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# Characterization of sewage quality and its spatiotemporal variations in a small town in Eastern Guangdong, China

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The domestic sewage in rural areas of South China is characterized by a relatively low concentration of organic pollutants; however, the factors causing this have not been carefully examined. This study conducted a comprehensive survey on two sewer networks in a small town of Eastern Guangdong, China, via grab water sampling at a frequency of once every 2 weeks lasting for 1 year. The sewage quality showed significant variations across the systems, while a gradual decrease in the concentrations of chemical oxygen demand (COD), total nitrogen (TN) and phosphorus (TP) from the upper to lower reaches of sewers could be observed. Storm events could have a flushing effect on TP in the upper reach of sewers, but a dilution effect on COD and TN in flat terrains. The diurnal pattern of sewage was largely impacted by the position of the manholes and water consumption difference between holidays and normal days. Both COD/TN and TN/TP ratios of the sewage showed a lognormal distribution dominating in the range of 2.0–3.0 and ∼10.0, respectively. The low ratio of COD/TN in the morning discharge peak could be attributed to the wide use of septic tanks in the area, while groundwater infiltration played more important roles in the basal flow conditions. This study could serve as a basic reference for designing and managing sewage infrastructure in rural areas of South China and highlights that prevention of groundwater infiltration is crucial to improve the efficiency of sewage infrastructure in high water table areas.

KEYWORDS
**sewage quality, groundwater infiltration, septic tanks, COD/TN, diurnal pattern**

## 1 Introduction

Septic tanks have been the sole treatment facilities for blackwater in many rural areas of China, while greywater was discharged without any treatment to local creeks, streams, or other water bodies via open or covered conduits, which were also used for stormwater management. This had led to the severe pollution of many water bodies, and the "black and odor water" problem (Li P. et al., 2023). To rehabilitate the polluted water bodies, many efforts have been made to build sewer networks (SNs) and decentralized sewage treatment facilities in rural areas and small villages in China in the past decade. This has significantly reduced the pollution loads to local water bodies and improved the environment quality. In this process, the national wastewater discharge standard (GB 18918-2002), which was implemented for the regulation of centralized sewage/wastewater treatment plants, has been widely adopted.

On the national level, however, the pollution strength of rural domestic sewage varies remarkably among different regions. For example, Eastern and South-central China showed significantly lower concentrations of pollutants than those in Northern China (Yu et al., 2015) . This distinct geological discrepancy in sewage quality across China may be attributed to the extremely uneven distribution of water resource and annual rainfall, unbalanced economic development, population, temperature and altitude (Wang et al., 2022). The geological variation indicates that different areas shall develop/adopt appropriate sewage management approaches in accordance with their local sewage characteristics.

In a typical combined sewer network, the sewage water quality was highly dependent on water usage, conveying distance, and rain intensity (Jia et al., 2021). Other factors, such as illicit discharges and sewer leakages, also affect the sewage quality greatly. Leakage of sewer pipes occurs frequently, due to many reasons including pipe failures, inappropriate sealing or illicit connections. This could lead to infiltration of groundwater or exfiltration of sewage depending on the groundwater table (Jia et al., 2021), thus having a great impact on the sewage flowrate and strength, and the surrounding environments (Lee et al., 2015). In addition, biological degradation of organic pollutants along the sewers could be an important factor leading to the low organic strength sewage. For example, the total chemical oxygen demand (COD) was estimated to be degraded at a rate of 4% $h^{-1}$ or 0.8% $km^{-1}$ in an interceptor sewer in Portugal, while the soluble portion (sCOD) was degraded at a much greater rate of 13% $h^{-1}$ or 3% $km^{-1}$ (Almeida et al., 2000). In another study in Denmark, a 1st-order reaction was used to describe the degradation of sCOD, which resulted in 2.7% $km^{-1}$ removal of total COD or 4.8% $km^{-1}$ of sCOD along the gravity sewer (Raunkjaer et al., 1995). A recent study in Yunnan, a province of South China with subtropic climate, indicated a 1st-order COD degradation rate constant of 0.05–0.07 $km^{-1}$, translating to a total degradation ratio of 16%—38% in the sewer system (Yang et al., 2021). It can be expected that the sewage characteristics within a rural SN could be highly variable, depending on community activities, location, season, and time, in addition to the diurnal patterns.

A number of previous studies have conducted surveys of sewage quality and its variations along sewers (Özer and Kasirga, 1995; Raunkjaer et al., 1995; Almeida et al., 2000; Yang et al., 2021). However, the spatial or seasonal variations of sewage quality within a single sewer network have not been examined in these studies. Moreover, groundwater infiltration to the sewers has not been considered in most of the reports, which might have biased the result. Our recent study has shown that groundwater accounted for approximately 10% of the sewage flow in a sewer in South China, even in the dry season (Li L. et al., 2023). As the decrease in COD and total nitrogen (TN) along the sewers could be the combined effect of biological degradation and dilution of unfiltered groundwater, reduce in the COD/TN ratio along the sewer is expected if biological degradation is the dominant process. This has yet been examined in literature. Therefore, this study aimed to investigate sewage characteristics in rural areas of China, with a focus on its spatial-temporal variations, and to evaluate the extent of biological degradation and groundwater infiltration in sewers.

To this end, a case study in Shantou, a city in Guangdong Province, South China was conducted. Two decentralized sewer networks in Heping Town of the city were selected for the survey via grab water sampling covering both dry and rainy seasons. The sewage received in wastewater treatment plants (WWTPs) in China is characterized by low chemical oxygen demand (COD) concentrations, low C/N ratios and high inorganic solids (Cao et al., 2019, 2020). For example, the influent COD in Chinese WWTPs has an average of ∼260 mg/L, approximately half of that in other countries (Cao et al., 2020); while this could be as low as 80 mg/L–150 mg/L in South China. This low influent sewage strength has been widely attributed to sewer leakage, and it is expected that with the improvement of sewer construction and management, the sewage characteristics in China could be reverted to be similar with other countries (Cao et al., 2019). However, this study shows that sewer leakage remains as a major problem in newly constructed sewers in rural areas of South China, and emphasizes the impact of groundwater infiltration to sewage quality in high groundwater table areas. More appropriate guidelines for planning, designing, and managing sewage collection and treatment facilities in rural areas of South China could be proposed from this study.

## 2 Materials and methods

### 2.1 Site description

Heping Town (center E: 116°28′ and N: 23°15′), located in Chaoyang District, Shantou City, Guangdong Province, was selected as the survey site. The average annual rainfall in Heping is 1768 mm, which is mostly (∼84.8%) distributed in the Wet Season (April to September), due to the subtropical monsoon climate. Heping Town is in the middle-lower reach of Lianjiang River, which flows through the middle of the township from west to east. The terrain on the north bank slopes from northeast to southwest, while it is low and flat on the south bank with intertwined rivers. The elevation of the plain is mostly between 1.5 and 2 meters above sea level.

Heping has a total area of 58.94 $km^2$, among which 24% is the urban and built-up land, while the rest is arable land. There are two water sources for the residents (the total population of ∼184,000) in the town: tap water and groundwater from house-owned wells. The average household water consumption, excluding groundwater consumption, is up to 160–200 liters per capita per day.

The whole town is divided into three sewage collection zones; a combined sewer network coupled with a wastewater treatment plant (WWTP) serves each zone. The WWTPs in the 1st, 2$^{nd}$, and 3rd zones have a treatment capacity of 25,000 $m^3$/d, 20,000 $m^3$/d and 15,000 $m^3$/d, serving an area of 15.86 $km^2$, 25.73 $km^2$ and 17.30 $km^2$, respectively. The sewer networks in the 2$^{nd}$ and 3$^{rd}$ zones, denoted as SN-II and SN-III, respectively, were selected for this study, because they were relatively new and constructed within the past 4 years. The sewers in SN-II and SN-III had a total length of 35.6 km and 46.2 km, respectively, with the nominal diameters in the range of 300–1000 mm (Figure 1). Industrial wastewater from local business firms, including poultry farmers and electronic hardware manufacturers, accounts for 45% in SN-II, while SN-III collects only domestic sewage.

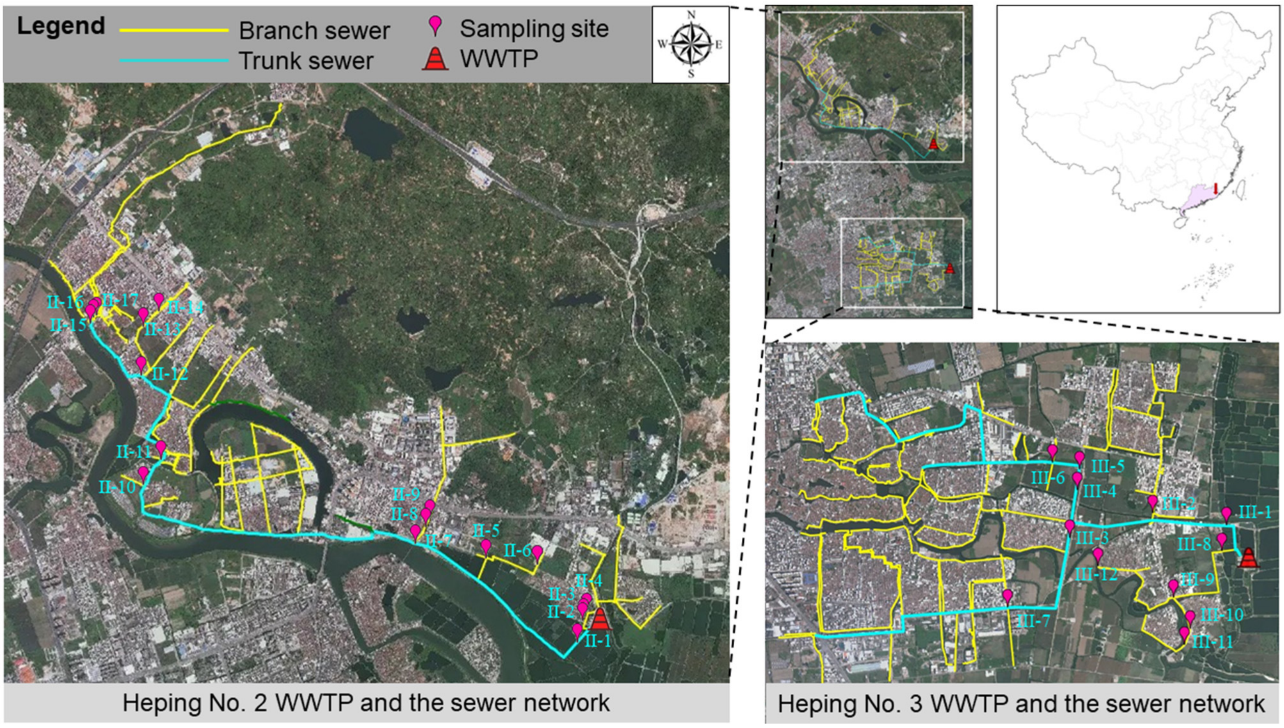


FIGURE 1
Sampling sites of the 2nd and 3rd sewer networks (SN-II and SN-III) in Heping Town, Shantou, Guangdong, China.

## 2.2 Sampling campaigns and chemical analyses

This study selected 6 manholes along the trunk sewer and 11 manholes of the branch sewer lines from SN-II, and 12 manholes along the trunk sewer from the SN-III (Figure 1). Water samples were collected from the selected manholes once every 2 weeks from July 2021 to March 2022. To understand the diurnal variations of sewage qualities in the SNs, 5 manholes from the SNs (II-5, II-1, III-12, III-2, and III-1) were selected to collect sewage samples once every 2 h for 24 h, on 05/10/2022, 22/02/20223 and 08/03/2023 (dd/mm/yyyy). In addition, a household greywater discharge outfall located beside II-7 was also sampled for the diurnal pattern analysis.

The sewage samples were stored in a cooler at 4°C and delivered to the laboratory immediately. Chemical oxygen demand (COD), Total nitrogen (TN), total ammonia nitrogen ($NH_4^+$-N or TAN), and total phosphorus (TP) in water samples were measured using spectrophotometric methods, according to China National Standards, i.e., HJ 828-2017, HJ 636-2012, HJ 536-2009, and GB11893-89, respectively.

## 2.3 Statistical analysis

Boxplots were used to present the distribution of COD, TP, TN and $NH_4^+$-N concentrations in each sampling site; the box ranges from the first (Q1) to the third quartile (Q3) of the distribution and represents the interquartile range (IQR), with whiskers extending to ±1.5 × IQR. Principal component analysis (PCA) was used to display the contributions of dry and wet weather conditions to the sewage strength variations. Student's *t*-test was used to determine the statistically significant difference between the means of two groups. Data processing and statistical analysis were performed in Excel (Office 365), SPSS 24 and Origin 2019b software.

# 3 Results and discussion

## 3.1 Characteristic of overall sewage quality

The COD, TN and TP concentrations of SN-II showed large fluctuations, varying within 5.1 mg/L-171.6 mg/L, 3.6 mg/L-70.0 mg/L, and 0.05 mg/L-7.80 mg/L, respectively. As shown in Figures 2A–D, the upper reach of the SN-II sewers (II-10-17) had much higher nutrient concentrations (TN, $NH_4^+$-N and TP) compared to the middle and lower reaches. Conversely, the middle reach (II-7–9) showed higher COD strength compared to other sampling sites, except the manhole just in front of the WWTP (II-1). Since industrial wastewater in SN-II was majorly distributed in the upper reach, the observations suggest that the industrial wastewater had slightly higher N/C and P/C ratios than the domestical sewage. The low organic strength of the domestical sewage could be due to the widespread usage of septic tanks in the study region. Overall, both of the organic strength and nutrient concentrations showed decreasing trends along the sewer.

The COD, TN and TP concentrations of SN-III varied within 21.4 mg/L -166.9 mg/L, 9.1 mg/L -73.1 mg/L, and 0.05 mg/L-5.50 mg/L, respectively (Figures 2E–H), which is similar to that of SN-II.

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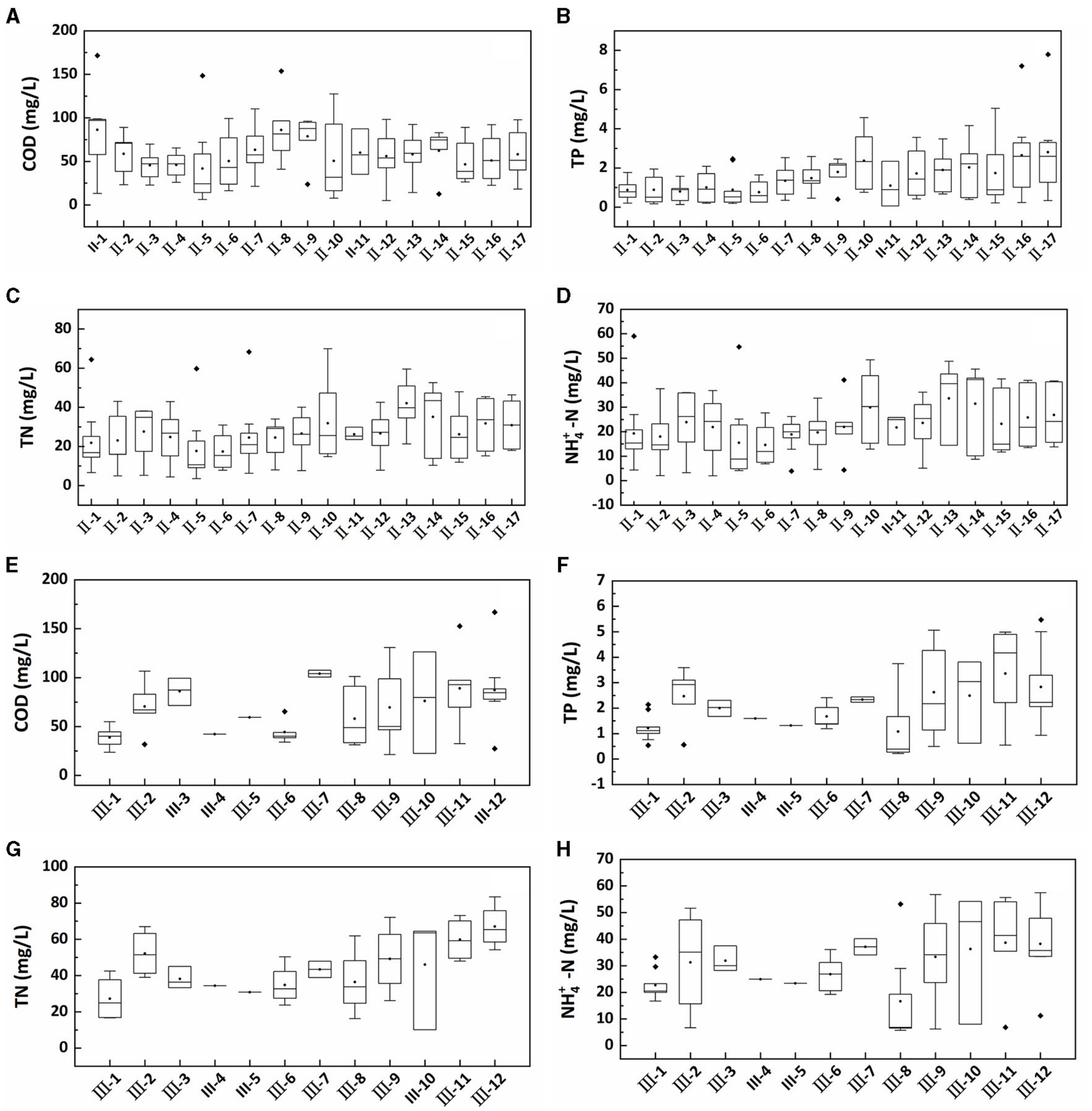


FIGURE 2
The boxplots of **(A)** COD, **(B)** TP, **(C)** TN and **(D)** $NH_4^+$-N concentrations in the sampling sites of the 2nd sewage network (SN-II); the boxplots of **(E)** COD, **(F)** TP, **(G)** TN and **(H)** $NH_4^+$-N concentrations in the sampling sites of the 3nd sewage network (SN-III).

Despite these general high variations, some sampling sites in SN-III showed very limited variations; for example, the sites III-3, 5, 6, and 7 showed low variations in both COD and nutrient concentrations. This may suggest that groundwater infiltration affected the sewage strength in SN-III greatly. Similar to SN-II, a gradual decrease in both COD and nutrient concentrations along the sewers was observed, especially for the branch sewers (III-12–8).

To estimate the contribution of biological degradation of organic matter in the sewers, the COD/TN, COD/$NH_4^+$-N and COD/TP ratios along the sewers were examined. However, a decrease in these ratios could not be observed in both sewer networks (data not shown). In addition, a short branch sewer section with minimal discharge connections was selected from SN-II (Manholes of II-14–12) to evaluate the degradation kinetics along the sewer. The distance between the manholes were 240 m (ii-14–13) and 785 m (ii-13–12). The zero order degradation constants for COD were in the range of 0.006 mg/L-m–0.018 mg/L-m, with a mean of 0.01 mg/L-m. This translates to a mean degradation rate of 14% sCOD·km$^{-1}$, corresponding well with the previous report of 14% sCOD·km$^{-1}$ (Almeida et al., 2000). However, the TN, $NH_4^+$-N, and TP all showed a much higher mean degrade rate of 45% km$^{-1}$, 48% km$^{-1}$, 53% km$^{-1}$ along the sewer, suggesting the factors other than biological degradation played a more significant role in regulating the sewage quality.

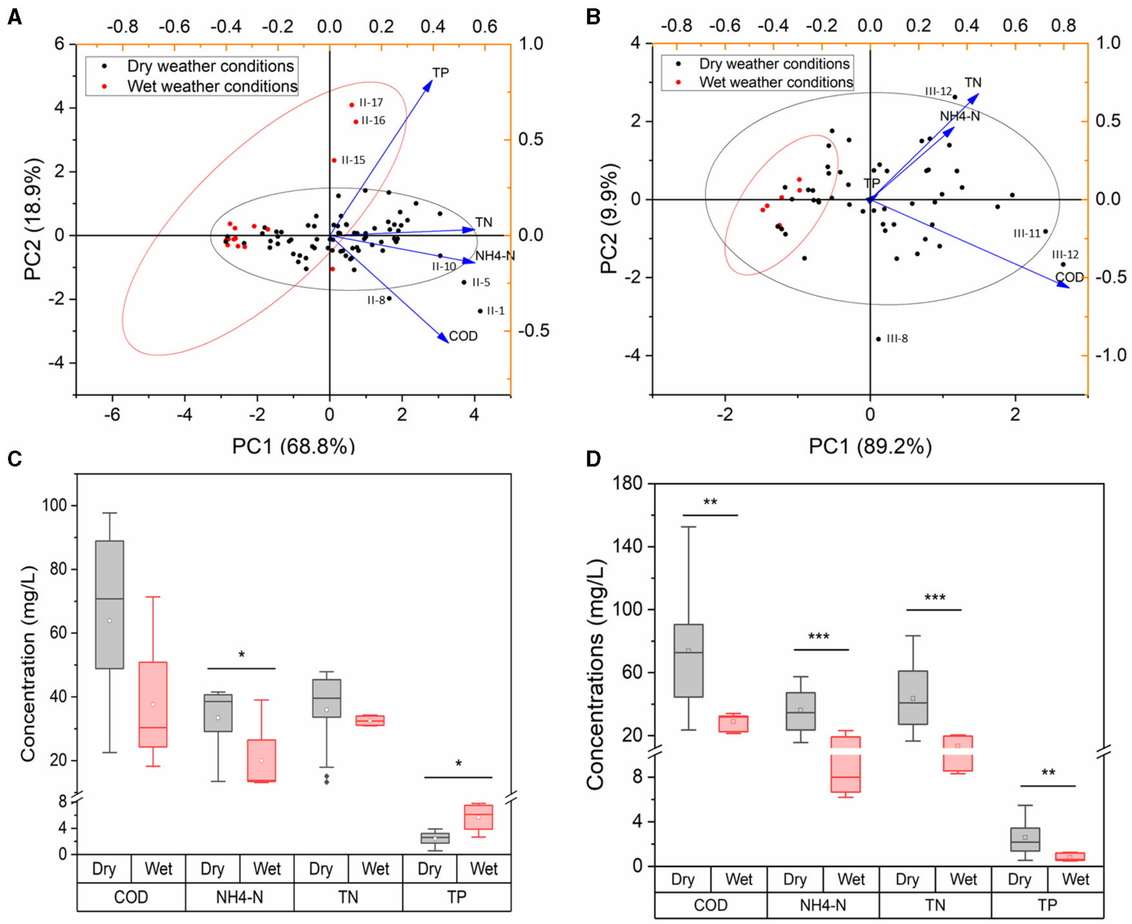


FIGURE 3
Principal component analysis (PCA) showing the variation of the sewage quality in **(A)** SN-II and **(B)** SN-III under dry and wet weather conditions, and the Boxplots showing the impact of dry/wet weather conditions on sewage quality from the sampling sites of **(C)** SN-II-15-17, and **(D)** SN-III-1, 2, 6, 9, 10-12. The asterisk mark (*) indicates the significant difference between the two groups: $^{*}p < 0.05$, $^{**}p < 0.01$, and $^{***}p < 0.001$.

## 3.2 Impacts of wet weather conditions

Among the sampling campaigns, four events were conducted under the wet weather condition (WWC), which was defined as the cumulative rainfall within 4 days before sampling was above 25 mm. The impacts of dry/wet weather conditions and the variations of the sewage quality were elucidated with the principal component analysis (Elemile et al., 2021). As shown in Figure 3A, TP was the primary factor affecting the sewage quality of SN-II in WWC, while TN and $NH_4^+$-N were the dominant factors in dry weather conditions (DWC). This is most pronounced in the upper branch sewers (II-15-17) and middle-lower trunk sewers (II-1, II-5, II-10). The principal component analysis of SN-III (Figure 3B), however, suggested limited impacts of TP on the sewage quality, while less variations in COD, $NH_4^+$-N and TN under WWC is prominent. The principal component analysis also reflects a strong positive correlation between $NH_4^+$-N and TN, which indicates the primary contribution of $NH_4^+$-N to TN.

In order to examine the impacts of weather condition on sewage quality in great details, *t*-tests of the water quality indicators between DWC and WWC were performed and plotted in Boxplots. As shown in Figure 3C, the wet weather condition resulted in a significantly higher TP (median 6.1 mg/L) compared to that (2.6 mg/L) in dry weather condition in SN-II. A large portion of the phosphorus could be associated with particles in sewage (Dueñas et al., 2003); storm events typically cause suspension and transportation of small/fine particles in runoff, which explains the increased TP concentrations under WWC. On the contrary, the median $NH_4^+$-N, COD and TN concentrations (13.8 mg/L, 30.3 mg/L, and 32.4 mg/L, respectively) in the WWC concentration in SN-II, were much lower than that (37.8 mg/L, 70.8 mg/L, and 40.0 mg/L, respectively) in DWC. This is even more prominent in SN-III (Figure 3D), as COD, $NH_4^+$-N, TN and TP in WWC were all significantly lower than those in DWC. These results indicate the consistent dilution effect of storm events on sewage strength, which is in accordance with previous reports, for example, in Erhai Lake Basin (Zheng et al., 2021).

The dilution effect of storm events is often observed on point pollution sources, e.g., combined sewer overflow and WWTP

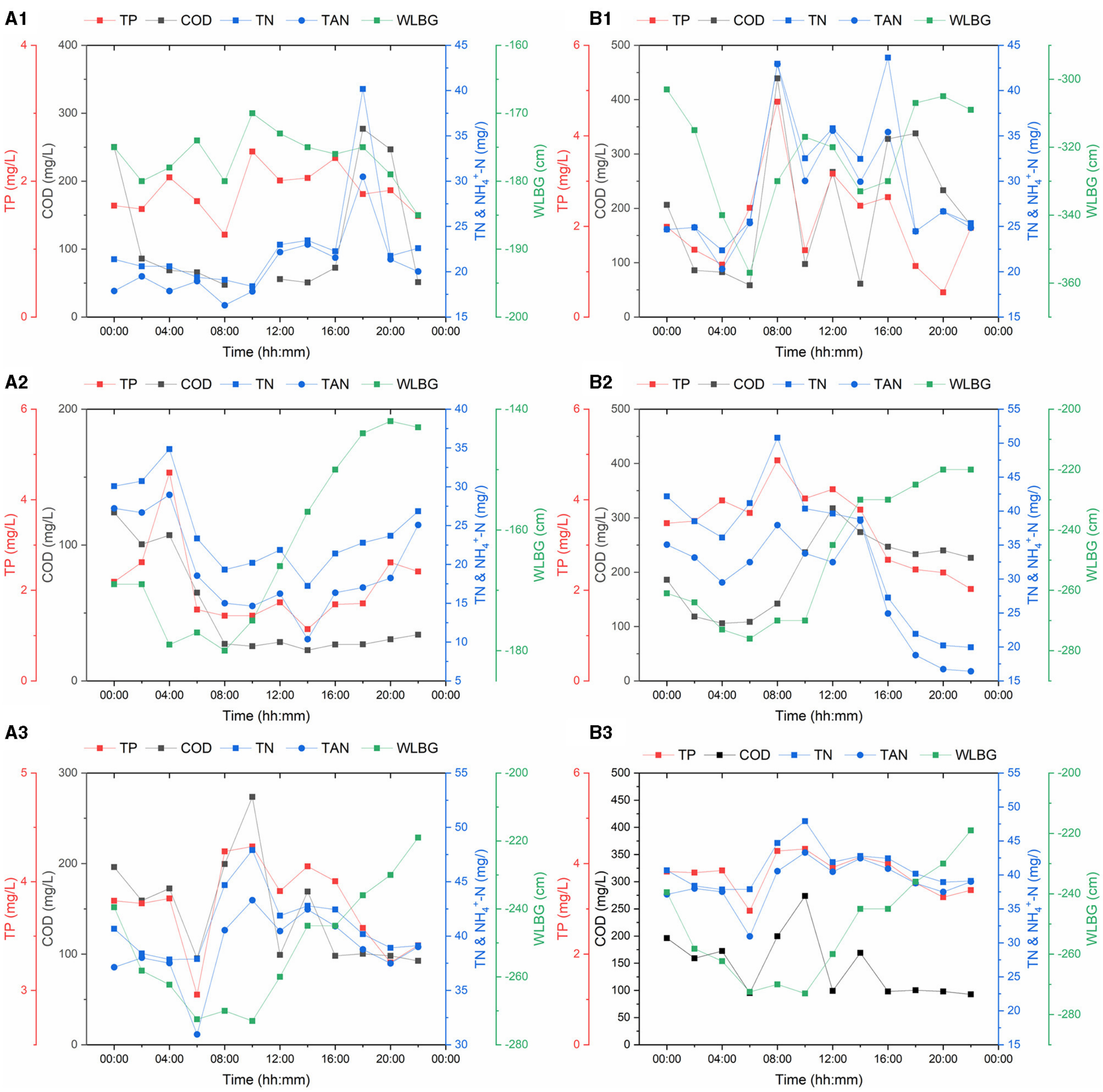


FIGURE 4
The diurnal variation of sewage quality from the sampling sites of SN-II-5 **(A)** and SN-II-7 **(B)** on the date of 05/10/2022, 22/02/2023 and 08/03/2023 (1-3), respectively.

effluent outfalls (Burns et al., 2019). Despite the flushing effect of TP in the upper branch sewers (II-15-17), the dilution effect on TP was ubiquitous in middle-lower reaches of the SN-II. This could be because that the manholes of II-15-17 connect to a branch sewer with a high slope along agricultural and forestry land (Figure 1), which facilitates the suspension and transportation of particles in soils. Whereas, the rest sewers are in the flat terrain, thus, contributing to less particle transportation. Moreover, the sampling campaigns were conducted at least 5 h after a storm event, which might have missed the initial flush spike of pollutants.

## 3.3 Diurnal pattern of sewage quality

According to the online monitoring data of the two WWTPs, the daily sewage discharge volume showed two peaks, i.e., from 1200 h to 1400 h and from 1800 h to 2000 h. This is similar to the previous research conducted in Taihu Lake and Chaohu Lake Basins (Wang et al., 2020; Xu et al., 2020).

Two sampling sites from each sewage network were selected for continuous water quality analyses at a sampling frequency of every 2 h for 24 h to understand the diurnal pattern of sewage quality in the networks. Figure 4 shows the result of sampling sites SN-II-5

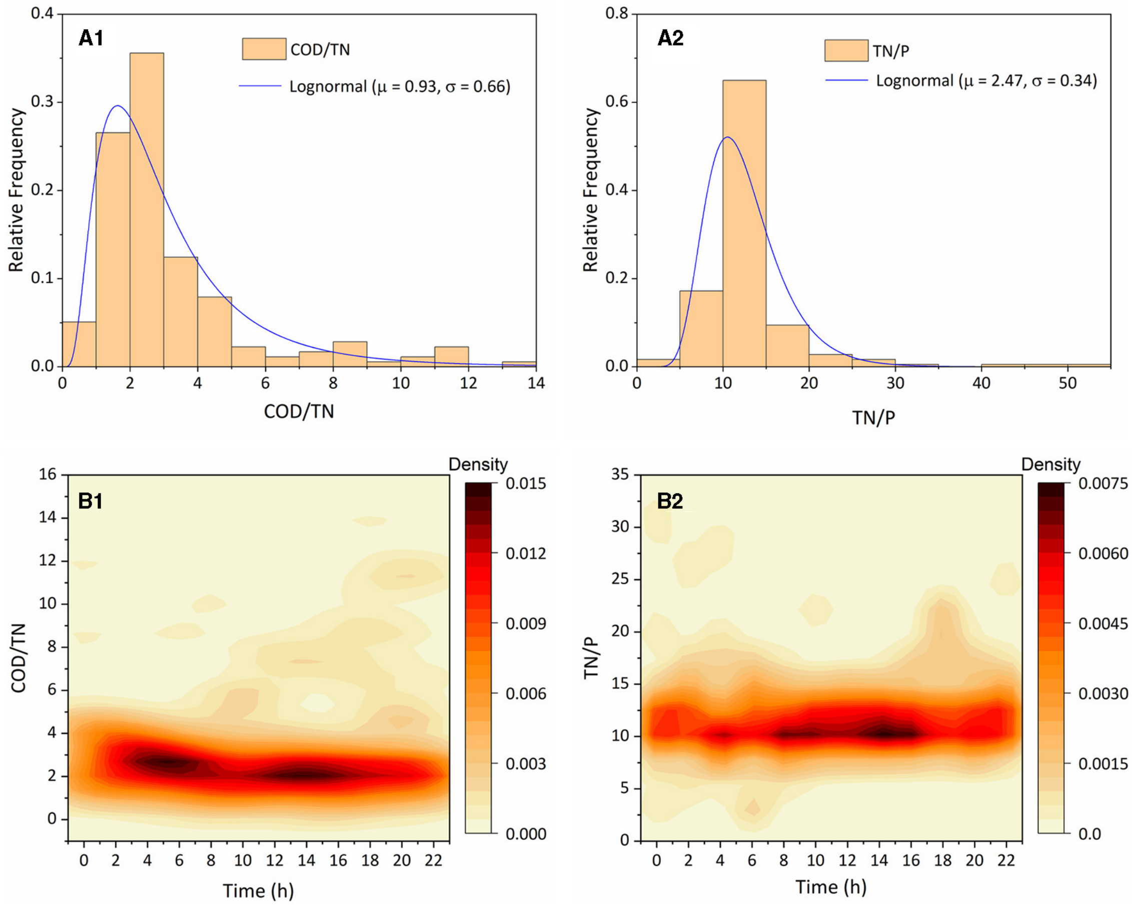


FIGURE 5
The relative frequencies of the COD/TN **(A1)** and TN/P ratios **(A2)** and their lognormal distribution fitting curves; the Kernel density distribution of the COD/TN **(B1)** and TN/P **(B2)** ratios with 24 h.

and SN-II-7, representing the branch and main sewers, respectively, where two peaks of sewage discharge could be identified. In the branch sewer of SN-II-5, the sewage strength (COD, TN and TAN) showed a weak peak at noon (12:00–14:00) and another strong peak at varying time, i.e., 18:00 on 05/10/2023, 04:00 on 22/02/2023, and 10:00 on 08/03/2023. This is most probably because that the sampling stie of SN-II-5 was located in a small community; as a consequence, the sewage discharge was influenced strongly by one or two families. Conversely, two peaks of sewage discharge emerged consistently at the same time in the main sewer of SN-II-7; one in the morning (08:00–10:00) and the other in the afternoon (14:00–16:00). Among the two, the afternoon sewage discharge peak had less strength than the morning peak. This observation is in accordance with the typical diurnal patterns of domestic sewage of previous reports (Raunkjaer et al., 1995; Bailey et al., 2019).

Noticeably, the sewage strength in terms of COD and TP varied by a much greater extent than the TN or TAN on 05/10/2022. For example, the minimum COD, TP, TN and TAN were 59 mg/L, 0.5 mg/L, 22 mg/L, and 20 mg/L, respectively, on SN-II-7; while their maximum records were 439 mg/L, 4.7 mg/L, 43 mg/L, and 43 mg/L, representing a 7.5-, 8.7-, 2.0-, and 2.1-fold increase, respectively, compared to the minimum value. While the variations for COD, TP, TN and TAN were in the range of 1.3–3.0 folds on 22/02/2023 and 08/03/2023. Similar results were also observed on other sites of SN-II-5, SN-III-12, and SN-III-2.

As there were no rainstorms on the sampling day and at least 3 days before that, the sewage strength variations were majorly due to the change in household water consumption and discharge in the study region. The 1st sampling day on 05/10/2022 was in the middle of the Chinese National Day holidays, during which local young residents who work in megacities, e.g., Guangzhou and Shenzhen, usually come back to visit their parents. Therefore, greater water consumption and sewage discharge were expected for the 1st sampling campaign. This was also evidenced by the on-line monitoring data of the WWTP influent flowrates, i.e., 14016 $m^3$/d, 11331 $m^3$/d, and 9149 $m^3$/d for WWPT-III, and 18868 $m^3$/d, 16614 $m^3$/d, and 16678 $m^3$/d for WWPT-II, on the sampling day of 05/10/2022, 22/02/2023 and 08/03/2023, respectively.

Supplementary Figure S1 in the supporting information (SI) shows the diurnal pattern of swage quality variations in SN-III. Sewage strength in the upper branch sewers, represented by III-12, showed two prominent peaks, in the morning (4:00–10:00) and evening (18:00–20:00), respectively. Compared to II-5, occurrence of the maximal sewage strength in III-12 was more consistent.

This could be due to that III-12 served more houses than II-5. In addition, III-12 was the starting point of a sewer, while II-5 was in the middle of a sewer; therefore, the sewage quality in III-12 was more prone to be affected by the houses discharging to it. The sewages in III-2 also showed completely different diurnal patterns as compared to others. The morning peak occurred more broadly from 2:00 to 10:00, while the typical evening peak appeared lately at night. This could be because that some adjacent food shops discharged sewage at night. These observations suggest that the water consumption and discharge profile in the local community plays an important role in shaping the distinct diurnal patterns of sewage characteristics, displaying a position-dependent profile.

### 3.4 Variations of COD/TN and TN/TP

The low ratio of COD/TN was identified to be a major problem in sewage collection and treatment in China, especially in South China. Therefore, the ratios of both COD/TN and TN/P were analyzed statistically to unravel their distribution and diurnal patterns. As shown in the histograms of Figure 5, both of COD/TN and TN/P ratios could be fitted with lognormal distributions. The most frequent (35.6%) ratios of COD/TN in the SN were in the range of 2.0-3.0, followed by the range of 1.0-2.0 (26.6%). The Kernel distribution of COD/TN (Figure 5B1) indicates two peaks: one in the range of 2.0–3.0 in the morning peak (3:00-7:00), and another one in the range of 2.0-2.5 in the afternoon peak (12:00—16:00). These two peaks occurred concurrently with the sewage discharge peak, suggesting that the low COD/TN ratio of sewage in the study area was less likely due to the degradation of organics along the sewers. Septic tanks are widely used in the study area as a pre-treatment of the black water from the toilets, which could be a primary reason leading to the low COD/TN ratio in the morning discharge peak. Instead, the gray water from kitchens, with a high COD/TN ratio, could be a major source of afternoon discharge peak, as evidenced by the occurrence of high COD/TN (8.0–10.0) peaks in afternoon and night samples.

In addition to sampling sewage from the manholes, greywater of kitchens collected from a household discharge outfall, located close to the manhole SN-II-9, was also sampled and analyzed. Due to the intermittent usage of water in the kitchen, no greywater samples could be collected out of the peak time (8:00–14:00) on 22/02/2023 and 08/03/2023. During the National Holiday (05/10/2022), more samples could be collected except for the mid-night (2:00-6:00). Compared to the sewage collected from manholes, the greywater samples showed a much higher COD concentration (245–3240 mg/L with a mean of 953 mg/L) and COD/TN ratio ($38.8 \pm 19.2$). However, dilution of the high organic strength kitchen greywater with low COD/TN greywater from bathrooms could eventually lead to the low COD/TN sewage in the sewers.

Compared to the COD/TN (Figure 5A1), the ratios of TN/P (Figure 5A2) were less variable, showing a dominant range of 10.0–15.0 (65.0%). This ratio is close to the treated sewage (Tong et al., 2020). The Kernel distribution of TN/P (Figure 5B2) indicates a single peak of ∼10.0 from 8:00 to 16:00, while the morning discharge peak from 3:00 to 7:00 of the COD/TN became weaker. Some night (1:00–4:00) samples with very low TP concentrations could be noticed from the few high TN/P ratio (>25.0) peaks in the figure as well. During this period, household water consumption and sewage discharge were at their minimal levels; therefore, the sewage samples representing the basal flow in the sewers might be primarily affected by groundwater infiltration (Yang et al., 2021).

Due to the high groundwater table in the study area, as evidenced from the high water level in the manholes, groundwater infiltration could be a more important factor resulting in the low COD/TN ratio of the sewage. Our recent study shows that groundwater accounted for approximately 10% of the sewage flow in the study area, even in the dry season (Li L. et al., 2023). To further quantify the relative contribution of biological degradation and groundwater infiltration to the sewage strength, a further study in a relatively long sewer without branch interconnections seems necessary. Despite this, this study clearly shows that prevent of groundwater infiltration to sewers is crucial in high groundwater table areas to improve the efficiency of sewage collection and treatment. More studies are needed to further identify the locations of highest infiltration flow and propose correction solutions.

## 4 Conclusions

This study investigated the characteristics of domestic wastewater components and discharge patterns in rural areas of South China and assessed the primary factors leading to low organic strength sewage. The following results could be drawn:

1) COD, TN, $NH_4^+$-N, and TP of the sewage all gradually declined along the sewers from the upper to lower reaches. Wet weather condition significantly altered the sewage strength in the sewers, showing a flushing effect of TP in the upper reach of sewers with a high slope, thus increasing the TP concentrations; while it showed a dilution effect on COD and N in flat terrains and considerably reduced the sewage strength.
2) The diurnal pattern of sewage generally showed two discharge strength peaks. However, these peaks emerged at various time depending on the position of the manholes and water consumption habit (holidays or normal days).
3) Both COD/TN and TN/P ratios of the sewage showed a lognormal distribution, with a dominant range of 2.0–3.0 and ∼10.0, respectively. The low ratio of COD/TN could be attributed to the wide use of septic tanks and groundwater infiltration.

## Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

## Author contributions

PS: Conceptualization, Investigation, Methodology, Resources, Writing—original draft. YLi: Investigation, Methodology, Data curation, Formal analysis, Writing—review & editing. HC: Data curation, Formal analysis, Investigation, Methodology, Writing—original draft. LL: Investigation, Methodology, Resources, Writing—review & editing. HX: Investigation, Methodology, Resources, Writing—review & editing. YX: Investigation, Methodology, Resources, Conceptualization, Writing—original draft, Writing—review & editing. BF: Data curation, Formal analysis, Investigation, Methodology, Writing—review & editing. YG: Data curation, Investigation, Writing—review & editing. ZB: Data curation, Investigation, Writing—review & editing. LM: Data curation, Investigation, Writing—review & editing. JW: Data curation, Investigation, Writing—review & editing. LY: Data curation, Investigation, Writing—review & editing. YLe: Data curation, Investigation, Writing—review & editing.

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## Conflict of interest

PS, LL, and HX were employed by the Guangdong Guangye Environmental Protection Industry Group Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note



## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frwa.2023.1278336/full#supplementary-material

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