Environment, Resource and Ecology Journal (2025)
Clausius Scientific Press, Canada

DOI: 10.23977/erej.2025.090202
ISSN 2616-3756 Vol. 9 Num. 2

Study on the Spatiotemporal Distribution Characteristics of Dissolved Oxygen and Its Multi-source Driving Mechanisms in Typical Urban River Sections

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Keywords: Dissolved Oxygen; Sediment Oxygen Demand; Pollution Input from Tributaries; Tidal River Networks; Urban Rivers

Abstract: This study takes the Nangang River in southern China as a case example to explore the causes of low dissolved oxygen (DO) levels in urban rivers located within tidal river networks. Through field sampling, real-time monitoring, and data analysis, this study systematically examines the impacts of factors such as water quality patterns in main and tributary rivers, sediment oxygen demand (SOD), water temperature, and tides on DO. The results show that the DO concentration in the Nangang River decreases along the river's length, with concentrations at sections 10#, 12#, and 14# falling below 6.0 mg/L during certain periods, indicating that the downstream areas are at long-term risk of oxygen depletion. The Siqing North tributary (DO < 3.0 mg/L, BOD_5 > 6.0 mg/L, NH_3-N > 2.0 mg/L) and the Tangwei tributary (pH > 9, ORP < 50 mV) create high-intensity pollution pulses in the main river, representing significant external sources of pollution. The sediment oxygen demand (SOD) at points 7# and 9# reached 0.53 and 0.42 $g \cdot m^{-2} \cdot d^{-1}$, respectively, far exceeding the hypoxia threshold of 0.3 $g \cdot m^{-2} \cdot d^{-1}$, and constituting an important endogenous factor contributing to the continuous decline of DO. A significant negative correlation was found between water temperature and DO ($r = -0.70$, $p < 0.01$), with water temperature having a stronger influence than COD and NH_3-N. Tidal analysis showed that during the water diversion period, DO concentrations rapidly decreased, with the non-compliance rate reaching 99.6% in August 2022, indicating that tidal input under high-temperature conditions has a negative effect on reoxygenation. This study identifies the synergistic regulatory effects of multi-source coupling mechanisms, including tributary pollution, sediment oxygen demand, water temperature, and tidal interference, on the evolution of DO. It suggests prioritizing source control of highly polluted tributaries, sediment restoration in areas with high SOD values, and optimization of gate scheduling during summer to achieve the dual objectives of managing DO risks and restoring urban river ecosystems.

1. Introduction

Dissolved oxygen (DO) is an indicator of oxygen levels in rivers, oceans, and other water bodies, playing a crucial role in biogeochemical processes[1]. It regulates the transformation of elements such as nitrogen, phosphorus, and carbon in water, which is significant for maintaining the health of aquatic ecosystems[2,3]. Studies have shown that when dissolved oxygen (DO) falls below 5.0 mg/L, various plankton cannot survive, while approximately 4.0 mg/L is the minimum concentration required to sustain fish populations[4]. In addition, DO is an important indicator reflecting water quality and self-purification capacity. High DO concentrations facilitate the degradation of various pollutants in the water, thereby purifying the water body[5]. The excessive input of anthropogenic nutrients, such as nitrogen and phosphorus, triggers abnormal algal proliferation, leading to the accumulation of large amounts of organic matter. The oxygen consumption during microbial decomposition is an important mechanism for the occurrence of hypoxia[6–8]. Changes in hydrodynamic conditions, such as dam construction and tidal influences, extend the hydraulic retention time, which further intensifies the oxygen consumption process in the water body[9]. Atmospheric reoxygenation, as well as the photosynthesis of algae and aquatic plants, are the primary sources of dissolved oxygen in water. The main consumption pathways of DO include respiration by aquatic organisms, the decomposition of organic matter in water or sediment, and the oxygen consumption of other reducible substances[10–12]. Low DO concentrations in rivers can have varying impacts on the growth and reproduction of aquatic plants, as well as the composition and distribution of microbial communities, which is detrimental to the healthy development of aquatic ecosystems[8,13].

In the Nangang River of Guangdong Province, China, we observed that the river's DO levels were relatively low, with most sections failing to meet the China's national surface water quality standard (GB3838–2002) Grade III standard (5.0 mg/L). However, the frequency of other indicators, such as ammonia nitrogen (NH_3-N) and permanganate index (COD-Mn), failing to meet Grade III standards was relatively low. The Nangang River is located within a tidal river network, influenced by tides, and belongs to the Pearl River Basin. After crossing Huangpu District, the Nangang River flows into the Dongjiang River. A water gate has been constructed at the river mouth for flood prevention and drainage. In this study, we obtained the spatial distribution of water quality and sediment oxygen demand through field sampling. We also analyzed the impact of tidal influences on the Nangang River using data from real-time monitoring stations, tidal records, and gate operation logs, ultimately investigating the causes of low DO levels in the Nangang River.

2. Materials and methods

2.1 Study Area

The study area, the Nangang River (NGR), is located in Huangpu District, Guangzhou City, Guangdong Province, China, and is part of the Pearl River Basin. The Nangang River is a first-order tributary of the Dongjiang North Mainstream of the Pearl River. It originates from the Muqiang Reservoir and flows from north to south through major urban residential and industrial areas, eventually merging into the Dongjiang North Mainstream. The river is 25.53 km long with a watershed area of 111.3 km². The Nangang River has 11 tributaries: Fangwei River (Fw), Zhushan Creek (ZS), Guiju Creek (GJ), Shuisheng Creek (SS), Tangwei Creek (TW), Shatian Creek (ST), Tianlong River (TL), Huapu Creek (HP), Siqing River (SQ), Bigang Creek (BG), and Honggang River (HG). Among them, the Siqing River is divided into two branches, which merge into the main stream from Siqing North (SQN) and Siqing South (SQS). A floodgate was constructed at the point where the Nangang River merges into the Dongjiang North Mainstream (between sampling points 13# and 14#). It was officially put into operation in June 2022 and serves primarily for flood control, drainage, and navigation. The total clear width of the floodgate is 48 m, divided into three sections, each 18 m wide. Real-time monitoring station is locted at sampling point 13. The downstream section of the Nangang River (south of sampling point 10) has a gentle channel slope. When the floodgate is open, the downstream section of the Nangang River is affected by tidal action. The water quality target for the Nangang River is Grade III.

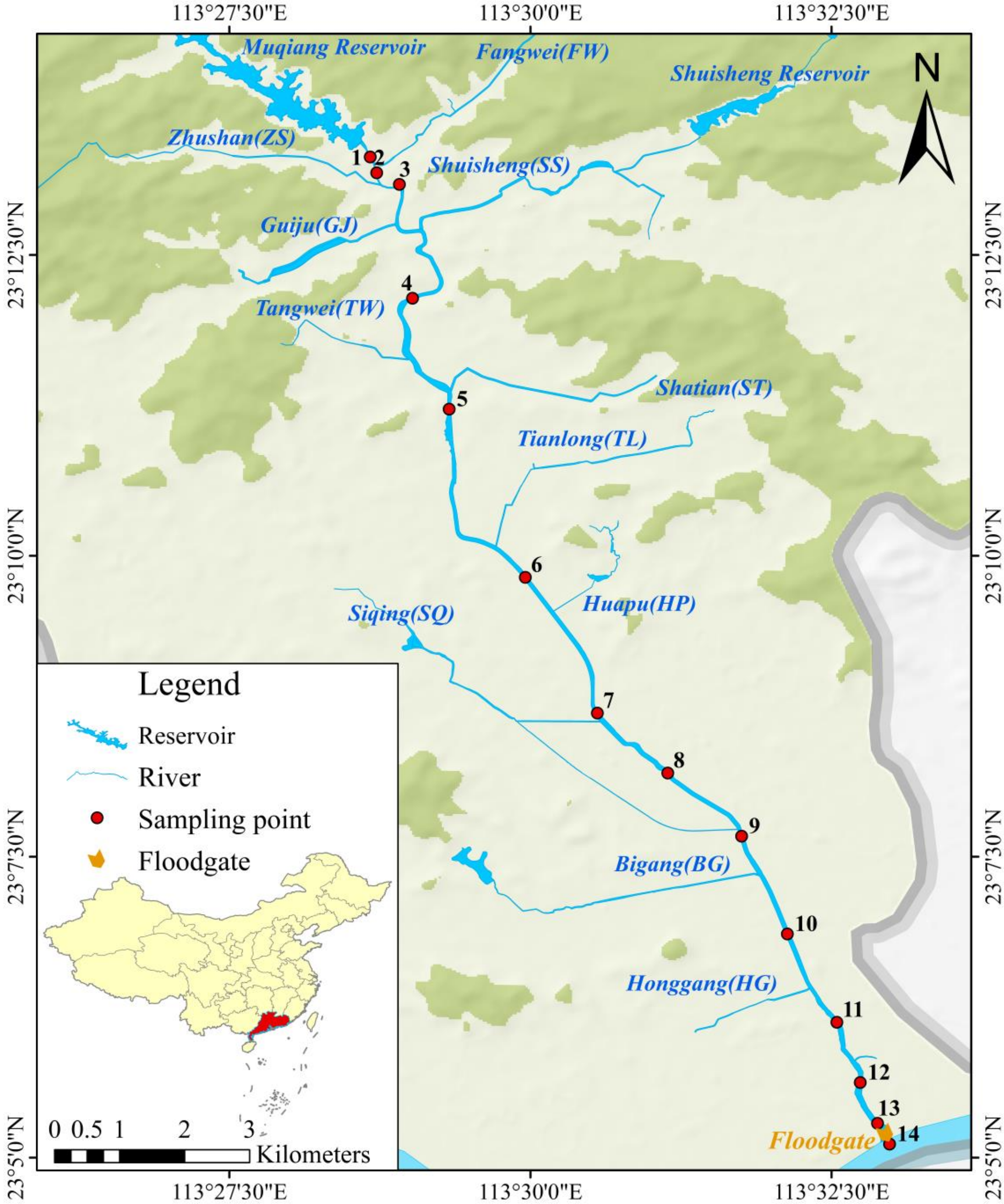

Figure 1: Study Area and Sampling Points

2.2 Data Sources and Collection Methods

2.2.1 Water Quality Data Collection

The water quality data are divided into field sampling data and real-time monitoring station data. The field monitoring data were obtained through on-site sampling and testing. The main stream sampling points are numbered 1# to 14#, as shown in Fig.1, with 14# being an outside point, where the water sample is from the Dongjiang River. The tributary sampling points are located at the confluences of the tributaries and the main stream, with a total of 12 sampling points. In March 2023, sampling and testing were conducted at 11 main stream sampling points and 12 tributary sampling points. Parameters analyzed on-site using a portable multiparameter instrument included dissolved oxygen (DO), pH, water temperature, electrical conductivity (EC), and oxidation-reduction potential (ORP). Measurements were taken every 2 hours from 8:00 to 18:00, with a total of 6 batches and 138 samples. Additionally, samples were taken every 4 hours from 8:00 to 18:00 at 9 sampling points between 9# and 13# (labeled G1 to G9) on the main stream and at 12 tributary sampling points. The parameters tested were BOD_5 and ammonia nitrogen, with a total of 3 batches and 63 samples. In September 2023, to investigate the impact of tides on water quality in the downstream section of the river, sampling and testing were conducted at 5 downstream sampling points (10# to 14#) on the main stream. The sampling period was from 8:00 to 18:00, with samples collected every 2 hours, resulting in 6 batches and 30 samples. The monitored parameters were DO, water temperature, and EC.

The real-time monitoring station data is provided by the institution to which the monitoring stations belong. The monitoring period was from April 2022 to February 2023. The monitoring frequency was once per hour. The analysis parameters include water temperature, DO, EC, ammonia nitrogen (NH_3-N), and permanganate index (COD-Mn).

2.2.2 Hydrodynamic Data Collection

Tidal data was obtained from the National Ocean Data Center website. The gate operation records and water level data inside and outside the gate were provided by the gate operation management authority. Precipitation, temperature, and other data were queried from weather websites.

2.2.3 Sediment Sampling

Sediment samples were collected from 7 representative sections of the main stream of the Nangang River: 1 section in the upstream (4#), 3 sections in the midstream (6#, 7#, 9#), and 3 sections in the downstream (11#, 12#,13#).

2.3 Data Processing

Missing values were identified and located in the real-time water quality data. Data, excluding EC, that exhibit large fluctuations in nearby periods were identified as outliers. After removing missing and outlier values, the data were classified by month and by day. Based on the gate operation records and tidal data, the changes in water quality at real-time monitoring stations were assessed when the gate was open. According to the Surface Water Environmental Quality Standards, data below Grade III were categorized as non-compliant data. Efficient data processing was performed using MATLAB R2022a.

During field sampling for water quality monitoring, each sample was measured three times. If anomalies were detected, the sample was re-collected and tested to avoid outliers. After measuring three sets of data for the same sample, the mean value was calculated and included in the overall dataset for analysis. This approach allowed for the acquisition of the spatial distribution of water quality in the Nangang River and the water quality of the incoming tributaries.

2.4 Analytical Methods and Indicator Determination

Dissolved oxygen, pH, water temperature, EC, ORP, and other water quality parameters were quickly measured on-site using a portable multi-parameter water quality analyzer. The NH_3-N concentration was determined using the Nessler reagent colorimetric method. The BOD_5 concentration was measured using the dilution and inoculation method to determine the 5-day biochemical oxygen demand. The sediment oxygen demand (SOD) was quantitatively analyzed in the laboratory using a closed-loop system[12,14].

The sediment oxygen demand (SOD) determination and representation, which refers to the oxygen consumption per unit time per unit area, is calculated using the slope of the dissolved oxygen distribution over time:

$$SOD=\frac{[DO(t-1)-DO(t)]\cdot V}{A_s\cdot \Delta t}\times 24 \tag{1}$$

In this formula, Δt represents the time period Δt1, where t-1 and t are the previous and subsequent time points within the Δt period, respectively. DO(t-1) and DO(t) refer to the dissolved oxygen concentrations at times t-1 and t. V is the volume of the overlying water, 24 is the conversion factor, and As is the surface area of the sediment in contact with the overlying water.

3. Results and Discussion

3.1 Mechanisms of the Spatial Gradient Influence of DO under the Coupling Effect of Main and Tributary Water Quality

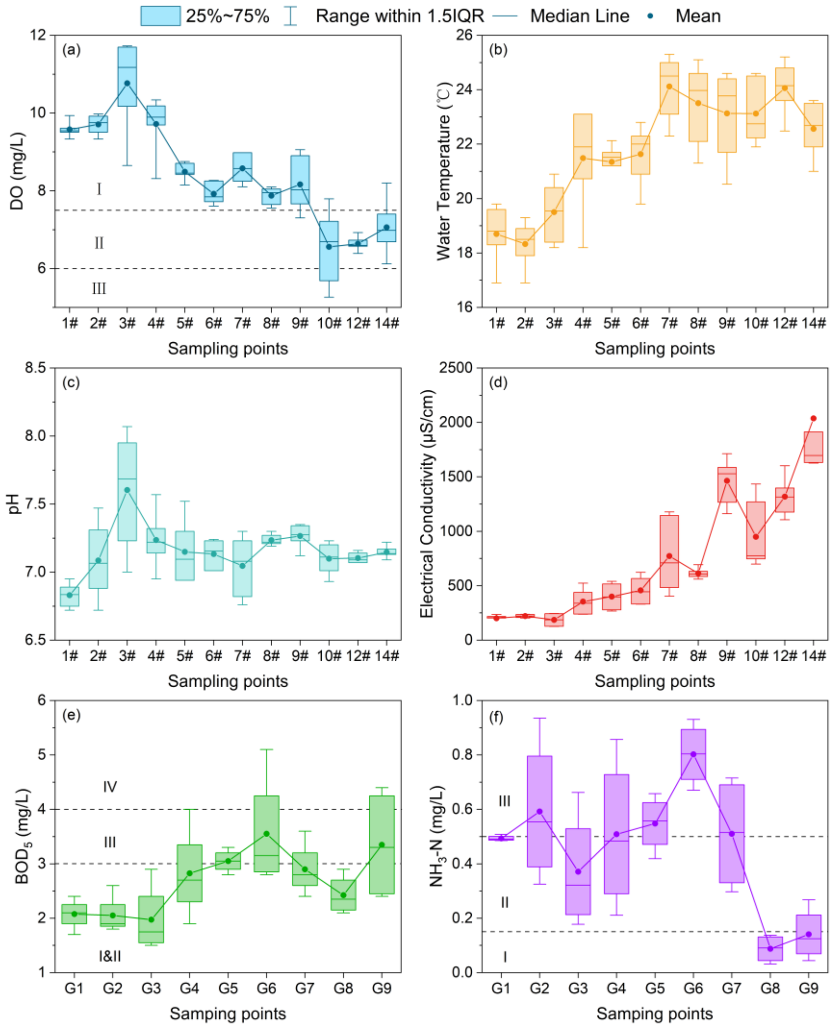

Figure 2: Water Quality Conditions of the Main River

Figure 2 shows the variations of key water quality indicators along the Nangang River mainstem in March 2023. Overall, the DO concentration shows a clear decreasing trend from upstream to downstream (Figure 2a). At sampling points 1#–3#, DO concentrations gradually increase and reach supersaturation at point 3#. From sampling points 4#–14#, DO concentrations gradually decrease, and at points 10#, 12#, and 14#, the DO concentrations fall below 7.5 mg/L, with some periods below 6.0 mg/L, indicating a certain level of oxygen depletion in the downstream of the Nangang River. Among them, the DO concentration at sampling point 14# (outside the gate) is generally higher than that at point 12# (inside the gate), suggesting that tidal input may have a positive effect on improving DO levels.

Overall, water temperature increases from upstream to downstream (Figure 2b), and its spatial variation shows a clear negative correlation with DO. This negative correlation is most pronounced in the 2#–7# section, indicating that water temperature may intensify the oxygen consumption process by lowering oxygen solubility and accelerating the decomposition rate of organic matter. The distribution of pH follows a similar trend to DO (Figure 2c), with higher values in the upstream and gradually decreasing downstream. This may be related to the consumption of alkaline substances and the distribution of organic pollution. The EC increases from upstream to downstream, reflecting the intensified accumulation of pollutants and tidal backflow effects in the downstream areas.

From the concentrations of BOD_5 and NH_3-N (Figure 2e and Figure 2f), pollutant concentrations at sampling points G1–G9 were within the Grade III limit for most periods, with the BOD_5 concentrations at G6 and G9 exceeding the limit during some periods. At points G8 and G9, NH_3-N concentrations even met Grade I standards. This indicates that the overall pollutant load control in the main river is relatively good, but attention should still be given to local areas with high values, as they may impose pressure on DO levels.

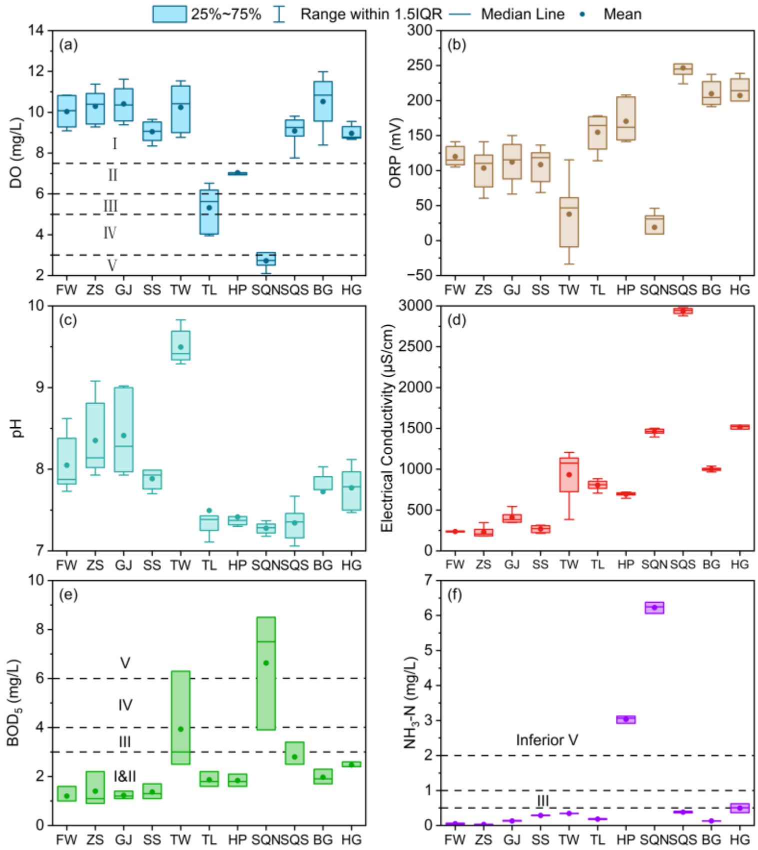

Figure 3: Water Quality Conditions of the Tributaries

Figure 3 further reveals the water quality differences among the 10 tributaries. Among them, Siqing North (SQN) and Tangwei (TW) exhibit the most significant water quality degradation: the DO concentration in SQN is below 3.0 mg/L, classified as Grade V water quality, with BOD_5 and NH_3-N concentrations exceeding 6.0 mg/L and 2.0 mg/L, respectively, indicating severe pollution. TW also shows typical organic eutrophication features, such as high pH (>9) and low ORP (<50 mV). The pollution input from these tributaries not only causes severe hypoxia locally but may also indirectly weaken the DO levels in the downstream of the main river through high oxygen consumption loads and pollutant transport.

Furthermore, although the Siqing South (SQS) tributary did not significantly affect the DO concentration in the main river, its inflow caused a significant increase in EC at sampling point 9#, indicating the presence of high concentrations of ion-based pollutants. However, EC decreased at sampling point 10#, suggesting that the increase in EC downstream is more likely due to tidal backflow rather than SQS input.

Therefore, the influence of tributaries on the main river's water quality shows significant spatial heterogeneity. Tributaries with high pollution levels, moderate flow, or those near tidal influence areas (e.g., SQN and TW) are important external sources of load that contribute to the decrease in DO in the middle and lower reaches.

3.2 Spatial Distribution Characteristics of Sediment Oxygen Demand in the River Channel and Its Driving Mechanisms on DO

Sediment oxygen demand (SOD) is one of the key internal mechanisms that cause a decline in DO in river systems, particularly in river sections with slow flow and significant sediment accumulation[14]. In this study, seven sediment sampling points were set up, with significant sediment deposition observed at points 7#, 9#, and 13#. Figure 4 shows the SOD values measured at each sampling point. The results show that the SOD values at sampling points 7# and 9# are 0.53 g m^{-2} d^{-1} and 0.42 g m^{-2} d^{-1}, respectively, both significantly higher than at the other sampling points. The main river segments corresponding to these two points (7#–10#) also show a clear decrease in DO concentration, suggesting that sediment oxygen demand may be an important cause of the DO decline in this section. Although the SOD at point 13# is relatively low (0.26 g m^{-2} d^{-1}), when combined with real-time monitoring data from the corresponding river section, it still shows a certain degree of DO suppression, indicating that sediment oxygen demand also plays an important role in downstream river sections.

SOD is controlled by various factors, such as the content of degradable organic matter in sediment, sediment structure, water temperature, hydrodynamic conditions, and interface diffusion rate[14–16]. At locations with high SOD, sediment organic matter accumulation, weak water mixing, and slow flow rates are often observed. These factors work synergistically to inhibit the reoxygenation process, exacerbating the hypoxic conditions of the water. It is worth noting that studies have pointed out that when SOD exceeds 0.2–0.3 g m^{-2} d^{-1}, it can significantly affect the surface DO in shallow rivers[12]. In this study, the SOD at points 7# and 9# is much higher than this threshold, posing a potential risk of localized oxygen depletion and even bottom-layer anaerobiosis. Furthermore, the sediment oxygen demand process is typically temperature-dependent. During the high-temperature summer period, SOD can increase significantly, further amplifying the reduction in DO concentration[14]. Therefore, under the dual influence of high temperatures and tides in the Nangang River, SOD and external pollutant load may jointly drive the long-term low DO levels in the middle and lower reaches of the river[17].

Therefore, there is a typical high-intensity sediment oxygen demand zone in the middle and lower reaches of the Nangang River, and its suppression effect on DO concentration shows significant spatial response characteristics. It is one of the important factors contributing to oxygen depletion in the river.

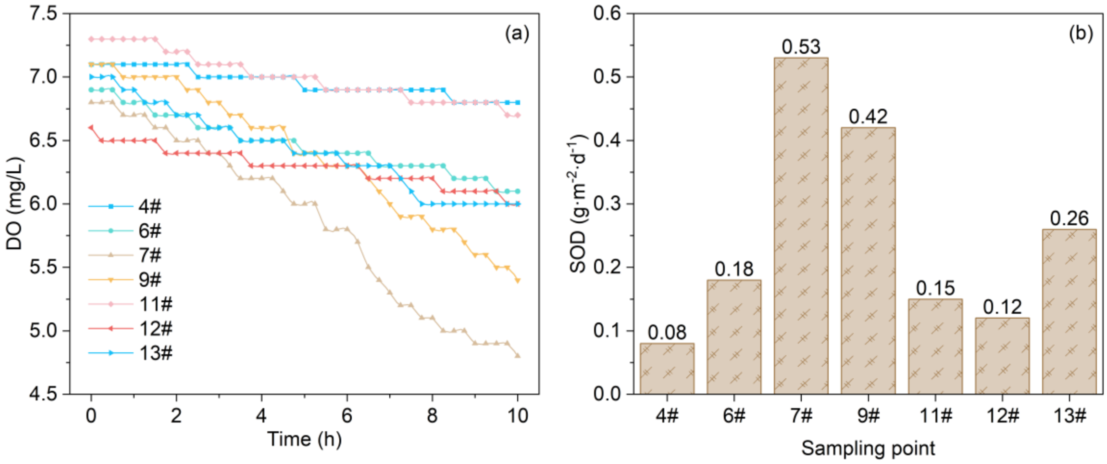

Figure 4: (a) Sediment Oxygen Demand Curve and (b) Sediment Oxygen Demand Rate

3.3 Seasonal Response Mechanism of DO Concentration Driven by Water Temperature

Water temperature is a key environmental factor influencing river DO concentration and has significant regulatory effects on the physical-chemical properties of the water and biological processes[3]. To further clarify the dominant role of water temperature in the DO variation process, this study systematically analyzed the relationship between the non-compliance rates of DO, COD-Mn, NH_3-N, and water temperature based on continuous monitoring data from April 2022 to February 2023 (Figure 5).

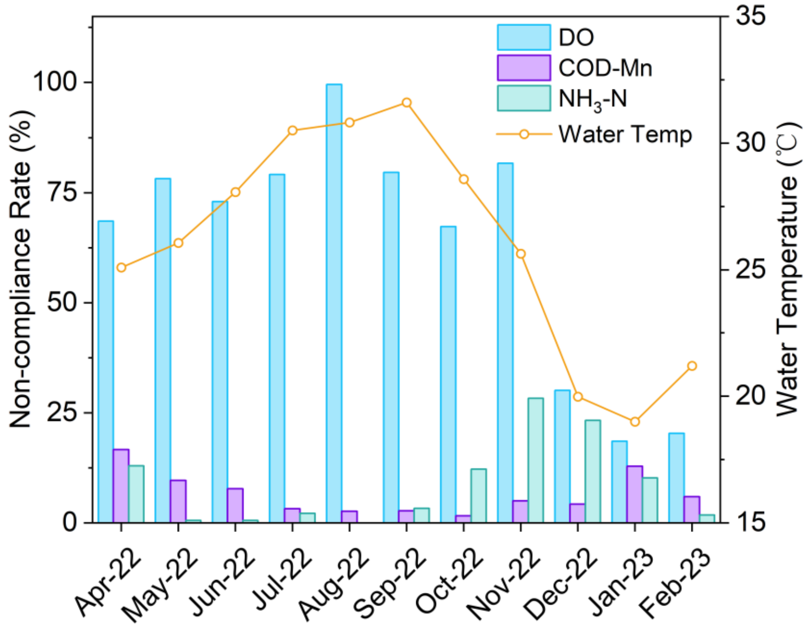

Figure 5: Non-compliance Rate and Water Temperature Comparison

The analysis results show that from July to September, the water temperature significantly increased, with the mean temperature being about 2–3 ℃ higher than in November. During this period, the DO non-compliance rate significantly increased, exceeding 50%. Meanwhile, the non-compliance rates for COD-Mn and NH_3-N were relatively low, ruling out the possibility that pollutant input was the dominant cause of the decline in DO. Further comparison revealed that although the NH_3-N non-compliance rate in November reached 28.3%, the DO remained relatively compliant. However, in July, despite lower pollutant loads, DO decreased, further validating the dominant role of temperature in controlling DO.

An increase in water temperature significantly reduces the saturation solubility of oxygen, limiting the reoxygenation capacity of the water. On the other hand, it promotes microbial activity and the rate of organic matter decomposition, enhancing the sediment oxygen demand process, thereby exacerbating the reduction in DO concentration[18]. In addition, the monthly and daily mean data shown in Figure 6 indicate a strong negative correlation between water temperature and DO concentration. Especially in all months except November, the trends of water temperature and DO concentration are clearly opposite, further emphasizing the decisive role of water temperature.

To further quantify the coupling relationship between water temperature and DO, Pearson correlation analysis was performed based on daily monitoring data. The results show a significant negative correlation between water temperature and DO concentration ($r = -0.70$, $p < 0.01$), indicating that the dominant effect of water temperature on DO fluctuations is particularly pronounced during high-temperature periods. In contrast, the correlations between DO and COD-Mn and NH_3-N are weak ($r = 0.01$ and $r = -0.03$, respectively) and do not reach statistical significance, further confirming that DO deficiency is primarily driven by water temperature rather than increased pollutant concentrations.

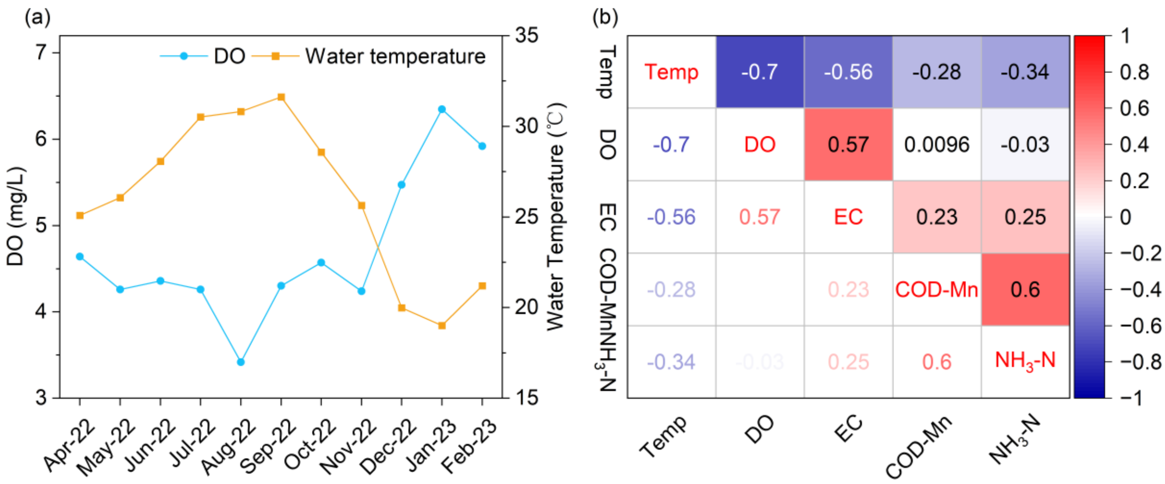

Figure 6: (a) Monthly Mean Water Temperature vs DO and (b) Correlation Analysis

3.4 Spatiotemporal Response Mechanism of DO Concentration under Tidal Influence

Tides, as a typical hydrodynamic driving factor in estuarine areas, can affect DO concentration by altering water exchange frequency, hydraulic retention time, and sediment disturbance frequency[6,9]. To systematically reveal the regulatory mechanism of tides on DO concentration, this study conducted a comprehensive analysis of a typical gate operation event in September 2023 and nine months of water diversion and discharge monitoring data from June 2022 to February 2023 (Figures 7 and 8).

The measured data show that during the gate closure period, the downstream DO concentration steadily increased, indicating the restoration of water self-purification and reoxygenation processes in the stagnant water environment. When the gate was opened at 12:00 and tidal water was introduced, the DO concentration at sections 10# to 13# rapidly decreased, with the most significant decline at point 13#, and it had not returned to the original level by 15:50. This phenomenon suggests that the incoming tidal water may carry low DO external water, and, accompanied by enhanced sediment disturbance, resuspension of organic matter, and increased interface oxygen consumption, it leads to a short-term exacerbation of oxygen depletion.

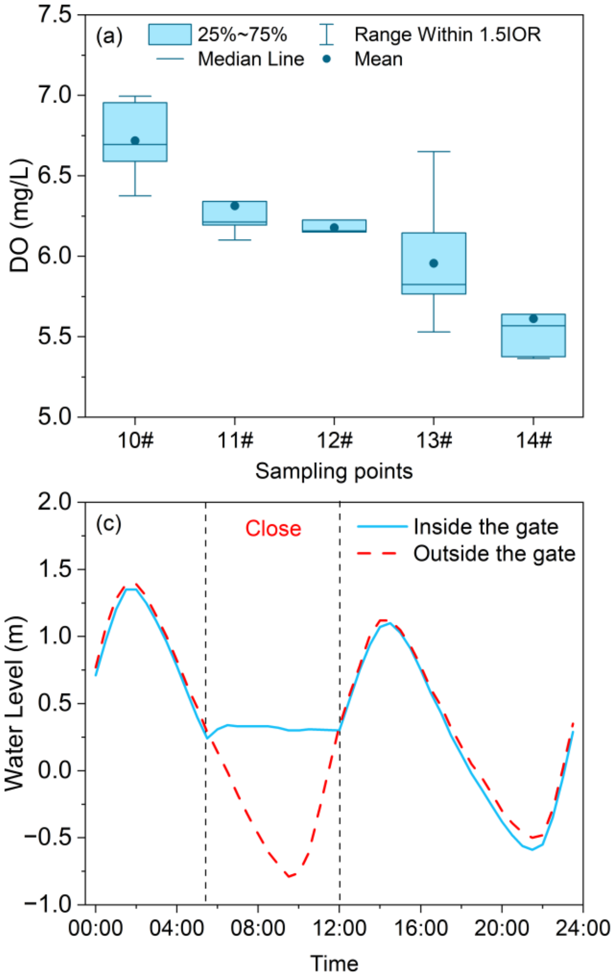

Figure 7: (a) Spatial Distribution of DO, (b) Temporal Distribution of DO, (c) Water Level Changes Inside and Outside the Gate, and (d) DO Changes at Sampling Point 13#

Figure 8 further compares the changes in DO and water temperature during the water diversion and discharge periods in different months. During high-temperature periods (July to September), the DO concentration during the water diversion period was generally lower than during the discharge period, and the water temperature was higher, indicating that tidal input did not produce an ideal reoxygenation effect and even triggered DO decline events. In the extreme case of August 2022, the DO non-compliance rate during the water diversion period reached 99.6%. In contrast, during the low-temperature season (December to February), water temperature significantly decreased during the water diversion period, and DO concentration was higher. Tidal input exhibited a clear reoxygenation effect, showing a positive regulatory characteristic.

In addition, the tidal input significantly extended the hydraulic retention time of the downstream water, forming a "retention effect," which limited the water renewal rate and exacerbated pollutant accumulation and oxygen-consuming reactions[19]. The effect of tides on DO has a clear dual nature, and its direction and intensity are interactively controlled by multiple factors, including the water temperature background, external water quality, sediment activity, and gate control patterns.

Therefore, under high temperature and poor external water quality conditions, tidal water diversion may lead to sudden DO depletion in the downstream, becoming an external driving mechanism for oxygen depletion events. In contrast, during low-temperature periods or when water quality is better, tidal input can significantly enhance reoxygenation levels, playing a role in mitigating water quality issues.

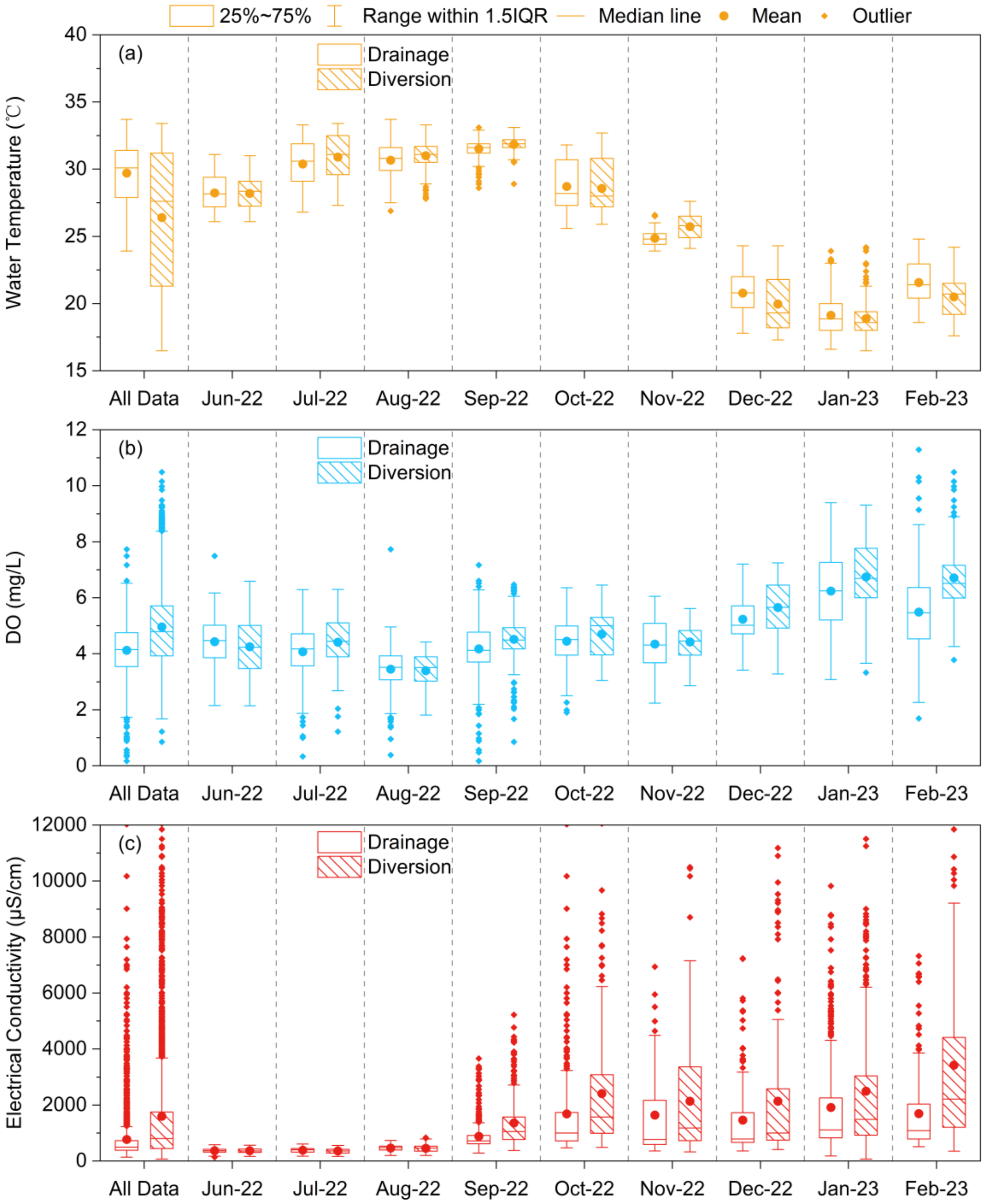

Figure 8: Comparison of Water Temperature (a), DO (b), and EC (c) during Discharge and Water Diversion

4. Conclusion

This study takes the Nangang River as the research subject and systematically explores the spatiotemporal distribution characteristics and multi-source driving mechanisms of DO variation in urban rivers through field monitoring and continuous real-time data. The study shows that the DO concentration gradually decreases from upstream to downstream along the main river, with DO < 6.0 mg/L commonly occurring at sections 10#, 12#, and 14# during high-temperature seasons, indicating a significant oxygen depletion risk. Among the tributaries, Siqing North and Tangwei exhibit heavy pollution characteristics with $DO < 3.0$ mg/L, $BOD_5 > 6.0$ mg/L, and NH_3-N > 2.0 mg/L, serving as important external load sources for downstream DO anomalies.

Sediment oxygen demand (SOD) as an endogenous mechanism cannot be overlooked. The SOD values at sections 7# and 9# are 0.53 and 0.42 g m^{-2} d^{-1}, respectively, indicating that sediment oxygen demand significantly inhibits the reoxygenation capacity of the middle and lower reaches. Water temperature is significantly negatively correlated with DO concentration ($r = -0.70$, $p < 0.01$), making it the dominant factor in the decline of DO during high-temperature periods. Additionally, the introduction of tidal water during high-temperature periods causes sediment disturbance and pollutant resuspension, leading to a sharp decline in DO concentration. During the water diversion period in August 2022, the DO non-compliance rate reached 99.6%. However, winter tidal water favors reoxygenation, showing a dual regulatory effect of tides on DO.

The DO variation in the Nangang River is significantly influenced by tributary pollution, sediment oxygen demand, increasing water temperature, and tidal disturbances. Future measures should be taken in aspects such as high-load tributary management, sediment remediation in high-SOD zones, and intelligent gate scheduling to achieve improvements in urban river water quality and the restoration of ecosystem health.

Acknowledgement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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