Water quality improvement measures at the Yagang cross-section in the Pearl River Delta based on the calculation of excessive pollutant fluxes

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ABSTRACT

The aim of this study was to quantify the sources of pollution in the Yagang River Basin. A 1-D hydrodynamic model and a 1-D water quality model were combined with the excessive pollutant flux analysis method to calculate pollution data of the Yagang area. The results showed that upstream pollution was the primary cause of water quality degradation for the Yagang Basin, exceeding the water quality standards. In addition, the pollution problem ranking of the entire basin was as follows: the Yagang area (30.4%) > the Foshan area (23.2%) > the Baini River Basin (13.1%) > the Liuxi River Basin (0.6%). In addition, the rainy season had the greatest influence on pollution concentrations. It was also concluded that if the boundary water quality could meet the inspection requirements (class IV water), and the internal research area sewage collection rate reached 60%, the ammonia-nitrogen (NH₃-N) in the river discharge would reach 35.7%. This would allow the water quality at the Yagang cross-section to reach standard class IV.

Key words | 1-D numerical model, excessive pollutant flux, the Yagang cross-section, water quality improvement

HIGHLIGHTS

- Pollutant flux in the different seasons have different results.
- Different rivers contribute different pollutant flux.
- Non-point source pollution from upstream is the key reason for the worsening water environment.

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doi: 10.2166/ws.2020.345
INTRODUCTION

Due to flat terrain and comfortable climates, plain areas are typically characterized by high population densities, developed industries and agriculture, as well as high urbanization (Song et al. 2016). However, water environment degradation in plain river networks caused by urbanization is becoming increasingly worse (Feng et al. 2012). In addition, a large number of gates and dams have been constructed in order to ensure adequate water supply. This has resulted in low flow rates, decreased river system connectivities, and insufficient pollutant degradation abilities (Deng et al. 2018). As a result, water pollution is aggravated. Therefore, there is an urgent need to identify the pollution sources and to propose water quality improvement measures. This study uses the Yagang cross-section in the Pearl River Delta (PRD) as an example. The PRD, located in southern China and the northern part of the South China Sea, consists of a typical tidal river network and an estuary (Figure 1). Due to the reform and opening-up policy, the PRD region has become one of the most densely populated and economically developed regions in China (Hu & Li 2009; Chen & Zhang 2020). Consequently, the plain river network in the PRD has received high nitrogen and phosphorus nutrient loads from increased agricultural activities, fish dike farming, and wastewater due to economic development and population increases (Nukapothula et al. 2019). Therefore, an analysis of the source of this pollution and the proposal of effective measures is very important.

Currently, the primary methods that have been used to determine pollution sources in water environments are the chemical mass balance (CMB) method (Miller et al. 1972), the isotope tracer technique, and water quality modeling. The CMB method is widely used for the analysis of the contribution of related pollution sources in the atmosphere (Cesari et al. 2016; Wang et al. 2016), but has not been frequently applied for water environments (Bao et al. 2020). Success in using the CMB method requires the identification of all sources that potentially could contribute to the study object, and this necessitates a source composition profile for each source in order to build a library (Gleser 1997). In addition, all of the source compositions should be measured exactly. Thus, it is a challenge to identify nitrogen (N) and phosphorus (P) sources in plain areas, where point sources and nonpoint sources are highly complex (Kaushal et al. 2011; Yi et al. 2020).

With the development of the isotopic-based technique, the tracing of stable isotopes has become a primary tool for the identification of pollution sources. Over the last 50 years, nitrogen isotopes have been considered an important tool for the study of point and non-point sources of N contamination in water bodies in different regions (Kruk et al. 2020). Additionally, the isotope tracer technique has also been used to identify the sources of heavy metals in soils and determine their chemical behaviors (Huang et al. 2020). However, the isotope technique is expensive and
time-consuming, and it is applicable for specific elements (for example, N). Therefore, it is difficult to conduct such studies in a plain river network.

Water quality modeling was then introduced for the analysis of pollution sources when monitoring data were insufficient (Huishu et al. 2018). For example, the export coefficient model (ECM) is applied in areas with flat terrains and complex river networks in order to predict the annual nutrient inputs to lakes and rivers and to analyze the primary contributors of pollution loads (Li et al. 2016). In addition, some numerical models, such as MIKE, EFDC, and the Delft 3D Model, have also been applied to provide estimations of pollutant fluxes and to calculate the mass balance of nutrients (Heeb et al. 2012), which is the basis for pollution source identification.

This study is based on hydrological water quality data from 2017. This is used to construct a complex river network mathematical model of the water environment combined with the excessive pollutant flux analysis method to simulate water quality changes at the Yagang cross-section. The aim of this study is to predict different affects of the pollution sources in different seasons and to propose an effective plan to provide a scientific basis for local governance in the future.

STUDY AREA AND METHODS

Study area

The Yagang cross-section is located on the Xi Channel, which flows through the bordering zone between

Figure 1 | The location of the study area, the primary rivers and cross-sections, and the division of the affected area, including the 1-D model boundaries.
Guangzhou City and Foshan City in the south-central portion of Guangdong Province (Figure 1). It is dominated by a subtropical monsoon climate with rain and heat in the same period. The annual mean temperature is between 21 and 23 °C, and the average precipitation over an entire year is 1,830.8 mm. The average evaporation over an entire year is 1,653.5 mm. Southeast winds and northwest winds are dominant throughout the year (Nichol et al. 2020). The upstream flow of the Baini River was calculated using 2017 rainfall data from the Sankeng Station combined with the runoff coefficient and catchment area. The 2017 discharge from the Liuxihe Reservoir and the rainfall data of Liuxihe Reservoir station were used to calculate the upstream discharge of the Liuxihe River combined with the runoff coefficient and catchwater area. The upstream flows in 2017 from the southwest sluice gate and the Lubao sluice gate were determined using the flow through the sluice gates and the precipitation in Foshan. These were combined with the runoff coefficient and the catchwater area. The downstream tidal levels and daily high and low tide statistics of the channel in 2017 (from medium and large stations and a buoy station) were also utilized (Leach et al. 2017b).

By considering the current major pollution sources and the current water environment, a zone surrounded by five cross-sections (M1, M2, M3, M4, and the Yagang cross-section) was considered the most polluted area. This area was then defined as the study area. It is situated in the zone between 23°2' and 23°42'N and 112°53' and 113°45'E. As the Yagang cross-section is located in a tidal reach, it receives pollutants from the upstream area, but also pollutants from the downstream area during a high tide period. Therefore, in order to identify the pollution sources, the area that could affect the water quality at the Yagang cross-section was divided into five areas based on a division of the catchment section and the water environmental control units (Leach et al. 2017a). Hydrologic and water quality data, the model boundaries, and the location of the precipitation station were supplied by the Guangzhou Environment Protection Bureau and the Hydrology Bureau of Guangdong Province. These data consisted of the upstream area and the downstream area, and the upstream area was divided into the study area, which was the upstream area of the Liuxi River, the upstream area of the Baini River, and the southwestern area of Foshan City.

Study methods

To simulate the characteristics of reciprocating flow in the river network more accurately, this study combined the Saint-Venant equations to solve the finite difference method, namely, the solution area was divided into continuous grids. Hence, the approximate solution of the partial differential equation was calculated sequentially using grid nodes, and the catch-up method of the Abbott-Ionescu six-point implicit finite difference method was used to solve the problem. In addition, in order to save time in the model calculation, this research used a 1-D hydrodynamic model and a 1-D water quality model for a river network area. Finally, this was combined with the pollutant flux method of weights into the river to predict when the pollutant would exceed the standard in the simulated research plan (Wei et al. 2020).

The 1-D hydrodynamic model

The 1-D hydrodynamic model of the plain river network was constructed on the basis of the complete dynamic wave formulation of the Saint-Venant equations (Liang et al. 2020). The discharge, \( Q(x,t) \), and the water level, \( Z(x,t) \), were considered the dependent variables. In addition, the model considered lateral source inflows and lateral sinks. The calculation equations can be expressed as follows:

\[
\begin{align*}
\frac{\partial Q}{\partial x} + BW \frac{\partial Z}{\partial t} &= q \\
\frac{\partial Q}{\partial t} + 2u \frac{\partial Q}{\partial x} + (gA - Bu^2) \frac{\partial A}{\partial x} + g \frac{n^2 u |Q|}{R^{3/2}} &= 0
\end{align*}
\]  

(1)

where \( x \) represents the distance coordinate; \( Q \) represents the discharge; \( B \) represents the width of the section; \( BW \) represents the regulated width of the section; \( Z \) represents the water level; \( t \) represents time; \( q \) represents the lateral inflow; \( u \) represents the average velocity of the section; \( g \) represents the gravitational acceleration; \( A \) represents the area of the section; \( n \) is the roughness coefficient; and \( R \) represents the hydraulic radius.
The 1-D water quality model

A 1-D water quality model was constructed on the basis of the mass equation and the momentum equation, which suggest that the pollutant is mixed completely in the section (Chen et al. 2019). It can be calculated using the following equation:

$$\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} = \frac{\partial}{\partial x} \left( E \frac{\partial C}{\partial x} \right) - KC$$

(2)

where \(x\) represents the distance coordinate; \(t\) represents time; \(u\) represents the average velocity of the section; \(C\) represents the pollutant concentration; \(E\) represents the convection diffusion coefficient; and \(K\) represents the attenuation coefficient.

Excessive pollutant flux analysis

The Yagang section is situated on a tidal reach, and the pollutant fluxes during the high tide period and the falling tide period were calculated. The calculation equation is expressed as follows (Wang et al. 2011):

$$W_{\text{high tide}} = \sum_{i=1}^{n} C_{i, \text{high tide}} \cdot Q_{i, \text{high tide}} \cdot 10^{-6}$$

(3)

$$W_{\text{falling tide}} = \sum_{i=1}^{n} C_{i, \text{falling tide}} \cdot Q_{i, \text{falling tide}} \cdot 10^{-6}$$

(4)

where \(i\) represents the time (d); \(W_{\text{high tide}}\) and \(W_{\text{falling tide}}\) represent the pollutant flux through the Yagang section during the high tide and the falling tide periods, respectively (t/a); \(C_{i, \text{high tide}}\) and \(C_{i, \text{falling tide}}\) represent the average pollutant concentration over one day at the Yagang section (mg/L); \(Q_{i, \text{high tide}}\) and \(Q_{i, \text{falling tide}}\) are the simulated discharge by the 1-D model at the Yagang cross-section during the high tide and falling tide period, respectively.

In this study, an excessive pollutant flux was proposed to estimate the contribution of the different areas to water quality at the Yagang cross-section. It represents the flux of pollutants through the section that exceeds the allowable flux. By considering the reciprocating flow in the plain river network, the calculation of the excessive pollutant flux considers only the falling tide period. It is calculated as follows:

$$W_{\text{excessive}} = \sum_{i=1}^{n} (C_i - C_s) \cdot Q_i \cdot 10^{-6}$$

(5)

where \(W_{\text{excessive}}\) represents the excessive pollutant flux (t/a); \(C_i\) represents the average pollutant concentration over one day at the Yagang cross-section (mg/L); \(C_s\) represents the water quality standard of the Yagang section (mg/L); and \(Q_i\) represents the simulated discharge by the 1-D model at the Yagang cross-section (m³/d).

The weight influence of a pollutant was calculated according to the proportional relation, which can be expressed using the following formulae:

$$\alpha_{\text{downstream area}} = \frac{W_{\text{high tide}}}{W_{\text{high tide}} + W_{\text{falling tide}}}$$

(6)

$$\alpha_{\text{upstream area}} = \frac{W_{\text{falling tide}}}{W_{\text{high tide}} + W_{\text{falling tide}}}$$

(7)

$$\alpha_p = \frac{W_{p, \text{excessive}}}{W' + \sum_{p=1}^{3} W_{p, \text{excessive}}} \times \alpha_{\text{upstream area}}$$

(8)

$$\alpha' = \frac{W'}{W' + \sum_{p=1}^{3} W_{p, \text{excessive}}} \times \alpha_{\text{upstream area}}$$

(9)

where \(\alpha_{\text{downstream area}}\) and \(\alpha_{\text{upstream area}}\) represent the weight influence of the pollutants from the downstream area and the upstream area, respectively; \(\alpha_p\) represents the weight influence of the pollutant from the different areas in the upstream area, except the study area (the upstream area of the Liuxi River, the upstream area of the Baini River, and the southwestern area of Foshan City); \(\alpha'\) represents the weight influence of the pollutant from the study area; \(W_{p, \text{excessive}}\) represents the excessive flux of the pollutants from different areas except the study area (t/a); and \(W'\) represents the pollutant discharge exceeding the water environment capacity, which is equivalent to the difference between the current emissions and the water environment capacity (t/a).
MODEL SETUP AND CALIBRATION

Model setup

The primary rivers (the Liuxi River, the Baini River, the Xi Channel, the Xinan River, as well as the Qian Channel) were generalized using 42 cross-sections. All the cross-sections were considered as trapezoids because of the flat bottom slope (Soudi et al. 2019).

The model consisted of four upstream boundaries and one downstream boundary. The water flow of the Baini River was calculated based on the 2017 precipitation data from the Sankeng precipitation station, and the discharge was calculated based on the Nedbør Afstrømnings Model (NAM). This rainfall-runoff model can be used alone or to calculate one or more runoff zones where the runoff is used as a side inflow into a hydrodynamic (HD) model’s river network to calculate the total watershed flow. The water flow of the Liuxi River was determined using the 2017 outflow discharge from the Liuxi Reservoir. The inflow discharge from the southwestern area of Foshan City was determined using the 2017 water discharge data at the Xinan sluice and the Lubao sluice. The water level of the downstream was based on daily monitoring data from the Zhongda gauging station and the Fubiaochang gauging station.

The water quality of the Baini River and the downstream were determined using daily monitoring data. The water quality of the Liuxi River was based on the data of the Liuxi Reservoir. The water qualities of the Xinan River and the Lubao River were determined using the Beijiang River. The hydrologic and water quality data, the model boundaries, and the location of the precipitation station were supplied by the Guangzhou Environment Protection Bureau and the Hydrology Bureau of Guangdong Province.

Industry and sewage plants were generalized as point pollution sources in the model scope, and the non-point sources (farmland and runoff pollution) were discharged in a uniform manner along the river.

Model calibration

The model was calibrated based on the water level data from the Yagang cross-section in January, April, and July 2017. Depending on the result of calibration, the roughness coefficient of the river was determined, which was between 0.016 and 0.035. The errors of the calculated and measured values are shown in Figure 2. The results show that the simulated water level was in reasonable agreement with the measured values, with an average relative error of less than 14%.

The water quality model (chemical oxygen demand (COD), ammonia-nitrogen (NH3-N), total phosphorus (TP)) was calibrated according to the 2017 monthly monitoring data from the Yagang cross-section. The average relative error of the calculated and measured values for the COD concentration was 11.01%, for NH3-N 10.63%, and for TP 11.98%. Based on the calibration results, the attenuation coefficients of COD, NH3-N, and TP were 0.08–0.12 d\(^{-1}\), 0.06–0.10 d\(^{-1}\), and 0.06–0.08 d\(^{-1}\), respectively. The errors of calculated and measured values are shown in Figure 3.

To further compare the simulated water levels with the measured values, this study used three model evaluation methods, namely, average relative error (MRE), root mean square error (RMSE), and correlation coefficient analysis (R\(^2\)). The evaluation process involved an error and correlation analysis of the measured values (M) and simulated values (S) that used the following formulations (Xu et al. 2020):

\[
RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (S_i - M_i)^2} \tag{10}
\]

\[
MRE = \frac{1}{N} \sum_{i=1}^{N} |S_i - M_i| \tag{11}
\]

\[
R^2 = \frac{\sum_{i=1}^{N} (S_i - \bar{S})(M_i - \bar{M})}{\sqrt{\sum_{i=1}^{N} (S_i - \bar{S})^2 \sum_{i=1}^{N} (M_i - \bar{M})^2}}, \tag{12}
\]

where \(N\) is the number of times of the total simulation; \(i\) is the number of times of the simulation; \(S_i\) is the value of the \(i^{th}\) simulation; \(M_i\) is the value of the \(i^{th}\) measurement; \(\bar{S}\) is the simulated average value; and \(\bar{M}\) is the measured average value.

The assessment results of the four stations (M1, M2, M3, and M4 in Figure 1) showed that the simulated water levels
fit well with the measured water levels, and the RMSE was less than 5 cm. In addition, $R^2$ of the water qualities were all greater than 0.90 (Table 1). The simulation results accounted for more than 90% of the actual situation. As a result, the constructed water quality model met the requirements for subsequent water quality research.

**RESULTS AND DISCUSSION**

**Results of the pollution flux for the different periods**

In this study, the period from December to March was considered the dry season (less rainy season), the period from
Figure 3 | Comparisons of the simulated and measured pollutant concentrations (COD, NH₃-N, and TP).
June to August was considered the wet season (rainy season), and the rest was considered the normal season (normal rain season) (Wang et al. 2020). The representative year of 2017 with a high concentration of NH$_3$-N was selected as the typical year for further analysis of the pollutant fluxes. The pollutant fluxes (COD, NH$_3$-N, and TP) during the high tide and falling tide period through the Yagang cross-section were calculated according to the method mentioned above. The results (Table 2 and Figure 4) indicate that the pollutant fluxes through the Yagang cross-section during the falling tide period were much larger than those during the high tide period. It was concluded that the upstream area had a greater influence on the water quality at the Yagang cross-section (Yi et al. 2020). An investigation was conducted on the mass fluxes of nutrients in the Pearl River Delta, and it was found that the upstream flux was the most important external source in the plain river network of the Pearl River Delta. This result was primarily ascribed to a high concentration of pollutants from the upstream area and cleaner water from the downstream area, which was diluted by fresh seawater. In addition, the result indicates that the pollutant flux of the normal season was larger than the other seasons due to larger nutrient loads with moderate discharges during the normal season.

The influence of the different areas in the upstream area on the water quality at the Yagang cross-section will be further discussed according to the method of excessive pollutant flux in the following section.

### Weight influence of pollutants from the upstream area and the downstream area

The weight influence of pollutants from the upstream area and the downstream area were calculated according to

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**Table 2 | The pollutant fluxes for the different periods (t/a)**

| Period      | High Tide |            | Falling Tide |
|-------------|-----------|------------|--------------|
|             | COD       | NH$_3$-N   | TP           | COD       | NH$_3$-N   | TP           |
| Wet season  | 10,509.44 | 1,273.27   | 180.64       | 35,000.34 | 3,909.31   | 549.26       |
| Normal season | 27,260.12 | 3,540.43   | 400.45       | 53,249.39 | 6,910.56   | 698.63       |
| Dry season  | 17,264.64 | 2,626.4    | 236.84       | 31,700.07 | 4,464.35   | 398.93       |
| The whole year | 55,034.21 | 7,440.1    | 817.94       | 119,949.8 | 15,284.23  | 1,646.81     |

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**Figure 4 | Proportion of the pollutant fluxes for different periods.**
Equations (6) and (7). As shown in Figure 5, the influence of the upstream area during the wet season was much greater than that in the normal and dry seasons. Previous studies show that the climate in the Pearl River Delta resulted in highly seasonal variations in water discharges (Xuan et al. 2020). Furthermore, during the wet season (April to September), high precipitation and runoff resulted in a greater loading of nutrients (Ou et al. 2019). However, during the dry season (October to March), decreased river discharges and strong northeasterly winds led to a well-mixed water column (Ye et al. 2017). In this study, it was assumed that the inflow discharge was the greatest during the wet season, and it would then carry a large amount of non-point pollution, which would lead to a greater influence. According to the 2017 water quality monitoring data, the primary pollution factor at the Yagang cross-section was NH$_3$-N, and the excessive multiple was 0.32 (the water quality standard of NH$_3$-N is equal to 1.5 mg/L). With regard to NH$_3$-N, the pollutant flux from the upstream area accounted for 67.3% for the entire year, and the downtown stream area accounted for 32.7%. Therefore, the water quality of the Yagang section could not meet the standard due to the large pollution load from the upstream area, which was the same as discussed above.

**Excessive pollutant fluxes of the different areas in the upstream areas**

The excessive pollutant fluxes in the four areas (the southwestern area of Foshan City, the upstream area of the Baini River, the upstream area of the Liuxi River, as well as the study area) were calculated based on Equation (5), and then the contributions from the areas were estimated. According to the water quality monitoring data, the concentration of COD did not exceed the water quality standard, and the excessive pollutant flux of COD was equal to 0. The results for NH$_3$-N and TP are shown in Figure 6. The contribution of the different areas varied significantly depending on the water period. The excessive pollutant flux from the study area was the largest for NH$_3$-N, which

![Figure 5](http://iwaponline.com/ws/article-pdf/21/4/1778/904043/ws021041778.pdf)  
*Figure 5* | Weight influence of pollutants from the upstream and downstream areas.
accounted for 30.4% for the entire year, while the upstream area of the Liuxi River accounted for only 0.6%. The contributions of the different areas to the water quality at the Yagang cross-section were ranked as follows: the study area > the southwestern area of Foshan City > the upstream area of the Baini River > the upstream area of the Liuxi River. For TP, the upstream area of the Baini River contributed a lot to the water quality at the Yagang cross-section and the study area; however, the upstream area of the Liuxi area had little influence. Some studies have shown that, in recent decades, non-point source phosphorus has become the priority source in many catchments, especially in highly agricultural watersheds (Ouyang et al. 2014). Therefore, the high contribution of the upstream area of the Baini River was attributed to the large farmland areas there which cause significant phosphorus pollution.

In terms of the different water periods, the excessive pollutant flux from the southwestern area of Foshan City during the wet season was evidently less than that of the normal season and the dry season, suggesting that the water quality of the inflow from Foshan City during the wet season could satisfy the standard. Therefore, the focus should be on improving the water quality of the inflow from Foshan City during the dry season in order to meet the water quality standard for the Yagang cross-section. In addition, compared to the normal season and dry season, the upstream of the Baini River had a greater influence on the Yagang cross-section during the wet season. According to the 2017 environmental statistics for Guangzhou and Foshan Cities, non-point pollution from farmland is serious in the upstream area of the Baini River, which leads to large nutrient loads in the river during the wet season (Hu et al. 2016). Measures need to be developed urgently to reduce non-point pollution in the Baini River. Also, no matter which water period, the study area was affected significantly by the water quality of the Yagang section. The study area is very close to the Yagang section; hence, the pollutants might not have been fully degraded, which would worsen the water quality of water bodies (Xu et al. 2020). Attention should be paid to reducing pollution from the study area.

Water quality improvement measures

According to the excessive pollutant flux analysis, the Yagang section suffers not only from pollutants from the upstream area but also from the downstream area. Detailed measures to improve the water quality are discussed in the following section.

Pollution reduction in the study area

Based on the 2017 environmental statistics for Guangzhou and Foshan Cities, the primary reason for the high concentration of NH$_3$-N at the Yagang cross-section was residential pollution, making up more than 70% of all the pollutant discharge. In the study area, outflows from the sewage pipelines were not enough, with only 30.5% of wastewater delivered to the sewage treatment plants through the pipeline network, and the rest discharged into the rivers directly (Wang et al. 2017). To reduce the pollution in the study area, the focus should be on increasing the collection and processing rate of sewage by optimizing the design of the

![Figure 6](http://iwaponline.com/ws/article-pdf/21/4/1778/904043/ws021041778.pdf)
pipeline network and improving the sewage treatment process. By considering the recent inlet and outlet concentrations of NH$_3$-N from sewage treatment plants, the NH$_3$-N reduction rate of the pollutant discharged into rivers was calculated for different sewage collection rates (Table 3).

**Water quality requirements of the different areas**

Based on the results of the excessive pollutant flux, different water quality improvement measure scenarios were designed and then simulated using the validated 1-D model. The most adverse hydrological case was considered. According to precipitation data from the Sankeng and Liuxi Reservoir precipitation stations from 2006 to 2017, the typical year (guaranteed rate = 90%) was determined using the P-III frequency curve to be 2011 (Zhang et al. 2019). Then, the discharges of the upstream boundaries were calculated based on the 2011 precipitation data. The high tide level and low tide level of the downstream boundary were determined to be water levels of 10 and 90% of the occurrence frequency according to daily monitoring data from 2016 to 2017 from the Zhongda gauging station and the Fubiaochang gauging station. The water quality at the Yagang cross-section is influenced by the four areas; thus, five groups of scenarios were established to consider the NH$_3$-N reduction rate in the study area and the water quality condition for the inflow from Foshan city, the Baini River, and the Xi Channel. The boundary conditions and the pollution sources of the model for all the cases are shown in Table 4. The upstream or downstream boundary water quality for the status quo in the area does not utilize any cross-sectional COD and total phosphorus averages to achieve the class IV water standard. However, no matter what the pollutant reduction plan, NH$_3$-N reached the class IV water standard. Under the condition of an improved boundary water quality, the NH$_3$-N collection rate reached greater than 80%, and the cross-section still could not achieve the class IV water standard (Liu et al. 2013). Due to sewage collection network damage, leakage, wrong or mixed connections, the confluent system, and other factors, it is generally impossible for the sewage collection pipeline system to collect 100% of the generated sewage into the system. However, the urban sewage pipe network system can send 80% of the generated sewage into the sewage treatment plant, which is a relatively high level in China (Jin & Yong 2011).

In the different scenarios, the concentrations of COD and TP at the Yagang cross-section were always able to meet the

| Number | Sewage collecting rate | NH$_3$-N reducing rate |
|--------|------------------------|------------------------|
| 1      | 50%                    | 25.4%                  |
| 2      | 60%                    | 35.7%                  |
| 3      | 70%                    | 45.9%                  |
| 4      | 80%                    | 56.2%                  |

**Table 4** Model simulation scenarios

| Model scenarios | Pollution sources | Boundary conditions |
|-----------------|-------------------|---------------------|
|                 | NH$_3$-N reducing rate of the study area | Upstream area | Downstream area |
| Group 1         | Baini River       | Inflow from Foshan City | Liuxi River | Xi Channel |
| 25.4%, 35.7%, 45.9%, 56.2% | Maintaining current situation | Maintaining current situation | Maintaining current situation | Maintaining current situation |
| Group 2         | Water quality standard | Water quality standard | Water quality standard | Water quality standard |
| 25.4%, 35.7%, 45.9%, 56.3% | Maintaining current situation | Maintaining current situation | Maintaining current situation | Maintaining current situation |
| Group 3         | Water quality standard | Water quality standard | Water quality standard | Water quality standard |
| 25.4%, 35.7%, 45.9%, 56.4% | Maintaining current situation | Maintaining current situation | Maintaining current situation | Maintaining current situation |
| Group 4         | Water quality standard | Water quality standard | Water quality standard | Water quality standard |
| 25.4%, 35.7%, 45.9%, 56.6% | Water quality standard | Water quality standard | Water quality standard | Water quality standard |

(Maintaining the current situation (class V water): COD = 15 mg/L, NH$_3$-N = 2.0 mg/L, and TP = 0.4 mg/L; Water quality standard (class IV water): COD = 10 mg/L, NH$_3$-N = 1.5 mg/L, and TP = 0.3 mg/L).
water quality standard. The simulated average concentration of NH$_3$-N over one month in the different scenarios is shown in Figure 7. The results suggest that the water quality at the Yagang cross-section depends on both the upstream area and the downstream area, and this agrees with the conclusions of other researchers (Zhou et al. 2014). Only when the water quality of the inflow from Foshan City, the Baini River, as well as the Xi Channel could be improved to meet the water quality standard, and the pollutant NH$_3$-N discharged to the rivers in the study area could be reduced by more than 45.9% (model scenario Group 4) would the water quality at the Yagang cross-section satisfy the water quality standard. In general, the water quality improvement of the Yagang section requires joint efforts from both the Guangzhou and Foshan governments (Zhou et al. 2015).

CONCLUSIONS

The excessive pollutant fluxes of different affected areas were calculated based on 1-D hydrological and water quality models. The results showed that both the upstream and downstream areas contributed to the water quality of the Yagang cross-section. Furthermore, the upstream area had a greater influence. For NH$_3$-N, the ranking of the contributions from the different areas in the upstream area was as follows: the
study area (30.4%) > the southwestern area of Foshan City (23.2%) > the upstream area of the Baini River (13.1%) > the upstream area of the Liuxi River (0.6%). In order to propose water quality improvement measures, a series of scenarios were simulated using the 1-D model. The results indicated that, to meet the water quality standard of the Yangtze cross-section, the water quality of the inflow from Foshan City, the Baini River, as well as the Xi Channel should be improved, and the NH3-N pollutant discharged to the rivers in the study area should be reduced by more than 35.7% by increasing the sewage collection and processing rate. Additionally, much attention should be paid to reduce the non-point source pollution caused by farmlands in the upstream area of the Baini River. In general, the calculation of excessive pollutant fluxes can serve as a method to identify pollution sources and divide pollution treatment responsibilities. This modeling can assist in the environmental management of the plain river network.

ACKNOWLEDGEMENTS

The authors thank the Shenzhen Science and Technology Program (KQTD2016022619584022). This work was supported by the Chinese National Science Foundation (Grant No. 51879070). This research was also funded by the Major Science and Technology Program for Water Pollution Control and Treatment of China (Grant No. 2018ZX07208007). We thank LetPub (www.letpub.com) for its linguistic assistance during the preparation of this manuscript.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 6 August 2020; accepted in revised form 16 November 2020. Available online 30 November 2020