




Applicability of water quality models around the world—a review

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Abstract

Water quality models are important tools used in the management of water resources. The models are usually developed for specific regions, with particular climates and physical characteristics. Thus, applying these models in regions other than those they were designed for can generate large simulation errors. With consideration to these discrepancies, the goal of this study is to identify the models employed in different countries and assist researchers in the selection of the most appropriate models for management purposes. Published studies from the last 21 years (1997–2017) that discuss the application of water quality models were selected from three engineering databases: SpringerLink, Web of Science, and Scopus. Seven models for water quality simulations have been widely applied around the world: AQUATOX, CE-QUAL-W2, EFDC, QUALs, SWAT, SPARROW, and WASP. The countries most frequently applying water quality models are the USA, followed by China, and South Korea. SWAT was the most used model, followed by the QUAL group and CE-QUAL-W2. This study provides the opportunity for researchers, who wish to study countries with fewer cases of applied water quality models, to easily identify the work from that region. Furthermore, this work collated central themes of interest and the most simulated parameters for the seven countries that most frequently employed the water quality models.

Keywords Engineering database · AQUATOX · CE-QUAL-W2 · SWAT · QUALs · water resources

Introduction

Continuous population growth and economic development gave rise to international concern regarding the pollution of water sources, which often surpasses the level at which a water body's aquatic system has the potential for self-purification (Zinia and Kroeze 2015; Liang and Yang 2019). Ashouri and Rafei (2018) argued that the most striking problem caused by human activity in most developing countries is pollution and the complications arising from it. Pollution of water resources affects local biodiversity and increases

wastewater treatment costs, which often makes treatment economically unviable. Therefore, the prevention of pollution is a crucial component of global economic management. Water quality models are important tools for effective water management, assisting decision-making by providing water quality simulations (Lai et al. 2011; Zhang et al. 2012a, b) and allowing testing of a variety of management actions (Hoang et al. 2019). Moreover, such models lower the need for water collection and analysis, which reduces costs in both resources and time (Whittaker et al. 2003; Srivastava et al. 2002; Arabi et al. 2006; Cools et al. 2011).

There are several existing reviews of water quality models. Cox (2003) compared six models for dissolved oxygen simulation (SIMCAT, TOMCAT, QUAL2E, QUASAR, MIKE-11, and ISIS) in lowland rivers. Borah and Bera (2003) compiled a summary of eleven watershed-scale hydrologic and non-point source pollution models: AGNPS, AnnAGNPS, ANSWERS, ANSWERS-Continuous, CASC2D, DWSM, HSPF, KINEROS, MIKE SHE, PRMS, and SWAT. Borah and Bera (2004) selected three watershed-scale hydrologic and nonpoint-source pollution models, SWAT, HSPF, and DWSM, and reviewed their applications based on the

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literature. Booty and Benoy (2009) compared the nutrient, sediment, and pathogen simulations of six watershed models: SWAT, AnnAGNPS, BASINS, GIBSI, AGNPS, and HSPF. Kannel et al. (2011) compared the processes, input data, model capability, limitations, model strengths, and applicability of six models: SIMCAT, TOMCAT, QUAL2Kw, QUAL2EU, WASP7, and QUASAR. Gao and Li (2014) selected eight water quality models (SWAT, WASP, QUALs, MIKE 11, HSPF, CE-QUAL-W2, ELCOM-CAEDYM, and EFDC) and compared their characteristics, abilities, and limitations. Although these articles provided detailed information on the chosen models, the countries where the models were applied were not part of the reviews.

Tan et al. (2019) reviewed SWAT model studies in Southeast Asia, with an emphasis on model applications, current challenges, and future research directions. Chinyama et al. (2014) claimed that a country's legislative environment is important for selecting the appropriate model for management purposes. Models are usually developed for a specific region, to suit a specific climate type and physical characteristics. Therefore, the application of these models in regions other than those they were designed for can produce large errors in the simulations. Thus, identifying the areas where models have already been successfully applied assists the selection of a model to use in a similar context.

Wang et al. (2016) performed a bibliometric analysis (i.e., a quantitative study of bibliographic material from 2000–2014) regarding the development and growth of the research field concerning river water quality assessment and simulation. Although their study was not focused on water quality models, but on keyword selection of water quality studies, the SWAT model was highlighted throughout the survey, being widely accepted as the most effective model for water quality analysis that has been developed in the past 15 years. The USA, followed by China and the UK, were the most significant contributors in this field of research. A bibliometric analysis by Sun et al. (2012) found that the ten most productive countries/territories in terms of articles addressing pollution research, in the years 1973–2008, were the USA, UK, Canada, France, Japan, Australia, Spain, Netherlands, Germany, and China. Wang et al. (2011) performed a bibliometric analysis of articles published in water resource journals from 1993 to 2008. The results showed that researchers mostly studied groundwater conditions and water quality parameters. The most popular techniques in the water resource research were modeling and adsorption. A similar study by Wang et al. (2009) analyzed articles published in the journal *Water Research* from 1967 to 2008. They found that the US Environmental Protection Agency (USEPA) was the most productive institute with regards to the relevant research, whereas among countries, Switzerland produced the most cited articles.

However, there were no studies regarding the application of water quality models by country in the literature. Hence,

there is a lack of studies in countries where water quality modeling applications are sparse. Moreover, only few review articles focused on developing and underdeveloped countries, making it difficult to advise on water quality modeling in these locations. One exception is the article by Bressiani et al. (2015), which presented a study of SWAT applications, over a period of 14 years, in Brazil. Further, Wambu and Ho (2016) performed a bibliometric analysis of drinking water research in Africa, from 1991 to 2013, and found that the ten most productive research institutes were located in South Africa and Egypt.

The objective of this study is to identify the models being used in particular countries and how these are influenced by their major themes of interest. This is intended to assist researchers in the selection of the most appropriate models for management purposes. To this end, articles from the past 21 years (1997–2017) addressing the application of water quality models were selected from three engineering databases: SpringerLink, Web of Science, and Scopus. From these databases, the research listed under “Water Quality Models” was first isolated. Some models that were widely applied to attributes other than water quality were discarded. SWIM, for example, was mostly used for simulation of the hydrological cycle: the Monte Carlo simulation is a statistical model used for many purposes. After analyzing the publications drawn from the databases, seven models were identified as the most used in water quality simulations: AQUATOX, CE-QUAL-W2, Environmental Fluid Dynamics Code (EFDC), QUALs (QUAL2E, QUAL2E-UNCAS, QUAL2K, and QUAL2Kw), Soil and Water Assessment Tool (SWAT), Spatially Referenced Regression on Watershed Attributes (SPARROW), and Water Quality Analysis Simulation Program (WASP).

Methodology

We performed a database search for articles by selecting the language “English,” marking the content type or document type as “Article,” without selecting the preview-only content in SpringerLink. Articles on AQUATOX were searched using the keyword “AQUATOX,” which resulted in 80, 31, and 32 articles in SpringerLink, Web of Science, and Scopus, respectively. The search for “CE-QUAL-W2” resulted in 77, 129, and 124 articles from the same databases. The “Environmental Fluid Dynamics Code” provided 50, 99, and 102 articles on EFDC. Articles on QUALs were searched using the keywords “QUAL2K,” “QUAL2KW,” and “QUAL2E,” resulting in 36, 27, and 114 articles from SpringerLink, 34, 24, and 92 articles from Web of Science, and 41, 25, and 93 articles from Scopus. The keywords “water quality” and “soil and water assessment tool” generated 487, 687, and 586 articles on SWAT, providing a total of 1766 articles. The exact phrase “Spatially Referenced Regressions on Watershed Attributes,” yielded

26, 21, and 42 articles on SPARROW. Finally, “Water Quality Analysis Simulation Program,” located 59 articles on WASP in SpringerLink, 58 in Scopus, and 52 in Web of Science.

Additional criteria were then adopted for the selection of articles: (1) at least one case study, using one of the above models, must have been described; (2) the application should have been for water quality simulations (this is important, as some models can be used for other purposes, and studies where the model was applied to only verify the flow of the water, for instance, were disregarded). The articles that met these criteria are listed in Appendix 1.

After analysis of the selected publications, each water quality model was briefly described and sorted by country of application. The central themes of interest and most simulated parameters were identified in the countries with most models.

Subsequently, statistical analysis was employed to identify main groups of countries using various models. Cluster analysis depicts a group of multivariate techniques, whose primary purpose is to aggregate objects based on their characteristics. Clusters should exhibit high internal homogeneity and high external heterogeneity. Thus, the objects within groups are expected to be close together when represented graphically, while different groups are expected to be distant. Multivariate analysis was used to create clusters and subsequently to depict the similarities within them, elucidating relationships among studies of the application of water quality models in various countries.

Water quality models

The following sections include brief descriptions of each water quality model. These include development, model system governing equations, strengths, assumptions and limitations, model linkage, and improvements.

AQUATOX

AQUATOX is a general, mechanistic ecological risk assessment model intended to evaluate past, present, and future direct and indirect effects from various stressors including nutrients, organic wastes, sediments, toxic organic chemicals, flow, and temperature in aquatic ecosystems (Park et al. 2008). AQUATOX is the latest in a long series of models, starting with the International Biological Program’s aquatic ecosystem model CLEAN first published in 1974 (Park 1974). The toxic fate model PEST was developed in the late 1970s (Park et al. 1982) to complement the CLEANER model. The models were linked to the Microsoft Windows interface to provide flexibility, capacity for additional compartments, and user friendliness (Park et al. 1995).

AQUATOX employs a fourth- and fifth-order Runge-Kutta integration routine (Park et al. 2008) and an adaptive step method to solve differential equations. The model simulates

the impact of pollution on living organisms and can be used for stratified lakes, reservoirs, rivers, and estuaries. The model assumes that the individual hydrologic segments are uniformly mixed, allowing the application to multiple river and reservoir segments. In addition to hydraulic and geometric data, the model also requires data on abiotic and biotic state variables, physical characteristics, remineralization, and ecotoxicology (Sharma and Kansal 2013). The model may explain fluctuations in the oxygen demand and toxicity arising from low oxygen levels and the presence of ammonia (Park et al. 1988). Some of the model governing equations (Sharma and Kansal 2013) are presented in Appendix 2.

AQUATOX’s strengths include the incorporation of ecological effects, Latin hypercube uncertainty analysis, nominal range sensitivity, and time-variable process rates analysis. It can simultaneously simulate up to 20 organic chemicals. The model has been coupled to the Microsoft Windows interface for greater flexibility and ease of use (Park and Clough 2014). According to Park et al. (2008), AQUATOX linkage options include: BASINS (Better Assessment Integrating Point and Nonpoint Sources), geographical information system (GIS) layers, HSPF (Hydrological Simulation Program—FORTRAN), SWAT, and GenSen (the display utility of BASINS, which also includes several statistical functions). Moreover, according to Park and Clough (2014), AQUATOX may be linked to CO2SYS, CO2calc, and other similar salt-water carbon chemistry models. Furthermore, AQUATOX has been successfully coupled with HSPF and the Upstate Freshwater Institute Lake Stratification Model No. 4 (UFILS4) for analysis of climate driven impacts on catchment hydrology and lake hydrodynamics (Taner et al. 2011). Model improvements include the work of Lei et al. (2008), who modified the AQUATOX model to simulate the time-dependent nitrobenzene distribution and its potential ecological impacts.

AQUATOX relies on certain assumptions and has several limitations. Namely, it does not allow for dynamic stratification, and toxic effects are presumed to be additive. Furthermore, macrophytes and algae are simulated assuming a steady state, while zooplankton and fish simulations exhibit avoidance behavior. Toxicant exchange via gill membranes is facilitated by the same mechanism as the uptake of oxygen. AQUATOX does not take into account metals and luxury uptake, and it is further limited as internal nutrients are not represented in algal bioenergetics (Sharma and Kansal 2013).

CE-QUAL-W2

CE-QUAL-W2 is a two-dimensional, longitudinal/vertical, hydrodynamics, and water quality model. Because the model assumes lateral homogeneity, it is best suited for relatively long and narrow water bodies exhibiting longitudinal and vertical water quality gradients. The model has been applied to rivers, lakes, reservoirs, estuaries, and combinations thereof

(Cole and Wells 2006). The CE-QUAL-W2 model employs a state-of-the-art numerical solution scheme (QUICKEST) to solve for the laterally averaged advection–dispersion equations (Debele et al. 2008). Some of the model governing equations (Cole and Wells 2006) are presented in Appendix 2.

The use of CE-QUAL-W2 is advantageous, because it is an open-source model capable of two-dimensional hydrodynamic simulation (Shokri et al. 2014). According to Liu et al. (2006), the model may be coupled with BASINS, which consists of several sub-models, including HSPF, QUAL2E, and SWAT, and is supported by GIS data. The model was also successfully coupled with the following: AnnAGNPS model for nonpoint source pollution loading simulations (Zhu et al. 2012), Nondominated Sorting Genetic Algorithm-II (NSGA-II) to produce a simulation-optimization method (Amirkhani et al. 2016), Precipitation-Runoff Modeling System (PRMS) hydrologic models for water temperature and daily streamflow simulation (Buccola et al. 2016), Coalbed Methane Produced Water Routing (CBMPRO) model to chart coalbed methane discharge and the transport of its associated constituents as input to CE-QUAL-W2 (Wang and Yang 2008), and Particle Swarm Optimization (PSO) module for reallocation of waste loads to a river–reservoir system (Afshar and Masoumi 2016).

Bowen and Hieronymus (2003) enhanced the sediment diagenesis of the model and developed an empirically derived light extinction prediction. Chung and Gu (2009) enhanced the model by incorporating a sub-model for toxic chemicals and applied this for atrazine management in the Saylorville Reservoir, Iowa. Shokri et al. (2014) added the volatilization calculation capability to the model for methyl tert-butyl ether (MTBE) simulations. Zhang et al. (2015) included the benthic sediment processes and sediment-water interactions in CE-QUAL-W2, which were originally oversimplified by descriptions of zero-order and first-order rates. Peng et al. (2016) added a manganese biogeochemical module to the model to evaluate manganese pollution processes. Further, the model was enhanced to simulate mercury (Zhu et al. 2017), and the fate and transport of volatile organic compounds (Afshar et al. 2017) in water bodies.

Water quality interactions are, by necessity, simplified descriptions of an aquatic ecosystem that is extremely complex. The model also includes a user-specified sediment oxygen demand (SOD) component that is not coupled to the water column. The model does not simulate kinetics in the sediment or at the sediment-water interface, i.e., a complete sediment diagenesis model. This limits the long-term predictive capabilities of the water quality portion of the model (Cole and Wells 2006).

Environmental fluid dynamics code (EFDC)

The Environmental Fluid Dynamics Code (EFDC) model was developed at the Virginia Institute of Marine Science

(Hamrick 1992). The EFDC model is a versatile surface water modeling system, which includes hydrodynamics, sediment transport, toxic contaminant transport, and water quality-eutrophication components (Wu and Xu 2011). In the EFDC model, equations that govern flow hydraulics are derived from the vertically hydrostatic boundary layer form of the turbulence equations of motion for an incompressible, variable density fluid (Wu and Xu 2011). Some system governing equations (Tech 2007) are provided in Appendix 2.

EFDC is highly versatile and can be used for 1-, 2-, or 3-dimensional simulations of rivers, lakes, estuaries, coastal regions, and wetlands. The solution technique constitutes a finite volume–finite difference spatial discretization with a staggered C grid. The EFDC model is capable of simulating a diverse range of environmental flows and transport problems, often addressing critical questions related to both the health of human beings and the health of natural ecosystems (Luo and Li 2009).

According to Zhu et al. (2016), EFDC can be coupled with any OpenMI-compliant model. For example, it can be coupled with InfoWorks-CS for hydrologic and hydraulic modelling in urban areas. Kim et al. (2014b) linked HSPF and EFDC, where HSPF outputs were used as boundary conditions in EFDC to simulate river hydrodynamics and biochemical reactions. WASP and EFDC were coupled in several studies for a hydrodynamic water quality model (Jia et al. 2011; Seo et al. 2012; Franceschini and Tsai 2010; Quijano et al. 2017). Chen et al. (2017) enhanced the EFDC model to simulate benthic and floating macroalgae as separate state variables and added a sediment diagenesis model to simulate interactions between the watershed load and the benthic nutrient flux.

QUALs

According to Brown and Barnwell (1987), the stream water quality model QUAL2E is intended for employment as a water quality planning tool for waste load allocations, discharge permit determinations, and other conventional pollutant evaluations. USEPA released a series of QUAL models: QUAL2E, QUAL2E-UNCAS, QUAL2K, and QUAL2KW. All are implemented in the Microsoft Windows environment. The QUALs are one-dimensional steady-state water quality models widely used for river simulations. QUAL2E was developed in 1985, and the model has since been improved and incorporated with other USEPA models such as HSPF and WASP5 in a GIS environment in the BASINS software (Cox 2003). QUAL2E-UNCAS is an enhancement of QUAL2E, allowing for uncertainty analysis along with water quality simulation. The QUAL2K model is also an updated version of QUAL2E, where most of the models' equations are the same, except for those for DO, BOD, and nitrate, which have been improved. A more detailed comparison between QUAL2E and QUAL2K is provided in the study of Park

and Lee (2002). QUAL2Kw is the newest and most improved version of QUAL2K. The model includes bottom algae and hyporheic zone simulations, which are essential for the simulation of shallow streams. Further, the sediment–water fluxes of dissolved oxygen and nutrients are simulated internally rather than being prescribed (Pelletier et al. 2006). Some system governing equations (Gao and Li 2014; Brown and Barnwell 1987; Pelletier and Chapra 2006; Sharma and Kansal 2013) are given in Appendix 2.

QUALs simulate point and nonpoint pollutant loadings. QUAL2E can simulate more than 15 constituents: biochemical demand, 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, dissolved oxygen, coliform bacteria, one arbitrary non-conservative constituent solute, and three conservative constituent solutes. In addition to these constituents, QUAL2Kw can simulate temperature, pH, carbonaceous biochemical demand, sediment oxygen demand, phytoplankton, and bottom algae. Moreover, the flow conditions can be considered to be either permanent or dynamic.

The model was successfully coupled in the following ways. Rousseau et al. (2013) developed an integrated modeling system that included the Revised Universal Soil Loss Equation (RUSLE), Erosion-the Productivity Impact Calculator (EPIC) of SWAT, and QUAL2E to evaluate the effects of different beneficial management practices on sediment and nutrient yields in a watershed. Salvetti et al. (2008) estimated surface runoff loading with QUAL2E for a dry weather scenario and BASINS-SWAT for the weather scenario. Salvetti et al. (2006) also applied QUAL2E simulation data as the input in SWAT for simulation of river nutrient loadings. Galbiati et al. (2006) developed an integrated surface and subsurface model using SWAT, groundwater models ModFlow and Mt3Dms, and QUAL2E to predict the leaching of water and nutrients from the soil surface to aquifers. Ryu et al. (2016) coupled QUAL2E with Streamflow Synthesis and Reservoir Regulation (SSARR) to perform hydrological and water quality modeling. Moreover, the model has been integrated with GIS (Yang et al. 1999) and the Generalized Watershed Loading Function (GWLf) for nonpoint source pollution simulations (Lin et al. 2010a), OTIS for advection-dispersion solute transport simulations (Bailey and Ahmadi 2014), and MODSIM river basin network flow model or estimating the quality of irrigation return flows (Dai and Labadie 2001). Ennet et al. (2008) linked QUAL2K to the Wennerblom (*f*lvsborg) diffused pollution model for water quality– and land-based pollution simulations. Fan et al. (2009) integrated HEC-RAS with QUAL2K to evaluate the impact of tidal effects on water quality simulation, which is not considered by QUAL2K. Lin et al. (2010b) applied the Integrated Watershed Management Model (IWMM) to evaluate the impact of nonpoint source pollutants discharged from agricultural areas into

the Houjing River, and the results were used as pollutant input to QUAL2K. Udías et al. (2014) developed an integrated tool using the Multi-Objective Evolutionary Algorithm (MOEA) and QUAL2K for a simultaneous multi-objective analysis of the influence of wastewater treatment plants.

Han et al. (2001) developed a QUAL2E-Reliability Analysis (QUAL2E-RA) model, incorporating the Advanced First-Order Second-Moment (AFOSM) and Mean-Value First-Order Second-Moment (MFOSM) methods into QUAL2E for stochastic water quality analysis. Zhao et al. (2013) modified nitrification algorithms to improve nitrogen parameters.

The assumptions and limitations of the QUAL models include provision of only one-dimensional simulation, while flow is assumed to be in a steady state. Moreover, the models do not simulate branches of the river system and no uncertainty component is included.

Soil and water assessment tool (SWAT)

SWAT is a continuous-time, semi-distributed, process-based river basin model. It was developed to evaluate effects of the nonpoint source pollution and alternative management decisions on water resources and large river basins (Arnold et al. 1998; Arnold et al. 2012). The model was developed in the early 1990s by the US Department of Agriculture's Agricultural Research Service (USDAARS) (Di Luzio et al. 2004; Gassman et al. 2007; Williams et al. 2008). Since, SWAT has undergone continued review and capability expansion. The first version (SWAT 94.2) had multiple hydrological response units (HRUs) incorporated. Versions 96.2, 98.1, 99.2, and 2000 were described by Arnold and Fohrer (2005), who also detailed the expanding global use of SWAT. More recently, Williams et al. (2008) described version 2005, and Douglas-Mankin et al. (2010) and Tuppad et al. (2011) described version 2009. SWAT 2012 allows modeling of many conservation practices, which were not included in prior versions, by entering their pollutant removal efficiencies (Seo et al. 2017). The main equations can be found in the study by Arnold et al. (1998). Some of the system governing equations (Neitsch et al. 2011) are provided in Appendix 2.

SWAT is an open source, with a large and growing number of model applications ranging from catchment to the continental scale (Abbaspour et al. 2015). Successful calibration of the hydrologic model SWAT, even under data scarcity, proves the potential of the model in data limited basins. Water resource managers, in particular, require an understanding of existing conditions and possible futures (Nyeko 2015).

Specific reported weaknesses (Almendinger et al. 2014; Beeson et al. 2014; Fohrer et al. 2014) clearly demonstrate the need for expanded testing and/or specific improvements (Gassman et al. 2014). SWAT is a hydrologic/water quality

model largely used to analyze the impact of different management scenarios on water supplies and evaluate the nonpoint source pollution in watersheds and large river basins. The model can simulate sediment erosion, nutrients (nitrogen and phosphorus), pesticide, bacteria, plants, and other variables. It can provide output at various temporal (daily annual) and spatial scales (HRU/field, reach, watershed) (Muenich et al. 2016). Moreover, the model divides a basin into sub-watersheds and the sub-watersheds into HRUs, and requires data on soil, land use, and slope combinations for each of those sub-basins, which improves modeling at the cost of enormous effort and time (Jayakrishnan et al. 2005).

SWAT comprises GIS interfaces that link maps of land use and occupation to SWAT plant types (Arnold et al. 1996). Noh et al. (2014) coupled a hydrodynamic water quality model CE-Qual-Riv1 with SWAT to simulate turbidity propagation in a stream. Ehtiat et al. (2018) linked SWAT, modular finite difference groundwater flow (MODFLOW), and modular 3-dimensional multi-species transport (MT3DMS) models to quantify the influence of changes in land and surface water resources on the subsurface water system. Ali and Bruen (2016) linked SWAT and HSPF to model phosphorus losses from agricultural land. Yazdi and Moridi (2017) developed an integrated model with SWAT and CE-QUAL-W2, and used it for simulating reservoir water quality. Meanwhile, SWAT was used for modeling of the surface runoff and transportation of the pollutant load. Brito et al. (2018) applied SWAT inputs to CE-QUAL-W2 for algae and trophic level management in a reservoir. Abouali et al. (2017) coupled SWAT with a model referred to as System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN) to simulate the impacts of wetland implementation scenarios in a watershed.

Wu et al. (2012) modified SWAT to better represent the influence of rising CO₂ levels on vegetation and watershed hydrology. Hoang et al. (2017) developed the SWAT-Hillslope (SWAT-HS) model to improve the simulation of saturation-excess runoff. Bai et al. (2016) modified the water temperature equation of SWAT to improve fecal coliform simulations in China. Fu et al. (2014) developed SWAT-CS, a modified version of SWAT (version 2009.10.1 Beta 3), to better represent the typical landscape of Canadian Shield catchments, thus improving hydrological process modelling in Canada. However, SWAT-CS did not consider nitrate modelling, which was later included in SWAT-CS_{enm} (SWAT-CS with an Enhanced Nitrate Module) by Zhang et al. (2016).

Spatially Referenced Regression on Watershed attributes

Spatially Referenced Regressions on Watershed Attributes (SPARROW), developed by Smith et al. (1997), is a watershed modeling tool that uses a hybrid statistical and process-based approach to estimate pollutant sources and contaminant

transport in watersheds and surface waters. According to Schwarz et al. (2006), SPARROW can be linked to deterministic process models to analyze the empirical importance of the surface runoff process, hence verifying the statistical significance of the estimates of surface runoff derived from these models. SPARROW employs a statistically estimated nonlinear regression model with contaminant supply and process components, including surface-water flow paths, non-conservative transport processes, and mass-balance constraints (Schwarz et al. 2006). Some model governing equations (Schwarz et al. 2006) are presented in Appendix 2. Moreover, SPARROW data can be linked to SAS/GIS data sets. Kim et al. (2014a) developed an integrated modelling network by linking SPARROW with a Bayesian downscaling algorithm and a eutrophication model for phosphorus cycling simulations. Robertson et al. (2016) developed a linkage between results from SPARROW and a water-quantity Precipitation Runoff Modeling System (PRMS) to project changes in streamflow and nutrient loading due to climate or land use change.

This spatially distributed model structure allows separate statistical estimation of land and water parameters that quantify the rates of pollutant delivery from sources to streams and the transport of pollutants to downstream locations within the stream network (i.e., reaches, reservoirs, and estuaries). This mechanistic separation in the model of the terrestrial and aquatic features of large watersheds and the emphasis on parameter estimation techniques is an important advancement in the use of water quality models to objectively evaluate alternative hypotheses regarding major contaminant sources and watershed properties that control transport over large spatial scales (Schwarz et al. 2006). Among the assumptions and limitations in the statistical estimation of parameters in SPARROW provides measures of uncertainty in model coefficients and water quality predictions (Schwarz et al. 2006).

Water Quality Analysis Simulation Program (WASP)

WASP is a well-established three-dimensional deterministic model (Di Toro et al. 1983), providing dynamic compartment-modeling for aquatic systems, including both the water column and the underlying benthos. The time-varying processes of advection, dispersion, point and diffuse mass loading, and boundary exchange are simulated in the model (Zhang et al. 2008).

Pollution in rivers is affected by many processes including advection, dispersion, attenuation, reaction between waterbodies, and reaeration. The general equation for solute transport takes into account advection–dispersion (Zhang et al. 2008). Some model governing equations (Sharma and Kansal 2013) are provided in Appendix 2.

The ability to function in a stable fashion without highly detailed (and often unavailable) input data is one of the

primary strengths of WASP (Rose and Pedersen 2005). According to Ambrose and Wool (2009), WASP has the ability to obtain hydrodynamic information from the following hydrodynamic models: EFDC (three dimensions), DYNHYD (one dimension, branching), RIVMOD (one dimension, no branching), CE-QUAL-RIV1 (one dimension, branching), SWMM/Transport (one dimension, branching), and SWMM/Extran (one dimension, branching). Moreover, the model has been successfully coupled with the following: Finite Element Hydrodynamic Model (FEM) for hydrodynamic simulation (Umgiesser et al. 2003; Canu et al. 2001), Modular Finite-Difference Groundwater Flow Model (MODFLOW), and Modular 3-D Transport Model (MT3D) for simulating the impact of hydraulic changes of surface water flows on groundwater (Jia et al. 2015), SWAT to estimate nonpoint source pollutant loads (Park et al. 2013; Ekdal et al. 2011), Hydrologic Engineering Centre (HEC-2) models to consider the effects of geometric channel conditions on water quality (Rim et al. 2006), Integrated Watershed Management Model (IWMM) to calculate pollution loadings as the input data for WASP (Lai et al. 2011), Finite Volume Coastal Ocean Model (FVCOM) to provide hydrodynamic information (Justić and Wang 2014; Wang et al. 2012), HSPF and EFDC for total maximum daily loads calculation; Regional Ocean Modeling System (ROMS) for hydrodynamic information (Defne et al. 2017), RCM-XPORT2 to predict polychlorinated biphenyl fate and transport (Meric et al. 2012), GIS platforms for enabling analysis of spatially distributed phenomena (Peng et al. 2010), and EPA’s Loading Simulation Program in C++ (LSPC) to simulate flow and runoff (Privette and Smink 2017). Version 6.1 of WASP does not include simulation of sediment dynamics as a function of shear stress at the sediment–water interface, and an independent specification of resuspension and deposition velocities is required (Rose and Pedersen 2005).

Wang et al. (2012) modified the WASP model to determine the effect of zooplankton on eutrophication, which is not included in the WASP model. They reported that the growth and death of zooplankton significantly contribute to phytoplankton nutrition and the levels of dissolved oxygen in the eutrophication process. Zhang and Rao (2012) modified the WASP model employing different temperature correction terms for the phytoplankton growth rate, mineralization rate of dissolved organic nitrogen, and zooplankton grazing on phytoplankton, which were implemented using the Ivlev formula.

Results

Seven water quality models were selected as the most frequently used in the past 20 years (1997–2017): AQUATOX, CE-QUAL-W2, EFDC, QUALs, SPARROW, SWAT, and WASP. One-thousand-ninety articles were analyzed to

identify various application sites of these models and determine whether the models had been used for water quality analysis. The research revealed the increasing use of water quality models over the course of 20 years. In Fig. 1, this evolution during these years (*x*-axis) is evident: the *y*-axis denotes the number of articles that include an application of one of the models to water quality.

Figure 2 shows the percentage of articles that discuss the applications of each model. Among the 1090 articles analyzed, 18 articles dealt with studies where more than one model was applied. These included EFDC and WASP [238][271][405][516][545][695][723][813][973][991], WASP and SWAT [245][679], CE-QUAL-W2 and SWAT [568][817][1024], QUAL2E and QUAL2K [684], QUAL2E and SWAT [764], and QUAL2K and WASP [887]. Thus, in total, 1108 instances of application of these models were identified. SWAT was clearly the most applied model, being applied in 591 articles, which is more than half the total studies considered (53.3%). The SWAT model was followed by QUALs (134 applications/12.1%), CE-QUAL-W2 (127 applications/11.5%), EFDC (107 applications/9.7%), WASP (72 applications/6.5%), SPARROW (47 applications/4.2%), and AQUATOX (30 applications/2.7%).

The QUALs depict a series of models: QUAL2E, QUAL2E-UNCAS, QUAL2K, and QUAL2Kw. Among them, QUAL2E was the most applied model (61 articles/45.5%), followed by QUAL2 (39 articles/29.1%), QUAL2KW (27 articles/20.1%), and QUAL2E-UNCAS (7 articles/5.2%) (Fig. 3). The wide application of the QUAL2E model can be expected, as this was the first model in the series and the simplest.

Table 1 lists the countries where the models were applied. The SWAT model was applied in the greatest number of countries (68) followed by QUALs (47), CE-QUAL-W2 (20), WASP (11), AQUATOX (9), EFDC (7), and SPARROW (6). The USA and China together were responsible for 60% of the applications of AQUATOX. CE-QUAL-W2 was mostly applied in the USA, Iran, and China. Differentiating the other models, EFDC simulations were more frequent in

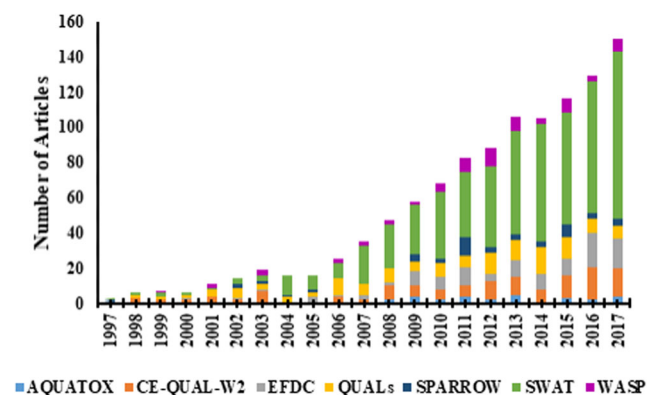
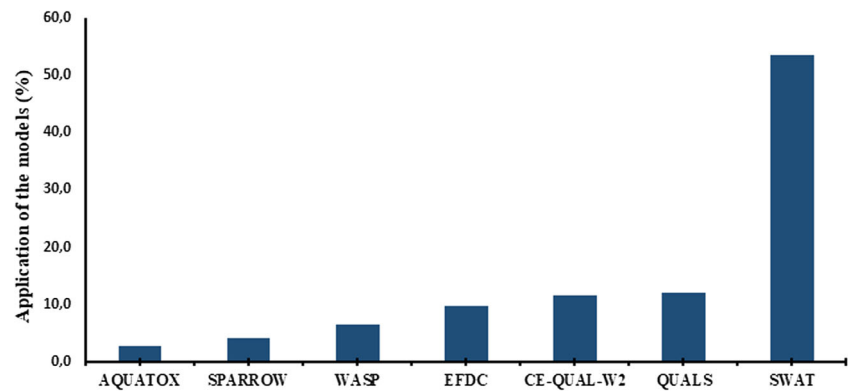


Fig. 1 Application of models to water quality during 20 years

Fig. 2 Application frequency of water quality models



China, followed by the USA and South Korea. QUAL2E is one of the simplest models that is extensively used in South Korea, Taiwan, India, and the USA. There were very few applications of QUAL2E-UNCAS, and most of those were in India. QUAL2K is most applied in China, followed by Taiwan and the USA. QUAL2KW simulations were performed mostly in the USA, followed by Iran and Portugal. SPARROW, SWAT, and WASP simulations were the highest in USA, Canada, and China.

Most models have been applied in the USA (AQUATOX, CE-QUAL-W2, SPARROW, SWAT, and WASP). However, with the exception of QUAL2KW, QUALs have been applied more frequently in developing countries such as South Korea, India, and China. This is probably because these are countries with fewer resources, providing less water quality data. Therefore, one-dimensional models, which are simpler and require less input data, tend to be chosen.

The seven countries that most frequently applied water quality models are shown in Fig. 4. SWAT is the most applied model in the USA, China, and Canada. In South Korea and India, SWAT and the QUALs are the most applied models. CE-QUAL-W2 is the most applied model in Iran, and QUALs are most applied models in Taiwan.

Van Griensven et al. (2012) realized a critical review of the use of SWAT in Nile basin countries (i.e., Tanzania, Uganda, Kenya, Rwanda, and Ethiopia). According to the authors, SWAT has been widely used due to free online access to basic

GIS data, even in data-scarce areas. However, SWAT modeling is not always appropriate, depending on the quality of the free databases available in these regions. Thus, SWAT was evaluated to give satisfactory to very good results in Nile basin countries. However, hydrological mass balances were not adequate due to unjustified losses. Other review articles found that SWAT was generally reliable in Brazil (Bressiani et al. 2015). Moreover, SWAT performed well in most Southeast Asia studies, despite the fact that the capability of the model is unknown in many Southeast Asian subregions (e.g., East Malaysia, Brunei, East Timor, and Singapore) (Tan et al. 2019). Further, the SWAT model demonstrated good to very good modelling performance for the USA (Jha et al. 2009; Jayakody et al. 2014; Jager et al. 2015; Panagopoulos et al. 2015; Rajib et al. 2016), China (Zhang et al. 2003; Wu and Chen 2009; Zhang et al. 2012a, b; Zhai et al. 2014; Chang et al. 2017), and Canada (Yang et al. 2010; Liu et al. 2016; Mekonnen et al. 2017). The model also exhibited reasonably good modelling performance for South Korea (Kim et al. 2011; Park et al. 2014; Lee et al. 2014; Jeong et al. 2016) and India (Pandey et al. 2005; Moses et al. 2015; Himanshu et al. 2017). However, in a study conducted in Canada, the SWAT model successfully predicted the flow and total nitrogen and total phosphorus in simulations, whereas it did not accurately simulate TSS and indicator bacteria transport (Frey et al. 2013). Moreover, some studies provided satisfactory results applying the CE-QUAL-W2 model in Iran (Afshar

Fig. 3 Application frequency of QUAL models in water quality modelling

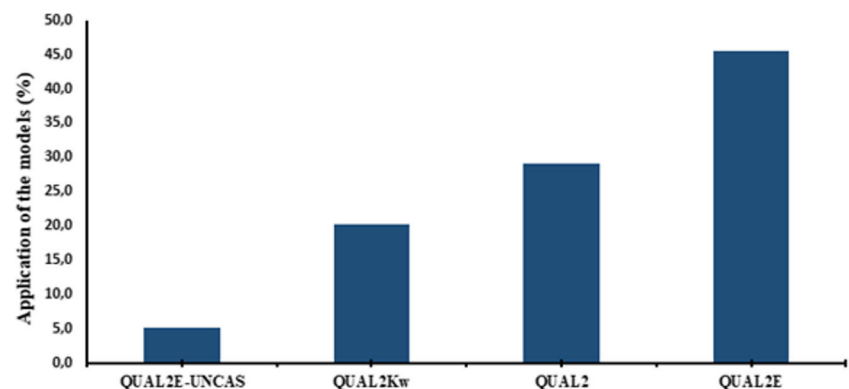


Table 1 AQUATOX, CE-QUAL-W2, EFCD, QUALs, SPARROW, SWAT, and WASP applicability around the world

MODEL	COUNTRIES	Nº OF ARTICLES	(%)	REFERENCES	MODEL	COUNTRIES	Nº OF ARTICLES	(%)	REFERENCES
AQUATOX	China	9	30.0	75, 157, 154, 498, 630, 804, 1050, 1051, 1064	SPARROW	USA	37	77.1	29, 34, 46, 69, 87, 106, 107, 108, 113, 232, 309, 350, 444, 571, 574, 575, 583, 595, 705, 709, 710, 737, 746, 747, 748, 749, 750, 751, 752, 757, 766, 781, 807, 810, 857, 955, 971
	USA	9	30.0	78, 124, 190, 418, 612, 734, 735, 806, 882					
	Turkey	4	13.3	27, 431, 432, 599					
	Denmark	2	6.7	572, 573					
	Italy	2	6.7	299, 310					
	France	1	3.3	864					
	Iran	1	3.3	21					
	Russia	1	3.3	74					
	United Kingdom	1	3.3	546					
	Total	30	100						
CE-QUAL-W2	USA	42	32.3	9, 63, 79, 101, 102, 109, 110 112, 115, 182, 188, 197, 221, 225, 241, 283, 286, 287, 330, 369, 370, 390, 391, 392, 486, 550, 618, 634, 763, 775, 785, 793, 817, 824, 852, 866, 872, 944, 958, 999, 1048, 1071	SWAT	USA	276	41.4	6, 19, 20, 32, 36, 40, 42, 48, 58, 59, 71, 88, 89, 90, 91, 105, 114, 116, 117, 119, 135, 136, 141, 142, 143, 146, 155, 156, 163, 164, 165, 166, 167, 168, 171, 172, 173, 174, 175, 179, 180, 184, 185, 186, 189, 195, 199, 206, 207, 208, 209, 213, 220, 222, 229, 233, 234, 242, 243, 244, 250, 266, 267, 273, 274, 275, 277, 284, 285, 288, 290, 291, 295, 296, 297, 298, 306, 311, 312, 313, 314, 320, 325, 329, 331, 332, 334, 336, 338, 339, 340, 348, 351, 354, 356, 373, 374, 376, 377, 378, 383, 384, 385, 389, 393, 394, 395, 396, 397, 399, 411, 415, 416, 417, 423, 424, 437, 439, 441, 442, 454, 461, 465, 468, 484, 485, 494, 495, 496, 497, 500, 505, 509, 522, 547, 548, 551, 552, 553, 564, 566, 584, 588, 589, 590, 596, 597, 598, 601, 602, 607, 608, 609, 614, 620, 623, 628, 629, 633, 637, 649, 650, 660, 661, 662, 663, 667, 670, 671, 672, 674, 675, 676, 678, 703, 704, 711, 717, 718, 719, 720, 722, 727, 728, 729, 730, 740, 741, 742, 744, 759, 774, 777, 778, 779, 780, 784, 787, 788, 789, 790, 791, 795, 799, 800, 801, 805, 809, 811, 815, 817, 819, 820, 821, 822, 837, 845, 849, 850, 851, 858, 860, 861, 862, 865, 867, 873, 892, 893, 894, 895, 896, 897, 898, 904, 906, 915, 916, 917, 920, 921, 932, 938, 945,
	Iran	32	24.6	7, 10, 11, 12, 13, 14, 15, 16, 43, 44, 104, 255, 256, 257, 324, 337, 446, 567, 617, 625, 632, 635, 691, 767, 768, 769, 772, 843, 844, 859, 1024, 1038					
	China	12	9.2	204, 357, 400, 527, 555, 578, 694, 875, 992, 1079, 1080, 1086					
	South Korea	11	8.5	178, 183, 322, 449, 464, 488, 491, 677, 685, 686, 1036					
	Taiwan	7	5.4	138, 187, 472, 473, 534, 535, 532					
	Canada	5	3.8	565, 770, 771, 891, 918					
	Portugal	4	3.1	39, 41, 231, 568					
	Cyprus	2	1.5	556, 557					
	Mexico	2	1.5	731, 732					
	Spain	2	1.5	414, 899					
Tunisia	2	1.5	1088, 1089						
Australia	1	0.8	474						
Botswana	1	0.8	690						
Brazil	1	0.8	228						
Mozambique	1	0.8	690						
New Zealand	1	0.8	341						
South Africa	1	0.8	690						

Table 1 (continued)

MODEL	COUNTRIES	Nº OF ARTICLES	(%)	REFERENCES	MODEL	COUNTRIES	Nº OF ARTICLES	(%)	REFERENCES	
EFDC	Switzerland	1	0.8	85	China	China	89	13.3	946, 947, 959, 960, 961, 962, 963, 964, 965, 966, 967, 968, 969, 970, 974, 975, 976, 977, 978, 982, 983, 984, 985, 986, 1008, 1021, 1026, 1028, 1030, 1037, 1041, 1063, 1077	
	Turkey	1	0.8	316						
	Zimbabwe	1	0.8	690						
	Total	130	100							
	China	52	48.1	150, 151, 203, 238, 280, 281, 282, 307, 318, 335, 358, 360, 363, 405, 406, 407, 469, 475, 508, 512, 513, 514, 515, 516, 560, 712, 715, 831, 838, 883, 884, 888, 936, 939, 941, 942, 950, 951, 952, 991, 993, 994, 997, 1003, 1031, 1042, 1044, 1045, 1046, 1055, 1074, 1087						
	USA	31	28.7	30, 118, 160, 237, 251, 271, 326, 365, 366, 367, 401, 402, 412, 445, 521, 543, 544, 545, 695, 696, 723, 853, 854, 868, 973, 988, 989, 990, 1082, 1083, 1085						
	South Korea	15	13.9	23, 169, 177, 200, 387, 426, 455, 457, 463, 651, 682, 812, 813, 840, 1033						
	Taiwan	3	2.8	535, 536, 537		Canada	Canada	32	4.8	45, 49, 83, 84, 252, 272, 305, 506, 539, 540, 541, 542, 561, 576, 579, 713, 714, 736, 764, 867, 972, 1009, 1010, 1011, 1012, 1013, 1014, 1015, 1016, 1034, 799, 1047
	Turkey	3	2.8	120, 434, 808						
	QUAL2E	Malaysia	2	1.9		440, 489	South Korea	South Korea	20	3.0
Canada		2	1.9	271, 438	German	19		2.8	3, 68, 270, 319, 323, 480, 481, 482, 483, 577, 702, 762, 802, 803, 911, 912, 925, 926, 927	
Total		108	100		Iran	Iran	16	2.4	26, 226, 375, 379, 380, 425, 436, 726, 760, 773, 796, 825, 856, 880, 881, 1024	
South Korea		18	29.5	22, 57, 132, 133, 176, 321, 327, 328, 372, 420, 456, 459, 460, 493, 631, 684, 765, 863		India	14	2.1	137, 342, 471, 559, 585, 586, 587, 615, 668, 669, 841, 878, 901, 902	
Taiwan		8	13.1	153, 520, 626, 627, 905, 1001, 1006, 1007	France	France	13	1.9	3, 80, 81, 82, 96, 97, 134, 212, 501, 701, 755, 876, 922	
India		5	8.2	292, 604, 688, 689, 708		Greece	12	1.8	3, 92, 279, 294, 664, 665, 666, 673, 700, 786, 908, 919	
USA		5	8.2	62, 144, 205, 582, 687	Spain	11	1.6	3, 196, 211, 223, 278, 593, 653, 654, 655, 697, 707		
Brazil		4	6.6	214, 657, 743, 928	Brazil	Brazil	8	1.2	77, 86, 201, 218, 499, 753, 869, 914	
Italy		4	6.6	54, 276, 782, 783		Ethiopia	8	1.2	50, 70, 76, 227, 230, 581, 761, 1023	
Turkey		4	6.6	433, 603, 855, 1032						

Table 1 (continued)

MODEL	COUNTRIES	Nº OF ARTICLES	(%)	REFERENCES	MODEL	COUNTRIES	Nº OF ARTICLES	(%)	REFERENCES
	Indonesia	3	4.9	605, 606, 879		Italy	8	1.2	3, 762, 52, 53, 121, 215, 216, 217
	Canada	2	3.3	764, 1072		Turkey	8	1.2	240, 245, 249, 253, 317, 647, 648, 762
	Australia	1	1.6	619		Belgium	7	1.0	3, 289, 345, 346, 347, 502, 848
	Belgium	1	1.6	923		Ireland	6	0.9	3, 35, 191, 192, 193, 194
	China	1	1.6	419		Japan	6	0.9	260, 261, 262, 409, 410, 935
	Egypt	1	1.6	611		Poland	5	0.7	3, 762, 562, 563, 699
	Iran	1	1.6	435		Tunisia	5	0.7	5, 47, 67, 447, 776
	Malaysia	1	1.6	592		UK	5	0.7	3, 98, 303, 304, 836
	Philippines	1	1.6	570		Austria	4	0.6	3, 762, 925, 926
	Slovenia	1	1.6	235		Slovakia	4	0.6	3, 762, 925, 926
	Total	61	100			Slovenia	4	0.6	762, 300, 301, 302
	QUAL2E-UNCAS	India	3	42.9	2, 55, 656	Vietnam	4	0.6	621, 698, 900, 448
		Brazil	1	14.3	51	Australia	3	0.4	622, 846, 847
		Croatia	1	14.3	931	Bulgaria	3	0.4	3, 762, 925
		Iran	1	14.3	8	Croatia	3	0.4	3, 762, 925
	USA	1	14.3	398	Hungary	3	0.4	3, 762, 925	
	Total	7	100		Laos	3	0.4	448, 458, 900	
QUAL2K	China	12	30.8	248, 263, 264, 368, 658, 1025, 1056, 1057, 1058, 1059, 1070, 1081	Moldova	3	0.4	3, 762, 925	
	Taiwan	7	17.9	145, 259, 519, 885, 886, 887, 1002	Norway	3	0.4	3, 664, 659	
	USA	4	10.3	236, 269, 569, 877	Portugal	3	0.4	3, 568, 754	
	Iran	3	7.7	613, 725, 842	Romania	3	0.4	3, 762, 925	
	Malaysia	3	7.7	525, 1039, 1040	Russia	3	0.4	3, 258, 762	
	Egypt	2	5.1	591, 733	Serbia	3	0.4	3, 762, 925	
	India	2	5.1	739, 933	Switzerland	3	0.4	3, 4, 762	
	Argentina	1	2.6	692	Ukraine	3	0.4	3, 762, 925	
	Colombia	1	2.6	65	Albania	2	0.3	3, 762	
	Estonia	1	2.6	254	Belarus	2	0.3	3, 762	
	South Korea	1	2.6	684	Bosnia	2	0.3	3, 762	
	Spain	1	2.6	909	Cambodia	2	0.3	900, 448	
	Turkey	1	2.6	66	Czech Republic	2	0.3	3, 762, 926	
	Total	39	100		Denmark	2	0.3	3, 549	
QUAL2KW	USA	7	25.0	198, 343, 616, 693, 907, 929, 930	Finland	2	0.3	3, 99	
	Iran	4	14.3	381, 624, 889, 1084	Macedonia	2	0.3	3, 762	
					Montenegro	2	0.3	3, 762	

Table 1 (continued)

MODEL	COUNTRIES	Nº OF ARTICLES	(%)	REFERENCES	MODEL	COUNTRIES	Nº OF ARTICLES	(%)	REFERENCES
	Portugal	3	10.7	636, 924, 792		Republic of Benin	2	0.3	93, 94
	Egypt	3	10.7	37, 38, 268		Sweden	2	0.3	3, 247
	Spain	2	7.1	792, 910		Thailand	2	0.3	56, 1022
	China	2	7.1	123, 355		Argentina	1	0.1	756
	India	2	7.1	429, 823		Benin	1	0.1	210
	Colombia	1	3.6	652		Bolivia	1	0.1	130
	Ecuador	1	3.6	344		England	1	0.1	890
	Greece	1	3.6	293		Estonia	1	0.1	3
	Nepal	1	3.6	430		Fiji	1	0.1	202
	South Korea	1	3.6	170		Georgia	1	0.1	762
	Total	28	100			Iraq	1	0.1	797
WASP	USA	21	28.8	64, 125, 126, 127, 128, 129, 131, 224, 271, 422, 453, 466, 545, 580, 695, 706, 758, 798, 95, 723, 973		Ivory Coast	1	0.1	470
	China	18	24.7	238, 265, 403, 404, 405, 504, 516, 934, 937, 940, 948, 991, 996, 1019, 1020, 1065, 1066, 1090		Jamaica	1	0.1	816
	Canada	8	11.0	28, 100, 271, 352, 353, 428, 443, 1060		Kenya	1	0.1	610
	Taiwan	8	11.0	152, 477, 478, 479, 518, 531, 887, 1027		Latvia	1	0.1	3
	Germany	4	5.5	103, 467, 523, 524		Lithuania	1	0.1	3
	South Korea	4	5.5	679, 745, 813, 814		Luxemburg	1	0.1	3
	Italy	3	4.1	122, 903, 913		Morocco	1	0.1	111
	Turkey	3	4.1	245, 246, 1029		Netherlands	1	0.1	3
	India	2	2.7	31, 600		North Korea	1	0.1	181
	Belgium	1	1.4	219		Pakistan	1	0.1	1
	Cameron	1	1.4	25		Taiwan	1	0.1	139
	Total	73	100			Total	666	100	

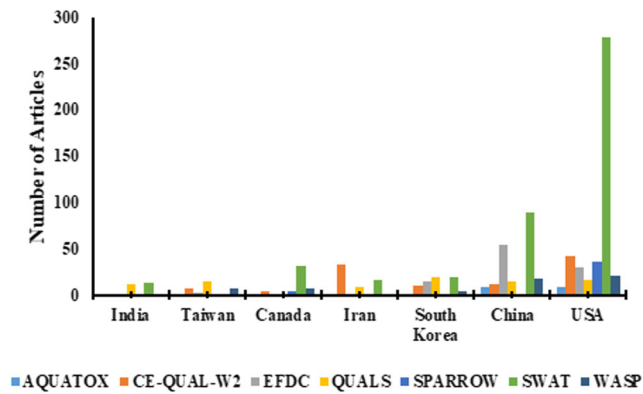


Fig. 4 Seven countries with the most frequent application of water quality models

et al. 2011; Khatami and Siosemarde 2016; Nourmohammadi Dehbalaei et al. 2016). The QUALs model exhibited satisfactory modelling performance in Taiwan (Ning et al. 2001; Fan et al. 2009; Tang et al. 2012). A study was conducted to evaluate the performance variations of a river with high ammonia and organic matters in southern Taiwan, and the overall model results of WASP proved to be better than those of QUAL2K (Tang et al. 2014). Although QUALs models have been widely used in South Korea, some studies have shown that these may not be most suitable for studies in this region. Park and Lee (2002) performed several modifications in the computer code to overcome the limitations of QUAL2E in modelling DO, BOD, nitrogen, phosphorus, and chlorophyll-a. Schroeder (1997) added a carbon pool, the mineralization of which consumes oxygen (BOD), to the QUAL2E model to study the influence of different biological and chemical factors on the oxygen balance. Hwang et al. (2014)

compared QUAL2E and CE-QUAL-RIV1 water quality simulation results, which indicated that QUAL2E was inadequate for simulation of the water gate operation on the river, and that CE-QUAL-RIV1 performs better in the water flow and water quality changes in the same conditions. Nevertheless, the QUALs presented satisfactory results in the modeling of basic parameters (DO, COD, BOD) in India (Ghosh and McBean 1998; Parmar and Keshari 2014; Sharma et al. 2017).

The articles addressing applications in these seven countries were analyzed to identify central themes and the most simulated parameters. The USA and Canada generally explored the same themes: research on agricultural management techniques, impact of use and occupation on water quality, and consequently, non-point sources of pollution, impact of climate change on water quality, sediment analysis, and analysis of one or more chemicals including ammonia, nitrogen, nitrate or nitrite, and phosphorus or phosphate (Tables 2 and 6). The frequent use of SWAT in the USA and Canada reflects these themes, since as mentioned previously, the model was designed for the study of different management scenarios and nonpoint source pollution, simulating sediment erosion, pesticides, bacteria, plants, and other variables.

China, Taiwan, South Korea, and Iran had similar model application patterns. They frequently simulated the main parameters of eutrophication (ammonia, nitrogen, nitrate, phosphorus, and biochemical oxygen demand/carbonaceous biochemical oxygen demand (Tables 3, 4, 5, and 7). Of these countries, only Iran did not include chlorophyll a, algae and phytoplankton as one of the main parameters, while China was the only one that did not include DO among the main parameters. Taiwan was more inclined to include suspended solids and sediments and also more complete research on eutrophication; however, less articles were produced in

Table 2 Main issues addressed in articles of studies performed in the USA

USA			
Theme	No. of articles	(%)	References
Agricultural, Land use, Best management practices, Nonpoint pollution	110	41.2	19, 40, 42, 48, 71, 90, 91, 105, 117, 143, 155, 156, 164, 165, 166, 207, 229, 244, 251, 274, 288, 295, 296, 297, 298, 313, 320, 325, 331, 332, 336, 354, 385, 393, 396, 411, 423, 424, 495, 547, 601, 614, 623, 628, 676, 704, 711, 717, 718, 719, 727, 728, 741, 744, 747, 787, 788, 791, 795, 799, 801, 805, 809, 820, 822, 837, 849, 850, 851, 862, 865, 892, 893, 894, 896, 906, 915, 945, 960, 961, 963, 965, 967, 968, 969, 970, 975, 976, 983, 986, 1063
Climate change	49	18.4	20, 29, 90, 112, 119, 135, 156, 165, 185, 199, 209, 220, 244, 267, 274, 306, 331, 351, 354, 384, 385, 390, 395, 415, 417, 494, 552, 584, 608, 660, 661, 738, 740, 741, 751, 785, 793, 882, 892, 896, 915, 916, 917, 932, 969, 975, 976, 984, 1026
Sediments	45	16.9	32, 36, 107, 116, 126, 142, 180, 233, 267, 291, 329, 332, 354, 389, 401, 411, 417, 465, 486, 566, 580, 588, 598, 607, 608, 609, 623, 629, 633, 637, 667, 674, 703, 757, 820, 860, 861, 893, 896, 947, 966, 974, 1037, 1041, 1071
Ammonia/nitrogen/nitrate/nitrite	34	12.7	29, 62, 119, 141, 142, 269, 273, 274, 275, 309, 350, 356, 374, 395, 396, 397, 494, 495, 509, 571, 574, 596, 597, 746, 747, 780, 781, 795, 800, 810, 873, 877, 893, 1026
Phosphorus/phosphate	29	10.9	6, 34, 40, 110, 114, 116, 195, 199, 208, 232, 269, 465, 484, 522, 588, 589, 720, 746, 747, 751, 791, 811, 849, 877, 921, 959, 960, 963, 964

Table 3 Main issues addressed in articles of studies performed in China

China			
Theme	No. of articles	(%)	References
Ammonia/nitrogen/nitrate/nitrite	107	39.8	123, 140, 148, 151, 157, 158, 159, 161, 162, 203, 238, 248, 265, 280, 307, 315, 318, 333, 349, 355, 358, 362, 364, 368, 371, 405, 408, 419, 476, 492, 504, 510, 511, 515, 516, 517, 526, 527, 528, 529, 530, 538, 554, 578, 630, 639, 640, 643, 644, 645, 646, 721, 794, 818, 827, 828, 830, 832, 833, 839, 875, 884, 888, 934, 940, 941, 943, 948, 950, 951, 952, 979, 981, 987, 996, 1003, 1004, 1005, 1017, 1018, 1019, 1025, 1031, 1035, 1042, 1043, 1044, 1046, 1049, 1052, 1053, 1054, 1056, 1057, 1058, 1059, 1061, 1065, 1067, 1068, 1069, 1070, 1073, 1074, 1081, 1086, 1090
Phosphorus/phosphate	88	32.7	123, 140, 148, 149, 151, 157, 203, 238, 280, 307, 308, 315, 318, 333, 349, 361, 362, 364, 371, 405, 408, 476, 492, 504, 511, 515, 516, 517, 526, 528, 529, 530, 554, 630, 639, 640, 643, 644, 645, 646, 818, 827, 828, 830, 831, 832, 833, 839, 875, 888, 934, 939, 940, 941, 948, 950, 952, 954, 979, 981, 987, 996, 1003, 1004, 1005, 1025, 1031, 1035, 1042, 1043, 1044, 1049, 1053, 1054, 1056, 1057, 1058, 1059, 1061, 1065, 1070, 1073, 1074, 1081, 1086, 1087
BOD/CBOD (carbonaceous biochemical oxygen demand)/(COD) chemical oxygen demand	30	11.2	157, 248, 264, 280, 333, 355, 368, 405, 516, 658, 884, 940, 951, 996, 1019, 1025, 1044, 1056, 1057, 1058, 1059, 1065, 1066, 1067, 1068, 1069, 1070, 1086, 1087, 1090
Algae/chlorophyll a/phytoplankton	24	8.9	151, 157, 203, 238, 307, 335, 400, 513, 630, 712, 804, 839, 888, 934, 939, 940, 948, 950, 952, 1003, 1031, 1042, 1046, 1065
DO (dissolved oxygen)	20	7.4	151, 157, 203, 238, 307, 335, 400, 513, 630, 712, 804, 839, 888, 934, 939, 940, 948, 950, 952, 1003, 1031, 1042, 1046, 1065

comparison to the other countries in this group. Taiwan's greater use of QUALs fits this pattern, as despite their simplification, QUALs can be used to simulate the main parameters of eutrophication. QUAL2E simulates DO, BOD, and algae, reported as chlorophyll a, phosphorus, and nitrogen (Brown and Barnwell 1985). In the same way, China, South Korea, and Iran could use QUAL2E to simulate eutrophication, since this is a relatively simple model that is able to simulate main parameters. Lastly, India, among the seven countries, carried out more simple analyses (Table 8), prioritizing studies on OD, COD, and sediments, with SWAT employed for sediment

simulation and QUALs for OD and COD (Tables 1, 2, 3, 4, 5, 6, 7, 8).

The 83 countries identified in the articles were grouped using 11 input variables in a multivariate cluster analysis. The variables were the total number of applications of water quality models in the country and the number of applications of each of AQUATOX, CE-QUAL-W2, EFDC, QUAL2E, QUAL2E-UNCAS, QUAL2K, QUAL2KW, SPARROW, SWAT, and WASP. Using Euclidean distance and the complete bonding method, clusters were formed as shown in the dendrogram (Fig. 5)

Table 4 Main issues addressed in articles of studies performed in South Korea

South Korea			
Theme	No. of articles	(%)	References
Ammonia/nitrogen/nitrate/nitrite	32	30.8	23, 24, 57, 170, 177, 321, 372, 388, 413, 426, 427, 450, 455, 456, 462, 487, 558, 594, 631, 679, 680, 681, 682, 684, 685, 686, 724, 745, 765, 812, 813, 863
Phosphorus/phosphate	25	24.0	23, 24, 57, 170, 321, 372, 427, 450, 455, 456, 459, 462, 487, 594, 631, 679, 680, 681, 683, 684, 724, 745, 765, 813, 863
Algae/chlorophyll a/phytoplankton	19	18.3	177, 321, 372, 426, 449, 455, 456, 457, 462, 488, 679, 682, 684, 685, 686, 745, 812, 813, 863
BOD (biochemical oxygen demand)/CBOD (carbonaceous biochemical oxygen demand)/(COD) (chemical oxygen demand)	19	18.3	23, 57, 132, 133, 170, 176, 177, 372, 386, 426, 456, 460, 487, 594, 631, 684, 765, 813, 863
DO (dissolved oxygen)	09	8.7	170, 176, 177, 321, 456, 679, 684, 812, 863

Table 5 Main issues addressed in articles of studies performed in Iran

Iran			
Theme	No. of articles	(%)	References
Phosphorus/phosphate	14	31.1	11, 12, 15, 226, 375, 436, 446, 567, 624, 625, 635, 844, 880, 1024
DO (dissolved oxygen)	13	28.9	8, 16, 26, 380, 381, 613, 625, 635, 725, 772, 842, 889, 1024
Ammonia/nitrogen/nitrate/nitrite	11	24.4	12, 15, 375, 446, 624, 625, 632, 726, 825, 844, 1024
BOD (biochemical oxygen demand)/	7	15.6	8, 381, 613, 624, 725, 842, 889

Forty-two countries formed five clusters with a level of similarity of 100. The elevated level of similarity is the result of the countries grouping according to the number of applications of a certain water quality model. The five groups that showed this level of similarity had 1, 2, 3, or 4 applications of a single model (either SWAT or CE-QUAL-W2). The first group with two

Table 6 Main issues addressed in articles of studies performed in Canada

Canada			
Theme	No. of articles	(%)	References
Phosphorus/phosphate	33	28.7	49, 69, 84, 252, 272, 305, 352, 353, 443, 451, 452, 539, 540, 542, 576, 579, 714, 736, 764, 867, 918, 956, 957, 972, 1009, 1010, 1011, 1012, 1014, 1015, 1016, 1060
Ammonia/nitrogen/nitrate/nitrite	28	24.3	45, 49, 69, 252, 272, 305, 352, 353, 443, 506, 539, 540, 542, 576, 579, 713, 714, 764, 867, 972, 1011, 1012, 1015, 1016, 1034, 1047, 1060, 1072
Agricultural/land use/best management practices/nonpoint pollution	23	20.0	45, 49, 83, 84, 252, 352, 506, 539, 540, 576, 579, 714, 764, 867, 957, 972, 1009, 1010, 1011, 1012, 1014, 1015, 1034
Sediments	22	19.1	45, 49, 83, 84, 305, 438, 452, 539, 540, 541, 542, 736, 764, 771, 972, 1009, 1010, 1011, 1012, 1013, 1015, 1016
Climate change	9	7.8	252, 305, 352, 353, 565, 576, 579, 714, 1009

Table 7 Main issues addressed in articles of studies performed in Taiwan

Taiwan			
Theme	No. of articles	(%)	References
Ammonia/nitrogen/nitrate/nitrite	18	26.1	138, 152, 187, 259, 477, 479, 518, 519, 520, 534, 626, 627, 885, 886, 887, 1001, 1002, 1027
BOD/CBOD (carbonaceous biochemical oxygen demand)/(COD) chemical oxygen demand	14	20.3	145, 152, 477, 259, 479, 518, 520, 626, 627, 885, 886, 1001, 1002, 1027
DO (dissolved oxygen)	11	15.9	138, 152, 477, 473, 479, 520, 534, 531, 626, 627, 1001
Phosphorus/phosphate	10	14.5	138, 152, 187, 259, 472, 479, 534, 626, 627, 1027
Algae/chlorophyll a/phytoplankton	8	11.6	138, 152, 472, 473, 531, 534, 535, 1006
Suspended solids/sediments	8	11.6	477, 479, 520, 532, 533, 537, 887, 1001

SWAT applications was composed of 11 counties: Albania, Belarus, Bosnia, Cambodia, Czech Republic, Finland, Macedonia, Montenegro, Republic of Benin, Sweden, and Thailand. Most of the studies realized in the countries of group 1 involved use of SWAT to verify the impact of climate and land use change on water availability and quality ([3], [56], [448], [762], [900]). The second group included 16 countries with a single application of SWAT, mostly involving management practices and agricultural development ([130], [210], [610], [797], [890]). The third group, comprising Austria, Slovakia, and Vietnam, had four applications of SWAT, and most of the articles studied sediment concentrations and yields in basins ([621], [698], [925], [926]). The following group comprised Bulgaria, Hungary, Laos, Moldova, Norway, Romania, Serbia, and Ukraine, each with three applications of SWAT. These studies involved pollutant transport in different geoclimatic conditions

Table 8 Main issues addressed in articles of studies performed in India

India			
Theme	No. of articles	(%)	References
Sediment	12	50.0	137, 342, 471, 559, 585, 586, 587, 668, 669, 841, 901, 902
BOD (biochemical oxygen demand)/(OD) oxygen demand	12	50.0	31, 55, 292, 429, 600, 604, 688, 689, 739, 823, 902, 933

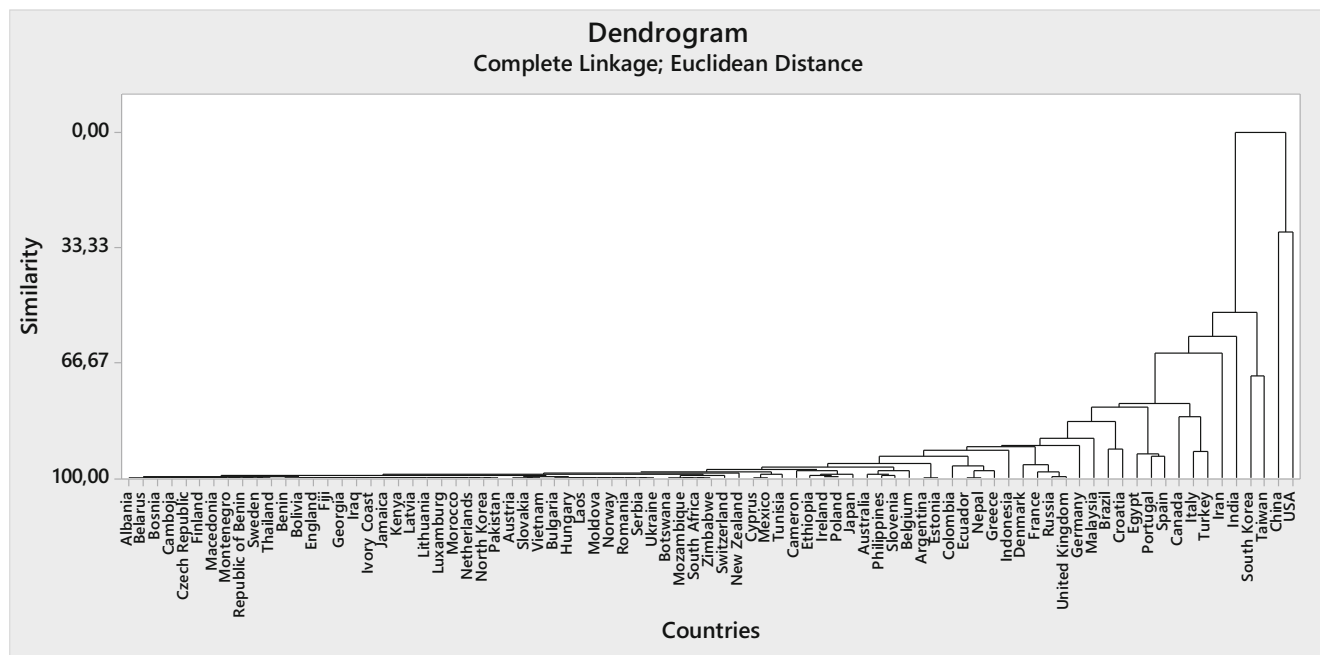


Fig. 5 Dendrogram of application similarities of water quality models between countries

([458], [659], [664]). A group containing only Botswana and Mozambique included one application of CE-QUAL-W2, which was used to simulate salinity intrusion in an estuarine environment ([691]). Of the 83 countries analyzed, six countries (Iran, India, South Korea, Taiwan, China, and the USA) showed similarity levels below 60.90 relative to the remainder of the countries. China and the USA formed a group with 26.29 similarity, since both countries had the highest number of model applications. The only model not applied in Chinese territory, according to this analysis, was QUAL2E-UNCAS, which had a single application in the USA, strengthening the justification for grouping the two countries together despite a low level of similarity. South Korea and Taiwan formed a group with a 68.08 similarity level. South Korea had 70 model applications, while Taiwan had 34 applications. Both included the application of CE-QUAL-W2, EFDC, QUAL2E, QUAL2K, SWAT, and WASP. One application of the QUAL2KW model in South Korea had no counterpart in Taiwan.

Discussion and conclusion

Surface water quality models experienced three important stages of development (Wang et al. 2013). The first stage (1925–1965) mainly involved Streeter–Phelps models (S–P models). They simulated basic interactions among different components of water quality in river systems, including sediment oxygen demand, hydrodynamic transmission, algal photosynthesis, and respiration. Moreover, the models were simple, one dimensional, steady-state, and focused on river systems. Early in this stage, a simple BOD–DO model was developed,

which was quite successful at the time in simulating river and estuary pollution (Burn and McBean 1985). In the second stage (1965–1995), models made rapid progress and were upgraded to two and three dimensions. Moreover, nitrogen and phosphorus cycling and the effects of sediments, phytoplankton, and zooplankton systems were included. In the third stage (after 1995), the economic development in most countries assisted in reducing nonpoint source pollution via government control. New methods were developed for specific scenarios, such as fuzzy inference systems, genetic algorithms, neural networks, and support vector machines (Gao and Li 2014).

Therefore, since 1997, the rate of application of water quality models has experienced significant growth. The SWAT model has been the most frequently applied algorithm for water quality modelling, followed by the QUALs and CE-QUAL-W2. The popularity of the SWAT model, in most countries, may reflect its ability to analyze the impact of different management scenarios on water supplies and the non-point source pollution in watersheds and large river basins over long periods of time. The model was developed by the US Department of Agriculture (USDA)–Agricultural Research Service, and it is the most commonly applied model in the USA. The use of water quality models is driven mainly by the legislation and regulations of each country. Therefore, these models are commonly specific to a country, institution, or water resource (Cox 2003). One of the main reasons for the widespread use of SWAT is that the model was integrated into the USEPA’s modeling framework, BASINS, for use by government agencies and watershed management authorities. The QUALs are one-dimensional models, indicating their simplicity and therefore ease of use, as modelers do not need

extensive specialization, the requirements of input data are low, and simulation times are short.

Moreover, there has been a tendency to apply simpler models, such as QUALs, in developing countries. However, there are exceptions. SWAT, which can be considered an intermediate model in terms of difficulty, as it is a two-dimensional model, has been applied in less developed countries such as Benin, Cambodia, and Ethiopia. Several criteria can be applied in choosing the appropriate model to be used in each country, especially with regard to the water body type and the simulated parameters. Clearly, knowing whether a model has already been successfully applied in the country to be studied makes it easy to evaluate the suitability of that model for the region. This study allows rapid identification of the models that have already been applied in particular countries, helping researchers establish future directions of research. The particular benefit of this review is that researchers aspiring to study countries with fewer water quality modeling studies can easily identify the relevant articles that apply to their region of interest. Furthermore, this review collated the central themes of interest and the most simulated parameters for the seven countries that most frequently applied water quality models.

Finally, some recommendations can be assembled from this study. China, South Korea, and Iran could use QUAL2E to simulate eutrophication, since this is a simple model capable of simulating the main eutrophication parameters (DO, BOD, and algae reported as chlorophyll a, phosphorus, and nitrogen). China could conduct further studies on OD, and Iran may include chlorophyll a, algae, and phytoplankton in more complete eutrophication studies. In addition, India should include more water quality parameters in studies, since the main parameters (OD, COD, and sediments) are greatly simplified. Food web studies, conducted with AQUATOX, are generally recommended to include fecal coliforms, using CE-QUAL-W2, QUALs, SWAT, SPARROW, and WASP models.

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