ABSTRACT

The water environmental carrying capacity (WECC) of a city can demonstrate a balance between the level of exploitation of the local water resources and the population growth and concomitant socio-economic development. To begin with, the definition of WECC was elaborated. Combined with hydraulic, hydrologic and water quality data, a one-dimensional water quality model was subsequently applied to simulate the water pollutants (chemical oxygen demand (COD)) in Tieling City. Then, a multi-objective model was applied to explore WECC. Economy, demography, and contaminant were selected as goals, taking into account the constraints of macroeconomic aggregates, water supply, water quality, and population. The results showed WECC could nearly carry all planned gross domestic product (GDP), population in the planning years 2015, 2020, and 2025 with the maximum COD of 30,681.7 t, but not for the condition of maximum COD of 15,709.0 t. That is, COD overload would occur if GDP and population develop as planned. Some measures must be taken to improve WECC in Tieling City, which are valuable for supporting the adjustment and planning for social-economic development.

Key words | multi-purpose model, one-dimensional water quality model, Tieling City, water environmental capacity, water environmental carrying capacity

INTRODUCTION

Water is the most important resource for the development of human society and is the foundation for the realisation of sustainable socio-economic development (Stahl et al. 2002; Zhang & Zhu 2005). Water pollution is a significant environmental problem in China. The shortage of water resources and environmental pollution have become important restricting factors in the sustainable socio-economic development of the country (Shao & Yu 2010; Peng & Yu 2013). In China, more than 20,000 smaller catchments show a significant role in sustaining the local development of ecosystem, economy, and society (Geng et al. 2010).

Liaohe River, is one of the largest scale rivers in China. The Tieling section of Liaohe River in the upstream of Liaohe River basin, plays a vital role in not only supporting local social-economic development but also influencing the others located at the downstream. But few people studied the social-economic development from a micro-view of water environmental carrying capacity (WECC) in Tieling City. In this paper, water environmental capacity (chemical oxygen demand (COD) is selected as a pollution factor based on the pollutant characteristics of Tieling) and COD allowable emission are calculated in detail at different design flow rates. What’s more, COD allowable emission is taken as a constraint to explore WECC, which makes study of WECC better as the linkage of actual capacity of accepting pollutant of the river and pollutant emission of social-economic development have been considered. Therefore, this study on the WECC has practical significance.

There are few specialized studies on WECC in countries other than China (Sun & Fu 2007; Huang & Song 2015).
Currently, academia does not agree on the concept of WECC. In recent years, scholars in China have developed different definitions of the concept of WECC (Zhao & Qian 2005; Yang et al. 2008; Cui & Liang 2010; Dou et al. 2010; Ye et al. 2013). According to the WECC concepts provided by the scholars fore-mentioned, the common feature is maintaining the integrity of the water environmental function and the use of the water resource. In this paper, WECC is defined as follows: ‘Within a certain period, in some areas (waters), the water can accommodate the maximum levels of pollutants, support the maximum number of people, and support the sustainable development of human socio-economic activities, if the water has the capacity of self-sustaining and self-regulation, can be used continuously, and a good ecosystem is maintained.’

In the 1990s, Guo & Tang and Cui investigated the relationship between WECC and social-economic development by system dynamics, which provides reference for sustainable development (Guo & Tang 1995; Cui 1998). Zhang & Zou studied WECC in Dianchi River basin by a multi-objective model (Zhang & Zou 2010). The study on social-economic development based on WECC in Qinhe River basin combined system dynamics and the optimal watershed system regulation approach was carried out by Ye et al. (Ye et al. 2013). Yan et al. studied WECC of Poyang Lake by statistical models. The results showed that coordinating levels of economic, social and environmental development is low in the Poyang Lake region (Yan et al. 2011). Wang et al. studied the WECC in China by dynamic successive assessment method, and the results showed that the potential for co-development of socio-economic and water environmental was harmonious and sustainable (Wang & Xu 2015). Peng et al. assessed the WECC of an industrial park in Zhuhai City, and the evaluation model was established to analyze the changes in WECC (Peng & Xu 2012). Reza et al. introduced a multi-objective method to research the water allocation in the Sefidrud Basin, taking in the economy, society and environment, which can provide a sustainable way for social-economy and environment (Reza et al. 2014).

In fact, WECC has double attributes related to society and nature, which is a complex large-scale system, including population, resources, environment, economics, ecology, and technology (Giupponi et al. 2004; Li et al. 2008). What’s more, economic growth, environmental protection (especially water environmental health), and population mutually reinforce and restraint. Only when we have clear understanding on water environmental conditions, can we have explicit policy parameters involving strategic policy on economic and demographic development (Gilmour et al. 2005; Yue et al. 2015), as well as pollutant emissions.

In this paper, a one-dimensional water quality model was used to calculate the water environmental capacity (COD). The multi-objective model was chosen to explore the WECC, involving social-economic development and water environmental protection, restricting the gross domestic product (GDP), population, water resources quantity, and water quality.

**MATERIALS AND METHODS**

**An overview of Tieling City**

Tieling City is located in the most northern part of Liaoning Province in China. The total city area size is 11,905.36 km². In 2011, the total population of Tieling City was 3.049 million. The GDP was 87.384 billion yuan in 2011, and the proportion among the primary, secondary, and tertiary industries was 20:53:27.

Tieling City has a humid and semi-humid monsoon climate, the average annual rainfall was about 700 mm. Seven water-quality monitoring sections were set up in the Liaohe River segment of Tieling City. The monitoring data for 2005-2011, the COD data, and the Surface Water Quality Standards (GB3838-2002) show that the average annual water quality of the river during the dry season in Tieling City was inferior (V class). During 2005–2008, the COD emission levels were markedly elevated, but the situation has improved slightly since 2009.

**One-dimensional water quality model**

The one-dimensional water quality model is based on the principle that pollutants only change along the flow direction, and the concentration is uniform in the direction perpendicular to the water flow. The basic equation is:

\[
\frac{\partial C}{\partial t} = E_x \frac{\partial^2 C}{\partial x^2} - u \frac{\partial C}{\partial x} - KC
\]  

(1)
where $C$, $E_s$, $u$, $K$, $t$, $x$ are the concentration of pollutants (g/L), river-flow dispersion coefficient (m²/s), section flat velocity (m/s), pollutant attenuation coefficient (1/s), time (s), and flowing distance of the river (m), respectively.

When the amount of input pollutants, average velocity, and the diffusion coefficient of the direction of flow are constant, the pollutant concentration of the river water is stable, disregarding the diffusion and generalising the multiple outfalls into one. Thus, the formula for the assimilative capacity of each unit is deduced by (Fu 1987):

$$W = 365 \times 0.0864 \left\{ Q_0 (C_S - C_0) + C_S \left[ Q_t \left( 1 - \exp \left( -\frac{kL_i}{86400u_i} \right) \right) \right] \right\}$$

(2)

where $W$, $k$, $C_0$, $C_s$, $Q$ are the assimilative capacities of the water bodies or the water environmental capacity (t/a), degradation factor (L/s), the concentration of water coming from the upper section (mg/L), water quality objectives for the water bodies (mg/L), and the designed section flow rate (m³/s), respectively.

(1) Calculating the segmentation of the river

The basic principles for dividing the calculating unit are as follows (Zhang & Zhao 2008). The objects of division and calculation in this paper are mainly the tributaries of the Liao River, such as the Zhaosutai, Liangzi, Qing, Chai, and Fan rivers (detailed in Table 1).

(2) The determination of the designed flow rate and the flow velocity

Taking into account the hydrological monitoring data of Tieling City for 2010–2011, we selected the 50% and the 90% guaranteed average monthly flow rates as the design flow rates (Wang & Luo 2014). Please refer to Table 2 for the detail.

### Table 1 | The division of the section function of the Liaohe River in Tieling City

<table>
<thead>
<tr>
<th>Calculating unit</th>
<th>Length/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fudedian–Zhaosutai rivers</td>
<td>63,614</td>
</tr>
<tr>
<td>Zhaosutai–Liangzi rivers</td>
<td>28,987</td>
</tr>
<tr>
<td>Liangzi–Qing rivers</td>
<td>18,854</td>
</tr>
<tr>
<td>Qing–Chai rivers</td>
<td>15,309</td>
</tr>
<tr>
<td>Chai–Fan rivers</td>
<td>45,891</td>
</tr>
<tr>
<td>Fan River–Zhuer Mountain</td>
<td>7,615</td>
</tr>
</tbody>
</table>

The design flow velocity corresponds to the design flow rate. Currently, the empirical relationship formula of flow velocity and flow rate to determine the design flow velocity is:

$$u = aQ^b$$

Where $Q$ is the design flow rate (m³/s); $u$ is the design flow velocity (m/s); and $b$ is estimated by the regression analysis method (Zhao & Wang 2012). With the logarithm on both sides, the formula is $\log u = b \log Q + \log a$. If $\log u = y$, $\log Q = x$ and the least squares method is employed.

(3) Determination of the integrated attenuation coefficient

The environmental planning of Tieling and the experimental results of the scientific and technological projects, as reflected in the Eleventh Five-Year Plan Water Environmental Capacity Simulation Technical Specifications Report of the Chinese Research Academy of Environmental Sciences, were used to estimate $K$. The COD integrated attenuation coefficient $K$ is 0.15 d⁻¹.

(4) Determination of the initial concentration $C_0$ and the target concentration $C_S$

The water quality objectives of the previous water functional area $C_S$ is the initial concentration of the next functional area $C_0$. The values of the water quality objectives $C_S$ of each functional area were based on the concentration values of the corresponding category in the Water Function Zoning of Liaoning Province and the Surface Water Quality Standards (GB3838-2002). The functional area of the main-streams of Liaohe River is drinking water source and agricultural water area of which water quality objectives (COD) are 20 mg/L.

### Multi-objective model

The WECC is part of a complex system. In this study, an improved multi-objective model was established, considering...
water supply, water quality, population, and economy. The model includes three objectives: an economic objective, of which the final goal is to maximize economy; a population objective, of which the final goal is to maximize population; and a pollutant objective, of which the final goal is to minimize pollutant. The model is presented as follows.

Objective functions:

1. Economic objective: Max\( (GDP) = m \cdot X_p + n \cdot X_s + t \cdot X_t \)
2. Population objective: Max\( (POP) = \text{POP}_u + \text{POP}_r \)
3. Pollutant objective: Min\( (COD) = \text{COD}_i + \text{COD}_l \)

Subject to:

1. Water supply constraint: \( X_p + X_s + X_t < X_z/\text{C}_0 \);
2. Economy constraint: \( m \cdot X_p + n \cdot X_s + t \cdot X_t > \text{GDP}_{\text{min}} \)
3. Population constraint: \( \text{POP}_{\text{min}} = \text{POP}_u + \text{POP}_r > (\text{POP}_{2011}(1 + I)^{n - 2011}) \)
4. Pollutant constraint: \( \text{COD}_s + \text{COD}_l < \text{COD}_e \)

All the above symbols' meanings are given in detail in Table A1 of the Appendix (available in the online version of this paper).

In the economic objective function, \( X_t = e \cdot \text{POP}_u + f \cdot \text{POP}_r \). For the economy constraint, \( \text{GDP}_{\text{min}} \) is obtained under the condition of annual growth rate of 7%. For the population constraint, 0.33 and 0.67 are the proportion of urban city population and rural population, respectively. In the pollutant objective function, \( \text{COD}_i = a \cdot b \cdot X_s \), is the COD discharged from industrial sewage (\( a \cdot X_s \)). \( \text{COD}_l = c \cdot d \cdot X_t \), is the COD discharged from domestic sewage (\( b \cdot X_s \)). \( \text{COD}_e \) is the allowable emissions calculated above.

The basic parameters of the multi-objective model are seen in Table 3. All the figures are based on the basic data of the Statistical Yearbook of Tieling City for 2012, Water Resources Bulletin of Liaoning Province for 2011, and the Hydrologic Yearbook of Liaohe River Basin for 2011, Code of Urban Wastewater Engineering Planning for 2011, First National Pollution Source Census–Urban Life Source Pollution Discharge Coefficient Manual for 2008, and First National Pollution Sources Census–Industrial Pollution Source Pollution Discharge Coefficient Manual for 2010. In Table 3, \( m, n, \) and \( t \) have uncertain trends, so they all maintain the current values. The \( e \) and \( f \) will be increase tardily with improvement of living standards. The

| Indexes | Units | Guarantee rate 50% | | | Guarantee rate 90% | | |
|---------|-------|-------------------|---|-------------------|---|---|
| m       | yuan/t| 25.2              | 25.2| 25.2              | 25.2| 25.2|
| n       | yuan/t| 310.1             | 310.1| 310.1             | 310.1| 310.1|
| t       | yuan/t| 179.4             | 179.4| 179.4             | 179.4| 179.4|
| e       | L/p-d | 135.1             | 158.3| 139.6             | 120.5| 123.3|
| f       | L/p-d | 51.1              | 56.6| 59.3              | 41.1| 46.6|
| a       | %     | 1.1327            | 1.1327| 1.1327            | 1.1327| 1.1327|
| b       | %     | 0.1197            | 0.1197| 0.1197            | 0.1197| 0.1197|
| c       | %     | 40.0390           | 40.0390| 40.0390           | 40.0390| 40.0390|
| d       | %     | 0.0332            | 0.0332| 0.0332            | 0.0332| 0.0332|
| i       | %     | 0.3               | 0.3| 0.3               | 0.3| 0.3|
| Wz      | ten thousand tons| 106,100 | 106,100| 106,100 | 106,100| 106,100|
| Xs      | ten thousand tons| 300 | 300| 300 | 300| 300|
| Xc      | ten thousand tons| 240 | 240| 240 | 240| 240|
| GDPmin  | billion yuan| 114,537 | 160,645| 225,312 | 114,537| 160,645|
| POPmin  | ten thousand people| 308.60 | 315.23| 317.95 | 308.14| 315.23|
RESULTS AND DISCUSSION

Water environmental capacity

After all the parameters had been determined, consistent with formula (2), calculation of the water environmental capacity in Tieling City was performed; see Table 4.

As shown in Table 4, the water environmental capacities (COD) were 25,189.7 t and 12,897.1 t in Tieling City respectively, obtained at a design flow rate of 50% and flow rate of 90%. What’s more, when the design flow rate was 50%, it was nearly twice as much as that at 90%, which presents a bearing capacity for COD in the Tieling section of the Liaohe River basin.

There is a coefficient of pollutants running into river between water environmental capacity and allowable emissions, which is the ratio of pollutants running into the river to pollutant emissions (Cheng et al. 2006; Yang 2006). According to the natural environmental characteristics of the Tieling section of Liaohe River basin, 0.821 is suitable for the rate of pollutant (COD) running into the river (Fu et al. 2010). Water environmental capacity and COD allowable emissions are shown in Table 5.

As shown in Table 5, for a design flow at the guarantee rate 50%, water environmental capacity (COD) and COD allowable emissions are 25,189.7 t and 30,681.7 t in Tieling City respectively, while for a design flow rate 90%, the values are 12,897.1 t and 15,709.0 t, respectively. In addition, compared to COD allowable emissions obtained at the design flow rate of 50%, it is nearly twice as much as obtained at design flow of 90%. The COD allowable emissions calculated were used for the multi-objective model as the water quality restraint.

Water environmental carrying capacity

In the multi-objective model, the method to ‘change majority to minority’ was adopted for the calculations by changing three optimisation objectives into a single objective by weight determination method (Zhang & Zou 2010), and then objective functions transformed into dimensionless after standardizing. According to the relationship of social economy and environment (Zhao & Shan 2013), the weights of economy, population, and pollutant are 0.43, 0.42, and 0.15 respectively. The calculations were done with the Matlab toolbox for solving the multi-objective model by the interior point method (Xue & Chen 2008). By solving the multi-objective model, the maximum GDP, population and minimum COD, carried by WECC for different pollutant restraints in different planning years, can be acquired as Table 6 shows.

Before solving the multi-objective model, the planned GDP is calculated by the GDP growth rate of 9% based on the Twelfth Five Year Plan of Tieling City. The planned GDP for the planning years 2015, 2020 and 2025 would be respectively 123.35 billion yuan, 189.78 billion yuan, and 292.01 billion yuan. What’s more, the planned population also is calculated by the population growth rate of 0.3% based on the present population situation of Tieling City. The planned population would be 3.086 million,
3.132 million and 3.180 million in 2015, 2020 and 2025, respectively.

The calculations of planned GDP and population aim to explore the room for GDP development and population growth by comparing the optimized values of the multi-objective model. Room for GDP development, population growth and COD emissions can be respectively presented by the formulas (3), (4) and (5):

$$R_{GDP} = \frac{GDP_{opt} - GDP_{pla}}{GDP_{pla}}$$  \hspace{1cm} (3)

where $R_{GDP}$ is the room for GDP development; $GDP_{opt}$ is optimized GDP obtained by the multi-objective model, billion yuan; $GDP_{pla}$ is the planned GDP obtained by GDP growth, billion yuan.

$$R_{POP} = \frac{POP_{opt} - POP_{pla}}{POP_{pla}}$$  \hspace{1cm} (4)

where $R_{POP}$ is the room for population growth; $POP_{opt}$ is optimized population obtained by the multi-objective model, $10^4$ people; $POP_{pla}$ is planned population obtained by population growth rate, $10^4$ people.

$$R_{COD} = \frac{COD_{cal} - COD_{opt}}{COD_{cal}}$$  \hspace{1cm} (5)

where $R_{COD}$ is the room for COD emissions; $COD_{cal}$ is COD allowable emission calculated by the one-dimensional model, t; $COD_{opt}$ optimized population obtained by the multi-objective model, t.

COD allowable emissions, obtained at the design flow rate of 50%, are the one case to evaluate the WECC. With the multi-objective model, optimized GDP for 2015, 2020 and 2025 would be 198.95 billion yuan, 202.12 billion yuan, and 263.68 billion yuan, respectively. In addition, in Figure 1, the solid line shows the economic development room decreases as year goes on. The economic development room for 2015 is 61.3%, which is the maximum in the planning years. From 2015, the room sharply decreases to 6.5% in 2020, then it drops toward a negative minimum (−9.7%), which occurs in 2025. A negative value indicates that there is no room for economic development. That is, WECC couldn't carry the planned economic development.

With the multi-objective model, the optimized population would be respectively 3.321, 3.323 and 3.364 million for the planning years. Figure 2 shows that the maximum population growth is 6.1% in 2020, while the minimum is 4.1% in 2015. That is, the WECC in Tieling City could carry the planned population growth.

With the one-dimensional water quality model, the value of calculated COD is 30,681.7 t. With the multi-objective model, optimized COD are 18,500.4 t, 19,384.9 t, and 21,049.1 t in 2015, 2020, and 2025 respectively. The room for COD emissions in the planning years are shown in Figure 3. The solid line manifests that COD emissions
room decreases with time passing. The maximum is 39.7% in 2015 and the minimum is 31.4% in 2025.

COD allowable emissions, obtained at the design flow rate of 90%, are the other one case to evaluate the WECC in Tieling City. With the multi-objective model, optimized GDP for 2015, 2020 and 2025 would be 126.27 billion yuan, 161.65 billion yuan, and 227.49 billion yuan, respectively. Economic development room is showed in Figure 4. The only positive value is 2.4% in 2015, indicating that there is some room to develop economy. Negative values occur in 2020 (−14.8%) and 2025 (−22.1%), indicating that there is no room for economic development, and the trend is more obvious with time passing.

With the multi-objective model, the optimized population are 3.08601 million, 3.136 million, and 3.183 million in 2015, 2020, and 2025 respectively. The room for people growth are depicted in Figure 5 by the solid line, which shows that all the values are not negative. That indicates WECC could carry the planned population for the planning years in Tieling City.

With the multi-objective model, the optimized COD are 14,237.6 t, 14,807.1 t, and 15,254.5 t in the planning years respectively. Figure 6 shows the COD emissions room for different planning years. The room represents downtrend with time passing. The room for COD emission is 9.4% in 2015 while the smallest is 2.9% in 2025, and the moderate is 5.7% in 2020. Compared with the WECC
obtained at the design flow rate of 90%, the WECC obtained at the design flow rate of 50%, has the advantages of high carrying capacity. That is, the WECC obtained at the design flow rate of 50% could carry larger economy, population, and pollutant.

CONCLUSIONS

This paper was started by further defining the concept of WECC as aforementioned. For the research models, the basic conditions of the study area were used, and the influencing factors such as water resources, economy, population, and pollutant on WECC were fully considered. The results of the one-dimensional water quality model showed that it can stand 25,189.7 t and 12,897.1 t COD obtained at a design flow rate of 50% and 90% in Tieling. The results of the multi-objective model were obtained with COD restraints of 30,681.7 t and 15,709.0 t, the presence of COD is not alarming as the WECC nearly could all carry the planned GDP (except for 2025) and population for the former design flow rate, but not for the latter. The room for GDP developments are 2.4%, 14.8% and 22.1%, and the room for population growths are 0.003%, 0.1% and 0.09% in 2015, 2020 and 2025 respectively. GDP could not develop as planned except for 2015. Population can increase only as a planned value while COD emission almost reaches the maximum. It needs to be particularly noticed that COD emissions would be severe overloaded in Tieling City if the development patterns for population, economy, and water utilization do not change. The planned GDP development and population growth can only occur if the net COD load is reduced.

Further measures have to be taken to improve the WECC to reduce the pressure on the water environment; the saving of agricultural water could be enhanced by improving the irrigation system and the irrigation methods. The industrial water saving efforts could be improved by implementing advanced water saving technology and equipment. The water conservation policy should be publicized to promote water saving. To reduce the pollutant emissions, the comprehensive administrative, legal, and economic measures could be relied on, as well as the full implementation of the remediation measures for heavy polluting enterprises, the construction of sewage treatment plants, and the ecological management of the river.

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