

A Review of Water Environmental Capacity Calculation

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Abstract: Water environmental capacity is an essential component of water environmental assessment and must be monitored and managed for economic, engineering, and human health reasons. Many efforts have been made to study methods for the calculation of water environmental capacity. This paper reviews available literature on water environmental capacity. The evolutionary history and application scenarios of major water quality models, and water environmental capacity calculation formulas are summarized. Through the analysis of calculation formulas for water environmental capacity, it is found that endogenous pollution factors influence the values of degradation coefficient K and retention coefficient R in water environmental capacity calculation though few studies consider such factors. Therefore, the quantification of endogenous pollution factors (particularly the rheological properties of bed sediments) is important and needs further study.

1 Introduction

As water environments are degrading globally, protecting them is becoming increasingly important [1-4]. Researchers are primarily concerned about developing effective scientific methods to evaluate artificial activities and natural events in the water environment, maintaining a favorable water environment, and repairing a damaged water environment.

Water environmental capacity is an essential component of water environmental

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assessment and must be monitored and managed for economic, engineering, and human health reasons [1-4]. Practically, many definitions of water environmental capacity have been put forward [2], but their essence is consistent and emphasizes three major elements: environmental objectives, water bodies, and pollutant capacities [3]. In general, water environmental capacity is defined as the maximum amount of pollutants that a water body can hold and still meet water quality standards [4].

This paper reviews available literature on water environmental capacity. The evolutionary history and application scenarios of major water quality models and water environmental capacity calculation formulas are summarized. The influence of degradation coefficient K and retention coefficient R in water environmental capacity calculation is analyzed. Lastly, the effects of endogenous pollution factors (particularly the rheological properties of bed sediments) on the values of degradation coefficient K and retention coefficient R in water environmental capacity calculation are discussed.

2 Overview of water environmental capacity calculation

The calculation of water environmental capacity generally includes two vital parts: the construction of a water quality model and the calculation of water environmental capacity [5].

2.1 Water quality models

Water quality models are based on mathematical equations that describe the change rules and mutual influence of pollutants in the water environment [6]. The first water quality model was a simple oxygen balance model developed by Streeter and Phelps in 1925 [6-8]. Until the 1970s, some new factors such as spatial variables, nitrogenous oxidation, photosynthetic and respiratory activity of algae, and other physicochemical factors enriched the Streeter-Phelps model [6, 9]. During 1970s and 1980s, water quality models underwent rapid development [6, 9, 10]. Multi-dimensional, convection-diffusion fields, and other complicated fields of pollutants were simulated [10]. Moreover, the influence of bed sediments was considered in models such as Water Quality Analysis Simulation Program (WASP) [11]. From the 1980s to the present, grey system theory, 3S (RS, GIS and GPS) technology, and stochastic mathematics have been widely applied to water quality models research and application [5, 6]. However, some scholars believe that the balance between the complexity of the models and the reliability of the results is the greatest challenge in the development of water quality models [12].

The major water quality models are the QUAL [13], MIKE [14], WASP [11], Soil and Water Assessment Tool (SWAT) [15], One-dimensional Transport with Inflow and Storage (OTIS) [16], Better Assessment Science Integrating point and Nonpoint Sources (BASINS)

[17], AQUATOX [18], CE-QUAL-W2 [19], and the Environmental Fluid Dynamics Code (EFDC) [20]. The basic calculation principles of these models are similar. Among those widely used models, QUAL2E, can be taken as a typical example. QUAL2E supposes that physical, chemical, and biological elements would meet the balance of hydrology and heat. In addition, advection and dispersion are counted in the mass balance equation [13]. The one-dimensional (1-D) mass balance equation can be written as follows:

$$V \frac{\partial c}{\partial t} = \frac{\partial(AE \frac{\partial c}{\partial x})}{\partial x} dx - \frac{\partial(AU)}{\partial x} dx + V \frac{dc}{dt} + S \tag{1}$$

where V is the volume, c is the concentration of the pollutants, t is the time, A is the unit cross-sectional area, E is the longitudinal dispersion coefficient, x is the distance in the direction of flow, U is the average velocity, and S is the external source (positive) or sink (negative) of the pollutants.

Each model has its dimensional characteristics. The application scenarios of the major water quality models are briefly summarized in Table 1 [10, 21, 22].

Table 1. Dimensional and application scenarios of major water quality models

Water quality models	Dimensional	Simulation characteristics	Application scenarios
OTIS	1D	Transport only	River
WASP	1D, 2D, 3D		River, lake, estuary, reservoir, offshore
EFDC	1D, 2D, 3D	Flow and constituent transport	River, lake, estuary, reservoir, offshore
CE-QUAL-W2	2D		River, lake, estuary
MIKE	1D, 2D, 3D		River, lake, estuary, reservoir, offshore, river network
QUAL2E/QUAL2K	1D		Watershed, river network
BASINS	System	Model System	Watershed, river, river network
AQUATOX	System		Watershed, river, river network

2.2 Water environmental capacity calculation formulas

Based on the definition of water environmental capacity and the mathematical models of water environmental capacity, scholars have derived formulas to calculate water environmental capacity [23]. After parameters such as concentration, volume, and discharge are given by the water quality models, water environmental capacity can be calculated by these formulas. It is generally considered that using formulas to obtain water environmental capacity is the simplest method [10, 23].

Water quality objectives, diffusion, assimilation, self-purification and others are determining factors of water environmental capacity [24]. The basic equation of water environmental capacity can be represented as follows [10, 24]:

$$W = Q(C_s - C_0) + KC_sV \quad (2)$$

where W is the water environmental capacity, Q is the flow discharge, C_s is the water quality standard, C_0 is the natural background concentration of the pollutants in the water, and K is the degradation coefficient of the pollutants. In general, the right side of Eq. (2) represents water dilution capacity and water self-purification capacity [24].

For nutrient salts, such as total nitrogen (TN) and total phosphorus (TP), the Dillion model is a widely used calculation model for estimating water environmental capacity of eutrophicated water bodies and is described as follows [25, 26]:

$$W = C_s Q_{out} / (1 - R) \quad (3)$$

where Q_{out} is the outflow discharge and R is the retention coefficient for nitrogen and phosphorus in the water body.

3 Discussion

While water quality models and water environmental capacity calculation formulas are well referenced, the selection of parameters has proven more difficult to address and predict because of the wide range of each parameter value and the lack of uncertainty assessment of their results due to their high complexity [8, 12, 27].

3.1 Endogenous pollution factors

According to Cai [28], water environmental pollution can be divided into exogenous pollution and endogenous pollution as follows: 1) exogenous pollution includes a series of natural pollution caused directly or indirectly by human activities, such as commercial and industrial activities, and agricultural production and 2) endogenous pollution typically refers to the pollution of a water body caused by the release of nutrient and inorganic salts from underwater bed sediments. Most water environmental capacity calculation methods consider the influence of exogenous pollution factors when evaluating the water quality of rivers and lakes, such as runoff-rainfall [29], tides [30], wind [31], etc. Although some literature is available on the influence of water temperature, aquatic animals, phytoplankton, and other endogenous pollution factors in water environmental capacity [32], few studies have considered groundwater [30], bed sediments [33], and other factors.

Endogenous pollution refers to the pollution of a water body caused by the release which is an internal dynamic process with many influencing factors, for example, the suspension, saltation, and erosion of sediment particles. The monitoring technology for endogenous pollutants is complicated as the influencing factors may be uncertain [28], making the

estimation of endogenous pollution more difficult than that of exogenous pollution. As a result, a few water quality simulation models have not paid sufficient attention to the influence of endogenous pollution factors on water environmental capacity, or have even ignored it [10].

3.2 Effects of bed sediments rheological properties on K and R

From Eq. (2) and Eq. (3), it can be seen that there are two vital coefficients, K and R , in water environmental capacity calculation as follows: 1) the K represents the self-purification capacity of a water body [24] and 2) the R indicates the degree of absorption or release of pollutants by a water body and is difficult to determine. Both K and R would affect the results of water quality simulation. When considering the values of K and R , bed sediments, phytoplankton, and other endogenous pollution factors are all essential.

First, bed sediments are important factors affecting K and R as they absorb or release heavy metals, toxic substances, nutrient salts, microbes, etc. [1, 34, 35]. Different mechanical properties of bed sediments have different adsorption and release capacities [35]. Thus far, some scholars have already experimentally investigated the effects of absorption or release of bed sediments on pollutants concentration [36-38]. However, few scholars have connected the rheological properties of sediments to the adsorption or release capacity of sediments [39, 40]. Bed sediments rheological properties (viscosity, yield stress, etc.) could indicate the state (degree of fluidization) of bed sediments, changing the exchange relationship between the pollutants and water bodies [35].

Recently, Yang et al. [41] found that the concentration of bed sediments in West Lake increased with depth below the bed surface, where bed sediments show strong non-Newtonian and shear-thinning behavior. The degree of fluidization of the bed sediments was influenced by the shear load, pattern, duration, and history, which determined the in-situ and real time yield stress [42, 43]. Even for sediments with the same water content or bulk density, those with different degrees of fluidization showed different yield stresses [43]. Because sediment fluidization is indirectly related to the yield stress, which is a major factor affecting the erodibility of bed sediments, it is generally recognized that the erodibility of bed sediments is mainly dependent on the degree of sediment fluidization [44]. Undoubtedly, the adsorption or release of pollutants in underwater bed sediments also depends on the degree of fluidization of bed sediments. The relationship between water environmental capacity calculation and rheological properties of bed sediments are shown in Figure 1.

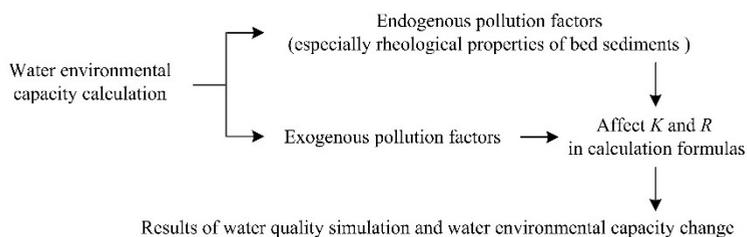


Figure 1. The relationship between water environmental capacity and rheological properties of bed sediments

Overall, the quantitative relationship between the mechanical properties (such as rheological properties) and the adsorption or release capacity of bed sediments urgently needs to be further investigated in the future to better determine the values of K and R in water environmental capacity calculation.

4 Conclusions

As water environment conditions are continuously undergoing change, the study of uncertainty variables is a hot issue in water quality models research. Both K and R are important parameters for evaluating water environmental capacity. In order to estimate endogenous pollution, the effects of the values of K and R should be considered. Under steady shear loadings induced by currents or waves, bed sediments exhibit strong non-Newtonian fluid and shear-thinning or fluidization behavior. The adsorption or release of pollutants in underwater bed sediments depends on the degree of fluidization of bed sediments. In future studies, it is necessary to conduct extensive laboratory tests to investigate the relationship between mechanical properties (such as rheological properties) and the adsorption or release capacity of bed sediments.

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