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Management of water quality targets based on river-lake water quality response relationships for lake basins – A case study of Dianchi Lake

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ABSTRACT

In a lake basin, there is a mismatch between river and lake water quality targets and a method for setting specific water quality targets for these rivers is urgently needed. Using Dianchi Lake as an example, we proposed a lake basin water quality management system based on the river-lake water quality response relationship, coupled with a Soil and Water Assessment Tool (SWAT) basin hydrological model and Environmental Fluid Dynamics Code (EFDC) lake water quality hydrodynamic model. River water quality control requirements based on the river-lake water quality response were proposed, under the premise that the Dianchi Lake water quality reaches the required standard. Then, water quality control targets for rivers were determined, and corrected for influencing factors, such as current river water quality and composition of flow. Our systematic approach efficiently identified key lake basin pollution sources, and accurately located key points for water quality improvement and pollution control. Combined with a correction for clean water source and current water quality of each river, the proposed water quality targets were practical and operable. Meanwhile, the EFDC model was used to verify the entire process to ensure that river water quality targets could be set to achieve lake water quality targets. To ensure that Dianchi Lake water quality can reach Class IV standard, the Chemical oxygen demand (COD) concentration would need to be maintained under 30 mg/L,Waihai total nitrogen (TN) below 7 mg/L, total phosphorus (TP) below 0.2 mg/L, and ammonia nitrogen (NH_3–N) below 2 mg/L.

1. 1Introduction

Lakes are not only an important ecological resource but also a supporter of a series of social and economic processes (Yang et al., 2019). Since the 1980s, basin water quality target management has gradually become the dominant mode of water environment management in developed countries and regions. The United States (Gilbert and Simpson, 1992; U.S.EPA, 1998; U.S.EPA, 2009), the EU (Hu, 2005), and Japan (Yang and Shang, 2010) have provided strong support for the recovery of damaged water bodies by establishing a relatively complete environmental benchmark system, setting appropriate environmental goals, and undertaking corresponding actions. Since the implementation of the “Eleventh Five-Year Plan”, China has gradually begun exploring basin water quality target management, however, judging from the current situation, the outcomes have not been ideal (Meng et al., 2008).

The core of basin water quality target management is to achieve water quality targets (Zhang et al., 2014), therefore, setting reasonable water quality targets is a prerequisite for effective management. Presently, the main basis for setting lake basin water quality targets is the Environmental Quality Standard for Surface Water, which classifies targets for the main water body functions from a macroscopic perspective. However, China is a vast country, so environmental characteristics of basins can differ markedly from one another. Therefore, water quality targets obtained from a functional classification may not accurately reflect actual water quality improvement needs of different water bodies, affecting the performance of target management. This is especially true for eutrophic lake basins, as rivers are the main conduit for nutrients entering lakes (Jin et al., 2018), so river water quality affects lake water quality directly. However, there are differences between the nitrogen and phosphorus water quality standards of rivers and those of lakes in the current assessment standards. Specifically, total nitrogen concentration is not a parameter used in the assessment of river water quality, and total phosphorus standards of rivers are not

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consistent with those of lakes, resulting in the disconnection of river and lake water quality targets. When controlling river pollution flowing into the lake is used as the measure to improve lake water quality, the lake pollution concentration often fails to reach the targets. Therefore, to meet national water quality standards, the effective connection between water quality targets of rivers and lakes should be considered, and a specific method for setting basin water quality targets established according to their own characteristics.

Thus far, some research on water quality targets of typical eutrophic lake basins, such as Taihu Lake (Chen et al., 2017b; Kai-Ming et al., 2012), Chaohu Lake (Zhu and Wang, 2004) and Dianchi Lake (Deng et al., 2011; Liu et al., 2017; Yao et al., 2019), has been carried out. But in most cases, only the overall water quality targets for basin rivers were proposed based on water environmental capacity calculated via the lake water quality model, which lacks the river-lake linkage of the water quality response relationship. Therefore, water quality targets of basin rivers' were not applicable, their feasibility was difficult to verify, and a comprehensive basin water quality target management system could not be established. To eliminate these shortcomings, we construct a lake basin water quality target management system based on the river-lake water quality response relationship coupled with SWAT and EFDC models. Taking Dianchi Lake, a typical eutrophic lake, as an example, we determined the optimum feasible water quality targets of the main rivers flowing into the lake, based on the premise of meeting the appropriate water quality standards of the lake.

2. Methodology

2.1. Research area overview

The Dianchi Lake Basin, located in the central Yunnan-Guizhou Plateau, lies to the southwest of Kunming city. It belongs to the Jinsha River system of the Yangtze River Basin and is located in the watersheds of the Yangtze, Honghe, and Zhujiang Rivers, with a total basin area of 2920 km^2.The Dianchi lake body approximates a bow-shape with the back of the bow pointing to the east. Since the ship lock was constructed in 1996, Dianchi lake has been divided into two interconnected, but almost independent parts: Caohai (DClake-CH) and Waihai (DClake-WH). The total area of Caohai is10.8 km^2 with an average depth of 2.5 m, while Waihai is the main body of Dianchi lake with a total area of 289.2 km^2 and an average depth of 4.4 m.

There are seven rivers that flow into Caohai Lake which are: the West Bank of Caohai (CHWB), Xinyunliang (XYL), Laoyunliang (LYL), Wulong (WL), Daguang (DG), Xiba (XB) and Chuanfang rivers (CF). Whereas, there are 23 rivers that flow into Waihai Lake, which are: the Cailian (CL), Jinjia (JJ), Panlong (PL), Daqing (DQ), Haihe (HH), Xiaoqing (XQ), Xiabahe (XBH), Yao'an (YA), Laobaoxiang (LBX), Xinbaoxiang (XBX), Guangpudagou (GPDG), Maliao (ML), Luolong (LL), Laoyu (LY), Liangwang (LW), Nanchong (NC), Yuni (YN), Baiyu (BY), Chaihe (CH), Dongda (DD), Zhonghe (ZH), Gucheng (GC), and small water flows in the West Bank of Waihai (WHWB) rivers (Fig. 1). As there is almost no water exchange between the Caohai and Waihai water bodies, they are recognized as independent, and thus separate models were built and applied for each. According to the Water Pollution Control Planning for Key Watershed (2011–2015), the Dianchi Lake Basin can be divided into five land control units, namely, west bank, south bank, east bank, and north bank of Waihai, and Caohai bank (Xu et al., 2016).

2.2. Overall methodology

By coupling the SWAT hydrological model and the EFDC hydrodynamic model of lake water quality, a lake basin water quality target management system based on the river-lake water quality response relationship, was established(Fig. 2). Firstly, the river-lake water quality response function was defined from multiple iteration calculations via the EFDC Model, and the contribution of each river to lake water quality at the key control stations was obtained from calculations using the proposed function. Secondly, the river water quality control requirements based on the river-lake water quality response relationship were proposed under the premise that the water quality of 10 measuring stations reached the required standard. Then, corrections to the river water control requirements were made using influencing factors, such as current river water quality, and water flow composition. Thereafter, the average annual and monthly water quality control requirements for the basin rivers' were determined. Finally, the model was used to verify whether the Dianchi Lake water quality could reach the assessment targets under the above river target settings. If not, then we revisited the previous steps and readjusted until the targets were achieved. The whole process can be described in the following steps:

Step 1, Response judgement - the aim is to establish a river-lake water quality response relationship, calculate the contribution of each river to the water quality of the lake's key control points, and identify the rivers that contribute more to the water quality of state-controlled monitoring sites in the rivers with poor water quality. It is crucial to strictly implement water quality control for major rivers. According to the importance of the water quality response, management strategies can be divided into three levels. The first level is for the rivers that contribute less than 5% to the water quality of the state-controlled monitoring sites in the lake; the second level is for rivers which contribute 5% to the water quality of state-controlled monitoring sites in the lake; the third grade is for other rivers. Three pollution load reduction strategies were proposed for each of the three levels. The first is aimed at a point source collection processing rate of 95% and a non-point source reduction rate of 30%. The second strategy specifies a point source collection and processing rate of 90%, and a surface source reduction rate of 25%. The third strategy is 85% for point source collection and 20% for point source reduction. According to the three sets of strategies corresponding to the above three levels, the annual average water quality concentration and water quality during the dry and rainy seasons under the corresponding strategies of each river were simulated and calculated. These results were set as the river water quality targets of this step.

Step 2: Water quantity evaluation - The river water in the Dianchi Lake Basin generally includes water discharged from upstream reservoirs, interval runoff, water discharged from wastewater treatment plants, uncollected wastewater, and water replenished by the Niulanjiang River. In this step, the water source of each river is identified and the quantity of clean water (not including other water sources that have not completely collected sewage and interval runoff) from each source measured. If the amount of clean water is greater than the river's ecological flow, the clean water source can stably maintain the river's ecosystem. If not, the possibility of water replenishment from surrounding water sources is investigated. If it is possible to replenish water from surrounding water sources, the river's water quality target is established according to the water quality of surrounding water sources. If it is not possible, then the current water quality will remain unchanged. If the water quality target is lower than in the previous step, the target value in the previous step will be adopted. However, if the target is higher than in the previous step, the target value in this step will be maintained.

Step 3: Water quality evaluation - The current water quality of the rivers in Dianchi Lake Basin were analyzed. For rivers with Class II ($COD \le 15$ mg/L, NH_3–$N \le 0.5$ mg/L, $TP \le 0.1$ mg/L and $TN \le 0.5$ mg/L) and Class III ($COD \le 20$ mg/L, NH_3–$N \le 1$ mg/L, $TP \le 0.2$ mg/L and $TN \le 1$ mg/L) water quality, their water quality must be maintained at the current level or above. For rivers with Class IV ($COD \le 30$ mg/L, NH_3–$N \le 1.5$ mg/L, $TP \le 0.3$ mg/L and $TN \le 1.5$ mg/L) and ClassV ($COD \le 40$ mg/L, NH_3–$N \le 2.0$ mg/L, $TP \le 0.2$ mg/L and $TN \le 2.0$ mg/L) water quality, the optimal water quality from 1990 to date was employed as the optimal water quality. Rivers with Class Inferior V water quality must be upgraded to Class V or above. If the water quality target

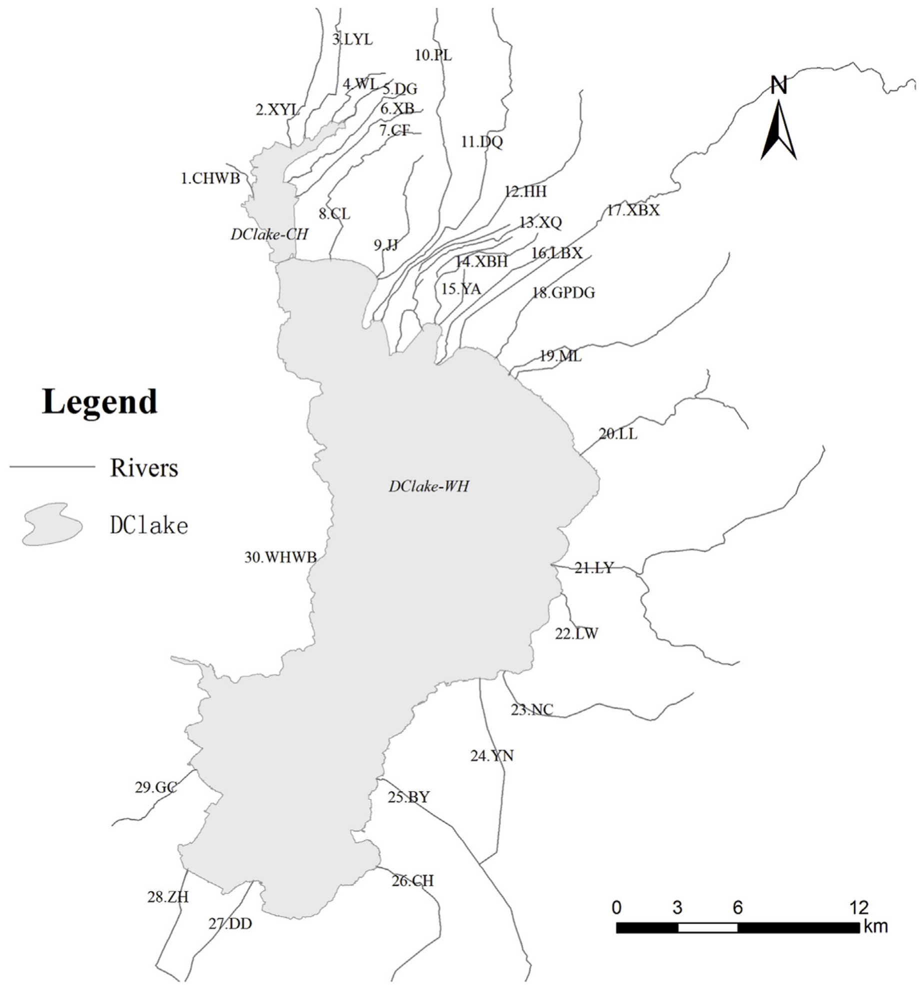

Fig. 1. Schematic diagram showing the water network in the Dianchi Lake Basin.

is lower than the one in the previous step, the target value in the previous step will be adopted. However, if the water quality target is higher than in the previous step, the target value in this step will be maintained.

Step 4, Compliance verification - the water quality targets of each river were used as boundary conditions and subjected to calculation with the EFDC Model. If the Dianchi Lake water quality target was reached, the river channel target was set within a reasonable range, if it was unreachable, it was adjusted until it was reachable.

2.3. Construction and verification of the land-water coupling model

For Dianchi lake Basin, the SWAT model was built and used to simulate the hydrological processes and transportation of pollutants of the land area. SWAT is a long-term distributed hydrological model with a robust physical mechanism developed by the Agricultural Research Service (ARS) of the U.S. Department of Agriculture (USDA) over 30 years (Gamvroudis et al., 2015; Meng et al., 2008; Shen et al., 2014; Tuo et al., 2016; Zeiger; Hubbart, 2016).The Dianchi Lake Basin comprises 30 sub-catchments, each of which corresponds to one of the 30 rivers flowing into the lake (Fig. 3).

The SUFI-2 algorithm with in SWAT-CUP software was used to carry out the calibration of SWAT parameters. Considering the features of Dianchi Lake Basin, 19 parameters were calibrated. The Nash-Sutcliffe Index (NS), the correlation coefficient of the linear regression (R^2) and relative error were selected for the calibration of the parameters of the SWAT model. The standard for evaluating the efficiency of the model reported by Moriasi et al. (2013), is when the relative error of the runoff is lower than 25%, NS is higher than 0.5, and the relative error of the water quality is lower than 50% (Gebremariam et al., 2014; Moriasi et al., 2013; Wang et al., 2015; Ye and Grimm, 2013; Yesuf et al., 2015), and the model precision can meet the simulation requirements of the study area. Calibration and verification of the model were conducted using the data collected from the hydrological stations and water quality monitoring stations of the rivers in the Dianchi Lake Basin. As there are few hydrological stations in the Basin that for long-term and systematic monitoring, five-year (2008–2010 and 2013–2014) daily runoff monitoring data were collected from Ganhaizi (Baoxiang River Basin) and Zhonghe Stations (Panlong River Basin), and were adopted for the calibration of parameters as well as the verification of the hydrological module. Following this, the water quality module was calibrated and verified. Monthly water quality monitoring data in 2017 from the hi-flow Panlong, Baoxiang and Chaihe Rivers into the lake in the north, east and south parts of the basin, respectively, were selected, to verify the water quality simulation results.

The obtained Nash-Sutcliffe Index (NS) and R^2 were 0.71 and 0.72, respectively, meeting the models precision requirements. Furthermore, the relative error of the water quality module was within 0.3, indicating that the model could be applied to the Dianchi Basin. For the Dianchi Lake water body, the EFDC model was built and used to simulate the water quality response process after the pollutants from the land area flowed into the lake. EFDC is a three-dimensional model sponsored by the United States Environmental Protection Agency (USEPA) which is designed to simulate water flow, sediment transportation and chemical processes in rivers, lakes, estuaries, reservoirs, wetlands, coastal areas and other water bodies (Chen et al. 2016, 2017a; Lee et al., 2017; Liu

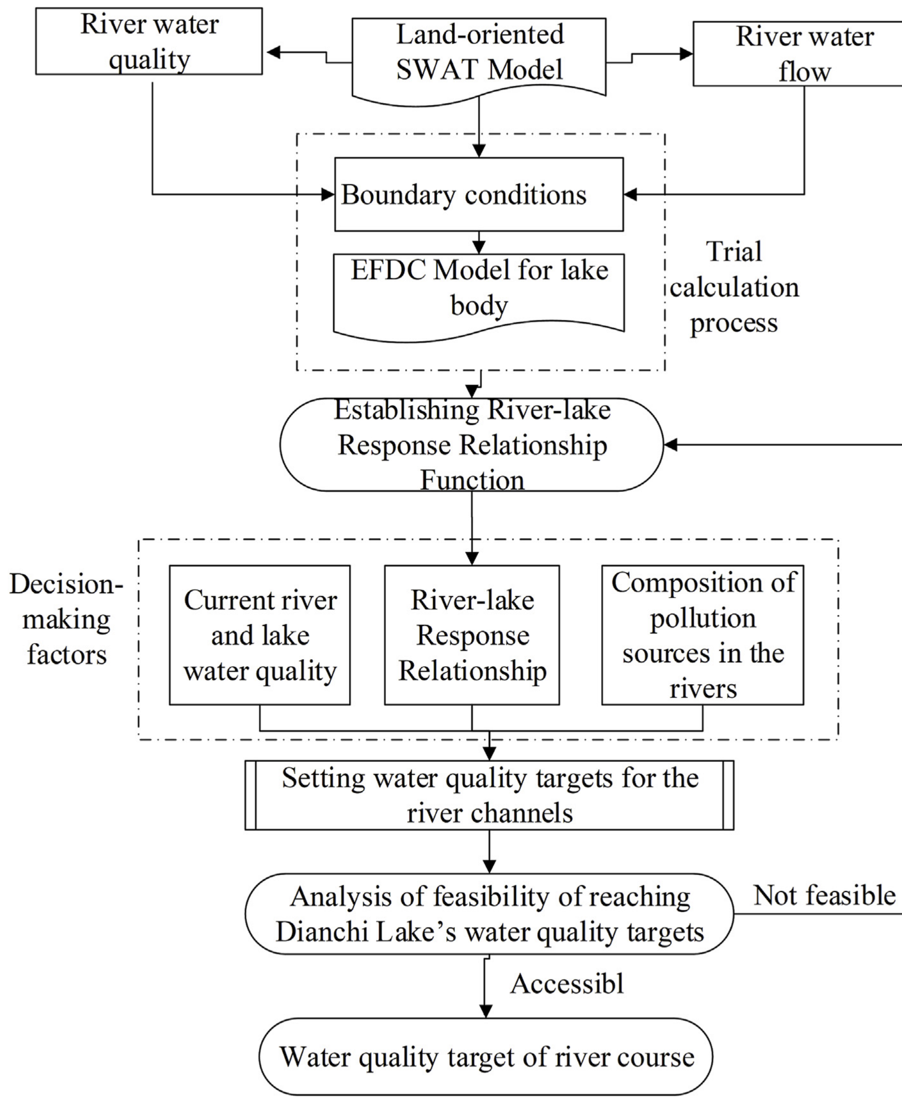

Fig. 2. System methodology.

et al., 2017; Quijano et al., 2017). In this study, the water quantity and quality data of the main rivers flowing into Dianchi Lake generated by the SWAT model were used as the input parameters to build the EFDC model, realizing the coupling of land and water. The Caohai area was divided into 347 grids using a 150 m × 150 m square grid and the Waihai area was divided by a 550 m × 550 m grid horizontally and separated into three layers vertically, which resulted in the generation of a total of 2865 grids from top to bottom.

Under normal circumstances, calibration of the EFDC model requires more than 3 years of continuous data, however, due to various Dianchi Lake treatment projects launched in the last five years, the boundary conditions of inflow and outflow hydrology varied significantly from year to year. Therefore, the long-term continuous calibration of the model could not be carried out. Thus, the calibration and verification of the hydrodynamics and water quality modules for Dianchi Lake were carried out over the period from January 1, 2017 to December 31, 2017 only. Three hydrodynamic module variables (i.e., water level, water temperature, and flow field) were calibrated and verified, while the calibration and verification of water quality was based on ten state-controlled monitoring sites in the Dianchi Lake. The calibrated parameters were mainly related to the processes of phytoplankton, carbon, nitrogen and phosphorous. As for the EFDC model, the relative error and the correlation coefficient of linear regression (R^2) between the simulated and observed values were used to evaluate model precision.

The 10 state-controlled monitoring sites include the Duanqiao (DQ) and CaohaiCente (CH–C) in Caohai Basin, and the Huiwanzhong (HWZ), Luojiaying (LJY), Guanyingshan East (GYS-E), Guanyingshan Middle (GYS-M), Guanyingshan West (GYS-W), Baiyukou (BYK), Haikouxi (HKX) and Dianchinan(DCN) in Waihai (Fig. 4).

For the hydrodynamic module, comparison between the simulated and the actual water levels of the Dianchi lake is shown in Fig. 5 It can be seen that the water level simulation results are in good agreement with the measured data. The R^2 reaches 0.99, which meets the requirement of the accuracy of the model simulation.

After calibration of the hydrodynamic module, the water quality module was constructed and calibrated. The EFDC model simulated the $COD_{cr,}$ TN, TP and NH_3–N water quality indexes in Dianchi Lake, and these values were compared with the measured values from the state-controlled monitoring sites (Table 1). It is noteworthy that the relative error is generally lower than 0.1, which indicates that the model could be used to support the subsequent analysis of the river-lake water quality response relationship.

2.4. Analysis of the water quality response relationship between inflow rivers and Dianchi Lake

Inflow river water quantity and quality data derived from the SWAT

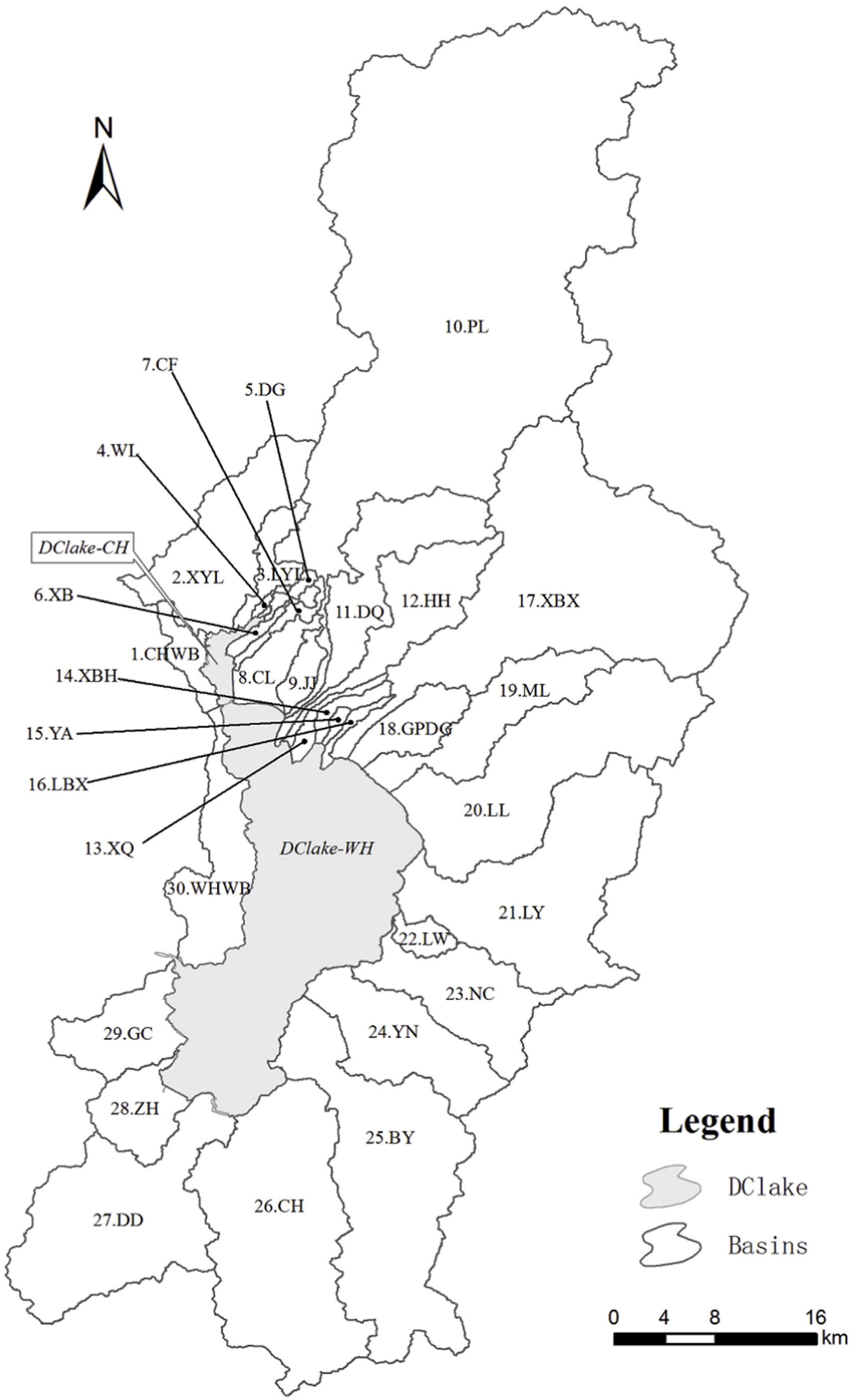

Fig. 3. Diagram showing the division of sub-basins in the study area.

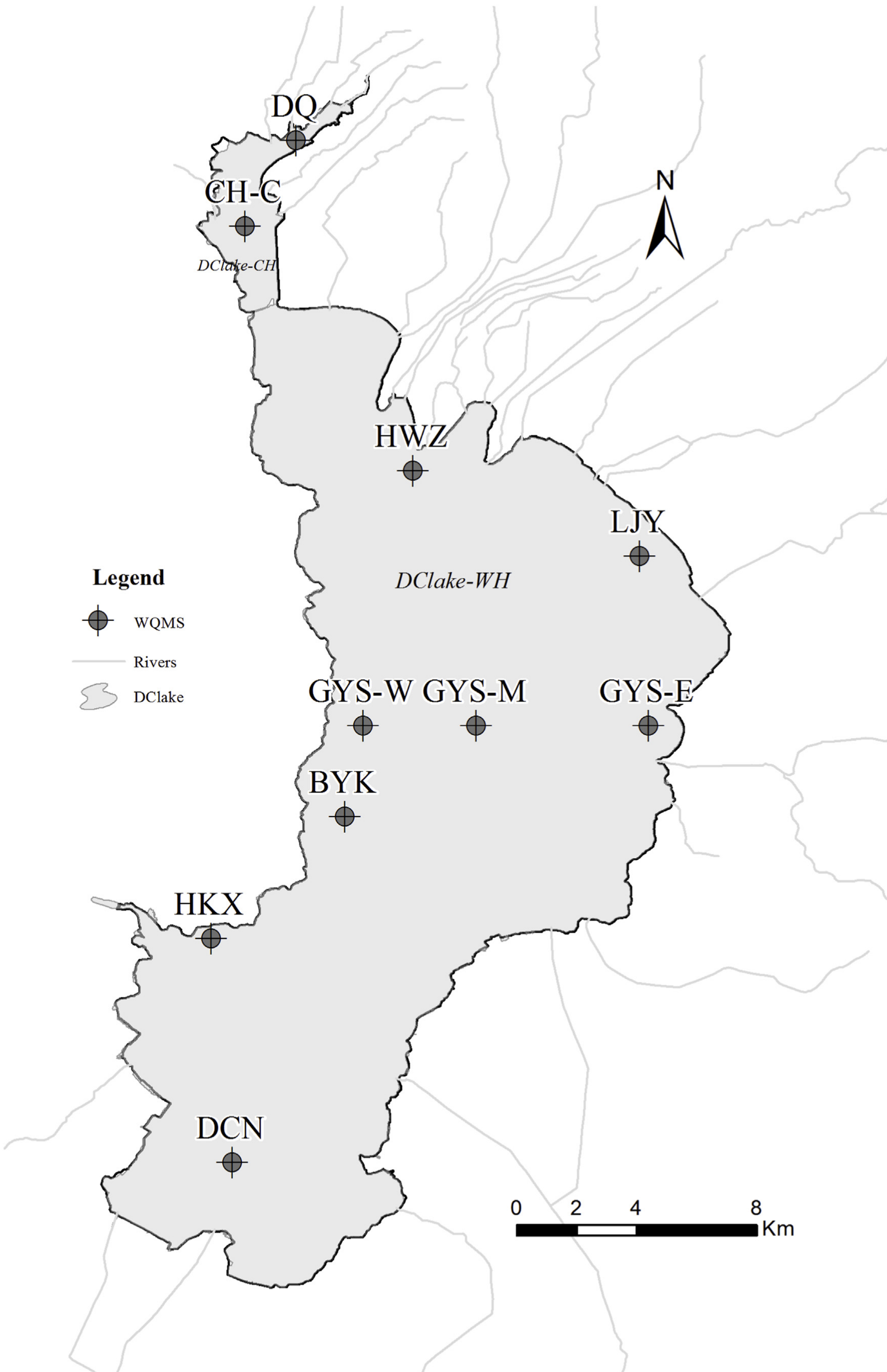

Fig. 4. Distribution of the state-controlled monitoring sites in the Dianchi Lake Basin.

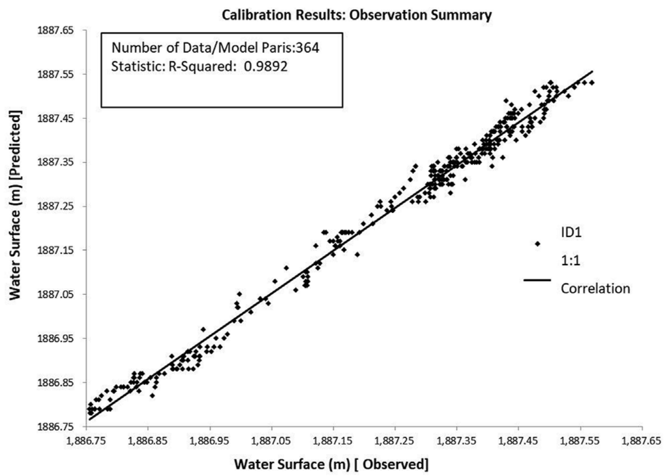

Fig. 5. Statistical analysis of the simulated-actual water level.

Table 1
Comparison between the simulated and measured values of the water quality model in Waihai Basin.

Index	Measured value	Simulated value	Relative error
COD_{cr}	41.8	41.3	0.0120
TN	1.956	1.878	0.0399
TP	0.134	0.136	0.0149
NH_3–N	0.292	0.323	0.1062

model were used as the input parameters to construct the lake EFDC model, and the coupling of the land-lake model was realized. After EFDC model calibration and verification, each rivers boundary conditions were closed step by step, and variations in water quality in each state-controlled monitoring site were analyzed. The quantitative effects of each river on water quality at each state-controlled monitoring site were obtained through multiple EFDC model iterations. The basic principle of the river-lake water quality response relationship is to identify the contribution of each source and sink component in each lake water quality response unit based on the control unit of the water quality module (Eqn. (1)).

$$\frac{\partial C}{\partial t}+\frac{\partial (uC)}{\partial x}+\frac{\partial (vC)}{\partial y}+\frac{\partial (\omega C)}{\partial z}=\frac{\partial}{\partial x}\left(K_x\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial C}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial C}{\partial z}\right)+Sc \tag{1}$$

Where C is the concentration of water quality state variables; u, v and w are the velocities in x, y and z directions, respectively; Kx, Ky and Kz are the turbulence diffusion coefficients in x, y and z directions, respectively. Sc is the source and sink inside and outside of each water quality response unit.

The river-lake water quality response relationship is established based on the test results of the model (Eqn. (2)).

$$C_{it}=f\,(C_{1t}Q_{1t},\ C_{2t}Q_{2t}\ldots C_{jt}Q_{jt},\ ) \tag{2}$$

Where C_{it} is the water quality of the ith section of the lake at time t, and C_{jt} is the water quality of the J river at time t.

3. Results and discussion

3.1. Water quality and quantity

3.1.1. Characteristics of current river water quality

Except for Guangpudagou, Wujia Baoxiang and Liujia Baoxiang rivers that were drying-up in the full year, each river inlet is selected as the monitoring point, every river will be monitored once a month In 2018 (Fig. 6). According the Dianchi Lake Basin, the average annual COD, NH_3–N, TN and TP concentrations are 20.37, 2.08, 6.65 and 0.25 mg/L, respectively. The highest average COD concentration of 73 mg/L was recorded in Yao'an River and the lowest was 8.09 mg/L in Jinzhi River; the highest average NH_3–N concentration of 19.6 mg/L was recorded in Yao'an River and the lowest of 0.12 mg/L was recorded in Gucheng River; the highest average TN concentration of 26.6 mg/L was recorded in Yao'an River and the lowest of 0.40 mg/L was recorded in Lengshui River; the highest average TP concentration of 1.82 mg/L was recorded in Yaoan River and the lowest of 0.02 mg/L was recorded in Lengshui River.

In general, except for the rivers which were drying-up in the full year, most of the rivers in the Dianchi Lake Basin maintained good and stable water quality. Water quality of 12 rivers (Panlong, Luolong, Daguan, Laobaoxiang, Dongdar, Dah, Chaihe, Xiba, Laoyu, Lengshui, Muyang and Jinzhi rivers) can reach Class III and among these rivers, Luolong, Lengshui and Muyang rivers water quality can also reach Class II. However, there were still 7 rivers with water quality of Class Inferior V, and among them, all the Yao'an River pollution concentration indicators exceeded the standard considerably. Furthermore, there were 13 rivers with water quality of Class IV to V. When setting the river water quality target, those classified as Class II and Class III should be maintained. Rivers with water quality classified as Class IV and Class V should be improved, and those classified as Class Inferior V should be improved to at least Class V.

3.1.2. River water flow composition characteristics

Analysis shows (Fig. 7) that with replenishment from the Niulanjiang River, the Panlong and Daguan river water flows increased more than other rivers with similar high flow that were replenished by the water discharged from wastewater treatment plants. Based on the percentages of water sources of each river, clean water sources account for more than 50% of each river's overall water flow. For 18 rivers (Cailian, Daqing, Zhonghe, Luolong, Laoyu, Maliao, Xinbaoxiang, Panlong, Xiba, Wulong, Xinyunliang, Chuanfang, Laoyunliang, Daguan, Lengshui, Muyang, Jinzhi and Jiancao rivers), their water was discharged from the upper water reservoir, from wastewater treatment plants and from Niulanjiang water-replenishment. Among these rivers, clean water sources of 12 rivers (Daqing, Maliao, Panlong, Xiba, Wulong, Chuanfang, Laoyunliang, Daguan, Jiancao, Jinzh, Lengshui and Muyang rivers) account for more than 80% of overall water flow. It indicates that these rivers have good water quality and also sufficient clean water sources.

Comparisons between the quantity of clean water sources and minimum ecological water requirements show that quantity of clean water sources of 13 rivers (Daqing, Honghe, Luolong, Laoyu, Maliao, Xinbaoxiang, Panlong, Xiba, Wulong, Xinyunliang, Chuanfang, Laoyunliang and Daguan rivers) satisfies their ecological water requirements, and that their water flow will not be affected after the decontamination process and their water quality reaches clean water standards (see Fig. 8).

3.2. River – Lake water quality response relationship within the Dianchi Lake basin

3.2.1. Water quality response relationship between the inflow rivers and Dianchi Lake

The SWAT model was used to simulate the daily water quality variations of the inflow rivers (flow-weighted average concentration), and the EFDC model was applied to simulate the Dianchi Lake. The river-lake water quality response relationship was analyzed using both the modeling and monitoring data. As depicted in Fig. 9, the Caohai and the Waihai COD and TP concentrations show an excellent response to the inflow rivers. With the arrival of the rainy season, the inflow river COD and TP concentrations increase as a result of surface runoff

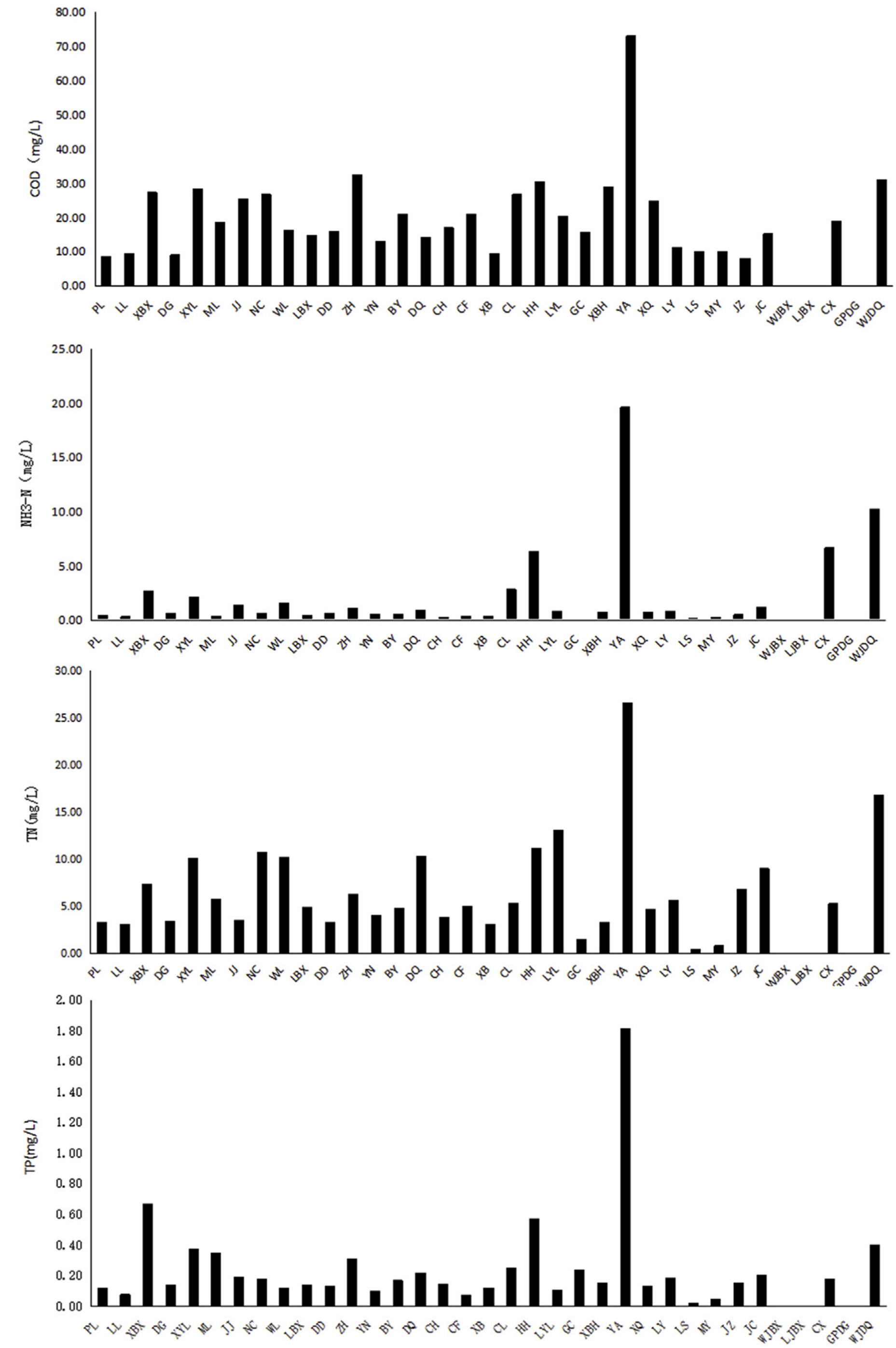

Fig. 6. River water quality status.

pollution, and their concentrations in the lake also increase, and then decrease later in the rainy season. However, a TN and NH_3–N response relationship between the inflow rivers and the lake is not apparent. For Caohai Lake, the NH_3–N concentration shows an upward increasing trend due to the inflow rivers in the rainy season, but lake TN fluctuates throughout the year, and shows no significant difference between the rainy and the dry seasons. For Waihai Lake, the TN and NH_3–N concentration varies throughout the year and shows no noticeable increase in the rainy season.

The response relationship of the river-lake concentrations of different pollutants is also entirely different. For Waihai lake, the average inflow river COD concentration was about 21 mg/L, but it increased to 42 mg/L after entering the lake. The TN concentration of the inflow rivers was approximately 7 mg/L, but it decreased to 2 mg/L in the lake. Inflow river TP concentration was 0.27 mg/L, but it declined to 0.13 mg/L in the lake, a smaller drop than for TN. The concentration of NH_3–N in the river was 2.27 mg/L, which significantly declined to 0.29 mg/L after entering the lake. The river-lake water quality response relationship for Caohai Lake has similar characteristics, but the range in variation is not as large as that of Waihai Lake. The average inflow river COD concentration into Caohai was about 14 mg/L, but it increased to 23 mg/L after entering the lake. The inflow river TN concentration was about 5 mg/L, and it decreased to 3.6 mg/L in the lake. The TP concentration of the inflow rivers was 0.44 mg/L, and it declined after entering the lake, but the overall change was not significant. The river NH_3–N concentration was 0.73 mg/L, which dropped sharply to

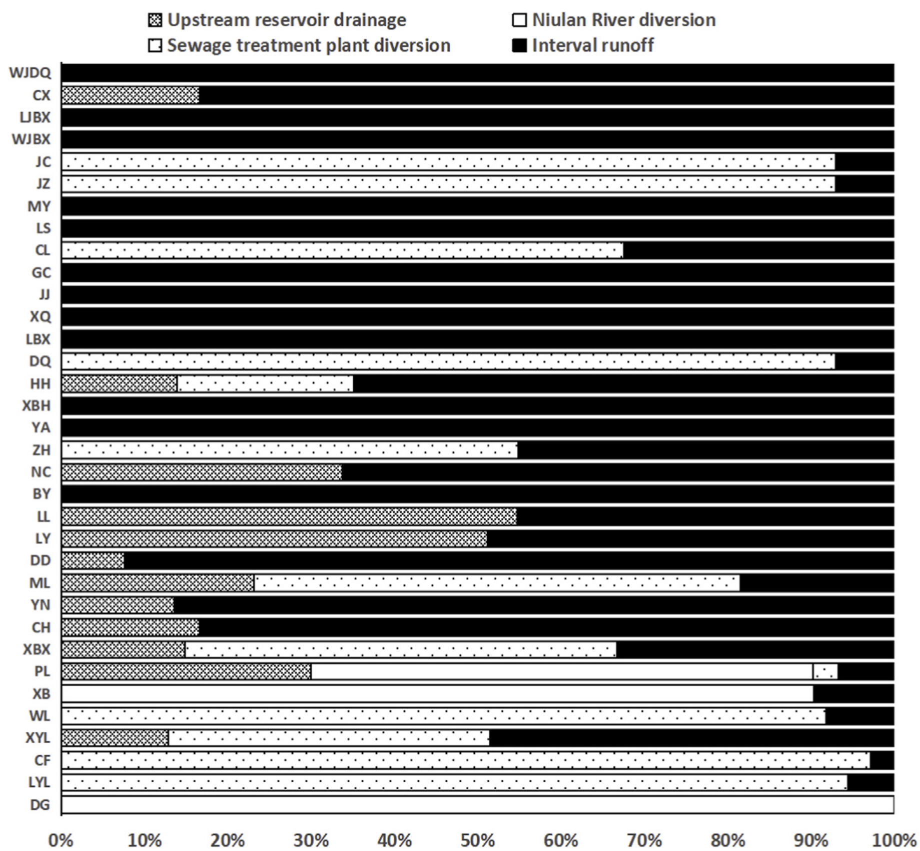

Fig. 7. Water composition ratios.

0.33 mg/L after entering the lake. This indicates that the lake has a significant purifying effect on nitrogen and phosphorus, especially on TN and NH_3–N, but in contrast, COD increases due to the cumulative impact of endogenous sources. This shows that inflow river COD pollution loads need to be strictly controlled. The control of TN by the lake contributes to self-purification of the lake body. The TP concentration response in the lake body is closely related to the inflow rivers, therefore, the river TP pollution loads need to be precisely controlled.

3.2.2. The contribution of inflow rivers to water quality at each state-controlled monitoring site

After multiple EFDC model iterations and a comprehensive analysis of the results, the impact of rivers on water quality at each state-controlled monitoring site was obtained quantitatively (Fig. 10). It is noteworthy that the Daguan and Wulong rivers in the Caohai Basin contributed the most (about 90%) to water quality at the Duanqiao site. The Chuanfang and Xiba rivers contributed the most (about 70%) to water quality at the Caohai Center Station. The Panlong River added the most to water quality at eight state-controlled monitoring sites in Waihai lake, followed by the Xinbaoxiang River, which may be because these rivers bring considerable pollution into Dianchi lake, up to 35% and 16% of total pollution loads, respectively. Furthermore, the extent of the contribution of these 2 rivers to water quality at each state-controlled monitoring site in the Waihai Basin was greater than 12% and 8%, respectively. Although both these rivers were distant from the Dianchinan site, they still contributed 22% and 11%, respectively, to

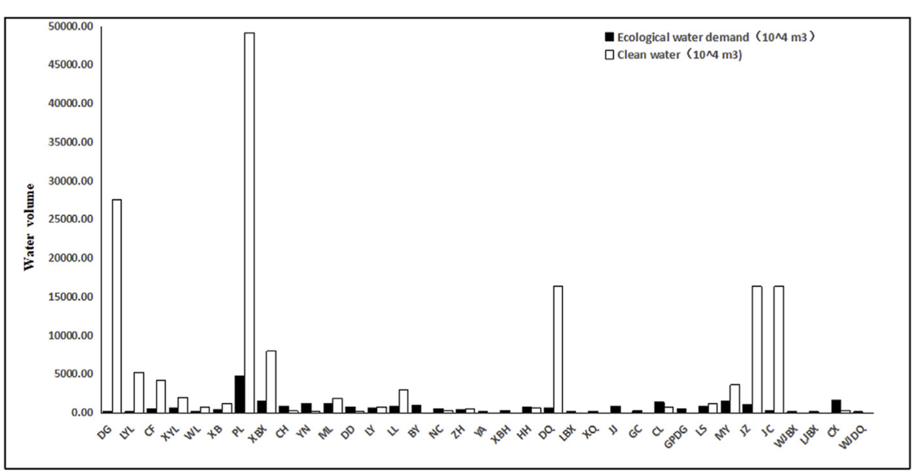

Fig. 8. Comparison of ecological water demand and clean water.

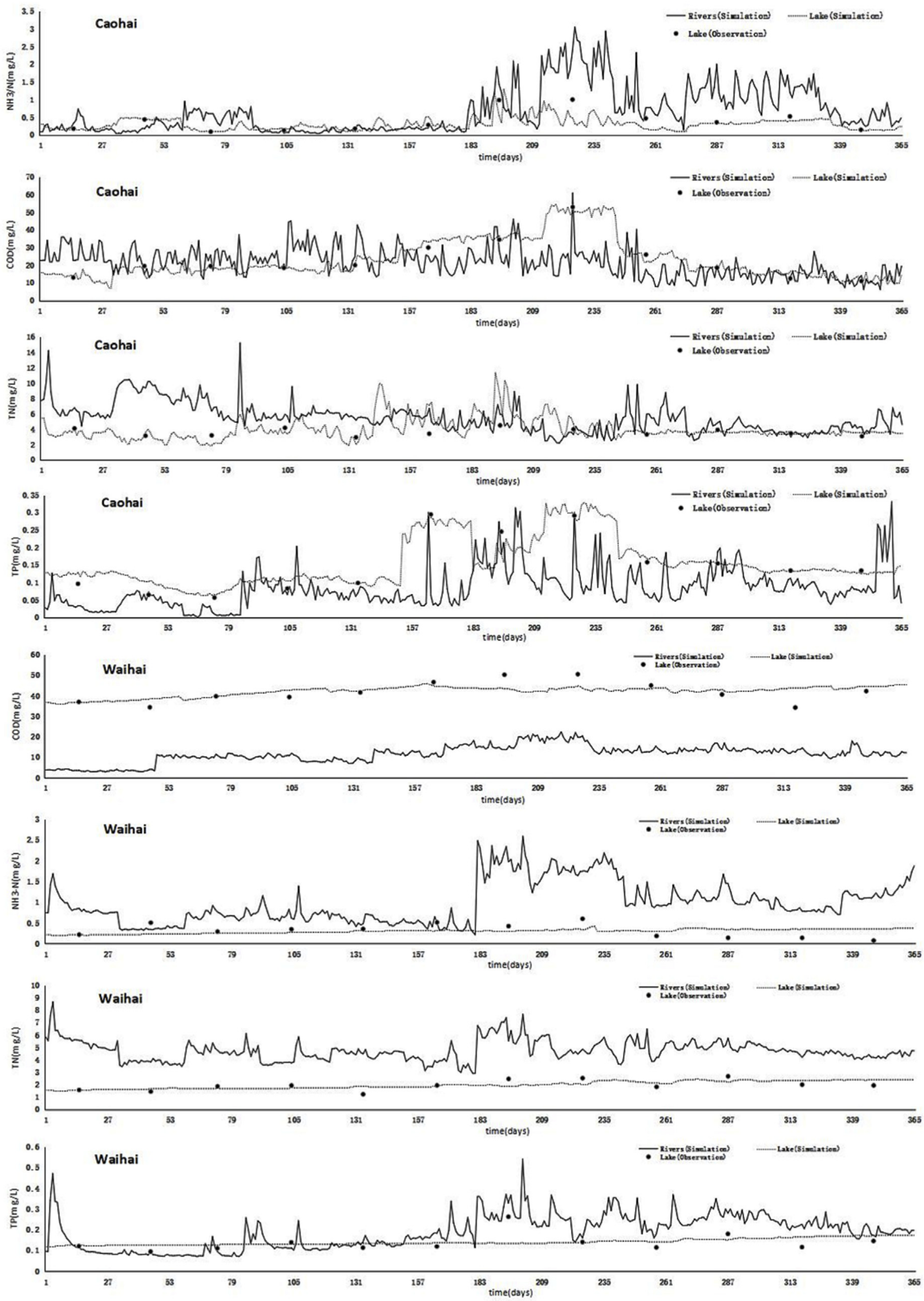

Fig. 9. Water quality response relationship between the inflow rivers and Dianchi Lake.

site water quality. Due to their close proximity, the Luolong and Laoyu rivers located in the East bank of Waihai accounted for 16% and 19% of the water quality of the two state-controlled monitoring sites, Luojiaying and Guanyinshan east site, respectively. The Dongda River and the Zhonghe River located in the south bank of Waihai, accounted for 15% and 9%, respectively, of the water quality of the neighboring Dianchinan site. Due to distance and flow field, some rivers account for a small proportion of the total pollution load into Dianchi lake, but they

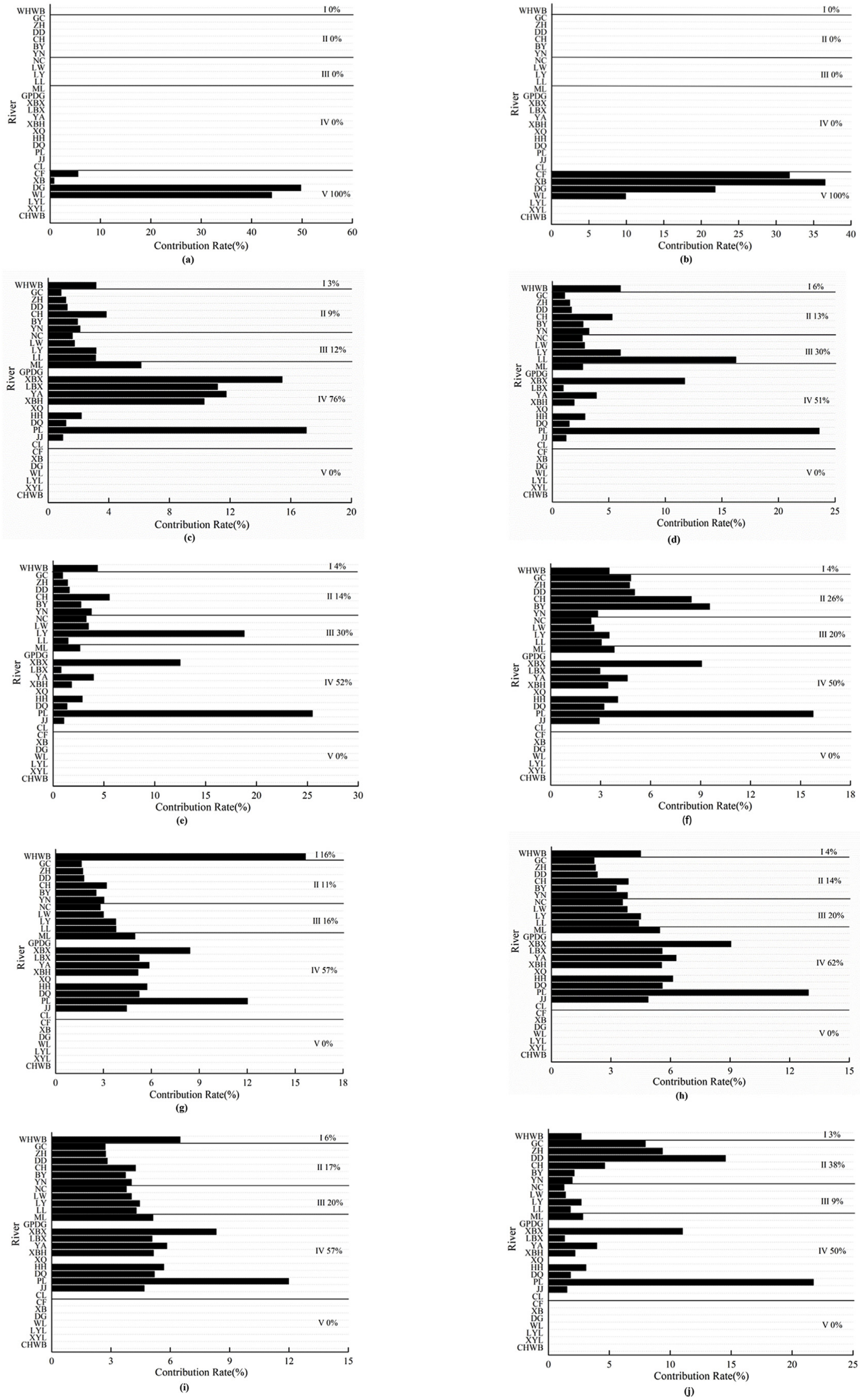

Fig. 10. The contribution of inflow rivers to water quality at monitoring sites.

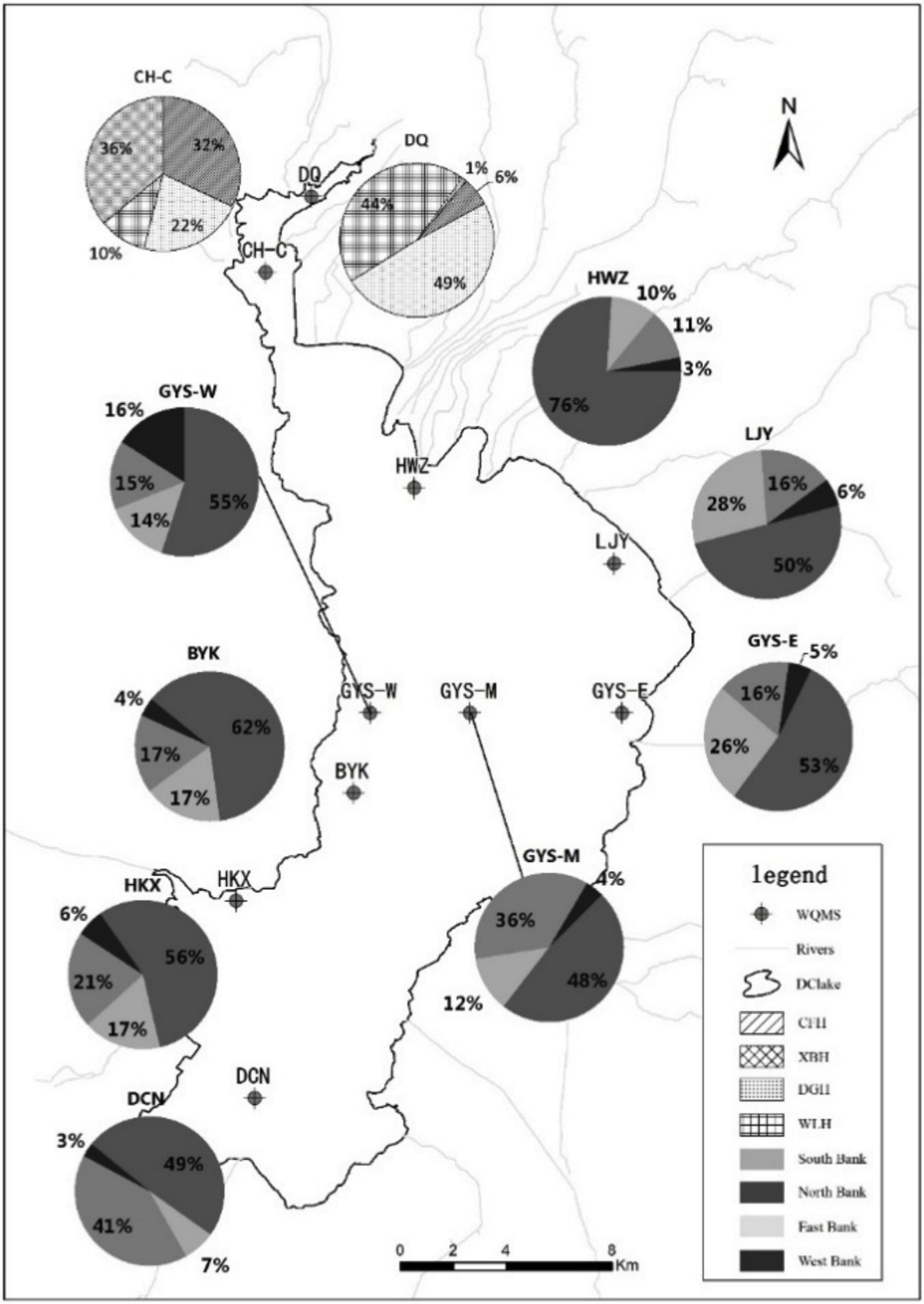

Fig. 11. The contribution of pollution load at each state-controlled monitoring site.

still contribute to a relatively large degree to water quality in some of the monitoring sites. For example, the pollution load of rivers in the west bank of Waihai accounted for only 4% of the total pollution load, but its contribution rate to the water quality of the nearby Guanyinshan west site reached 16%. The pollution load of the Yao'an, Xiaba, and the Laobaoxiang rivers accounted for less than 1% of the total pollution load, but their contribution rates to water quality of the nearby Huiwan Middle site were 12%, 10%, and 11%, respectively.

I: West sub catchment of Waihai; II: South sub catchment of Waihai; III: East sub catchment of Waihai; IV: North sub catchment of Waihai; V: Caohai sub catchment; (a) DQ; (b)CH–C; (c)HWZ; (d)LJY; (e)GYS-E; (f)GYS-M; (g)GYS-W; (h)BYK; (i)HKX; (j)DCN.

In summary, due to the diversity of pollution loads brought about by different rivers flowing into Dianchi Lake, and the impact caused by location and flow field, the contribution of water quality of each river to water quality of every state-controlled monitoring site is significantly different (Fig. 11).The north bank of Waihai contributed greatly to Dianchi Lake water quality, the pollutant load flux flow which accounted for 65.7% of the total pollution flux flowing into the lake, and which also contributed over 50% to water quality of 8 state-controlled monitoring sites in Waihai. These results signify that pollution control on the north bank of Waihai plays a major role in improving Dianchi lake water quality.

According to the analysis above, water quality of Daguan, Wulong, Panlong and Xinbaoxiang rivers makes up more than 5% of the water quality of all the state-controlled monitoring sites. They should be classified as first level control rivers; in addition, the "Thirteenth Five-Year Plan" proposes that "the water quality of the Caohai Basin stably reaches Class V, and water quality of the Waihai Basin stably reaches Class IV (CODcr $\leq$ 40 mg/L)" (Kunming Environmental Protection Bureau, 2016). Furthermore, among the 10 state-controlled measuring sites, water quality at Caohai Center and Duanqiao in the Caohai Basin, and at Waihai Lake Basin, Guanyinshan West, Guanyinshan Middle and Huiwan Center are all still struggling to reach acceptable water quality targets. The demand for water quality improvement in these areas is relatively high. The rivers that contribute to water quality in Waihai Basin are not only the PanLongjiang, Xinbaoxiang, Wulong, but also the Chuanfang, Baiyu, and Chaihe rivers. These rivers should be classified as rivers subject to second level control, and the remaining rivers should be classified as subject to third level control. Three river levels will be subjected to water quality control with standards specified in Class I, Class II, and Class III pollution control strategies.

The composition of the pollution load into each Dianchi sub-basin lake is presented in Fig. 12. The Daguan and Panlong rivers are the major water channels replenished by the Niulanjiang River, with highwater flows and high load percentages of replenishment. Around 93.8% of wastewater from point-sources (very close to the required 95%) within the basins of the two rivers are collected and treated. Non-point source pollution loads account for about 9.4% of the total pollution load. Reducing the total pollution load by 30% will lead to a definite improvement in their water quality. In the basin of the Wulong, Xinbaoxiang and Chuanfang rivers, there are several partial areas of urban villages where the rate of wastewater collection is slightly lower than the Panlong and Daguan rivers. Their river water quality would be significantly improved by controlling point and non-point pollution sources. The Baiyu and Chaihe rivers are mainly located in rural areas where rural and agricultural non-point pollution sources make up a high percentage. However, the percentage of collected and treated point source is low, only 60%, while the non-point sources account for a high percentage. The water quality of rivers in this area can be dramatically improved by bio-control of point source and non-point sources. Additionally, water pollution in Guangpudagou, Haihe, Jinjia, Yaoan, Wujia, Liujia and Xiaoqing rivers originates mainly from uncollected domestic point sources. The water quality of these water channels would be dramatically improved after implementation of a pollution control strategy.

3.3. Establishment of water quality targets of rivers flowing into Dianchi Lake

As the Xinyunliang and Laoyunliang river and stream courses in the west bank of the Caohai Basin are diverted through engineering measures, it is expected that these rivers may not flow into Caohai Lake in the future, and the water quality of the streams in the West Bank of Waihai cannot be guaranteed. Therefore, in this study only the water quality targets of the remaining 26 rivers flowing into Dianchi Lake are discussed (the Xiaoqing and Guangpudagou rivers are connected to the lakeside interception system as a temporary measure, so their water quality targets are also included in this section). Based on river-lake water quality response relationships and the current water quality and quantity of each river, each river's water quality management targets were determined. Each river's water quality targets were set as boundary conditions and the EFDC model used to verify the feasibility of the targets. Model results show that with these targets settings, Dianchi Lake water quality can reach the required standard, indicating that the targets were set at reasonable levels.

From the first, to the third step of the water quality settings, the requirements of managing and controlling river water quality inflowing into Dianchi Lake are gradually raised (Table 2). With verification via the lake water quality model and response identification in the first step, the rivers that have major influence on the lake's water quality at the key controlled sections were identified according to the analysis of the river-lake water quality response relationship. The concentration of the two indicators, COD and NH_3–N, in rivers flowing into the lake are greatly reduced compared with the current water quality, and the concentration of TN and TP are reduced in a certain extent. After the correction of the second and third steps of water quantity and quality response, the concentration of two indicators TN and TP, of the rivers flowing into the lake are greatly reduced. After the river water quality adjustment via the three steps, the final concentration of the four indicators in the lake body meet the target requirements.

Assuming that river water entering the lake can reach the annual water quality control targets, the monthly water quality control requirements of each river were derived from the monthly water quality characteristics of each river and the seasonal characteristics of the pollution control plan. The simulated management and control requirements can then be verified by inputting them into the EFDC model for Dianchi Lake. Results show that the average annual lake water quality can reach the standard, if the monthly water quality targets of the rivers are set at reasonable levels.

Fig. 13 shows the ranges in the water quality targets of the main rivers flowing into Dianchi Lake (fluctuations are expected in each month of the year). No obvious significant fluctuations in the water quality targets of 4 rivers in the Caohai Basin could be found, the all targets were strict in the mass. The Wulong River had relatively broad water quality targets, whereas the Daguan and Xiba rivers had stricter water quality targets with their COD, TN and TP below 10 mg/L, 2 mg/L and 0.1 mg/L, respectively. The two rivers are the water supply channels through which water from the Niulangjiang River that an External water diversion project flows into Caohai Lake and their water quality is good, so although strict targets were set for them, the gap between current water quality and the target is small.

The water quality targets of the rivers flowing into Waihai Lake were not as strict as those for Caohai Lake. This is mainly because Waihai has a large storage capacity and relatively strong self-purification ability. In terms of 4 water quality indicators, the overall water quality targets of the Yao'an (YA) and Guangpudagou rivers were relatively broad. In particular, the COD target concentrations of the two rivers were significantly higher than that of other rivers, mainly because the rivers have poor water quality which is difficult to improve, and they have low water flow, so there is no real need to set a high control target. The strictest water quality targets were set for the Luolong River, with target concentration ranges of COD, NH_3–N, TN

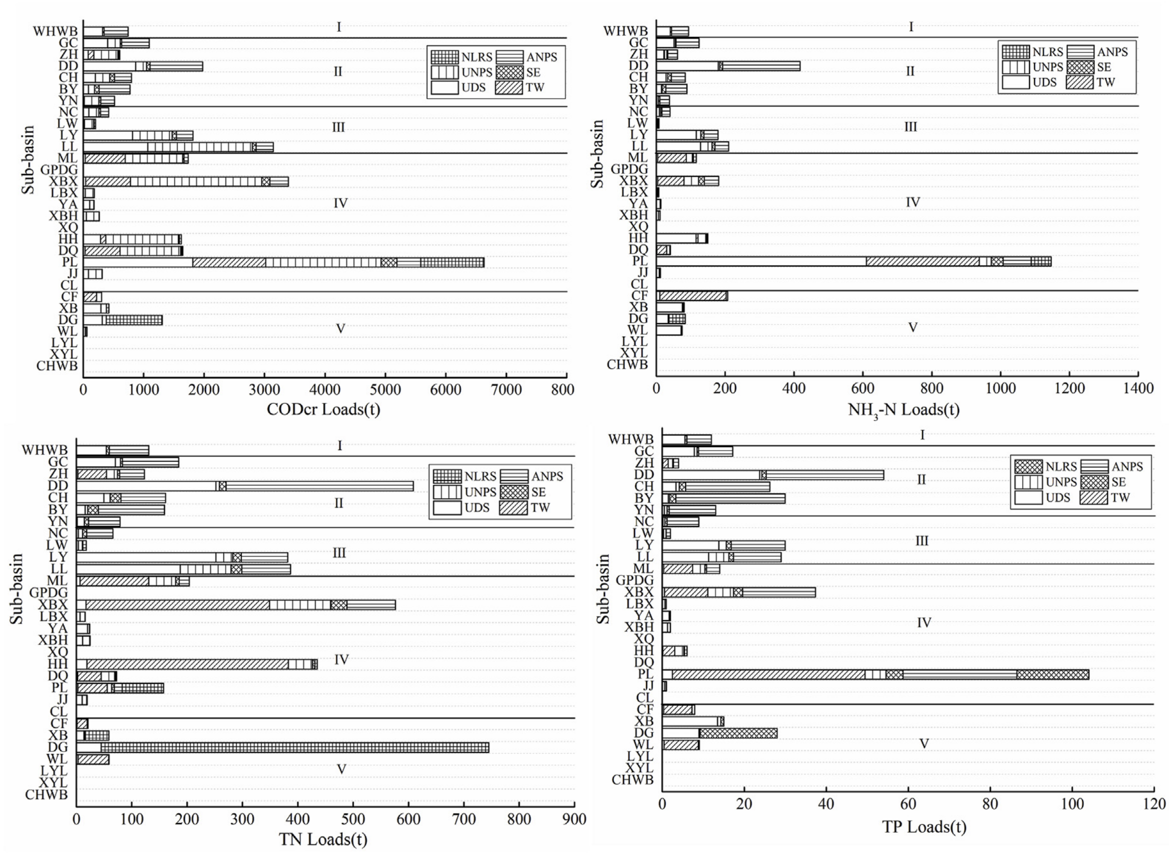

Fig. 12. Pollution load composition entering each sub-basin of Dianchi LakeI : West Sub catchment of Waihai; II: South Sub catchment of Waihai; I II: East Sub catchment of Waihai; IV: North Sub catchment of Waihai; V: Caohai Sub catchment. UDS:Uncollected domesticsewage ; TW: Tail water ; UNPS:Urban non-point sources; ANPS:Agricultural and rural non-point sources SE:Soil erosion; NLRS: Niulang River sources.

Table 2
Stepwise water quality change table.

Step	COD (mg/L)	NH_3–N (mg/L)	TP (mg/L)	TN (mg/L)
Current	20.37	2.08	0.25	6.66
1st step	19.34	0.94	0.19	6.66
2nd step	17.04	0.84	0.17	6.03
3rd step	14.19	0.35	0.13	4.86

and TP of 9–17 mg/L, 0.4–0.7 mg/L, 2–7 mg/L and 0.05–0.3 mg/L, respectively. The reason for this strict control is that the river has a high water flow which brings a high pollution load into Dianchi Lake. However, there is no significant gap between the current water quality situation of the Luolong River and its water quality target.

Considering the cumulative effect of COD in the lake body, its target should be set relatively strictly, except for instances where the concentration of individual rivers is controlled below 40 mg/L, all the others' should be controlled below 30 mg/L, which is up to or better than Class IV; the concentration of rivers flowing into Caohai must be controlled below 2 mg/L, while most rivers flowing into Waihai have low control requirements, the concentration should be controlled below 10 mg/L. The TP concentration of all rivers must be controlled below 0.2 mg/L, to reach Class V at least, the NH_3–N concentration can be maintained, according to the requirement of eliminating inferior class V, and control of the NH_3–N concentration below 2 mg/L is needed.

4. Conclusions

Based on the river-lake water quality response relationship, a lake basin water quality management system was established that coupled a SWAT basin hydrological model and an EFDC lake water quality hydrodynamic model. A river-lake water quality response function was established by setting the output data of the SWAT model as the input data of the EFDC model. Then the contribution of each river to water quality of the lake's key control points was calculated via the function and rivers identified that contribute more to poor water quality of the state-controlled sections. Next, key rivers whose water qualities should be strictly managed and controlled were precisely pinpointed and a stepwise pollution control strategy was established. River water quality control requirements, which are based on the river-lake water quality response, were proposed under the premise that water quality at 10 measuring stations reached the required standard.After correction for actual water quantity and quality responses under the clean water sources and water qualities of each river, the proposed system proved to be both practical and operable. The whole process was verified by the EFDC model to ensure that river water quality targets were set at reasonable levels that reach the required standard. The proposed management system is a highly promising method for improving the accuracy and efficiency of pollution control in lake basins.

Using the above system, the main water quality control objectives of rivers flowing into the Dianchi Lake were proposed. The Caohai and Waihai Lakes COD and TP concentrations showed a good response relationship with the COD and TP concentrations in the inflow rivers. The river-lake response of TN and NH_3–N was not obvious. From the perspective of river-lake pollutant concentration, the lake COD concentration was much higher than in the rivers flowing into the lake, indicating a cumulative effect in the lake. An obvious improvement in the lake COD concentration will be observed only when its concentration in the rivers flowing into Dianchi Lake is strictly controlled. The lake TN and NH_3–N concentration was much lower than that in the

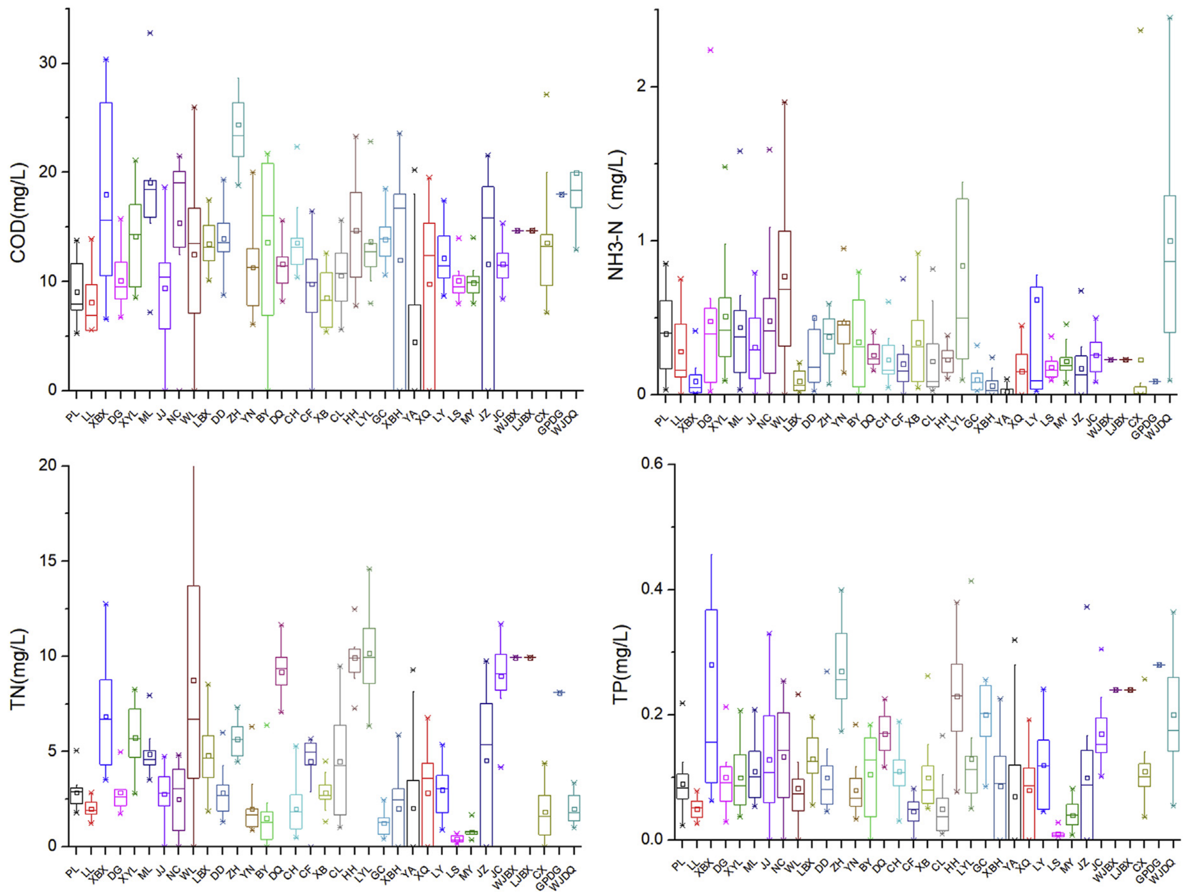

Fig. 13. Water quality goals for flows into the lake.

rivers flowing into the lake, suggesting that the lake has a strong capacity to dilute them. Compared with Dianchi Lake, the required concentration of TN and NH_3–N in the rivers flowing into Dianchi Lake could be slightly lowered, as the lake TP concentration is close to, or slightly lower than, that in the rivers flowing into the lake. This indicates that the TP concentration in rivers flowing into the Lake is closely related to the lake's concentration, and that the river's concentration should be precisely controlled. Through comprehensive analysis, the recommended water quality targets for the main rivers in the Dianchi Lake Basin are that the concentration of COD be maintained under 30 mg/L, for TN under 7 mg/L, for TP under 0.2 mg/L, and for NH_3–N under 2 mg/L.

CRediT authorship contribution statement

Jia He: Conceptualization, Methodology, Investigation, Writing - original draft. **Xue Wu:** Software, Validation, Formal analysis, Visualization. **Ying Zhang:** Validation, Formal analysis, Visualization. **Binghui Zheng:** Resources, Writing - review & editing. **Di Meng:** Resources, Supervision, Data curation. **Hongbin Zhou:** Software, Writing - review & editing. **Lu Lu:** Writing - original draft, Data curation. **Weiming Deng:** Writing - review & editing. **Zhi Shao:** Writing - review & editing. **Yinhui Qin:** Writing - review & editing.

Declaration of competing interest

The authors declared that they have no conflicts of interest to this work.

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References

Chen, L., Yang, Z., Liu, H., 2016. Assessing the eutrophication risk of the Danjiangkou Reservoir based on the EFDC model Ecological Engineering 96, 117–127.
Chen, L., Yang, Y., Chen, J., Gao, S., Qi, S., Sun, C., Shen, Z., 2017a. Spatial-temporal variability and transportation mechanism of polychlorinated biphenyls in the Yangtze River Estuary. Sci. Total Environ. 598, 12–20.
Chen, X.U., Wan, R.R., Qian, M.A., Yang, G.S., 2017b. The Research in the Revised Plan of Water Quality Standard of the Nitrogen and Phosphorus for the Inflow Rivers in the Northwest of the Taihu Lake Resources & Environment in the Yangtze Basin.
Deng, Y., Zheng, Y., Guo, F.U., Lei, K., Liu, R., Zhang, L.A., Zicheng, L.I., 2011. Application of route analysis method in the water pollution control planning in Lake Dianchi Catchment. J. Lake Sci. 23, 520–526.
Gamvroudis, C., Nikolaidis, N.P., Tzoraki, O., Papadoulakis, V., Karalemas, N., 2015. Water and sediment transport modeling of a large temporary river basin in Greece. Sci. Total Environ. 508, 354–365.
Gebremariam, S.Y., Martin, J.F., Demarchi, C., Bosch, N.S., Confesor, R., Ludsin, S.A., 2014. A comprehensive approach to evaluating watershed models for predicting river flow regimes critical to downstream ecosystem services. Environ. Model. Software 61, 121–134.
Gilbert, R.O., Simpson, J.C., 1992. Statistical Methods for Evaluating the Attainment of Cleanup Standards.
Hu, B.B., 2005. The System of Water Environmental Standard in European Union Research of Environmental Sciences, vol. 18. pp. 45–48.
Jin, Z.J., Jin-Hua, L.I., Zhang, C.M., Yang, F.L., Zhao, H.G., Zhou, B.X., Hai, Y.E., 2018. Construction and Engineering Application of Pollution Control Technology System for Urban River in Dianchi Watershed China Water & Wastewater.

Kai-Ming, H.U., Pang, Y., Wang, H., 2012. On the total nitrogen balance and water quality controllable target in. Taihu Lake Advances in Water Science 23, 555–562.

Lee, I., Hwang, H., Lee, J., Yu, N., Yun, J., Kim, H., 2017. Modeling approach to evaluation of environmental impacts on river water quality: a case study with Galing River, Kuantan, Pahang. Malaysia Ecological Modelling 353, 167–173.

Liu, Y., et al., 2017. A Study on the Impacts of External Pollution Control on Water Quality of Caohai. Dianchi Lake Environmental Science & Technology.

Meng, W., Tao, L.Z., Nan, Z., Lin, H.L., 2008. The Study on Technique of Basin Water Quality Target Management II:Water Environmental Criteria,Standard and Total Amount Control Research of Environmental Sciences.

Moriasi, D.N., Gowda, P.H., Arnold, J.G., Mulla, D.J., Ale, S., Steiner, J.L., Tomer, M.D., 2013. Evaluation of the hooghoudt and kirkham tile drain equations in the soil and water assessment tool to simulate tile flow and nitrate-nitrogen. J. Environ. Qual. 42, 1699–1710.

Quijano, J.C., Zhu, Z., Morales, V., Landry, B.J., Garcia, M.H., 2017. Three-dimensional model to capture the fate and transport of combined sewer overflow discharges: a case study in the Chicago Area Waterway System. Sci. Total Environ. 576, 362–373.

Shen, Z., Qiu, J., Hong, Q., Chen, L., 2014. Simulation of spatial and temporal distributions of non-point source pollution load in the Three Gorges Reservoir Region. Sci. Total Environ. 493C, 138–146.

Tuo, Y., Duan, Z., Disse, M., Chiogna, G., 2016. Evaluation of precipitation input for SWAT modeling in Alpine catchment: a case study in the Adige river basin (Italy). Sci. Total Environ. 573, 66–82.

U.S.EPA, 1998. Water quality criteria and standards plan: priorities for the future. Interim Final Report.

U.S.EPA, 2009. National Recommended Water Quality Criteria Clean Water Act.

Wang, C., Zhang, H., Tang, W., Shan, B., Rong, N., 2015. Structure Analysis of River Pollution Source in the Haihe River Basin Acta Scientiae Circumstantiae.

Xu, X., Wu, X., He, J., Wang, L., Ye, H., 2016. Research on the pollution characteristics of Dianchi watershed(1988-2014) and identification of countermeasures. J. Lake Sci. 28, 476–484.

Yang, B., Shang, X.L., 2010. The enlightenment of environmental protection legislation and pollutant emission standards in Japan. Environmental Pollution and Control 32, 94–97.

Yang, K., et al., 2019. Spatial-temporalvariation of lake surface watertemperature and its driving factors inYunnan-Guizhou Plateau. Water Resources Research.

Yao, Y.-H., Ma, W., Guo-Wu, Shi, Jiang, R.-C., Shu, G.-B., 2019. Fine Management of Water Quality Target on Rivers into Dianchi Lake Journal of Yangtze. River Scientific Research Institute.

Ye, Lin, Grimm, Nancy B., 2013. Modelling potential impacts of climate change on water and nitrate;export from a mid-sized, semiarid watershed in the US Southwest. Climatic Change 120, 419–431.

Yesuf, H.M., Assen, M., Alamirew, T., Melesse, A.M., 2015. Modeling of sediment yield in Maybar gauged watershed using SWAT, northeast Ethiopia. Catena 127, 191–205.

Zeiger, S.J., Hubbart, J.A., 2016. A SWAT model validation of nested-scale contemporaneous stream flow, suspended sediment and nutrients from a multiple-land-use watershed of the central USA. Sci. Total Environ. 572, 232–243.

Zhang, X., et al., 2014. Risks and countermeasures in water quality target-oriented watershed management. Acta Sci. Circumstantiae 34, 2660–2667.

Zhu, Y., Wang, F., 2004. Water Quality in Chaohu Lake Watershed and the its Envirnmental Object' S Administration & Technique of Environmental Monitoring.