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Water environment characteristics and control countermeasures of typical hilly cities in Southeast China

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ABSTRACT

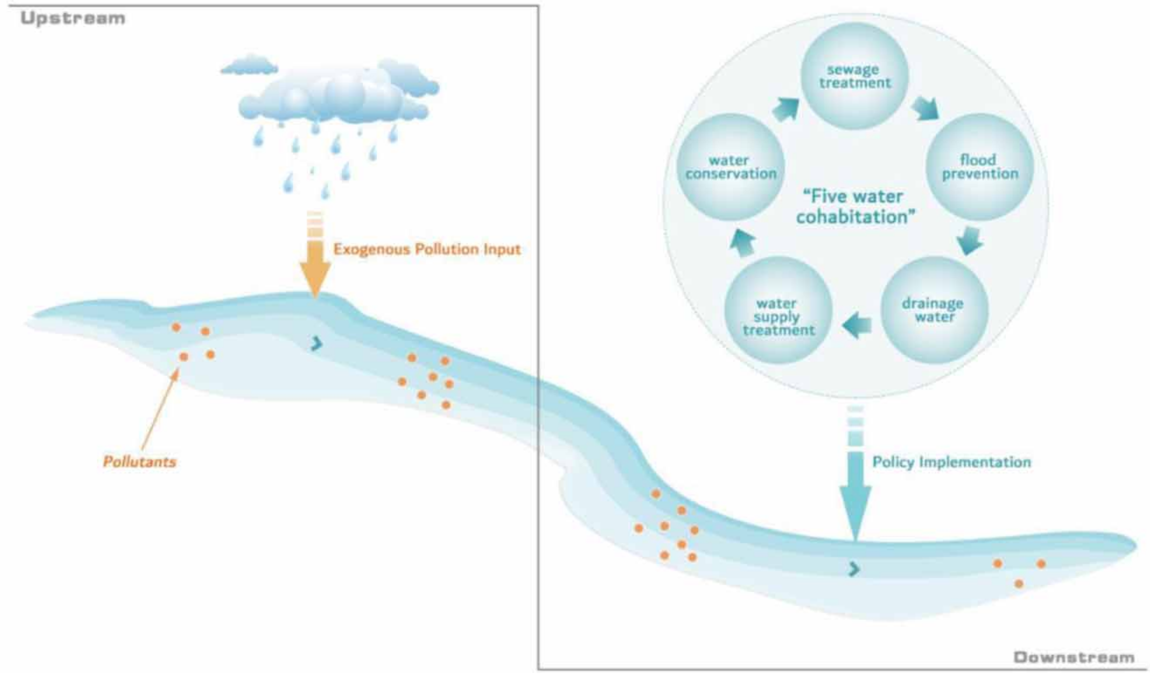
Due to population growth and economic development, problems such as uneven distribution of freshwater resources and degradation of water quality are becoming increasingly prominent. Many measures have been adopted to address water resources issues; however, few studies have focused on specific changes in water quality after policy implementation. In this study, Yiwu City, Zhejiang Province, a typical hilly city with a well-developed water system, was selected to analyze the changes in water quality. By analyzing the rainfall series and hydrology characteristics, and water quality characteristics, this paper revealed the water environment characteristics and put forward some suggestions for water management in hilly cities. Results showed that the historical rainfall time distribution is uneven, and the water environment capacity of urban inland rivers exhibits strong variability in Yiwu City. The contents of ammonia nitrogen (NH_3-N) and total phosphorus (TP) decreased significantly since the policy implementation of 'Five water cohabitation'. Urban rivers presented regional pollution and surface source pollution characteristics, and the water quality fluctuated significantly with the increase in rainfall. At the same time, the study confirmed that scientific water replenishment measures can effectively improve water quality, providing reference ideas for the protection and management of China's urban water environment.

Key words: five water cohabitation, hilly city, water environment characteristics, water quality, water replenishment

HIGHLIGHTS

- The water environment shows high variability in water rise and falls in the southern hilly cities.
- The policy implementation of 'Five water cohabitation' can significantly improve water quality.
- Scientific water replenishment measures are one of the measures to effectively improve the water environment.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Global precipitation patterns have changed, including increases in inter-annual precipitation variability and the frequencies of extremely dry and wet periods, which results in an imbalance in the distribution of water resources (O'Gorman & Schneider 2009; Smith 2011; Singh *et al.* 2013; Eamen *et al.* 2020). Water resources are facing many problems such as non-uniform regional distribution and water quality degradation in China (Varis & Vakkilainen 2001; Huang *et al.* 2019; Tao *et al.* 2020), and closer attention should be paid to how to protect and manage water resources (Hering *et al.* 2015).

Water resources are important resource support for social development, while the contradiction between water supply and demand is continuously highlighted, due to the rapid urbanization brings urban expansion and population gathering, especially in the faster economic development of China's coastal areas (Bouwer 2002; Brown *et al.* 2009; Feely *et al.* 2010; Shi *et al.* 2020; Tao *et al.* 2020; Zhang *et al.* 2021). Previous studies have shown that a long-term bidirectional causality between economic growth and water pollution discharge in China, in particular in highly built-up urban areas (Zhang *et al.* 2017). Due to the low natural runoff and insufficient water environment carrying capacity, coupled with a large amount of sewage received from residents and industry, lead to serious water pollution situation of hilly urban rivers in southeastern China (Bouwer 2000; Cai *et al.* 2003; Xu *et al.* 2021). At present, there are many water environment problems in hilly cities in Southeast China, such as the continuous increase in development intensity, unreasonable development methods and spatial layout, serious trends in nitrogen and phosphorus pollution and eutrophication, and the lack of monitoring and management (Xu *et al.* 2016; Yang *et al.* 2020). Furthermore, with pressure from industrial and municipal wastewater discharges, and non-point source pollution from fertilizer, pesticide, and manure runoff from agriculture and aquaculture, water quality is deteriorating and declining in rivers and groundwater sources (Huang *et al.* 2013). Exploring the characteristics of water pollution in economically developed areas of China, especially in densely populated urban rivers, and the mode of management is an urgent need to strengthen water environment management and enhance regional competitiveness and sustainable development ability (Huang *et al.* 2019).

In order to improve China's water resources quality, various measures have been taken in recent years, and significant accomplishments have been achieved (Mu *et al.* 2016; Zhou *et al.* 2017; Deng *et al.* 2018; Huang *et al.* 2019; Pan & Tang 2021). Zhejiang Province, located in the Southeastern coast of the People's Republic of China, has a dense water system and the water quality is relatively good in upper reaches, lakes and reservoirs; however, opposite in those reaches at downstream plain areas and urban areas (Yang *et al.* 2015; Ahn & Kim 2017). In the context of the increasingly serious water pollution, frequent floods and low utilization of water resources, a policy 'Five water cohabitation' was released by the government of Zhejiang Province on November 29, 2013 (Yang *et al.* 2015; Chi 2017). This policy highlights water management from five aspects: sewage treatment, flood prevention, drainage water, water supply treatment and water conservation, and the implementation of the policy is divided into three phases: 2013–2015, 2015–2017, and 2017–2020 (Chi 2017). This policy has achieved some successes and provided references with other places, however, how these actions actually affect water quality remains to be studied.

Yiwu City is located in the centre of Zhejiang Province, the eastern edge of the Jinqu basin, with a total area of 1,105.4 km^2 (29°2′–29°33′N, 119°49′–120°17′E) (Cong *et al.* 2021). The city is surrounded by mountains on the north, east and south, and undulating hilly terraces in the middle, with a stepped slope from northeast to southwest. The landscape is dominated by hills, accounting for 34.4% of the total area. Yiwu City belongs to the subtropical monsoon climate zone, with a multi-year average rainfall of 1,348.5 mm and a multi-year average evaporation of 1,342.1 mm. Inter-annual and intra-annual rainfall distribution is uneven, with an inter-annual variation of 900–2,032 mm, concentrating 52% of the total annual rainfall from March to June (Xu *et al.* 2016). The rapid urbanization of Yiwu City has led to an increase in surface runoff and a decrease in groundwater recharge, evapotranspiration, and soil water storage. Meanwhile, changes in hydrological components were usually observed near urban areas and in rainy seasons (Yang *et al.* 2020). Feng *et al.* (2008) found that the residents suffered serious water crises in Yiwu City in the summer of 2003 when record high temperatures appeared with only 30% of the regular precipitation from July to October. In 2013, when the 'Five water cohabitation' was launched, the concentrations of COD, total phosphorus and ammonia nitrogen exceeded the V standard for surface water (GB3838-2002) of Yiwu City, showing the typical characteristics of a city with water quality shortage. There is a significant conflict between the supply and demand of water resources, especially in the season of drought and low rainfall.

Based on the above background, this study selects Yiwu City, Zhejiang Province, a typical hilly city with a well-developed water system, to (a) analyze the changes in water quality since the 'Five water cohabitation'; (b) reveal the differences between the upstream and downstream in water quality and pollution characteristics under different water conditions; and (c) explore the sources of water pollution and propose solutions. By summarizing the main measures and effectiveness of water pollution management in Yiwu City, with a view to providing a reference for the next phase of urban inland river water environment pollution management priorities.

2. MATERIALS AND METHODS

2.1. Study region

In this study, the rivers of Yiwu City, Chengnan River and Liudu River, belong to the Yiwu River system, which is part of the Qiantang River basin (Figure 1). Among them, Chengnan River is formed by the confluence of Chengxi River, Chengzhong River and Chengdong River, with a total length of about 8.3 km, a watershed area of 25.5 km^2, an average river width of about 13 m, and a watershed carrying a population of about 269,000 people; the main river of Liudu River has a total length of about 15 km, a watershed area of 37 km^2, a river width of 2–10 m, and a watershed carrying a population of about 70,000 people.

2.2. Data and methodology

The data used in this paper mainly includes two components: the precipitation data used in this hydrological analysis were obtained from the hydrological station of Yiwu City, and the flow information was obtained from field observations by our team. More specifically, the water quality analysis data were divided into three time periods: August 2013–March 2015, May 2017–December 2017, and April 2021–August 2021, of which August 2013–March 2015 and May 2017–December 2017 were provided by the Yiwu Ecological Environment Bureau, and April 2021–August 2021 were obtained from our project team's actual measurements. To analyze the sources of pollutants in urban rivers, a day-by-day water quality monitoring of urban inland rivers was conducted during rainfall and non-rainfall periods in August 2020. Meanwhile, hydrological measurements on June 12 (cumulative rainfall of 21 mm in the previous 3 days) and October 30 (no rainfall in the previous 5 days) were conducted in2018, using Liudu River as the study site, and explored the effects of water replenishment measures on the river water quality. Using a UV–Visible Spectrophotometer (Cary 100 UV-VIS, USA), the concentrations of ammonia nitrogen (NH_3-N) in water bodies were analyzed based on the Nessler's reagent spectrophotometry method (HJ 535-2009) and total phosphorus (TP) contents were determined by ammonium molybdate spectrophotometry method (GB/T 11893-1989). Meanwhile, the permanganate index (COD_{Mn}) was measured by the UV-Visible Spectrophotometer (Cary 100 UV-VIS, USA) according to international standards (ISO 8467–1986).

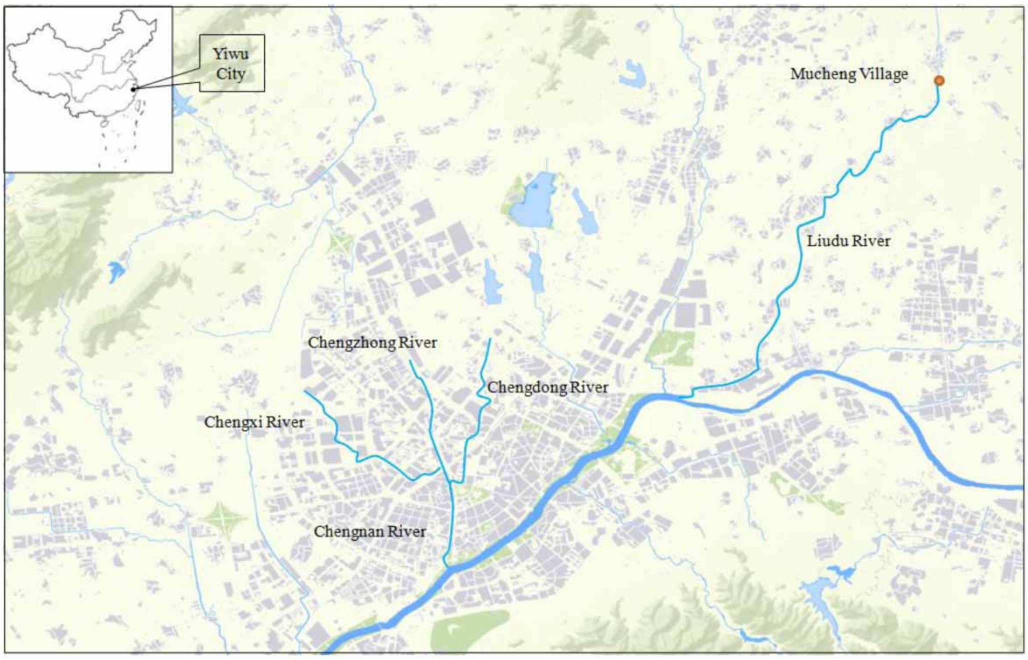


Figure 1 | Water system diagram in Yiwu City.

2.3. Statistical analysis

In order to compare the changes in water quality at different stages of the 'Five water cohabitation', the average values of NH_3-N and TP, as well as the reduction rate of nutrients, were calculated in Chengnan River, Chengxi River, Chengzhong River, and Chengdong River within Yiwu City in three time periods: August 2013–March 2015, May 2017–December 2017, and April 2021–August 2021, respectively. Meanwhile, the average values of NH_3-N and TP were calculated separately in upstream and downstream to compare the water quality characteristics of different reaches of the river. To explore the effect of rainfall on water quality, the average values of NH_3-N and TP were calculated separately on rainy and non-rainy days. The correlation between water quality and flow in the Liudu River was calculated based on simultaneous monitoring data using a regression approach. All analyses and graphing were conducted using Microsoft Excel.

3. RESULTS

3.1. Hydrological characteristics in Yiwu City

Based on the Yiwu hydrological station statistics, the multi-year average number of days without rainfall is 260 days during 1936–2014, and the longest consecutive days without rainfall is 21.7 days on average; the longest of which is in 1936, with no rain days lasting up to 84 days. According to the on-site hydrological measurements of Liudu River conducted by our project team on June 12 (21 mm of accumulated rainfall in the previous 3 days) and October 30 (no rainfall in the previous 5 days), 2018, the flow rates of its upstream Mucheng Village section were obtained as 0.92 and 0.08 m^3/s, respectively; the flow rates of its downstream inlet section were 1.08 and 0.14 m^3/s, respectively. At the same time, from August 21 to 23, 2020, temporary hydrological observation was carried out in Chengnan River and its tributaries during the non-rainfall period, and it was found that the river was basically in a discontinuous flow phenomenon.

3.2. Variation in water quality in different rivers during three stages

The water quality of Yiwu City showed obvious differences in different rivers during the three stages. The water quality of Chengnan River and its upstream Chengxi River, Chengzhong River and Chengdong River within Yiwu City showed significant differences in three time periods: August 2013–March 2015, May 2017–December 2017 and April 2021–August 2021 (Table 1, Figure 2). The average value of NH_3-N was 9.35 mg/L in August 2013–March 2015, while it decreased to 1.43 and 0.88 mg/L in May 2017–December 2017 and April 2021–August 2021, respectively, with an average reduction rate of 85.99 and 90.75% (Table 1). The average value of TP was 1.04 mg/L in August 2013–March 2015, while it decreased to 0.30 and 0.23 mg/L in May 2017–December

2017 and April 2021–August 2021, respectively, with an average reduction rate of 70.83 and 77.46% (Table 1).

Table 1 | Changes and reduction rates of main pollutants in rivers in Yiwu urban area

			May 2017–December 2017		April 2021–August 2021	
Indicators	**River**	**August 2013–March 2015 Monitoring values (mg/L)**	**Monitoring values (mg/L)**	**Reduction rate (%)**	**Monitoring values (mg/L)**	**Reduction rate (%)**
NH_3-N	Chengxi River	9.48	0.90	90.46	1.43	84.94
	Chengzhong River	13.82	2.97	78.48	0.96	93.03
	Chengdong River	5.98	0.46	92.25	0.22	96.28
	Chengnan River	8.11	1.40	82.78	0.91	88.74
	Average values	**9.35**	**1.43**	**85.99**	**0.88**	**90.75**
TP	Chengxi River	1.05	0.33	68.70	0.36	65.38
	Chengzhong River	1.41	0.41	71.21	0.21	84.87
	Chengdong River	0.67	0.19	71.26	0.12	82.76
	Chengnan River	1.03	0.29	72.16	0.24	76.85
	Average values	**1.04**	**0.30**	**70.83**	**0.23**	**77.46**

The bolded values indicate the mean values of the monitoring values and reduction rate at each stage.

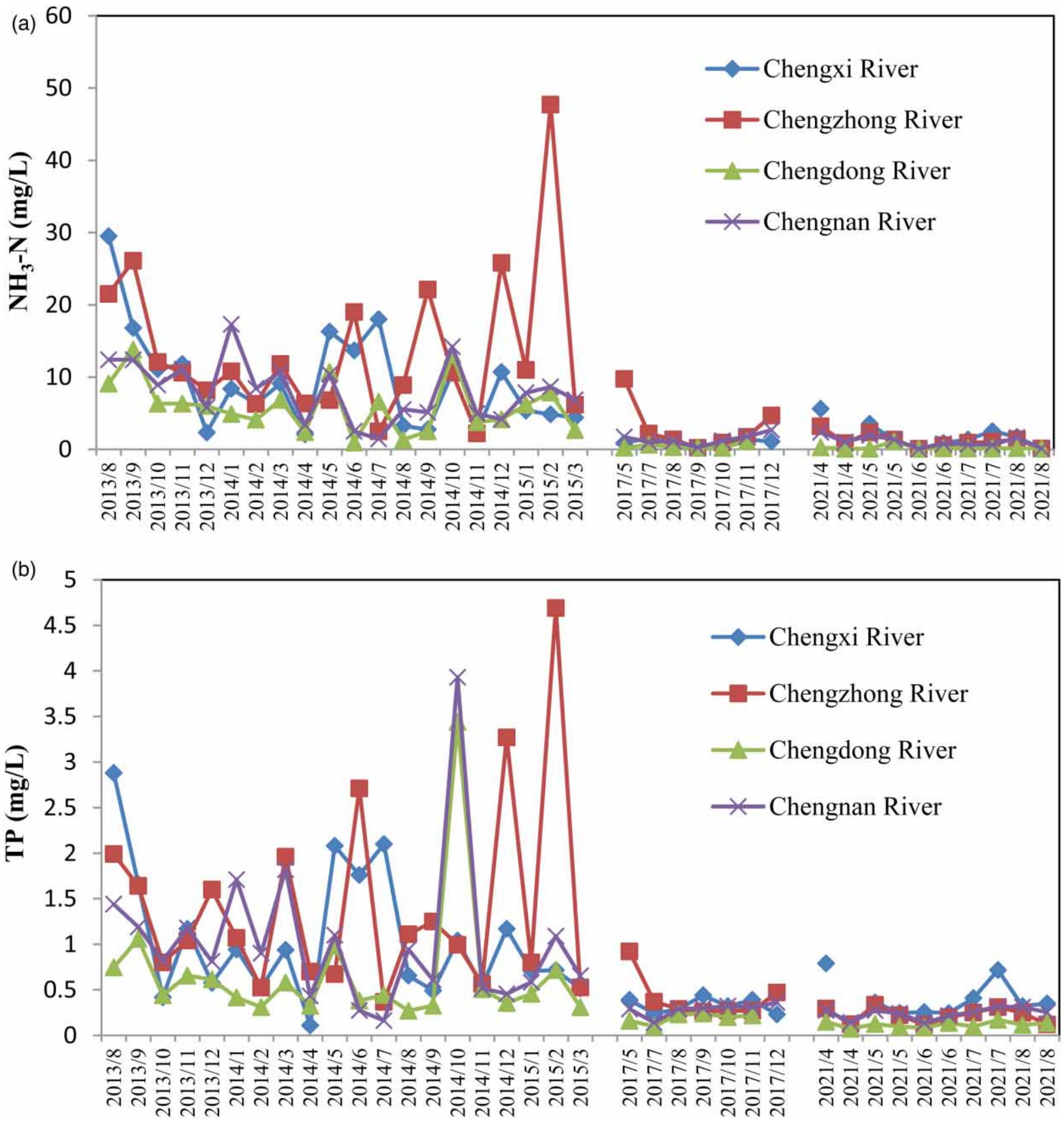


Figure 2 | Changes in water quality of inland rivers in major cities of Yiwu City: (a) NH_3-N and (b) TP.

Water quality varied significantly in different rivers of Yiwu city: the water quality of Chengdong River was relatively the best, followed by Chengxi River, and the Chengzhong River was relatively the worst (Figure 2).

3.3. Water pollutant differences in upstream and downstream

To study the interception of pollution along the river and its impact on water quality, the differences in water quality between the upstream and downstream rivers in Yiwu City were analyzed, using the average data of water quality from May 2017–December 2017 and April 2021–August 2021. Comparing nutrient indicators

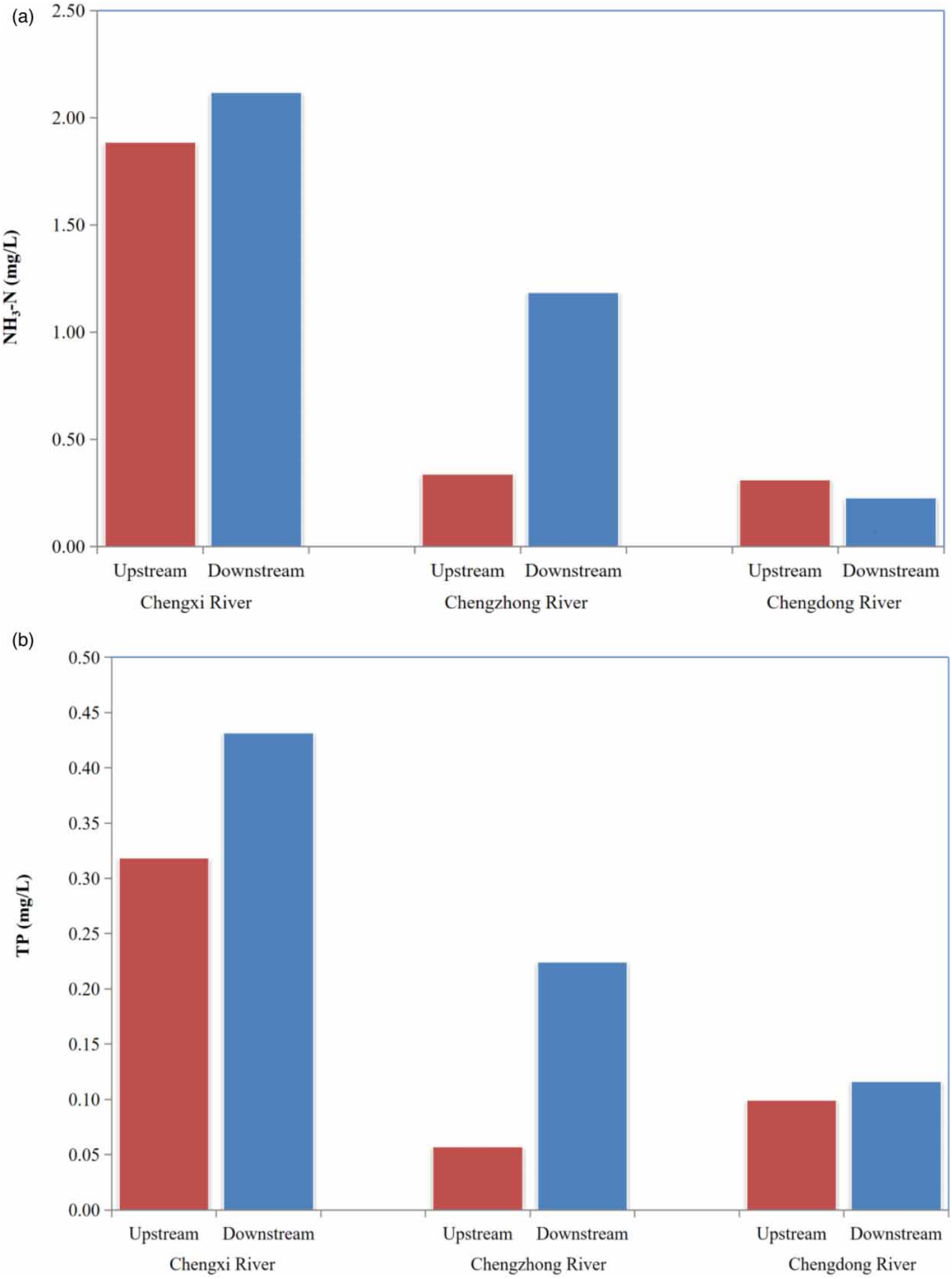


Figure 3 | Comparison of main indicators of water quality in upstream and downstream rivers of Yiwu City: (a) NH_3-N and (b) TP.

NH_3-N and TP, results showed that the downstream was 1.35 and 1.12 times higher than the upstream of Chengxi River, respectively; the downstream was 3.92 and 3.52 times higher than the upstream of Chengzhong River, respectively; and the values were 1.17 and 0.73 in Chengdong River, respectively (Figure 3).

3.4. Pollution sources and improvement measures

The differences in water quality indexes of urban inland rivers in rainy and non-rainy periods were compared, and the results showed that NH_3-N and TP showed significant differences in the water bodies of monitored rivers (Figure 4). With the increase in rainfall, the concentration of NH_3-N in all monitored rivers increased by 16.8 times in Chengnan River and 1.69–4.82 times in tributaries; and TP concentration increased by 1.41 times in

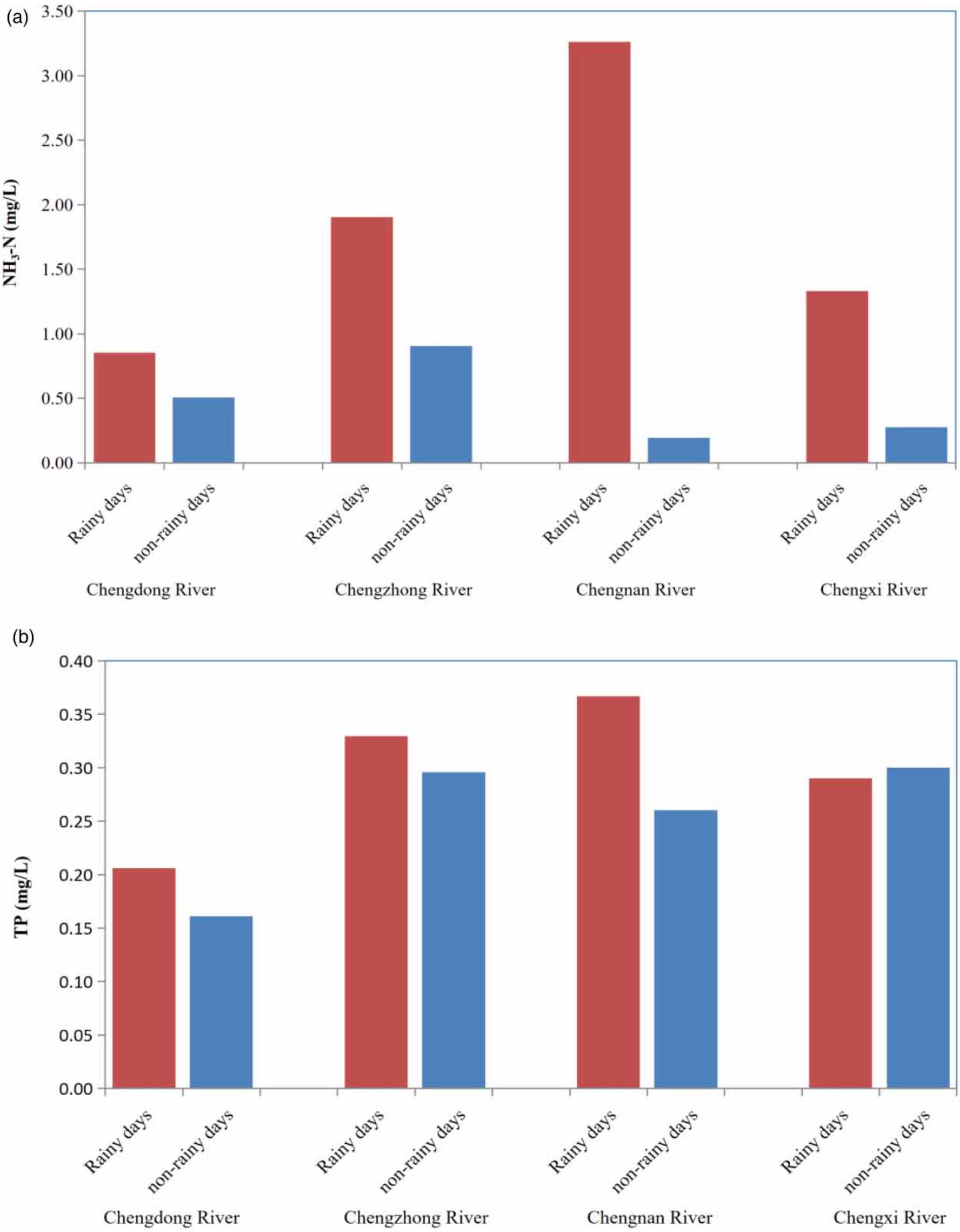


Figure 4 | Comparison of main indicators of water quality on rainy and non-rainy days in August 2020: (a) NH_3-N and (b) TP.

Chengnan River and 0.97–1.28 times in tributaries with rainfall (Figure 4). In the meantime, the results of simultaneous monitoring of water quality and discharge in Liudu River showed that, with the increase of discharge, the concentration of water pollutants increases synchronously from upstream to downstream (Figure 5).

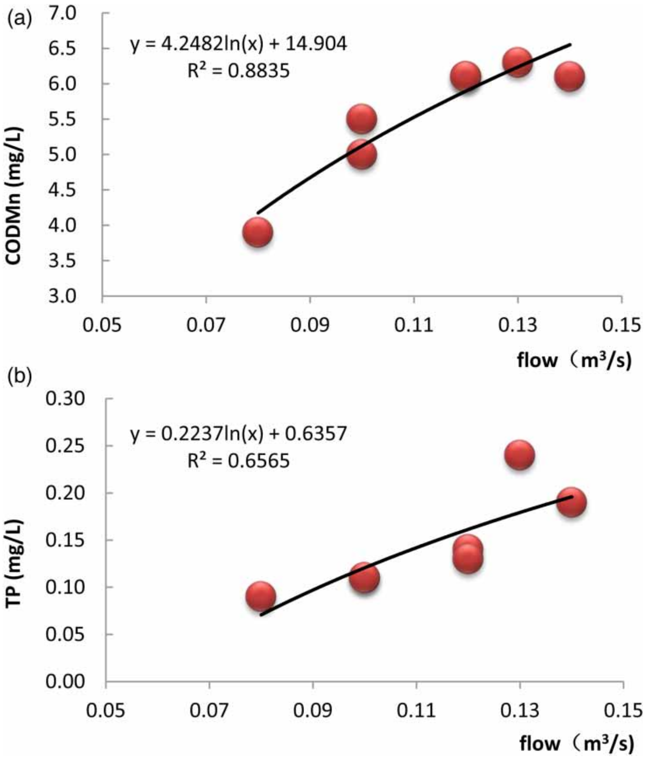


Figure 5 | Simultaneous observation results of water quality and flow along the Liudu River: (a) COD_{Mn} and (b) TP.

The water quality of Liudu River before and after the implementation of water replenishment was monitored and compared. The results showed that the water replenishment flow during the monitoring period was 0.315 m^3/s, about 1.6 times of the upstream. In addition, after the implementation of water replenishment, the water quality indicators have been greatly improved; the concentration of TP and NH_3-N has the greatest reduction, reaching 80.0 and 69.1%, respectively (Table 2).

Table 2 | Comparison table of water quality before and after water replenishment in Liudu River

Monitoring sites	Water replenishment	Water quality indicators NH_3-N (mg/L)	COD_{Mn} (mg/L)	TP (mg/L)
1#	Before	4.73	5.7	0.42
	After	0.95	4.2	0.08
	Reduction rate (%)	79.9	26.3	81.0
2#	Before	3.75	5.5	0.39
	After	0.85	4.1	0.08
	Reduction rate (%)	77.3	25.5	79.5
3#	Before	1.32	4.8	0.24
	After	0.75	3.9	0.09
	Reduction rate (%)	43.5	18.8	62.5
4#	Before	3.03	5.5	0.34
	After	0.74	4.1	0.01
	Reduction rate (%)	75.6	25.5	97.1
Combined reduction rate (%)		69.1	24.0	80.0

4. DISCUSSION

4.1. Hydrological characteristics of hilly cities

Hydrological conditions are the decisive factors in the water environment characteristics of urban rivers (Lee *et al.* 2002; Brown *et al.* 2009). In highly built-up urban areas, most rivers receive sewage discharged by residents and industry. In addition, the runoff of such rivers is small, and river water mainly depends on urban rainfall. These together lead to the relatively poor self-purification capacity of the river (Zhang *et al.* 2017, 2021). Urban rivers have a small catchment area and no transit water resources to replenish them, river runoff mainly comes from local rainfall in Yiwu City, showing the characteristics of rainfall increases river runoff, without rain, the flow is broken and dried up. Consistent with previous findings, the smaller the catchment area of a watershed, the more sensitive the runoff response to rainfall, thus showing surge and fall characteristics (Shimojima & Sawa Da 2000; Lee *et al.* 2002; Liang *et al.* 2011). The temporal distribution of rainfall determines the strong volatility of the water environment capacity of the urban rivers in Yiwu City, coupled with the small environmental capacity of river water bodies and fragile ecosystems; it is difficult to rely on natural runoff to maintain the self-purification capacity of the rivers.

4.2. Analysis of the variation in water quality in different rivers during three stages

The water quality showed obvious differences in different rivers during the three stages, and it has greatly improved since the policy implementation of 'Five water cohabitation' in Yiwu City. In the first phase of the 'Five water cohabitation' launched in Zhejiang Province, from August 2013 to March 2015, the interception rate was low, the pollution load into the river was large, and the river was seriously polluted; in the third phase of the 'Five water cohabitation' in May 2017–December 2017 and April 2021–August 2021, the regional interception and emission reduction capacity has been greatly improved, pollutants entering the river have been significantly reduced, and the river water quality has been significantly improved (Table 1, Figure 2). Similar to our research, previous studies have shown that, in the face of water shortage, economic losses can be reduced by almost 50% by adopting appropriate management practices, such as prioritization of water allocation, using alternative water sources, and water re-use technologies (Eamen *et al.* 2020).

Water quality showed significant differences in different rivers in Yiwu City: the water quality of Chengdong River is relatively best, followed by Chengxi River, and the Chengzhong River is relatively the worst (Figure 2). Which may be caused by differences in population, economic density and infrastructure in the catchment area. According to the survey, the river basin has a high concentration of older neighborhood with relatively weak environmental infrastructure in Chengzhong River, resulting in its relatively poor water quality. As rapid urbanization brings about urban expansion and population gathering, the contradiction between water supply and demand is constantly highlighted, which can be mitigated through the implementation of national policies and the impact of human activities (Chi 2017; Zhou *et al.* 2017; Huang *et al.* 2019).

4.3. Sources of pollutants in water bodies and management measures

While addressing the pollution of urban rivers, two major types of sources can be distinguished: endogenous and exogenous pollution; exogenous pollution generally refers to point source pollution (e.g., municipal and industrial wastewater outflows, fish farming) and urban surface source pollution (runoff from agricultural or urban lands, atmospheric deposition) (Bouwer 2000; Brown *et al.* 2009; Matej-Lukowicz *et al.* 2020; Xu *et al.* 2021; Zhang *et al.* 2021). Point source pollution is generally easy to monitor, while urban surface source pollution is usually more problematic to quantify and increases with rainfall significantly (Zhang *et al.* 2010; Frey *et al.* 2015; Wang *et al.* 2021). In this study, the river's concentration of water quality is significantly higher during the rainfall period than during the non-rainfall period, exhibiting obvious characteristics of urban surface source pollution, and the concentration increases further downstream (Figure 4). Furthermore, as the flow rate increases, the water concentration increases simultaneously from upstream to downstream (Figure 5), which may indicate that the water bodies along the catchment are polluted to some extent. Consistent with the present study findings, urban surface source pollution that enters surface waters with rainfall–runoff processes results in increasing nutrient concentrations from upstream to downstream (Wang *et al.* 2018; Xu *et al.* 2021). Urban surface pollution may be caused by two aspects: on the one hand, by rainfall washing the pollutants deposited on the surface into the river; on the other hand, due to incomplete interception of sewage or incomplete separation of rain and sewage in some areas along the route, the sewage stored in the pipes during the non-rainfall period is washed or overflowed into the river by rainwater, resulting in poor water quality downstream of the river (Lee *et al.* 2002; Ahn & Kim

2017; Matej-Lukowicz *et al.* 2020; Xu *et al.* 2021). For the above issues, it was found that water quality can be effectively improved through hydration measures, after the implementation of water replenishment, the water quality indicators have been greatly improved (Table 2). Consistent with the present study, with the increase of distribution quantity, the improvement effect of the river water quality was increased gradually (Yixin *et al.* 2019; Hua *et al.* 2021).

Considering the pollution characteristics of urban rivers with insufficient water environment capacity, incomplete interception of sewage and surface source loads, in addition to the above water replenishment measures, and countermeasures for continuous improvement in three major areas can be taken, such as emission reduction, capacity increase and regulation. First, through analysis of the spatial characteristics of water quality, targeted key areas to carry out pipe network leakage and rain, sewage pipeline misconnection and leakage to mapping, improve the underground pipe network system to reduce sewage into the river; second, through strengthening the planning of watershed ecological restoration system, restoring the ecological functions of river and lake banks, reducing the amount of surface source pollution into the river, and achieving the healthy and sustainable development of river and lake water ecosystems; third, scientific and effective water diversion and allocation is an important measure to achieve river and lake water system connectivity and improve the water environment; finally, by combining a variety of monitoring techniques, improve the monitoring network system, further improve real-time monitoring and response capabilities.

5. CONCLUSIONS

Southeastern hilly cities are dominated by small watersheds, and runoff mainly comes from local rainfall, showing high variability in water rise and fall, combined with the low self-purification capacity of rivers in the dry season, which leads to prominent water pollution problems. In this paper, the result of the study on Yiwu City, a typical hilly city, shows that the ‘Five water cohabitation’ measures can effectively improve water quality. However, the urban rainfall process is extremely uneven, resulting in strong fluctuations in the capacity of the urban water environment. Urban areas show regional pollution and surface source pollution characteristics, and there are obvious differences in water quality spatial differences and fluctuations with rainfall. At the same time, this study finds that scientific water recharge measures can effectively improve water quality and provide reference ideas for the protection and management of hilly urban water environments. However, the frequency and extent of extreme weather events have been increasing in recent years, rainfall is unevenly distributed across regions, and rainfall–runoff processes have exacerbated urban surface source pollution, bringing new challenges to urban water environment management.

AUTHOR CONTRIBUTIONS

A.Y. designed the study; L.H. and Z.W. collected the data; A.Y. analyzed the data; A.Y. and J.H. led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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