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Water environmental capacity calculation based on uncertainty analysis: a case study in the Baixi watershed area, China

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Abstract

Water environmental capacity (WEC) is an important concept in environmental science. A basic theory applied in EIA (Environmental Impact Assessment), WEC is also an indispensable factor in District Environmental Planning and total water pollutant control planning. The results of most calculating methods for WECs are fixed values that correspond to designed conditions and are not practical WECs. Instead of a fixed value in calculating WEC, confidence probability and uncertainty analysis should be combined with the river model. Consequently, the feasible WEC in different hydrological periods can ensure the precision and reliability of the load allotment. In this study, a useful method, Monte Carlo simulation, was combined with a water quality model to calculate the WEC and quantify the impact of a range of input values on the WEC. A case study of nitrogen and phosphorus WEC calculation was conducted in the Baixi Reservoir watershed area in Ningbo City, Zhejiang Province, China. The results show that the WEC values of TN under 90% confidence probability were 5.30 T/period during the wet period, 8.35 during the dry period, and 9.83 during the middle period. In comparison, the values under 80% and 70% were 10.80, 16.39, 18.79 , and 15.94, 23.99, 27.71 T/period, respectively. The WEC values of TP were also obtained. The uncertainty analysis-based WEC could help policy makers to set better goals for different hydrological periods, especially in an area dominated by non-point source pollutants.

Keywords：Water environmental capacity; Monte Carlo simulation; uncertainty analysis

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1. Introduction

Water environment capacity (WEC) is the load quantity of certain pollutants during certain times, in a certain unit of water, given the condition that water can fulfill certain environmental objectives [1]. WEC is indicative of the capacity of the body of water to accept pollutants without destroying its own function [2]. The more the water environment capacity, the more the potential exploitability, and the more pollutants can be contained without a decline in environmental function. To ensure that water quality is high enough to meet the requirements of a water environment functional zone (WEFZ), in recent years, controlling the total amount of pollutants going into bodies of water has been done by the environmental protection departments in China. As a basic theory applied in controlling the total amount of pollutants, the calculation of WEC plays the most important role. Three important factors that affect water environment capacity are: water environment characteristics, pollutant characteristics, and the emission approaches and emissions spatials of pollutants.

According to the Approved Technical Guidelines for National Water Environment Capacity designed by the Chinese Academy for Environmental Planning [3], there are many models and equations to calculate the WEC of rivers, lakes, and reservoirs. These models are divided into three types: zero-dimensional, one-dimensional, and two-dimensional models. For study, it is important to select the proper water quality simulation model. In the Zhang Weinan Canal sub-basin[4], a one-dimensional water quality model was chosen to simulate pollutant degradation in the rivers. The one-dimensional model was also used in other areas including Chaping River, Sichuan Province [5], Binhai NW Area of Tianjin [6], and Three Gorges Reservoir [7]. According to WANG et al. [8], the WEC for every month in different parts of Chengtan River was arrived at by using a mathematical model that can be expressed as a method of controlling concentration at the last part of the river. Besides, investigating different methods for water quality parameter determination also plays an important role when calculating the WEC [4]. Han et al. [9] determined the appropriate parameters, looking at the basin divided unit as the basic unit of the WEC, based on the results of the division of basin surface water and the comprehensive comparison of the multiple water quality model. For non-point sources in the river catchment area, Chen et al. [10] computed the quantities of TN and TP that entered the river by means of an export coefficient model, based on the investigation of the application and emission quantities (QAE) of total nitrogen (TN) and total phosphorus (TP).

Additionally, in calculating WEC, uncertainty analysis must be taken into consideration. In a practical river system there are many uncertainties in terms of variable information while calculating WEC, such as background concentration and the degradation coefficient of controlling pollutants, especially those during different hydrological periods. The more variable the information, the more flexible the WEC will be. Particularly in regions that are polluted mainly by non-point source (NPS) pollutants, the randomness and dynamics of the occurrence of the pollutants increase the uncertainty. To reduce the uncertainties, Li and Hong [11] proposed a new uncertainty model for calculating WEC by means of transforming the grey interval value parameters into blind number parameters of the model. Application shows that the model is feasible and reliable. In an article by Shu and Ma [1], sensitivity analysis was performed to identify the critical model parameters from 17 indexes. Uncertainties associated with the water quality parameters were also projected into matrices and vectors through Monte Carlo simulation [6].

However, the results of all the methods referred to above are still fixed values that correspond to designed conditions and are not practical WECs,. But it is subjective and unscientific to select a fixed value to represent a practical WEC value.

In this study, the study area is the key source of drinking water for Ningbo City. There are no industrial districts in the area, and water quality is affected mainly by runoff, which carries away NPS pollutants. So uncertainty analysis is critical for WEC calculation. The uncertainty of the models consists of three parts: structural uncertainty, input data uncertainty, and parameter uncertainty [12]. Here, uncertainty of input data was focused on and the analysis of input data values for the model were obtained by using a random number generator. And the WEC outputs were obtained and analyzed using the Monte Carlo simulation approach. This method has been tried in the calculating of the total nitrogen (TN) and total phosphorus (TP) WEC in some areas [13, 14]. To reflect the characteristics of NPS pollution, a hydrological year was divided into three periods: the wet period, the dry period, and the middle period.

2. Study area and methodology

2.1 Study area

The Baixi River is located in the east of Zhejiang Province. It runs a 66.5 km course from its source to the end and is the longest river in Ninghai County. Found in a temperate and subtropical zone, Baixi enjoys a mild climate and plenty of water. Flooding generally occurs between May and October, when monsoon season brings much precipitation. Mean annual flow velocity of the river where a dam is located is $8.92\text{m}^3/\text{s}$, and the discharge volume and the mean annual sediment load are $2.81\times10^8\text{m}^3$/year and 3.91×10^4 T/year. Mean temperature here ranges from the lowest -9.6°C to the highest 39.7°C, with an average of 16.1°C. Mean annual evaporation capacity reaches 1091.2 mm. NNE / SE is the predominant wind direction.

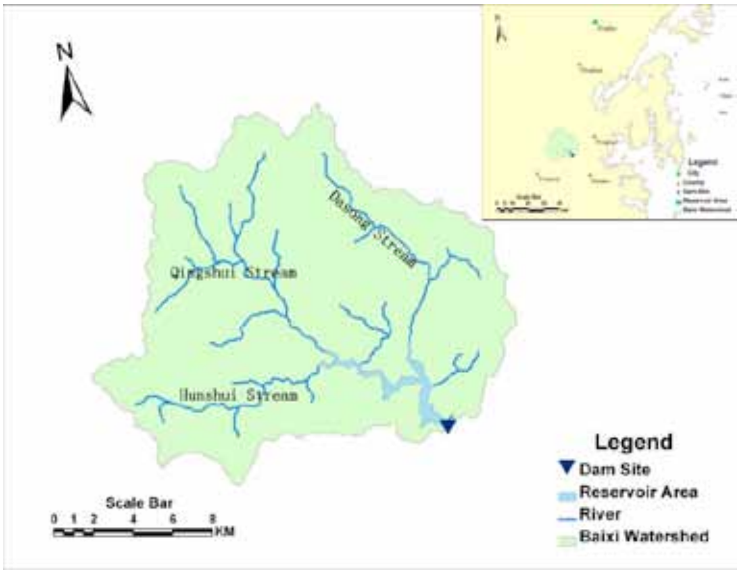

Fig. 1. Baixi Reservoir basin

The Baixi Reservoir dam, which was finished in 1998, is located in the main stream of the Baixi River, 29km to Ninghai County and 107 km to Ningbo City. The dam was built for water supply, flood control, electricity production, and irrigation. It is a degree Ⅱ dam (storage volumes$\geq$0.1billion m^3) according to the Standard for Flood Control (GB50201-94) [15]. The total upstream area of the Baixi Reservoir is 254 km^2, accounting for 40% of the whole river basin. The three main branches are Dasong, Hunshui, and Qingshui, which flow into Baixi Reservoir, see

Fig. 1. Around the reservoir is a mountainous area with agricultural vegetation, secondary forest, and planted forest. Forestry land makes up 64.5% of the whole land area, research indicates. And the vegetation coverage of the basin can go as high as 70%. According to an investigation by the Baixi Reservoir Administration Bureau on sources of pollutants, there are few point pollution sources, whereas non-point sources dominate in the watershed.

To analyze the degradation coefficient of TN and TP, data were obtained from other areas that were similar to the studied area. Monthly water discharge (2006 to 2009), and monthly storage volumes of the reservoir (2006 to 2009) were obtained from the Baixi Reservoir Authority. Monthly TN loads and TP loads were collected from the Ningbo Hydrological Station and the environmental monitoring station of Ninghai County.

2.2 Methodology

In order to provide a decision-making basis for better gross control of NPS pollutants (TN and TP in this article), the WEC calculations of different hydrological periods were obtained. According to changes of hydrological flow and historical records, the wet period for Baixi Reservoir is July, August, and September; the dry period is January, February, March, and December; and the middle period is April, May, June, October, and November.

According to the Environmental Quality Standards for Surface Water (GB3838-2002) of China, the water quality degree of Baixi Reservoir is degree II, namely, concentrations of TN and TP are less than 0.5mg/L and 0.025mg/L, respectively.

To calculate WEC with limited data, a simple and proper water quality simulation model is needed. In this study, the adopted model can be expressed as [3]

$$W = (c_s - c_0)V/\Delta T + kVc_s + (c_s - c_0)q \tag{1}$$

where c_s is the targeted concentration of the water quality (mg/L), c_0 is the background concentration of the water quality (mg/L), V is the storage volumes over a hydrological period (m^3), ΔT is the number of days in a period (d); k is the degradation coefficient of TN or TP (d^{-1}), and q is the discharged flow volumes of the reservoir over a period (m^3/d). The equation is simple and does not require many detailed data about a reservoir. Thus, this technique can be applied to the WEC calculation for the Baixi Reservoir, where NPS pollutants are the main pollutants and it is difficult to calculate the source distance before they flow into the reservoir.

Combined with the water quality simulation model, the Monte Carlo simulation approach was selected to calculate WEC. Monte Carlo means using random numbers as a tool to compute something that is not random. The Monte Carlo Simulation performs sampling from a possible range of input parameter values, followed by model evaluation for the sampled values [16]. This method is often used when the model is complex, nonlinear, or involves more than just a couple of uncertain parameters. The conventional MC simulation procedure has three steps [16]: (1) randomly sample considering the probability distribution for the input variable; (2) input the combination of all of the random sampling values into the model and run the simulation; and (3) statistically analyze the output results. This method is conceptually simple, theoretically sound, and flexible, and it can handle both small and large uncertainties in the input quantities. Monte Carlo simulation is categorized as a sampling method because the inputs are randomly generated from probability distributions to simulate the process of sampling from an actual population. The best available random number generators are perfect to generate input numbers in this sense for nearly all practical purposes. This method has been widely used in analyzing the uncertainties of water quality models and estimating the parameter values [17, 18].

In this study, the prior distribution analysis for input parameters of the model was obtained using Microsoft Excel 2007. And 10,000 simulation values of input parameters were obtained randomly according to the prior distribution analysis. The WEC calculation, as well as the probability distributions of the WEC results, were analyzed using the Monte Carlo simulation approach.

3. Results and discussion

3.1 Distribution of parameters

Error! Reference source not found. presents the prior distributions and the range values of the input parameters of the TN and TP WEC model in different periods [3, 19]. It can be seen from Table 1 that all the parameters obey the uniform distribution except *q*. The value ranges of the parameters in different periods are also listed.

Table 1. Prior distributions for the input parameters of TN and TP WEC model in different periods

name of parameters	prior distribution	hydrological period	pollutants	range of value
c_0 (mg/L)	uniform distribution	the wet period	TN	0.38~1.7
			TP	0.01~0.182
		the middle period	TN	0.35~1.7
			TP	0.005~0.039
		the dry period	TN	0.36~1.08
			TP	0.01~0.035
V (m^3/d)	uniform distribution	the wet period	max	12749.37
			min	4565.78
		the middle period	max	14171.28
			min	5722.79
		the dry period	max	13876
			min	6171.12
k (d^{-1})	uniform	all the periods	TN	0.008~0.01

	distribution		TP	0.019~0.062
q (10,000m^3/d)	normal distribution	the wet period	μ	88.85
			σ	42.09
		the middle period	μ	64.72
			σ	26.90
		the dry period	μ	49.77
			σ	8.76

3.2 Uncertainty analysis of outputs

The outputs of the 10,000 simulations are listed in descending order. The positive values are WECs that can be allocated, and the negative values are caused by excessive pollutants flowing into the reservoir. Cumulative frequency of positive output values was calculated and the probability distributions of the TN and TP WEC in different periods are presented in Fig. 2 and Fig. 3.

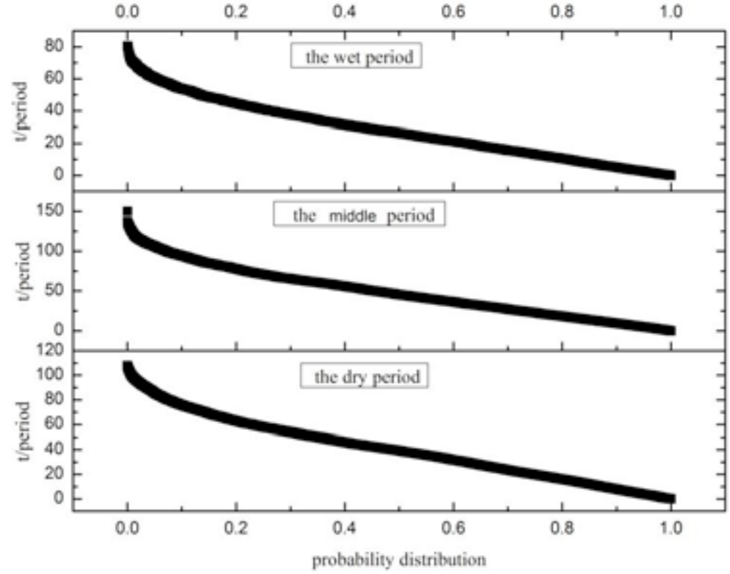

Fig. 2. Probability distributions of TN WEC in different periods

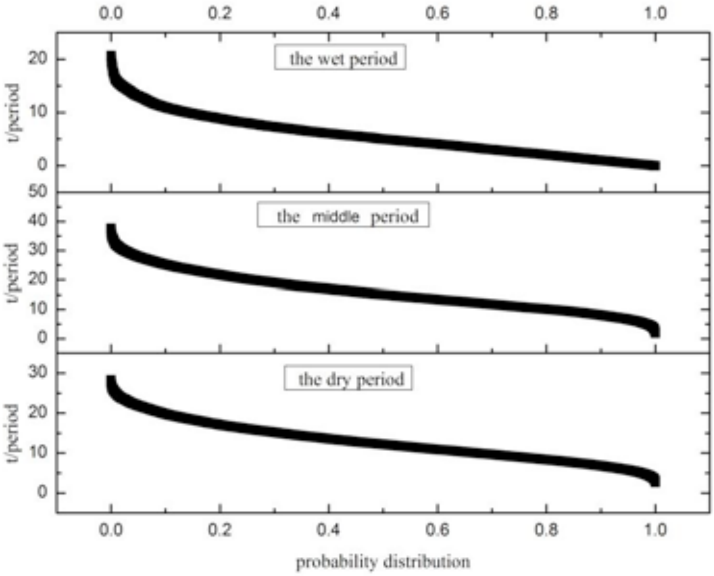

Fig. 3. Probability distributions of TP WEC in different periods

Fig. 2 and Fig. 3 show that either TN WEC or TP WEC decreases with the increase of probability distribution in the same period. This can be explained that a higher probability distribution presents a higher time frequency for water body to meet the water quality target. For example, probability distribution 0.9 means the probability that the water are within requirements during a period is 90%. And from Fig. 2 and Fig. 3, TN or TP WEC values of different periods under certain probability distribution can be grasped. Furthermore, the WEC of TN and TP in three different probability distribution -- 70%, 80%, 90% -- were picked out for comparison (see Table 2 and Table 3).

Table 2. WEC of TN in different confidence probabilities in different hydrological periods

confidence probability	the wet period	the middle period	the dry period
70%	15.94	27.71	23.99
80%	10.8	18.79	16.39
90%	5.3	9.83	8.35

Table 3. WEC of TP in different confidence probabilities in different hydrological periods

confidence probability	the wet period	the middle period	the dry period
70%	3.07	11.87	9.72
80%	2.12	10.2	8.4
90%	1.06	8.2	6.9

Interestingly, it can be seen from Table 2 and Table 3 that the WEC exhibits a temporal variability depending on whether it relates to the middle period＞the dry period＞the wet period. Selecting 90% confidence probability for example, the WEC for TN and TP in the middle period are the highest, which are 9.83 T/period and 8.2 T/period, respectively. This is because during the middle period, the storage volumes are large enough to contain more pollutants and, at the same time, the discharged flow volumes are also at a high enough level to carry pollutants away.

The WEC in the wet period is the lowest, 5.3 T/period and 1.06 T/period, respectively. This is caused by three things: First, NPS pollutants are always determined by the hydrological process of the basin, where runoff and drainage are the motivation and carrier of NPS [20], making pollutant concentration in a wet period higher than in other periods [21]. Second, in a wet period there is much more precipitation than in other periods at the Baixi Reservoir watershed. Runoff and drainage flow into the reservoir mingled with nitrogen and phosphorus pollutants and result in the lower WEC. Furthermore, agriculture is the dominant industry in the Baixi watershed area, and pesticides and chemical fertilizer are the main sources of nutrients, including nitrogen and phosphorous. So, during this period much agricultural fertilization adds more TN/TP to the soil, and this can be washed out easily by rainfall. In a dry period, reservoir regulation -- storing winter flood water for irrigation in spring and for power generation -- and less rainfall bring the WEC calculation to between that of the other two periods. The same phenomenon can also be seen when the confidence probabilities are 80% and 70%.

Such a temporal variability is different from that of the Changle River [16] area, whose order of WECs is: the wet period＞the middle period＞the dry period. This is mainly because the Changle River is a natural river whose flow volumes correspond to the hydrological periods, while the Baixi River is regulated by Baixi Reservoir, and so the water volume in the reservoir in a wet period is no more than that in a middle period for the purpose of flood control, although the amount of pollutants is larger. And in a dry period, the water is stored for use, and this increases the WEC of the Reservoir. Additionally, a more remarkable temporal variability of the pollution load can also result in this phenomenon.

3.3 Discussion

The degradation coefficients of the three periods are the same. They were recorded and obtained according to the previous study and no real data were monitored. This may affect the outputs of the simulation. Thus, if possible, more monitoring work on the degradation coefficient needs to be done to enhance the accuracy of WEC calculation.

Generally, traditional approaches commonly use certain flow conditions, such as ADF, Q90, Q75, and 7Q10, for calculating WEC [22]. Then a fixed WEC value is obtained. But here, to reduce the uncertainties and to reflect the characteristics of NPS pollution, a year was divided into three hydrological periods, and in each period, 1,000 values of each parameter were generated according to statistics and monitoring of the recent four years before 1,000 outputs were obtained. Each result is a WEC under a certain condition. Proper WEC values can be selected as targets for pollutant control according to different requirements.

After 10,000 simulations, some output values are negative, namely, environmental background value exceeds WEC. And the probability of TN is 34.46% during the dry period, 63.21% during the middle period, and 75.04% during the wet period. For TP, only during a wet period, the background value exceeds WEC, and the probability is 62.84%. This phenomenon proves that TN and TP more easily pollute a body of water during a wet period. From the outputs, we find that the required reduction for TP in a wet period reaches 38.45×10^3 kg. For TN, the required reduction can reach 345.94×10^3 kg in a wet period, 299.82×10^3 kg in a middle period, and 60.76×10^3 kg in a dry period. These results will be used as a reference for pollution reduction based on pollution control.

4. Conclusions

The results show that the WEC value of TN under 90% confidence probability is 5.30 T/period during a wet period, 8.35 during a dry period, and. 9.83 during a middle period, respectively. In comparison, the values under 80% and 70% were 10.80, 16.39, 18.79, and 15.94, 23.99, 27.71 T/period. The WEC values of TP were also obtained.

The Monte Carlo simulation method was used to analyze the uncertainty of the WEC results, to arrive at more reasonable and scientific TN and TP WEC values under different confidence probabilities in different periods. This method is suitable and practical for similar basins with obvious seasonal precipitation differences. For basins without seasonal precipitation differences, deciding which method is best needs further investigation.

WEC is a kind of limited and renewable resource, and to exploit the water environment capacity completely, rationally, and continuously, a balance point needs to be found between environment concerns and social, and economic development. Environmental capacity can be a good indicator. The uncertainty analysis -based WEC can enable decision makers to determine load reductions and allocations given different hydrological periods. And different measures of controlling the total amount of pollutants can be applied to realize the improvement of water quality.

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