion and future perspectives

With the development of water quality models, the ability to manage water quality has improved, but there continues to be challenges. The models need a substantial amount of data, and the data needs to be valid, complete and systematic. Models do not include mechanisms of pollutants and are not clear about the migration of contaminants in the media transformation process, so there could be large deviation between the facts and the simulation depending on the assumptions. If the parameters chosen are not accurate, the result will be inaccurate.

According to the understanding and application of all models in different areas of analysis and the problems faced, the current trends in water quality model development are as follows:

3.1 Combination models

With the development of water quality models, more and more elements are considered. The individual models cannot simulate all elements, so there is a need for

combination models. A combination model can include two or three individual models that simulate different elements. For estuaries [83], it took three models: a hydrodynamic model, a sediment model, and a biogeochemical model, to provide a suitable result. There are very few coastal and estuarine areas that be examined with such a complex model to examine possible scenarios. A combination model was used to help test potential hypotheses and realistic future states of the estuary and in response to anthropogenic and environmental changes relating to sewage treatment improvements, river flow and changes in storm water/catchment contribution (e.g., urban to forest).

3.2 Application of artificial intelligence methods

Models described in Section 2 are mechanistic models, and they have quantified the existing physical, chemical and biologic processes, but they cannot control their own rules, and for this, non-mechanistic models should be used. Non-mechanistic models can run according to the law of the water environment system using the data from experimental observation, eliminating uncertainty caused by mechanistic models. The observed experimental data can be processed by non-mechanistic models to provide many system parameters and environmental parameters for mechanistic models, so the combined model will be more reliable and accurate.

There are some models that combine computer algorithms (such as neural networks), genetic algorithms and fuzzy reasoning, and support vector machine algorithms. To improve success, there will be more water models combined with computer algorithms in the future.

4 System integration

The integration of remote sensing, geographical information and global position systems (RS, GIS and GPS) has been called 3S [84]. 3S uses powerful data acquisition, storage, management, query and retrieval capabilities to solve the problems of traditional water quality models in collecting and processing massive amounts of data. RS can facilitate access to information in the soil, vegetation, topography and water sides of the interface, to determine runoff characteristics and model parameters to provide effective technical means. GIS has great advantages in spatial analysis and could allow representation of water environment information from a single table of data into intuitive graphics and moving images. GPS has the ability to determine precise and accurate time and speed. Some models have already been incorporated with GIS, such as MIKE 11, SWAT and HSPF. Therefore, incorporation of 3S will be an important trend for water quality models.

5 Conclusions

Hydrologic/water quality models are important for management, planning and pollution control for government, so eight models are described in this review. Each model is described from its intended use, development, simulation elements, basic principle and applications. There are one-dimensional models for rivers (e.g., SWAT, MIKE 11 and QUAL-2E), two-dimensional models for lakes and reservoirs (e.g., CE-QUAL-W2), and three-dimensional models for estuaries (e.g., WASP and ELCOM-CAE-DYM). With the increasing importance of water quality, more and more elements are included in models to assist in studying and managing water quality, and there are some challenges: the models need a substantial amounts of data that should be valid, there could be large deviation between the facts and the simulation depending on the assumptions because models do not include mechanisms of pollutants and are not clear about the migration of contaminants, and we cannot determine the accuracy of the selected parameter, so the result will be inaccurate. With the complexity of water quality issues, the first trend for water quality modeling is combination models which can solve some problems that single model cannot, the second trend is application of artificial intelligence models that can use experimental data for mechanistic models as parameters, and, finally, system integration known as 3S which can effectively solve the problem of large amount of data.

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