

Dynamic Water Environmental Capacity Calculations of Rivers Based on Hydrological Processes



Wei Deng, Jing Ma, Long Yan and Ying Zhang

Abstract The process and mechanism of the water environmental capacity, and the coupling mechanism between it and the hydrological processes were studied. Then, a dynamic approach based on the hydrologic processes was developed in which distributed hydrological and water environmental capacity models were coupled to solve the problem in a traditional way. The Tieling Section of the Liao River Basin was taken as the study area for the purpose of demonstrating the proposed method. The results indicated that the water environmental capacity was uneven during different times and spaces. The results also explained that, contrary to the dynamic methods which separately calculated the years with different frequencies, seasons, or months, the traditional method was too conservative to make full use of the water environmental capacity.

Keywords Water environment management · Dynamic water environmental capacity calculation · Distributed hydrological model · Hydrologic process

1 Introduction

Water pollution is one of the most serious water issues in China, which is essentially due to a severely overdrawn water environment carrying capacity (WECC). Therefore, it is important to regard the WECC as a rigid constraint for the future sustainable development of China's economy and society. The water environmental

W. Deng (✉) · J. Ma · L. Yan · Y. Zhang
China Institute of Water Resources and Hydropower Research, Beijing, China
e-mail: dwsylar@163.com

J. Ma
e-mail: jingma@iwhr.com

L. Yan
e-mail: xiangyangyl@163.com

Y. Zhang
e-mail: cwzhangying@iwhr.com

capacity (WEC) is usually used as a quantitative indicator of carrying capacities of the water environment. In China, the WEC is normally defined as the maximum amount of pollution the system allows within a unit of time and in given hydrological conditions, discharging patterns, and water quality targets [1]. The calculation methods include analytical formula [2, 3], model trial [4, 5], and system optimization methods [6, 7]. Regardless of the method used, the WEC is calculated under designed hydrological conditions (usually the most withered month average discharge in a 90% assurance rate, or the most withered month average discharge during the most recent ten years) without consideration being given to the uncertainty of the hydrology within a time scale according to the definition. Furthermore, the design hydrological conditions are often derived from the analysis of the hydrological station data, which also ignore the influence of the hydrological process along the rivers. Many mathematical approaches have been introduced to improve the calculation methods. These have generally included negative mathematical methods [8], a stochastic differential equation [9] and stochastic optimization models [10]. These approaches have been found to only partially solve the uncertainty problem of hydrology and water quality. The water environmental capacity is considered to be closely related to the hydrological factors, and two-dimensional or three-dimensional hydrodynamic models have been developed and applied on a small scale, such as in lakes [11] and reservoirs [12]. However, the excessive data requirement has been found to limit further applications on larger scales. A dynamic accounting method which uses the historical hydrographic data of hydrological stations has also been introduced to solve the problem [13]. However, due to the limitations of the layouts of the hydrological stations, it cannot dock well with the computing unit and the spatial changes of the hydrological elements.

The changes of the water environments are the associated phenomena of the water cycle. The WEC is a significant quantitative indicator of the water environment, and is hypersensitive to the river runoff and hydrodynamic conditions. Therefore, based on the study of the process and mechanism of the water environmental capacity, and the coupling mechanism between it and the hydrological process, a dynamic WEC calculation method was developed in which the distributed hydrological and water environmental capacity models were coupled in order to solve the hydrological uncertainty problem for which the traditional methods had previously ignored. The Tieling Section of the Liao River Basin was taken as the case study area for the purpose of demonstrating the proposed method, and to explore the feasibility of the application on a large scale. The results potentially provided technical support for both future dynamic and delicate water environmental management.

2 Methods

2.1 Study Area

Tieling City (41°59'–43°29' N, and 123°27'–125°06' E) is in the northeastern section of Liaoning Province, east of Jilin Province, and west of the Inner Mongolia Autonomous Region. The total area of Tieling City is 13,000 km². With the rapid development of the economy and society, the pressure on the water environment has increased. The total discharge of the waste water increased from 75 million tons in 2008, to 86 million tons in 2013. Also, this special geographical location has led to serious pressures from pollution which originates from the upstream. In this study, seven rivers which had drainage areas of at least 500 km² were chosen, including the Liao, Zhaosutai, Qing, Chai, Fan, Kou, and Erdao Rivers (Fig. 1). The basic calculation units were the 19 water function zones (including 5 types) (Fig. 1) in these seven rivers. In Fig. 1, AWCR, PDCR, BR, TR, DWSR, respectively, are the agricultural water consumption region, the pollutant discharge

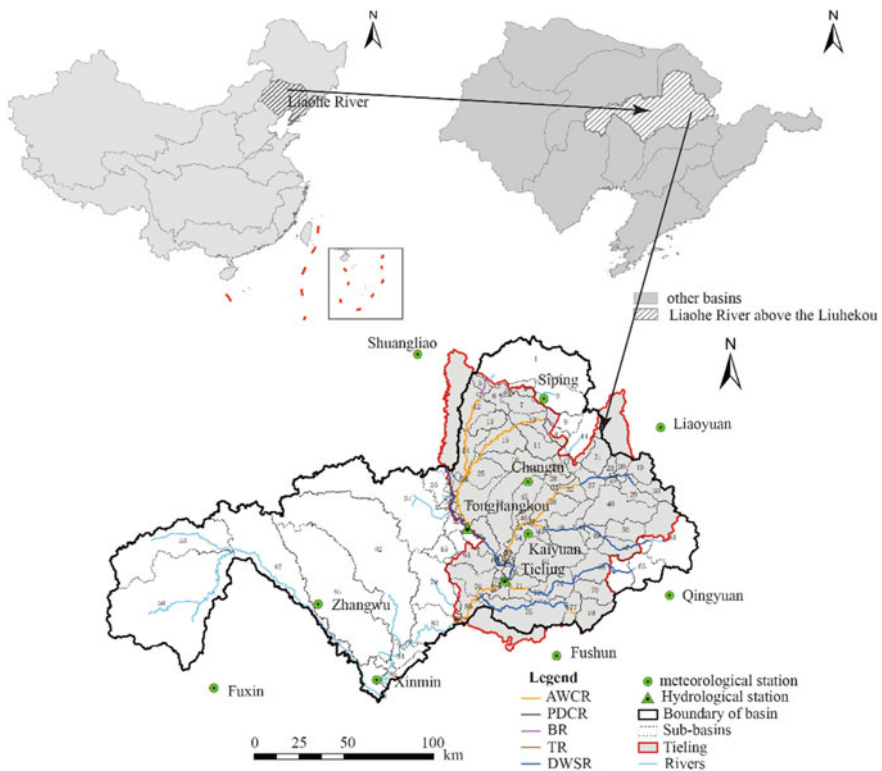


Fig. 1 Location of basin, distribution of water function zones and delineation of sub-basins

control region, the buffer region, the transitional region and the drinking water source region.

The seven rivers were mainly located in the Liaohe River Basin above Liuhekou, of which the total area was 30,000 km². A distributed hydrological model was established in the river basin.

The control pollutant index of the Liao River Basin was COD (chemical oxygen demand) and NH₃-N, according to the planning documents of the management department of the Liao River Basin. Also, the water environmental monitoring results for the Tieling section of the Liao River also showed that the primary pollutant was NH₃-N. Therefore, this study focused on the COD and NH₃-N levels in the basin.

2.2 *Framework and Methodology*

In this study, a dynamic method was developed to calculate the WEC, which was composed of a distributed hydrological model, an empirical model for the conversion between the discharge and flow velocity, and a water environmental capacity calculation model.

Distributed Hydrological Model. The water environmental capacity is closely related to the hydrological and rainfall-runoff processes, and even is the direct driver of the formation of non-point source pollution [14]. Therefore, the analysis of hydrological process of a river basin laid the foundation for the calculation of the dynamic water environmental capacity in this study. The river basin was divided into several sub-basins using GIS, with consideration given to the basin's natural boundary (watershed terrain, DEM, characteristics of the water system); monitoring station (mainly included the hydrologic and water quality station); management factors (mainly the location of the water function zone); and the characterization of the pollutant emission. The sub-basins were nested with the water function zone, which formed the basic coupling unit of the distributed hydrological and calculation models of the WEC. Furthermore, based on the soil, land use, slope, and other characteristics, the sub-basins were divided into hydrological response units (HRUs), which were used as the basic computing units of the hydrologic simulation. Then, the hydrological cycle of the sub-basins was obtained by the simulation of the runoff yield and concentration. Finally, the hydrological factors required by the dynamic calculation of the WEC, such as water yield and outlet runoff, were output.

Empirical Model for the Conversion Between the Discharge and Flow Velocity. As the distributed hydrological model was unable to output the discharge, the dynamic flow velocity data were updated from the data obtained from the distributed hydrological model by an empirical model, which was obtained by a linear fitting of the observation data of the hydrological stations.

Under normal circumstances, an empirical formula for the conversion between the discharge and discharge flow velocity can be given by Eq. (1) as follows [15]:

$$u = \alpha Q^\beta \quad (1)$$

where u (m/s) is the average velocity of the river; Q is the discharge of the river section; and α and β are the parameters which can be determined by the observational data.

Then, Eq. (1) was converted to a linear form (Eq. (2)) as follows:

$$y = a + bx \quad (2)$$

where $y = \ln u$, $x = \ln Q$, $a = \ln \alpha$ and $b = \beta$; and a and b are the parameters which can be determined by the observational data.

Dynamic Water Environment Capacity Calculation Model. The basic calculation unit of the WEC is usually the water function zone (in this study, the sub-basin combination was the basic calculation unit). The water quantity and pollutant balance in every river link of the sub-basin is conceptualized in Fig. 2.

The water quantity balance equation in the river link is as follows [16]:

$$\Delta V_i = Q_{i-1} + R_i + Q_{ai} - q_i - Q_i \quad (3)$$

The water quality balance equation in the river link is as follows [16]:

$$\Delta C_i = \frac{Q_{i-1}C_{i-1} + W_P + R_iC_{Ri} + Q_{ai}C_{ai} - C_i(\Delta V_i + Q_i) - C_{qi}q_i - W_d}{V_i} \quad (4)$$

where ΔV_i is the incremental discharge of the river link i ; Q_{i-1} is the inflow discharge; Q_i is the outflow discharge; q_i is the local water withdrawal; R_i is the local water yield; Q_{ai} is the inflow of the tributary into the river link; V_i is the water storage of the river link i ; C_{Ri} is the pollutant concentration of the local water yield (dependent on the non-point source pollution); C_{ai} is the pollutant concentration of the tributary; C_{i-1} and C_i are the pollutant concentrations of the inflow and outflow, respectively; C_{qi} is the pollutant concentration of the local water withdrawal; W_P is

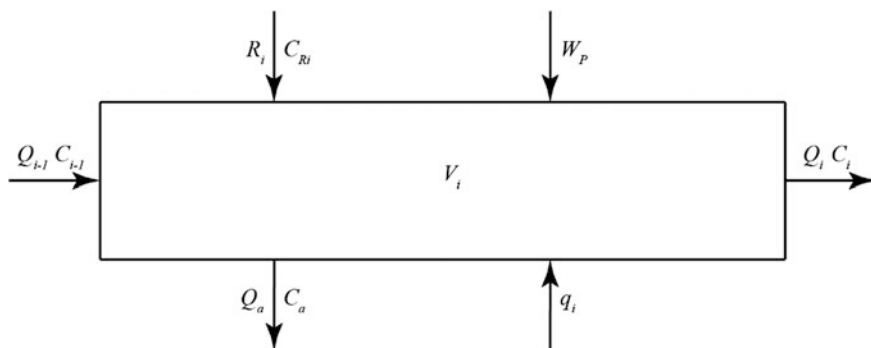


Fig. 2 Water quantity and quality balances in the river link

the total point source pollution load of the river link i ; ΔC_i is the incremental pollutant concentration of the river link; and W_d is the pollution degradation amount of the river link.

The time scale management is generally months or years (the time scale for this study was months) in which the water quality can be considered stable [16]. That meant that the ΔC_i could be assumed to be 0. Then, the WEC was obtained by Eq. (5) as follows:

$$W_i = W_P + R_i C_{Ri} = C_i(Q_{i-1} + R_i + Q_{ai}) + (C_{qi} - C_i) - Q_{i-1}C_{i-1} - Q_{ai}C_{ai} + W_d \quad (5)$$

Therefore, C_i is the water quality target in the time scale management in this study. As the water quality target was often set up to consider the requirements of the water withdrawal, it could be assumed that C_{qi} was equal to C_i . Then, Eq. (5) could be converted to Eq. (6) as follows:

$$W_i = W_P + R_i C_{Ri} = C_i(Q_{i-1} + R_i + Q_{ai}) - Q_{i-1}C_{i-1} - Q_{ai}C_{ai} + W_d \quad (6)$$

where $C_i(Q_{i-1} + R_i + Q_{ai}) - Q_{i-1}C_{i-1} - Q_{ai}C_{ai}$ is the dilution capacity; and W_d is self-purification capacity which could then be divided into four parts: the pollutant degradation of the upper reaches (W_{ds}), tributary (W_{dz}), point source pollution (W_{dp}), and non-point source pollutants (W_{dm}).

Also, the W_d could be calculated using the water quality model. A one-dimensional steady water quality model was used in this study when considering the large-scale applications. This one-dimensional steady water quality model is described by Eq. (7):

$$C = C_0 e^{-K \frac{x}{u}} \quad (7)$$

where C is the pollutant concentrations following the degradation; C_0 is the initial pollutant concentration; u is the average velocity of the river; L is the distance along the channel; and K is the degradation coefficient.

According to Eq. (7), W_{ds} and W_{dz} can be computed by Eqs. (8) and (9), as follows:

$$W_{ds} = (1 - e^{-K \frac{L}{u}}) C_{i-1} Q_{i-1} \quad (8)$$

$$W_{dz} = \sum_{j=1}^n (1 - e^{-K \frac{x_j}{u}}) C_{aij} Q_{aij} \quad (9)$$

where Q_{aij} is the inflow of the tributary j into the river link; C_{aij} is the pollutant concentration of the tributary j ; x_j is the distance from the end of the river link to the tributary j ($j = 1, 2, \dots, n$, n is the number of the tributary); and L is the length of the river link.

W_{dP} and W_{dM} are related to the pollutants entering the river and the route of the pollutant emission. If the pollutant emission was simplified to emission through a generalized outlet, then W_{dP} and W_{dM} could be obtained by Eq. (10), as follows:

$$W_{dg} = W_{dP} + W_{dM} = \left(1 - e^{-K \frac{x_G}{u}}\right) (W_P + R_i C_{Ri}) \quad (10)$$

where W_{dg} is the pollutant degradation of the generalized outlet discharge; and x_G is the distance from the generalized outlet to the end of the river link. The specific location of the generalized outlet is determined by the analysis of the current pollutants entering the river, and the route of the pollutant emission.

Finally, the WEC calculation model of the river link was obtained using Eq. (11) as follows:

$$W_i = e^{-K \frac{x_G}{u}} C_i (Q_{i-1} + R_i + Q_{ai}) - e^{K \frac{x_G - L}{u}} Q_{i-1} C_{i-1} - \sum_{j=1}^n (e^{K \frac{x_G - x_j}{u}}) C_{aij} Q_{aij} \quad (11)$$

The WEC calculation model was coupled with the empirical models for conversion between the discharge and flow velocity and distributed hydrological factors in the sub-basin, and the output of the WEC in each sub-basin. The hydrological factors in Eq. (11), such as the local water yield, the inflow discharge, inflow of the tributary and average velocity of the river were dynamic data which could be output by the distributed hydrological and empirical models.

3 Data Preparation

Distributed Hydrological Model. A SWAT (soil and water assessment tool) was selected to be used in this study. A SWAT is a basin or watershed scale model developed at the USDA-ARS [17] and has a strong physical mechanism. The model showed good applicability in large areas and had been applied and verified in many regions of the world.

The necessary data for a SWAT model include a digital elevation model (DEM), soil, land use, and weather data. However, other data, such as river discharge, reservoir information, sediment, pesticide, fertilizer, chemical, and water quality data are optional for the model development [18]. The basic data, and its sources and uses, are listed in Table 1.

Empirical Model for the Conversion between the Discharge and Flow Velocity. This model included the discharge and velocity data from the hydrological stations.

Dynamic Water Environment Capacity Calculation Model. This model included the degradation coefficient K and length data (distance from the end of the river link to the tributary and the length of the river link). The K of the COD was set

Table 1 Basic data for the research

| Data type | | Data type | Source | Usage |
|-----------------------------|-----------------|--|---|-------------------------------|
| DEM | Raster graphics | Elevation, slope, slope length and slope direction of river channel | USGS, 30 m resolution | SWAT (water cycle simulation) |
| Land use | Raster graphics | Spatial distribution of land use type | Chinese Academy of Sciences, 1:250000 | SWAT (water cycle simulation) |
| Soil | Raster graphics | Spatial distribution of soil types | FAO, 1:1000000 | SWAT (water cycle simulation) |
| | Database | Physical and chemical properties of soil | FAO | SWAT (water cycle simulation) |
| Meteorological data | | The maximum and minimum temperature, daily precipitation, relative humidity, solar radiation, wind speed | 10 meteorological stations within or around the calculation area (Fig. 1) | Basic hydrologic data |
| Hydrological data | | Monthly mean discharge and velocity | 10 hydrological stations in the calculation river (Fig. 1) | Basic hydrologic data |
| Data of water function zone | | Length data | <i>"The report of water environment function zones of Tieling"</i> | WEC calculation |

between 0.05 and 0.2, and the K of the NH₃-N was set between 0.05 and 0.15, as per the "Guideline for Check and Ratification Technology of National Water Environmental Capacity" and the research results put forward by Meng [19]. The length data was determined by the water function zone of Tieling City.

4 Results and Discussion

4.1 Calibration, Validation, and Simulation of the SWAT Model

The basin was divided into 88 sub-basins according to the DEM, river water system, and distribution of the water function zone. Then, the sub-basins were subdivided into 1,624 HRUs based on the soil, land use, slope, and other characteristics of the study region. The sub-basins were nested with the water function

Table 2 Results of the hydrological simulation

| | Hydrological station | NSE | R ² |
|-------------------------|----------------------|------|----------------|
| Calibration (1991–2000) | Tongjiangkou | 0.71 | 0.72 |
| | Tieling | 0.83 | 0.84 |
| Validation (2008–2010) | Tongjiangkou | 0.65 | 0.85 |
| | Tieling | 0.76 | 0.86 |

zone, which formed the basic coupling unit of the distributed hydrological and calculation models of the WEC. The basic corresponding relationship between the water function zone and sub-basins is shown in Fig. 1.

The observational flow rate data of two typical hydrological stations (Tieling and Tongjiangkou) were used for the calibration and validation. The model calibration was performed using a monthly time scale. The calibration period was from 1991 to 2000, and the validation period was from 2008 to 2010. Two quantitative statistics, the Nash-Sutcliffe efficiency (*NSE*) and the coefficient of determination (*R*²), were used to evaluate the performance of the model in this study. The results of the hydrological simulation were shown in Table 2.

Generally speaking, a score of the *R*² which was above 0.5 was considered acceptable. Regarding the *NSE*, the simulation results were “excellent” when the *NSE* > 0.75 in both the calibration and validation periods, and the simulation results were “good” when the 0.65 < *NSE* < 0.75 in both the calibration and validation periods [20]. Therefore, the simulation results of the Tieling Station were determined to be “excellent”, and the simulation results of the Tongjiangkou Station were determined to be “good” in this study. This implied that the results of the model were reliable, and could thereby be used to calculate the WEC.

4.2 Fitting the Results of the Discharge and Velocity

A least squares linear fitting was applied; and the main parameters of the empirical model for the conversion between the discharge and velocity of each station, as well as the linear regression coefficients, were obtained (Table 3). The results showed that the fitting effect was relatively ideal when *r* was above 0.8 in all the stations except the Songshu Station (*r* = 0.79). These results confirmed that the empirical model was reliable for the computation of the WEC.

4.3 Dynamic Calculation Result of the WEC

In this study, the hydrological process between 1991 and 2010 was simulated; and the related discharge data were obtained by the calibrated SWAT. Then, the

Table 3 Results of least squares linear fitting

| Rivers | Hydrological station | α | β | r |
|-----------------|----------------------|----------|---------|------|
| Liao River | Fudedian | 0.12 | 0.44 | 0.93 |
| | Tongjiankou | 0.04 | 0.42 | 0.93 |
| Chai River | Chaihe | 0.15 | 0.43 | 0.95 |
| Qing River | Kaiyuan | 0.29 | 0.23 | 0.90 |
| | Bakeshu | 0.26 | 0.31 | 0.95 |
| Fan River | Guanliangjiao | 0.10 | 0.44 | 0.81 |
| Zhaosutai River | Wangbaoqing | 0.19 | 0.41 | 0.91 |
| Kou River | Songshu | 0.42 | 0.23 | 0.79 |
| Erdao River | Baoli | 0.29 | 0.39 | 0.97 |

discharge data were transformed to velocity data using the empirical model. Finally, the WEC of the Tieling Section of the Liao River Basin was calculated. The location of the sewage outfall was difficult to generalize when the lack of data regarding the two extreme cases ($x_G = L$ and $x_G = 0$) was considered in this study. The results are shown in Table 4 and Figs. 3 and 4.

The annual average WEC of COD and $\text{NH}_3\text{-N}$ were determined to be 30,620 ton/year and 1,504 ton/year, respectively, when $x_G = L$; and 25,764 ton/year and 1,243 ton/year, respectively, when $x_G = 0$. The WEC of the COD and $\text{NH}_3\text{-N}$ were found to be 10,551 ton/year and 513 ton/year, respectively, in the most unfavorable conditions (when the frequency was 90%, and $x_G = 0$). For the most optimistic conditions (when the frequency was 10%, and $x_G = L$), the WEC of the COD and $\text{NH}_3\text{-N}$ were determined to be 55,640 ton/year and 2,418 ton/year, respectively.

There were found to be great differences among the WEC during years with different frequencies. For example, the WEC in especially dry years was less than half that in the normal years, or even a quarter of that in the especially wet years.

Table 4 The WEC (ton/year) in flood and non-flood season with different frequencies

| Frequency (%) | $x_G = L$ | | | | $x_G = 0$ | | | |
|----------------|--------------|------------------------|------------------|------------------------|--------------|------------------------|------------------|------------------------|
| | Flood season | | Non-flood season | | Flood season | | Non-flood season | |
| | COD | $\text{NH}_3\text{-N}$ | COD | $\text{NH}_3\text{-N}$ | COD | $\text{NH}_3\text{-N}$ | COD | $\text{NH}_3\text{-N}$ |
| 10 | 37,382 | 1,928 | 18,258 | 904 | 35,462 | 1,844 | 16,165 | 817 |
| 25 | 32,336 | 1,642 | 11,817 | 579 | 30,320 | 1,560 | 9,633 | 489 |
| 50 | 17,676 | 867 | 9,311 | 444 | 16,292 | 809 | 7,695 | 379 |
| 75 | 9,676 | 475 | 6,848 | 321 | 8,648 | 431 | 5,440 | 265 |
| 90 | 7,386 | 348 | 5,538 | 251 | 6,296 | 305 | 4,255 | 208 |
| Annual average | 20,418 | 1,013 | 10,202 | 491 | 17,129 | 826 | 8,636 | 417 |

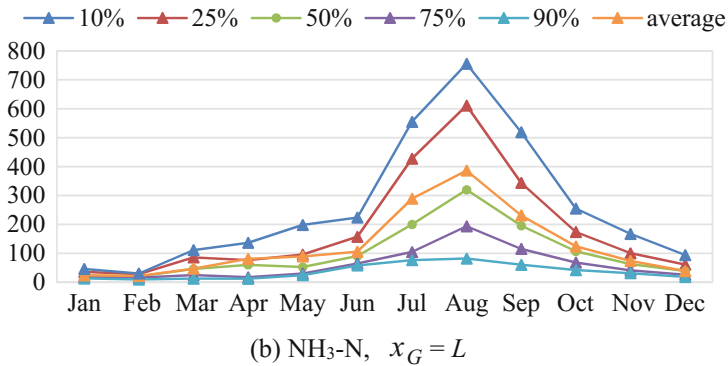
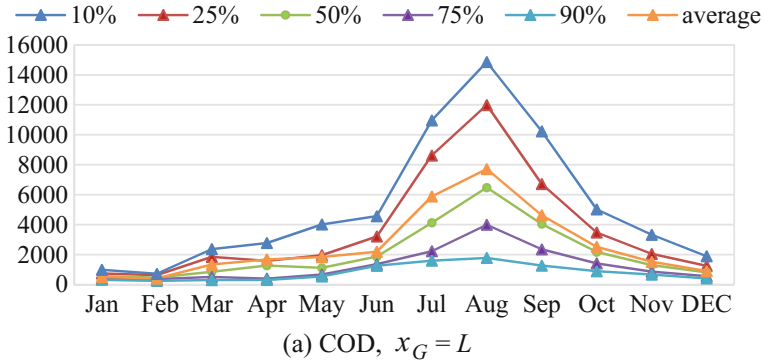


Fig. 3 The WEC (ton/year) in different months during years with different frequencies **a** COD, $x_G = L$ **b** NH₃-N, $x_G = L$

The WEC in the flood (from June to September) and non-flood seasons was also found to be uneven, and the capacity during the flood seasons was above 60%. The differences of the WEC among the months were more obvious; and August was determined to account for 20% of the entire year, while February accounted for only 1–2%. These findings revealed that the traditional method, which did not consider the annual and inter-annual variation of the hydrology, tended to be conservative. However, the dynamical method was able to make a greater use of the WEC.

In this research study, specifically related to these seven rivers, the WEC ranked consistently in different frequencies, from top to bottom, as follows: the Liao, Zhaosutai, Kou, Erdao, Qing, Chai, and Fan Rivers. The capacity of the Liao River made up a significant share (more than half) of the entire region, with the annual average WEC of the COD and NH₃-N determined to be 15,246.13 ton/year and 762.31 ton/year, respectively.

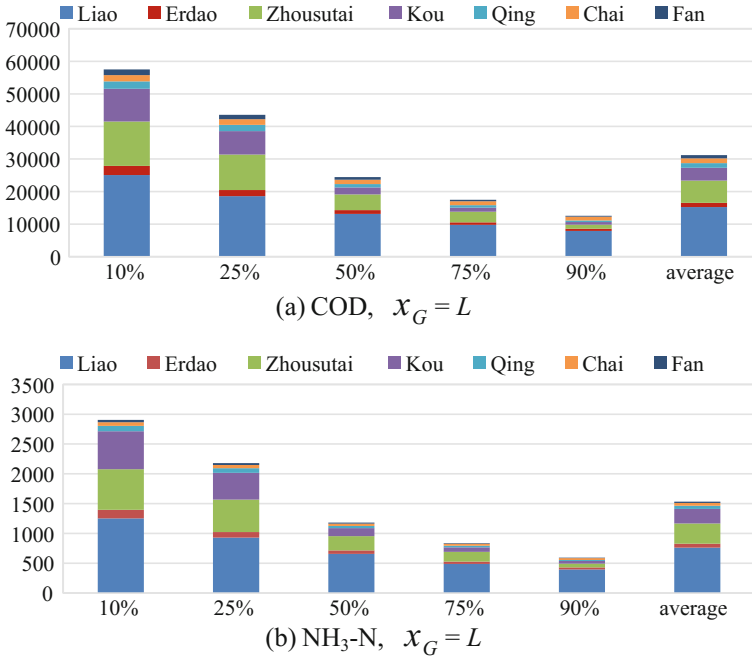


Fig. 4 The WEC (ton/year) in rivers during years with different frequencies **a** COD, $x_G = L$ **b** NH₃-N, $x_G = L$

5 Conclusions

- (A) In this research study, by using the analysis of the hydrological factors which led to the changes of the WEC, along the coupling mechanism between the hydrological factors and the WEC, a dynamic calculation method of the WEC based on the hydrologic process was developed. In this method, distributed hydrological and water environmental capacity models were coupled.
- (B) The Tieling Section of the Liao River Basin was taken as the case study area, for demonstrating this method. There were great differences among the WEC observed in both time and space which suggested that the dynamic method was able to consider the annual and inter-annual variations of the hydrology in a more scientific manner. The calculation results could potentially be used as a scientific basis for future pollutant emission reductions.
- (C) In this study, the sewage outfall was generalized as two types of extreme cases (the beginning and end of the river link) due to the limited observational data. That meant that the calculation results of the two extreme cases were the upper and lower thresholds. Moreover, a scientific calculation of the pollutant discharges, as well as the pollutants discharged into the river, should be

conducted to analysis the environmental assets and liabilities. These calculations could ultimately provide scientific support for future water environmental management processes.

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