Journal of Environmental Management 90 (2009) 1534–1543

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Development of a water quality loading index based on water quality modeling

Tao Song [a,b,*], Kyehyun Kim [b]

[a] Natural Disaster Research Center, Room D503, Geographical and Environmental Building, Sun Yat-Sen University, Guangzhou 510275, PR China
[b] Department of Geoinformatic Engineering, Inha University, Inchon 402751, Republic of Korea

ARTICLE INFO

Article history:
Received 12 December 2007
Received in revised form
20 October 2008
Accepted 22 November 2008
Available online 19 December 2008

Keywords:
WQI
Water quality modeling
QUAL2E
GIS

ABSTRACT

Water quality modeling is an ideal tool for simulating physical, chemical, and biological changes in aquatic systems. It has been utilized in a number of GIS-based water quality management and analysis applications. However, there is considerable need for a decision-making process to translate the modeling result into an understandable form and thereby help users to make relevant judgments and decisions. This paper introduces a water quality index termed QUAL2E water quality loading index (QWQLI). This new WQI is based on water quality modeling by QUAL2E, which is a popular steady-state model for the water quality of rivers and streams. An experiment applying the index to the Sapgyo River in Korea was implemented. Unlike other WQIs, the proposed index is specifically used for simulated water quality using QUAL2E to mainly reflect pollutant loading levels. Based on the index, an iterative modeling-judgment process was designed to make decisions to decrease input pollutants from pollutant sources. Furthermore, an indexing and decision analysis can be performed in a GIS framework, which can provide various spatial analyses. This can facilitate the decision-making process under various scenarios considering spatial variability. The result shows that the index can evaluate and classify the simulation results using QUAL2E and that it can effectively identify the elements that should be improved in the decision-making process. In addition, the results imply that further study should be carried out to automate algorithms and subsidiary programs supporting the decision-making process.

1. Introduction

Water quality modeling is an ideal approach to simulate physical, chemical, and biological changes in water bodies (James, 1984). It involves the prediction of water pollution using mathematical simulation techniques. It can also be used to predict water quality in terms of the real observed data at a high frequency and over a long period of time. Thus far, a number of water quality models have been widely applied to assess water quality. These include QUAL2E (Brown and Barnwell, 1987), WASP5 (Ambrose et al., 1993), CE-QUAL-W2 (Cole and Buchak, 1995), and HEC-5Q (USACE, 1986). Rahman and Salbe (1995) modeled the impacts of diffuse and point nutrients on the water quality of the South Creek catchment in Australia using HEC-5Q. Wu et al. (1996) simulated the investigating effect of reservoir operation on water quality using WASP. Tufford and McKellar (1999) used spatial–temporal definition and WASP to analyze the water quality of a large reservoir on the South Carolina coastal plain in the United States.

Among the existing water quality models, QUAL2E, developed and released by USEPA (United States Environmental Protection Agency) in 1985, is one of the most popular models (Cox, 2003). It is an enhanced steady-state model used mainly to simulate the inflow and water quality of rivers and streams. The basic theory of QUAL2E is based on the assumption that the major transport mechanisms, advection and dispersion, are significant only along the main direction of flow (Brown and Barnwell, 1987). First, a river is modeled as a string of computational elements with the same hydrogeometric properties (e.g., slope, cross-section, and roughness) and biological rate constants (e.g., BOD growth and decay rates, and algal settling rates). For each element, balance of the hydrologic flow is assumed to be maintained as

$$Q_i = Q_{i-1} + Q_{x_i} \quad (1)$$

where Q_i is the flow of element i to the downstream element, Q_{i-1} is the flow from the upstream element, and Q_{x_i} is the flow of inputs or withdrawals. Similarly, the material balance should also be kept in QUAL2E, and both advection and longitudinal dispersion are considered as the movers. The material balance can be written as

$$\frac{\partial C}{\partial t} = \frac{\partial(A_x D_L(\partial C/\partial x))}{A_x \partial x} - \frac{\partial(A_x \overline{U} C)}{A_x \partial x} + \frac{\partial C}{\partial t} S \quad (2)$$

* Corresponding author. Natural Disaster Research Center, Room D503, Geographical and Environmental Building, Sun Yat-Sen University, Guangzhou 510275, PR China. Tel.: +86 136 6248 7331.
E-mail addresses: taosong_chn@yahoo.com.cn (T. Song), kyehyun@inha.ac.kr (K. Kim).

0301-4797/$ – see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jenvman.2008.11.008

where A_x is the cross-sectional area, D_L is the dispersion coefficient, $\overline{U}$ is the mean velocity, C is the constituent concentration, t is the time, and S is the external sources or sinks. The term $\partial C/\partial t$ denotes the gradient of the constituent concentration, and the term $\partial C/\partial x$ means the change of the constituent concentration along the distance. Thus, the transport and fate of each constituent can be mathematically derived by Eq. (2). A total of 15 constituents are simulated in QUAL2E, among them the dissolved oxygen (DO), biochemical oxygen demand (BOD), temperature, algal concentration as chlorophyll-a, coliform bacteria, four forms of nitrogen and two forms of phosphorus.

QUAL2E has been actively applied to the water quality simulation of dendriform rivers and streams mixed with branching tributaries. Chaudhury et al. (1998) simulated the dissolved oxygen content in the Blackstone River in the USA. Ning et al. (2001) assessed a pollution prevention program using a QUAL2E simulation analysis. Park and Lee (2002) implemented a water quality modeling of the Nakdong River in Korea using QUAL2E. McAvoy et al. (2003) developed a risk assessment approach for untreated wastewater using QUAL2E. Moreover, with the aid of GIS, a system for creating, storing, analyzing, and managing spatial data and associated attributes, water quality modeling can be interfaced with an environment, allowing users to create interactive quires, spatial analyses, and cartographic outputs. Grunwald and Qi (2006) modeled water quality in the Sandusky watershed in the USA using the Soil and Water Assessment Tool (SWAT) and GIS. Paliwal et al. (2007) simulated the water quality of the Yamuna River in India by QUAL2E with GIS.

However, the management of water quality today requires easy-to-understand and intellectual decision-support for national and local governments (WHO and UNICEF, 2005). This requirement motivates the development of more applicable and effective water quality assessment functions in a user-oriented framework. Although the current approaches of water quality modeling can provide reasonable simulation of water quality changes in aquatic systems, a decision-making process that can facilitate deliberate and optimal judgments and decisions based on modeling results is needed for governments, especially for non-expert users involved in government testing.

The decision of water quality is a branch of multi-criteria decision analysis (MCDA), which is a set of systematic procedures for analyzing complex decision problems (Malczewski, 1999). Viewing the MCDA in water quality, the water quality index (WQI) can be employed as a tool to translate multiple variables into a single suitable criterion and establish background levels of water quality based on the water quality standards for a given aquatic system (Ott, 1978). This simplifies the report of water quality and improves the understanding of water quality issues by integrating complex data and generating a score that describes water quality status and evaluates water quality trends (Boyacioglu, 2007). Following the introduction of Horton's Quality Index, the first formal water quality index (Horton, 1965), a number of water quality indices have been developed for general and specific uses. Examples are NSF WQI (Brown et al., 1970), Prati's Implicit Index (Prati et al., 1971), CCME WQI (CCME, 2001), OWQI (Cude, 2002), and UWQI (Boyacioglu, 2007). However, all of these indices were developed to address monitored aquatic systems. As such, they are not suitable for application to water that is not monitored but can be simulated by water quality modeling. Hence, a specific WQI for the water quality modeling result is required, as this can facilitate the decision-making process by translating the complex and obscure modeling result to a simple and intelligible description.

Therefore, this paper introduces a new water quality index called QUAL2E water quality loading index (QWQLI). As a specific WQI for water quality simulated by QUAL2E, the index was designed to provide an effective criterion for identifying river elements whose pollutant loads should be mitigated. Through this index, a recurrent modeling-judgment process is proposed to outline the improvement actions on pollutant loads. Furthermore, GIS can facilitate representation of the modeling result and convert the QWQLI indexing to a map with spatial versatility.

2. Study site and QUAL2E modeling

The study area of the present work is the main channel of the Sapgyo River, the longest tributary of Geum River system in South Korea (Fig. 1). Flowing in a north-eastern direction, the main channel is approximately 31 km long. As monitored by the Ministry of Construction and Transportation (MOCT), the flow rate of the river is approximately 120–160 m^3/s in the rainy season. Along the river, there are a number of point sources (e.g., population, industry, livestock, and fisheries) and non-point sources (e.g., land uses) that discharge water pollutants into the river. In 2004, as observed by the Ministry of the Environment (MOE), the average concentrations of BOD, COD, DO, T-N, and T-P in the Sapgyo River basin ranged from 2.9 to 3.4 mg/L, 4.8 to 4.9 mg/L, 8.1 to 9.6 mg/L, 1.6 to 1.7 mg/L, and 0.029 to 0.034 mg/L, respectively. The water quality of the river has been declining over the last ten years.

By means of QUAL2E, the main channel was divided into five reaches and further subdivided into a total of 31 elements (Fig. 1). In the figure, each element is conceptualized with its sequence and flag numbers, and the length of each element is 1 km. In total, there is one headwater element (element 1) and seven input elements (elements 7, 10, 13, 20, 25, 27 and 29) by which water pollutants are input into the river. As shown in Table 1, the input pollutants at these elements were the major input data of the modeling. For each input source, the input pollutants were regarded as the pollutants discharged by the area in which the source was located. The amount of discharged pollutants was calculated using the generated pollutants after they were mitigated by water treatment facilities. The generated pollutants were computed to evaluate the scales of the point and non-point sources generating pollutants. To calculate the generated pollutants, the unit load coefficient (ULC) and a set of equations calibrated by NIER (the National Institute of Environmental Research, Korea) were used (NIER, 2001).

QUAL2E can simulate 15 constituents, as mentioned in Section 1. In this study, 10 of these 15 constituents were involved in the modeling, including the temperature, BOD, DO, chlorophyll-a, four forms of nitrogen and two forms of phosphorus. The total amount of different existing types of nitrogen (organic N, NH_4-N, NO_2-N and NO_3-N) in water can be indicated by T-N (total nitrogen). Similarly, the total amount of different types of existing phosphorus (organic P and PO_4-P) can be indicated by T-P (total phosphorus). The modeling result of 2004 is listed in Table 2. The results can also be viewed in a GIS layer (Fig. 2). In the figure, the elements are viewed as different gray scales (or colors) according to different BOD (T-N or T-P) loadings. GIS can support the common spatial queries of the modeling result, complex spatial queries, and analyses.

To validate the modeling result, two monitoring stations along the main stream were selected. The water quality data at these two stations were monitored during each month from 2000 to 2004. The oxidation and settling rates of BOD and different existing types of nitrogen and phosphorus were calibrated in the validation procedure. Algal photosynthesis and sediment oxygen demand (SOD) were also considered due to their direct effects on DO. After the validation, Fig. 3 shows comparisons of the simulated and observed BODs, T-Ns and T-Ps. According to the figure, the simulation curves rise sharply at element 7, where a pollutant source is located. This indicates that the discharged pollutants from this source caused a steep decline in water quality. Furthermore, a slight discrepancy between the simulated and observed values exists at these two stations. Overall, the modeling result reflects the water quality changes along the main channel.