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Spatiotemporal water quality variations in the urbanizing Chongqing reach of Jialing River, China

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ABSTRACT

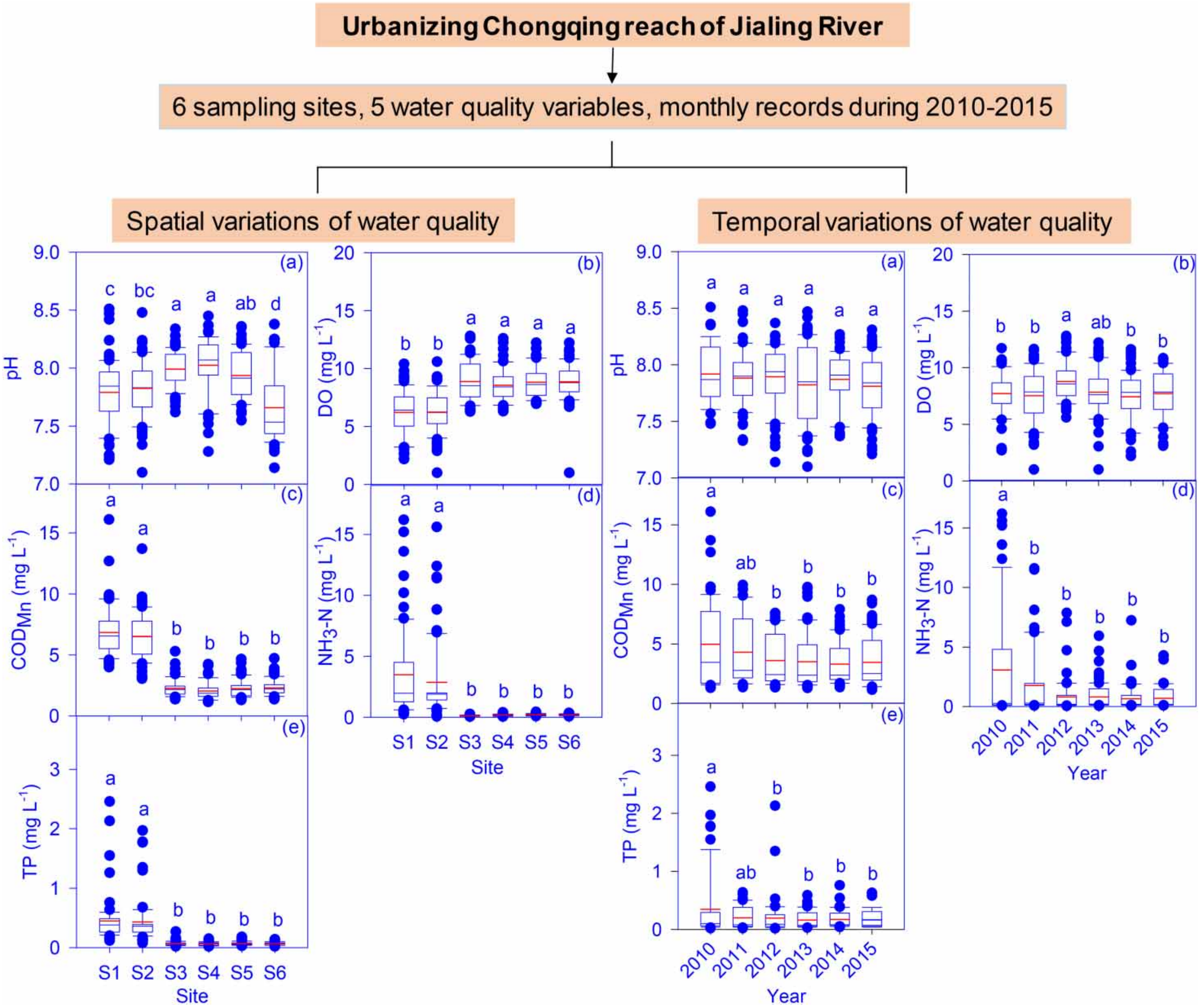
Water quality in rivers usually exhibits markedly spatiotemporal variations as affected by urbanization, while the magnitude of these effects remain unclear. This study aimed to investigate the spatiotemporal water quality variations in the urbanizing Chongqing reach of Jialing River and its tributary using a 6-yr multisite dataset (January 2010–December 2015). Water quality variables including pH, dissolved oxygen (DO), permanganate index (COD_{Mn}), ammonia nitrogen (NH_3-N) and total phosphorus (TP) were deciphered. Results showed that the trunk river displayed respectively 1.2 and 39.8% higher pH and DO concentration but 66.9, 94.7 and 85.2% lower COD_{Mn}, NH_3-N and TP concentrations relative to the tributary ($P < 0.05$), due largely to the dilution effects occurring in the trunk river. The dry season presented respectively 1.3, 18.2, 102.8 and 32.5% higher pH, DO, NH_3-N and TP concentrations than those in the wet season ($P < 0.05$). DO concentration showed significant inter-annual variations ($P < 0.05$), and COD_{Mn}, NH_3-N and TP concentrations all presented markedly declining trends from 2010 to 2015 ($P < 0.05$). Significant relationships among the study variables were found in different spatiotemporal scales ($P < 0.05$). Our results are valuable to optimize strategies for sustainable water quality management in rivers experiencing urbanization worldwide.

Key words: aquatic ecosystem, environmental deterioration, hotspots, non-point source, seasonal variation, urbanization

HIGHLIGHTS

- Spatiotemporal water quality variations in the lower Jialing River are examined.
- Trunk Jialing River shows better water quality condition than its tributary river.
- Lower river pollutant concentrations are found in the wet season rather than the dry season.
- Pollutant concentrations decline in the lower Jialing River from 2010 to 2015.
- Water quality variables display marked links across various spatiotemporal scales.

GRAPHICAL ABSTRACT



INTRODUCTION

Rivers are the key linkages between terrestrial ecosystems and reservoirs (lakes) and/or marine ecosystems, and historically provide the most valuable sources of water for human development (Ripl 2003; Grill *et al.* 2019). Rivers provide the amount of available freshwater to support the human activities, such as domestic life, industrial and agricultural production (Safari *et al.* 2021). However, the urbanization driving the rapid development of industry and agriculture has subjected rivers to an increased stress, and therefore unbalancing the river ecosystem and accelerating the degradation of water quality in rivers (van Vliet *et al.* 2017). Accordingly, identifying the water quality conditions in rivers during urbanization is conducive to making the protection strategies taken by the local government departments.

The pollutants degrading river water quality are generally stemmed from point and non-point sources, which are both strongly driven by human activities, e.g., urbanization (Walsh *et al.* 2005; Brooks *et al.* 2006; Schliemann *et al.* 2021). The point input sources, such as industrial operations and domestic sewage, commonly continually discharge to the rivers over time by a pipe or at a specific site (Ramsey & Szynkiewicz 2019) and significantly alter the water quality, while they are relatively simple to be monitored and controlled by treatment at the head (Varol 2012). In contrast, the non-point input sources like runoff from upper fertilized cropland are relatively more difficult to be quantified as a result of the dispersed distribution in a wide area and significant shifts with time owing to the weather effects (Carpenter *et al.* 1998; Voutsa *et al.* 2001).

Water quality in rivers is usually characterized by significant spatiotemporal variations due to the urbanization process, which causes the changeful intensities in point and non-point source pollutions. The high concentrations of pollutants in river systems are at specific time periods making polluted hot moments (McClain *et al.* 2003; Dwivedi *et al.* 2018), and at specific locations creating polluted hotspots (Luthy *et al.* 2015). These hot moments and spots collectively reflect the sharp changes in water quality in rivers under different spatiotemporal scales (Bernhardt *et al.* 2017). Previous studies have focused on the spatiotemporal water quality variations around the world (Ahipathy & Puttaiah 2006; Xie *et al.* 2013, 2015). For instance, Fraga *et al.* (2021) analyzed the temporal and spatial trends of surface water quality in the Doce River basin, Minas Gerais, Brazil. Schliemann *et al.* (2021) reported the water quality in the South Platt River in the Denver metropolitan area, Colorado, USA, and identified spatiotemporal hotspots for the study river. However, the spatiotemporal water quality variations are strongly dependent on the intensities of human activities and changing climate, and some conflicting findings are usually obtained due to the specific objectives in different study sites (Iida *et al.* 2011; Stevenson *et al.* 2012). Therefore, the characteristics of spatiotemporal variations in water quality are thus still unclear (Dragun *et al.* 2011; Safari *et al.* 2021; Schliemann *et al.* 2021), and more data are urgently needed to interpret the dynamic changes in water quality in some specific sites, which is expected to contribute greatly to the optimization of strategy for the universal sustainable management of water quality worldwide.

The Jialing River is one of the main tributaries in the upper reach of the Yangtze River, and is also the largest tributary of the Three Gorges Reservoir Area (TGRA). Therefore, the water quality conditions of Jialing River, to a large extent, play the pivotal role in ensuring the water environmental security of Yangtze River and TGRA (Wu *et al.* 2012a). The downstream of Jialing River flows through several urbanizing administrative districts of Chongqing City and directly discharges to the Yangtze River, resulting in substantial input of point and non-point pollutants to the waterbody and significant water quality degradation (Long *et al.* 2011). Liangtan River, the main tributary of lower Jialing River, strongly affects the water quality conditions of the trunk Jialing River (Gong *et al.* 2013). In recent years, the rapid urbanization, such as the development of urban industry and agriculture, has brought enormous negative impacts on the water quality of the Chongqing reach of Jialing River and its tributary (Long *et al.* 2011; Gong *et al.* 2013), which in turn may limit the future sustainable development in society, economy and ecology of the adjacent urban regions. Although protection measures have been implemented to prevent the water quality from deteriorating and to further achieve the improvement of water quality by the local government, the spatiotemporal water quality variations resulting from the urbanization driven by human activities in the urbanizing Chongqing reach of Jialing River, to the best of our knowledge, are not well determined.

In this study, a 6-yr multisite dataset (January 2010–December 2015) collected from the lower trunk Jialing River and its tributary Liangtan River were interpreted in detail to determine the spatiotemporal water quality variations in the urbanizing Chongqing reach of Jialing River. Considering vast areas of urbanization and required sustainable water quality management, this study will contribute greatly to understanding the extent of spatiotemporal variations in water quality and for optimizing strategies for advancing water resources management. The specific objectives of this study are to: (1) determine the spatial and temporal variations in selected water quality variables, and (2) disclose the potential relationships among these variables.

MATERIALS AND METHODS

Study area

The Jialing River (102°33′–109°00′E, 29°18′–34°30′N) originates from the Qinling Mountain and flows through Shanxi, Gansu, Sichuan Provinces and Chongqing Municipality, presenting a drainage area of approximately 159,800 km^2 and a length of 1120 km (Figure 1). The Jialing River basin has a slow tilt from the northeast and northwest edge with altitudes of 1500–3000 m to the downstream (Wu *et al.* 2012a). The regional climate in Jialing River basin is characterized by a subtropical monsoon climate with an average temperature of 15 °C. The Beibei hydrological station, located in the export of Jialing River, recorded the average annual rainfall of 1098 mm with over 80% occurring in the wet season from May to September, the average annual evaporation of 709.4 mm, and the average annual runoff of 65.9 billion m^3 (Wu *et al.* 2012b). The overlying soils in the basin mostly consist of brown soil, yellow-brown soil and purple soil. The upstream of Jialing River basin is related to the provinces of Shanxi and Gansu characterized by agriculture such as food production and breeding of livestock and poultry (Wu *et al.* 2012a, 2012b). The midstream is related to Sichuan Province which is the important production base of livestock, grain and economic crops. The downstream is across several urbanizing districts of Chongqing

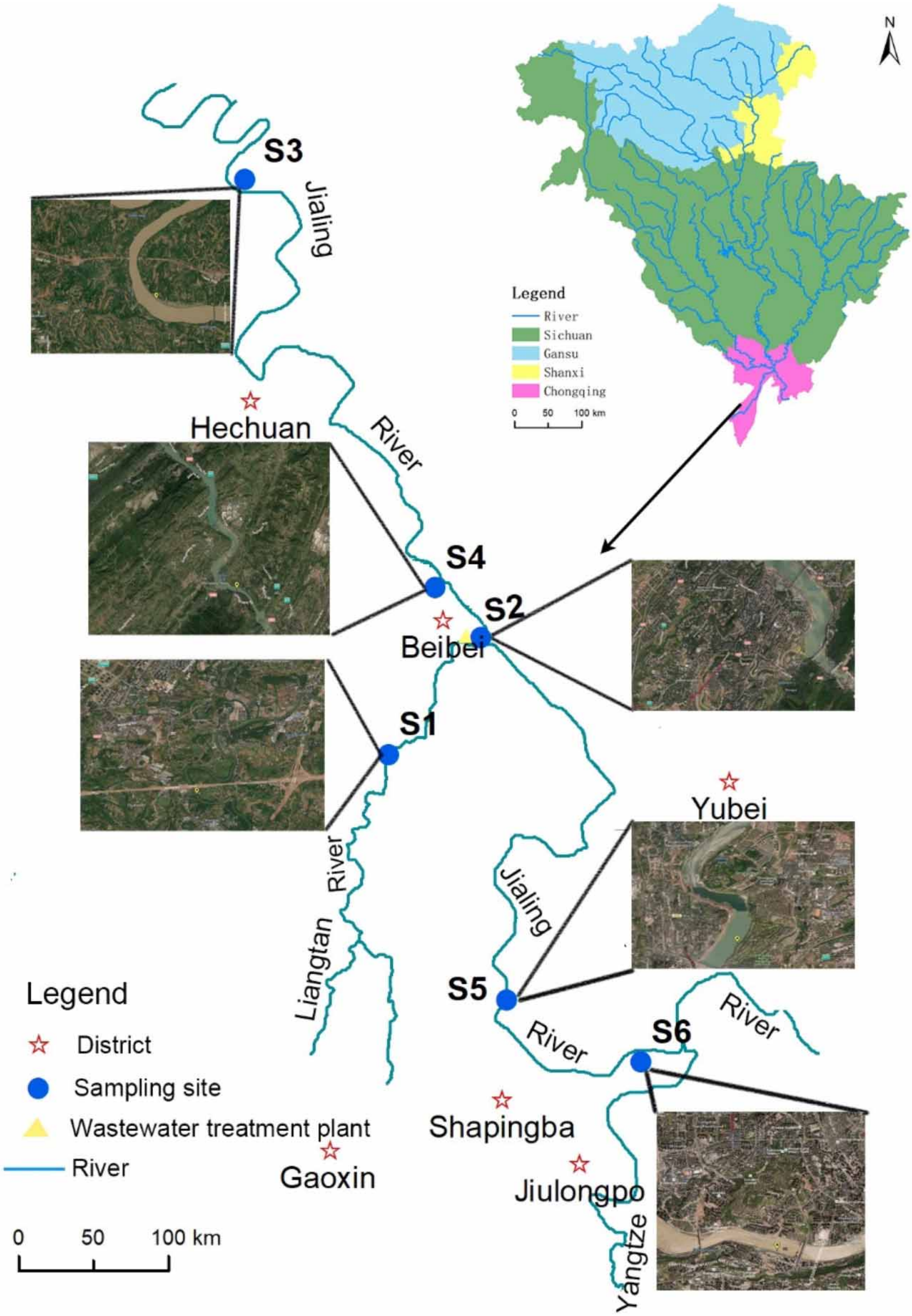


Figure 1 | Location map of the sampling sites. S1, Xixiqiao; S2, Longfenghekou; S3, Jinzituo; S4, Beiwenquan; S5, Liangtuo; S6, Daxigou.

Municipality including Hechuan, Beibei, Yubei, Shapingba, Yuzhong and Jiangbei and flows into the Yangtze River at the Chaotianmen, being also the important producer of grain and economic crops (Wu *et al.* 2012a, 2012b).

The water network of Jialing River appears visually branched, and many tributaries are evolved along the trunk of Jialing River (Figure 1). Therein, the Liangtan River is the main tributary of the lower Jialing River, and has a drainage area of 525 km^2, a length of 79 km and average annual discharge of 6.43 $m^3 s^{-1}$. The Liangtan River is also located in the advanced economic circle of Chongqing Municipality and is subjected to severe water pollution due to intensive human activities e.g., urbanization over the past decades (Gong *et al.* 2013). Its water quality was categorized to the weakest grade during 2001–2005 according to the Environmental Quality Standards for Water Quality (2002) (Table S1). The degraded aquatic ecosystems in Jialing River and its tributary have become a growing concern because of the demands for sustainable development of local society, economy and ecology. Thus, characterization of the spatiotemporal water quality variations in the lower Jialing River is thus very helpful for the local water environmental agency to make rational decisions on the water resources allocation and water quality protection.

Sample collection and measurements

To investigate the spatiotemporal water quality in the urbanizing Chongqing reach of Jialing River, a total of six observation sites were selected in the lower of Jialing River and its tributary (Figure 1). These observation sites were: site 1 (Xixiqiao), site 2 (Longfenghekou), site 3 (Jinzituo), site 4 (Beiwenquan), site 5 (Liangtuo) and site 6 (Daxigou), respectively. Among them, sites 1 and 2 are set in the tributary Liangtan River, and sites 3, 4, 5 and 6 are distributed in the lower trunk Jialing River, covering the starting point of Chongqing reach of Jialing River to the exporting point into the Yangtze River. Additionally, the Beibei wastewater treatment plant is situated at the upstream approximately 150 m away from site 2 and thus the water quality of the treated water was also able to be assessed.

Sample collection in each site was conducted monthly from January 2010 to December 2015 (Figure 2). *In situ*, the immediate measurements of pH and dissolved oxygen (DO) were preferentially implemented using a portable multi-parameter meter (Minisonde5x, Hach, USA) at a depth of around 0.5–1 m from the water surface of the platform of the intake tower. Simultaneously, water samples for further measurements of other water quality variables were collected using a 2.5 L grab sampler

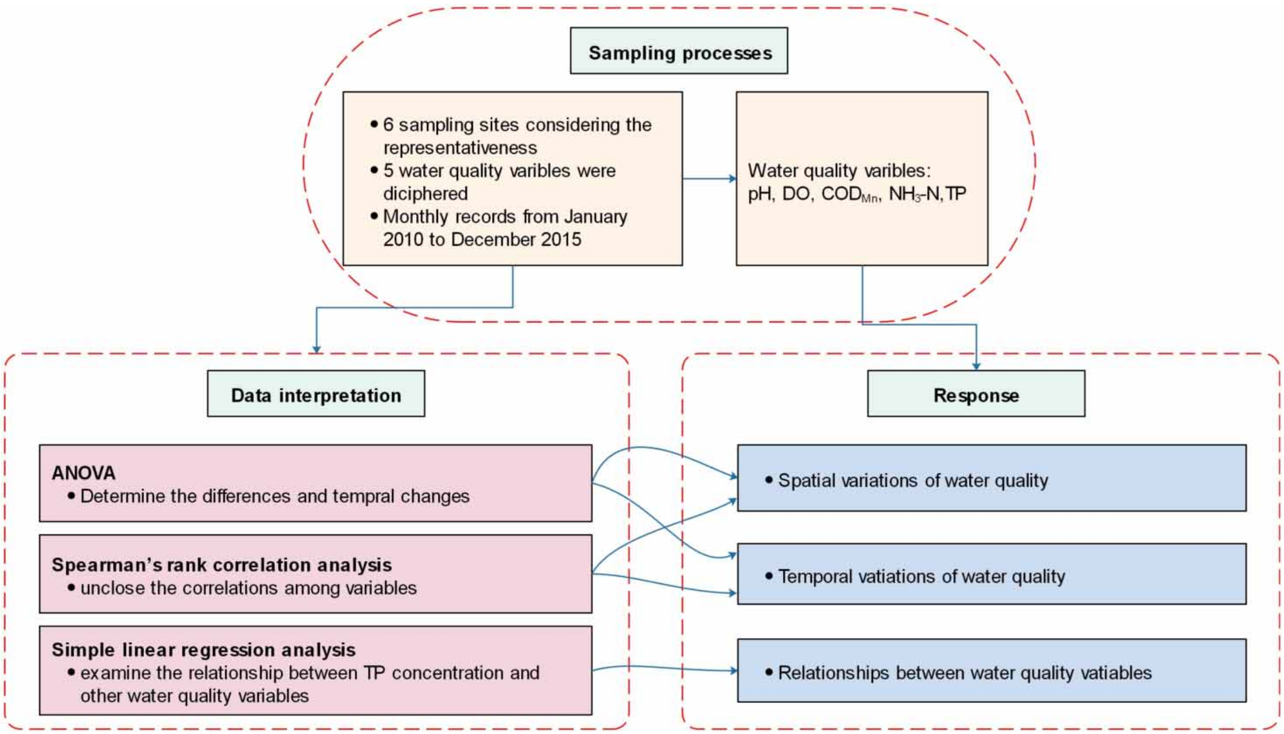


Figure 2 | Flowchart for the adopted methodology in this study.

and then were filled into duplicate polyethylene bottles (~500 mL) which had been pre-washed with the river water corresponding to the sampling depth at each site. All obtained water samples were sealed using a plastic bag and kept in the dark at 4 °C, until being processed immediately on return to the laboratory within 24 hr.

In the laboratory, the duplicate bottles of water samples experienced distinct test procedures. One bottle of the water sample was filtered through a 0.45 μm glass microporous fiber membrane to measure the ammonia nitrogen (NH_3-N) concentration by using the spectrophotometric method with salicylic acid. The other bottle of water sample was unfiltered and directly used to measure the permanganate index (COD_{Mn}) and total phosphorus (TP) using potassium permanganate titration after reduction by sodium oxalate and molybdenum blue colorimetric method after addition of potassium peroxodisuphate, respectively. These analytical methods for NH_3-N, COD_{Mn} and TP were performed following the standard Chinese protocols (SEPA 2002). In this study, the concentrations of DO, COD_{Mn}, NH_3-N and TP were measured in mg L^{-1}.

Statistical analysis

One-way analysis of variance (ANOVA) followed by Tukey's (or Tamhne's when equal variances were not assumed) post hoc multiple comparison test was conducted to determine the differences in water quality variables among sampling sites, and to compare the monthly, seasonal and annual changes in these variables, respectively. Spearman's rank correlation analysis was used to unclose the correlations among these study variables. Simple linear regression analysis was used to examine the relationship between TP concentration and other water quality variables after all variables were $\log_{10}$-transformed. A $P <$ 0.05 was considered statistically significant. All statistical analyses abovementioned were implemented using SPSS 22.0 (IBM, Armonk, New York, USA).

RESULTS

Spatial variations of water quality

The spatial variations of water quality in the trunk Jialing River and its tributary are shown in Figures 3 and S1. During 2010–2015, pH varied significantly from the highest value in site 4 (Beiwenquan, 8.02) to the lowest value in site 6 (Daxigou, 7.66) ($P < 0.05$), with an average value of 7.86 ± 0.27 (Figure 3(a)). However, average pH was 1.2% higher in the trunk river than in the tributary ($P < 0.05$). DO concentration was 39.8% higher in the trunk sites 3–6 than those in the tributary sites 1–2 ($P < 0.05$), ranging from 8.97 ± 1.26 mg L^{-1} (site 6, Daxigou) to 6.21 ± 1.86 mg L^{-1} (site 1, Xixiqiao) with an average of 7.89 ± 1.98 mg L^{-1} (Figure 3(b)). In contrast, the concentrations of COD_{Mn}, NH_3-N and TP were 66.9, 94.7 and 85.2% lower in the trunk sites 3–6 than those in the tributary sites 1–2, respectively (Figure 3(c)–3(e)) ($P < 0.05$). Specifically, COD_{Mn} concentration ranged from 6.84 ± 2.02 (site 1, Xixiqiao) to 2.04 ± 0.69 mg L^{-1} (site 4, Beiwenquan) with an average value of 3.81 ± 2.50 mg L^{-1}. NH_3-N concentration varied from 3.49 ± 3.48 (site 1, Xixiqiao) to 0.13 ± 0.04 mg L^{-1} (site 3, Jinzituo) with an average value of 1.24 ± 2.42 mg L^{-1}. TP concentration ranged from 0.45 ± 0.40 (site 1, Xixiqiao) to 0.06 ± 0.03 mg L^{-1} (site 4, Beiwenquan), with an average of 0.21 ± 0.29 mg L^{-1}.

Temporal variations of water quality

Monthly, pH and DO concentration were both the highest in February (8.06 ± 0.23 and 9.72 ± 2.42 mg L^{-1}, respectively) and the lowest in June (7.73 ± 0.27 and 6.91 ± 1.65 mg L^{-1}, respectively) (Table 1). COD_{Mn} was the highest in February (4.18 ± 3.78 mg L^{-1}) and March (4.18 ± 3.37 mg L^{-1}), and the lowest in December (3.19 ± 1.90 mg L^{-1}) (Table 1). NH_3-N concentration showed the highest value in February (1.93 ± 3.63 mg L^{-1}) and the lowest value in August (0.51 ± 0.72 mg L^{-1}) (Table 1). TP concentration presented the highest value in April (0.32 ± 0.53 mg L^{-1}) and the lowest values in June (0.15 ± 0.11 mg L^{-1}) and October (0.15 ± 0.12 mg L^{-1}) (Table 1).

Seasonally, pH was 1.3% higher in the dry season (7.91 ± 0.27) than in the wet season (7.81 ± 0.26) ($P < 0.05$) (Figure 4(a)). DO concentration was 18.2% higher in dry season (8.43 ± 2.10 mg L^{-1}) than in the wet season (7.13 ± 1.50 mg L^{-1}) ($P < 0.05$) (Figure 4(b)). COD_{Mn} concentration was slightly different between the two seasons ($P > 0.05$) (Figure 4(c)). NH_3-N and TP concentrations were respectively 102.8 and 32.5% higher in the dry season (1.57 ± 2.95 mg L^{-1} and 0.23 ± 0.37 mg L^{-1}, respectively) than in the wet season (0.78 ± 1.22 mg L^{-1} and 0.17 ± 0.13 mg L^{-1}, respectively) ($P < 0.05$) (Figure 4(d) and 4(e)).

In addition, pH did not show a significant inter-annual difference ($P > 0.05$), while the DO concentration showed significant inter-annual variations ($P < 0.05$), ranging from 8.78 ± 1.71 mg L^{-1} in 2012 to 7.44 ± 2.10 mg L^{-1} in 2014. Concentrations of COD_{Mn}, NH_3-N and TP also showed considerable inter-annual differences ($P < 0.05$) (Figures 5 and

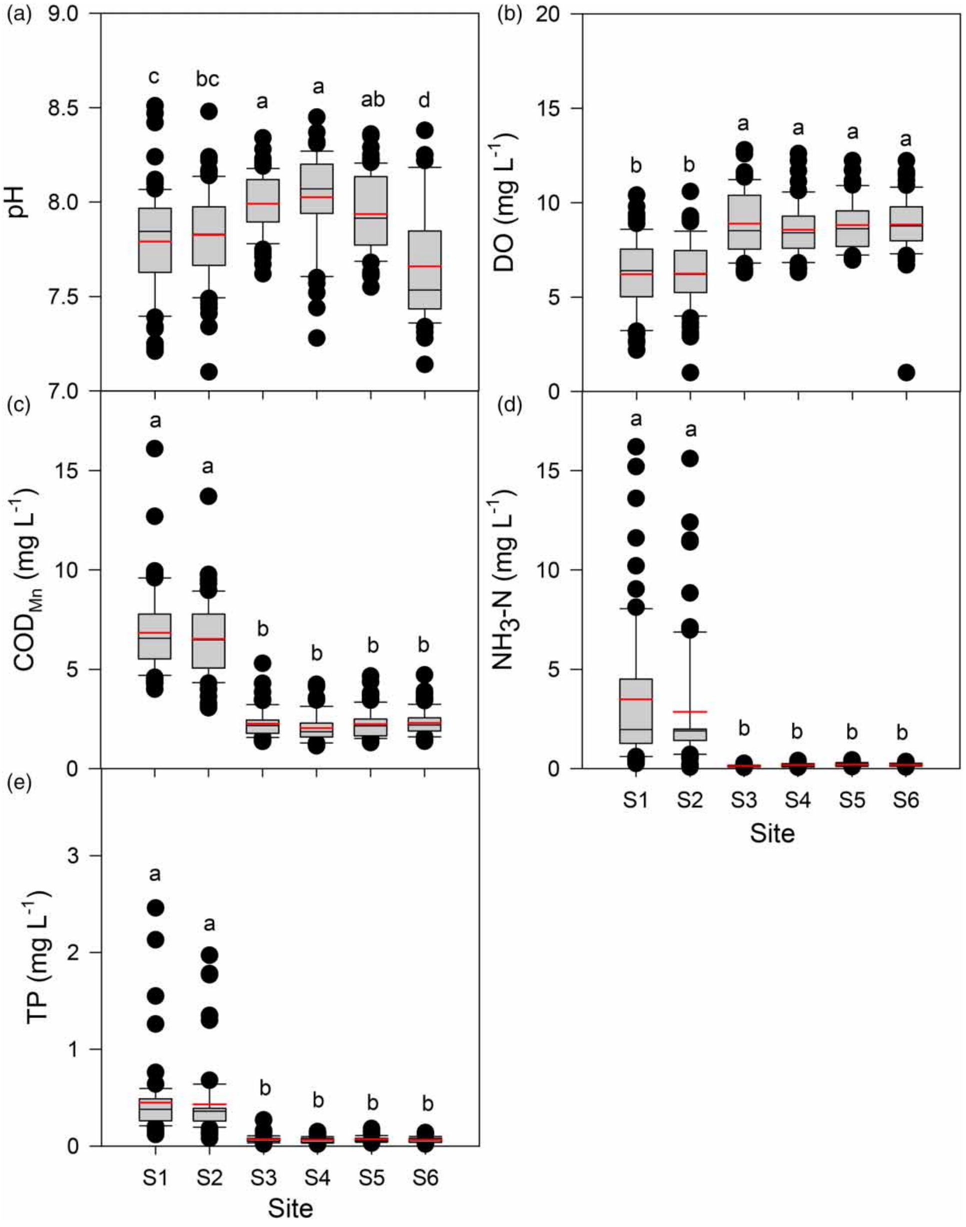


Figure 3 | Spatial variations in pH (a) and concentrations of DO (b), COD_{Mn} (c), NH_3-N (d) and TP (e) in the urbanizing Chongqing reach of Jialing River during 2010–2015. Mean data are red lines, Median data are black lines, 25th and 75th percentiles data are lower and upper edges, 10th and 90th percentiles are lower and upper bars and $<$10th and $>$90th percentiles data are lower and upper dots outside, respectively. Different lowercase letters above the upper dots indicate significant differences among sampling sites. S1, Xixiqiao; S2, Longfenghekou; S3, Jinzituo; S4, Beiwenquan; S5, Liangtuo; S6, Daxigou.

S1). Therein, COD_{Mn} and NH_3-N concentrations ranged from 4.97 ± 3.62 and 3.09 ± 4.69 mg L^{-1} in 2010 to 3.30 ± 1.71 and 0.65 ± 1.07 mg L^{-1} in 2014, respectively. TP concentration varied between 0.35 ± 0.56 mg L^{-1} in 2010 and 0.16 ± 0.15 mg L^{-1} in 2013.

Relationships between water quality variables

Spearman's rank correlation analysis showed the different relationships among water quality variables within each sampling site and each month, season and study year. In particular, TP concentration was always closely correlated with pH, concentrations of DO, COD_{Mn} and NH_3-N in site 4 ($P < 0.05$), but was not in other sites ($P > 0.05$) (Table S2). TP concentration was

Table 1 | Monthly variations in pH and concentrations of DO, COD_{Mn}, NH_3-N and TP in the urbanizing Chongqing reach of Jialing River during 2010–2015

		Month											
Variable	**Index**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
pH	N	33	33	33	33	34	35	35	33	31	34	35	35
	Min	7.33	7.54	7.21	7.36	7.14	7.25	7.31	7.37	7.34	7.36	7.10	7.23
	Max	8.38	8.51	8.42	8.25	8.35	8.45	8.48	8.47	8.25	8.24	8.25	8.31
	Mean	7.91	8.06	7.99	7.89	7.81	7.73	7.78	7.90	7.81	7.86	7.79	7.86
	Std	0.28	0.23	0.27	0.24	0.23	0.27	0.26	0.25	0.27	0.24	0.30	0.27
DO	N	32	32	32	32	33	34	34	32	31	33	34	34
	Min	3.90	3.10	2.20	2.70	3.05	2.20	2.60	3.90	4.20	4.60	5.00	4.40
	Max	12.22	12.60	12.81	9.90	9.94	9.46	10.81	10.24	9.99	10.72	10.52	11.63
	Mean	9.01	9.72	8.79	7.57	7.07	6.91	7.23	7.20	7.27	7.67	7.82	8.50
	Std	2.39	2.42	2.54	1.66	1.26	1.65	1.61	1.44	1.57	1.48	1.34	1.78
COD_{Mn}	N	33	33	33	33	34	35	35	33	31	34	35	35
	Min	1.15	1.36	1.16	1.16	1.23	1.74	1.43	1.52	1.28	1.31	1.34	1.40
	Max	7.90	16.10	12.70	9.80	8.50	9.06	9.95	7.84	9.57	8.40	7.90	7.28
	Mean	3.51	4.18	4.18	3.93	3.56	4.16	4.25	3.77	4.16	3.53	3.36	3.19
	Std	2.30	3.78	3.37	3.02	2.30	2.41	1.95	1.98	2.17	2.22	1.93	1.90
NH_3-N	N	33	33	33	33	34	35	35	33	31	34	35	35
	Min	0.11	0.08	0.10	0.10	0.10	0.07	0.05	0.07	0.06	0.07	0.06	0.08
	Max	10.20	15.20	13.60	16.20	4.90	8.12	2.61	3.74	3.81	9.04	7.28	6.76
	Mean	1.64	1.93	1.75	2.62	1.13	0.98	0.58	0.51	0.66	0.91	1.09	1.14
	Std	2.64	3.63	3.20	4.66	1.50	1.77	0.73	0.72	0.90	1.79	1.80	1.70
TP	N	32	29	29	29	31	32	32	30	29	31	30	31
	Min	0.02	0.02	0.03	0.02	0.04	0.05	0.06	0.04	0.04	0.03	0.03	0.02
	Max	1.77	2.46	1.97	2.13	0.63	0.39	0.48	0.49	0.40	0.48	0.68	0.55
	Mean	0.22	0.31	0.27	0.32	0.18	0.15	0.18	0.17	0.18	0.15	0.17	0.17
	Std	0.33	0.55	0.45	0.53	0.17	0.11	0.11	0.14	0.12	0.12	0.17	0.18

significantly correlated with pH in November and December ($P < 0.05$), and was always considerably correlated with DO, COD_{Mn} and NH_3-N concentrations in all months ($P < 0.05$) (Table S3). TP concentration showed close relationships with DO, COD_{Mn} and NH_3-N concentrations ($P < 0.05$), but not with pH ($P > 0.05$) in both dry and wet seasons (Table 2). Further, TP concentration was always markedly correlated with pH, concentrations of DO, COD_{Mn} and NH_3-N in 2011, 2014 and 2015 ($P < 0.05$) (Table S4).

Additionally, simple linear regression analysis showed that TP concentration had significant negative relationships with pH ($n = 364$, $P < 0.01$) and DO concentration ($n = 364$, $P < 0.001$), but significant positive relationships with COD_{Mn} ($n = 364$, $P < 0.0001$) and NH_3-N concentrations ($n = 364$, $P < 0.0001$) across the whole spatial and temporal scales (Figure 6).

DISCUSSION

The water quality in the urbanizing Chongqing reach of Jialing River displayed significant spatial variations, showing relatively lower pH and DO concentration but higher COD_{Mn}, NH_3-N and TP concentrations in the tributary Liangtan River than those in the trunk Jialing River. This result suggested that more severe water quality degradation occurred in the tributary Liangtan River relative to the trunk Jialing River, due largely to the intensive human activities in the tributary. Gong *et al.* (2013) assessed the water quality of the Liangtan River and concluded that the pollutions in the river mainly originated from the adjacent urban wastewaters, wastewaters from industries and the intensively cultivated lands along the river. Moreover, the Liangtan River flows through the city center of the Gaoxin, Shapingba and Beibei Districts in which are burgeoning urbanizing areas, the substantial pollution, such as wastewaters from treatment plants and industrial operations, domestic sewage and runoff from impervious surfaces which were primarily caused by the urbanization, collectively resulted in the diminished water quality (Walsh *et al.* 2005; Brooks *et al.* 2006; Xie *et al.* 2013). Although the trunk Jialing River is also

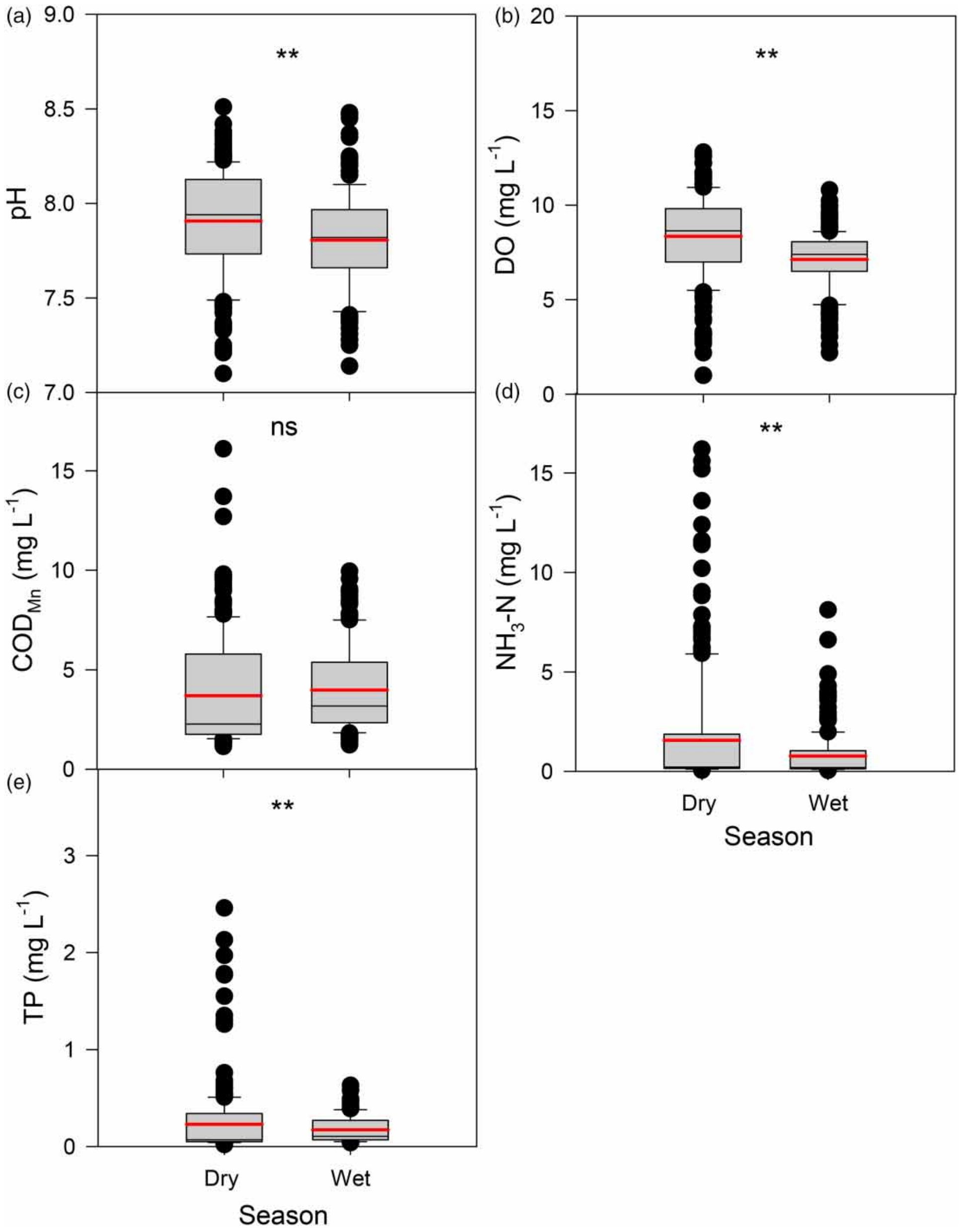


Figure 4 | Seasonal variations in pH (a) and concentrations of DO (b), COD$_{Mn}$ (c), NH$_3$-N (d) and TP (e) in the urbanizing Chongqing reach of Jialing River during 2010–2015. Dry season, October-April; Wet season, May-September. Mean data are red lines, Median data are black lines, 25th and 75th percentiles data are lower and upper edges, 10th and 90th percentiles are lower and upper bars and <10th and >90th percentiles data are lower and upper dots outside, respectively. Different lowercase letters above the upper dots indicate significant differences among sampling sites. **, significant at $P < 0.05$; ns, not significant.

confronted with similar environmental circumstances, the large amount of flow discharge from the upstream could markedly dilute the pollutants and thus was conducive to preventing the water quality from further degrading (Vega *et al.* 1998; Dragun *et al.* 2011; Moatar *et al.* 2017).

Our results found an average pH value of 7.86 across all sampling sites, suggesting that the study river water overall had alkaline properties. This was likely related to the combined effects of anthropogenic sources, flow discharge and carbonate rocks distributed around the study area (Safari *et al.* 2021). Generally, the pH value of natural river water is mostly regulated by the equilibrium of carbonate-bicarbonate-carbon dioxide system, while the input pollutants (e.g., organic matters) unbalance the nature of water, therefore resulting in acidification in river water (Spry & Wiener 1991; Ramsey &

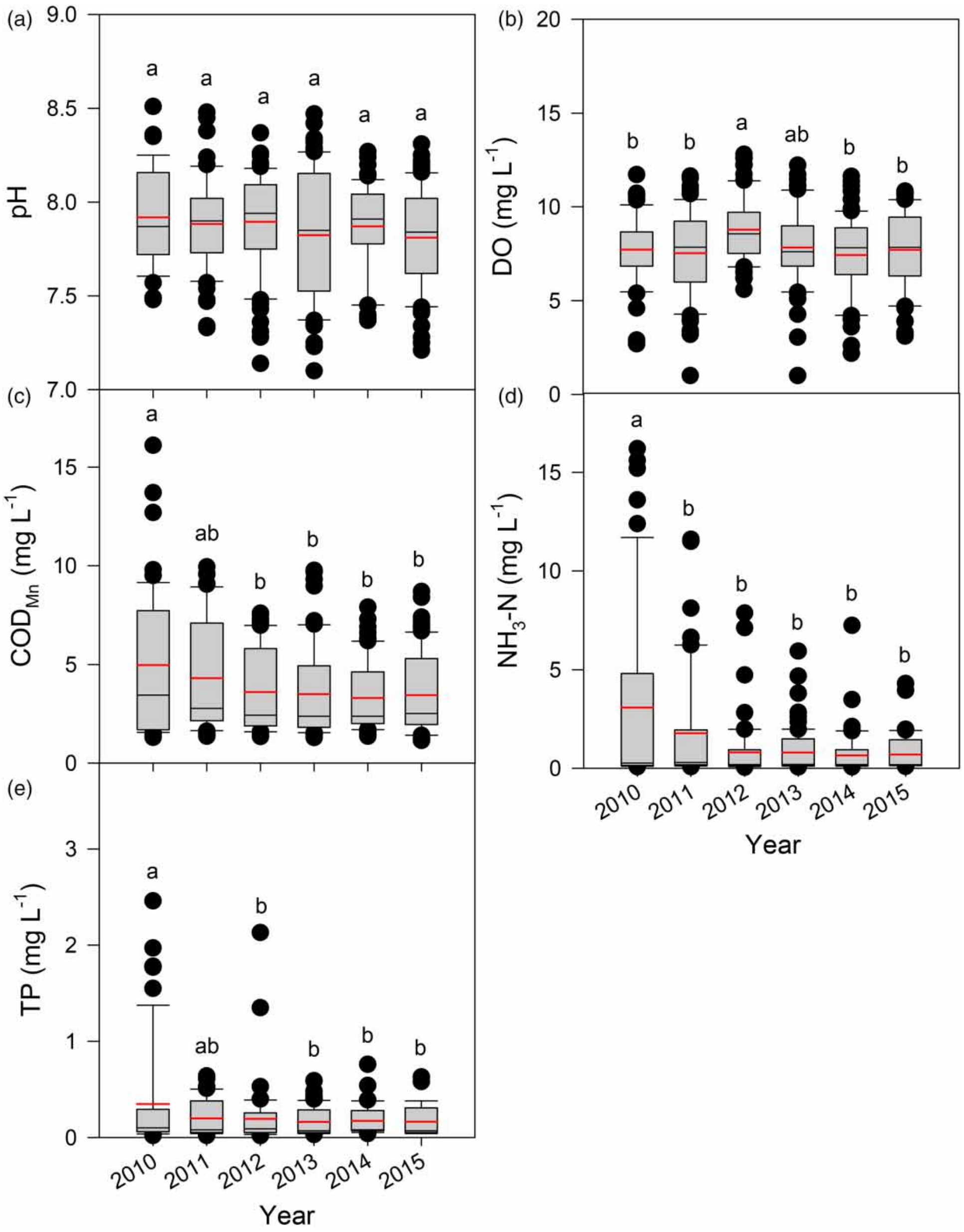


Figure 5 | Annual variations in pH (a) and concentrations of DO (b), COD$_{Mn}$ (c), NH$_3$-N (d) and TP (e) in the urbanizing Chongqing reach of Jialing River during 2010–2015. Symbols of boxplot represented as follows: Mean data are red lines, Median data are black lines, 25th and 75th percentiles data are lower and upper edges, 10th and 90th percentiles are lower and upper bars and <10th and >90th percentiles data are lower and upper dots outside, respectively. Different lowercase letters above the upper dots indicate significant differences among sampling sites.

Szynkiewicz 2019). Slightly alkaline pH is preferable in river water since some pollutants such as heavy metals can be removed by carbonate and bicarbonate precipitates (Ahipathy & Puttaiah 2006; Clark *et al.* 2014). In this study, the alkaline river water was also recorded overall which implied the rare existence of organic and inorganic oxidation substances. This was further supported by the observed higher DO concentration (average 7.89 mg L^{-1}) and lower COD$_{Mn}$ concentration (average 3.81 mg L^{-1}) relative to the polluted waters referring to the Environmental Quality Standards for Water Quality (2002). This result was also responsible for the significant relationships between pH and DO as well as COD$_{Mn}$ concentrations in this study.

Table 2 | Spearman' rank correlations between pH, and concentrations of DO, COD_{Mn}, NH_3-N and TP in dry and wet seasons in the urbanizing Chongqing reach of Jialing River

Season	Variable	DO	COD_{Mn}	NH_3-N	TP
Dry	pH	0.357**	−0.151*	−0.142*	−0.048
	DO		−0.548**	−0.455**	−0.406**
	COD_{Mn}			0.805**	0.791**
	NH_3-N				0.847**
Wet	pH	−0.061	0.054	−0.010	−0.004
	DO		−0.519**	−0.499**	−0.589**
	COD_{Mn}			0.698**	0.758**
	NH_3-N				0.724**

**Correlation is significant at the 0.01 level (2-tailed).

*Correlation is significant at the 0.05 level (2-tailed).

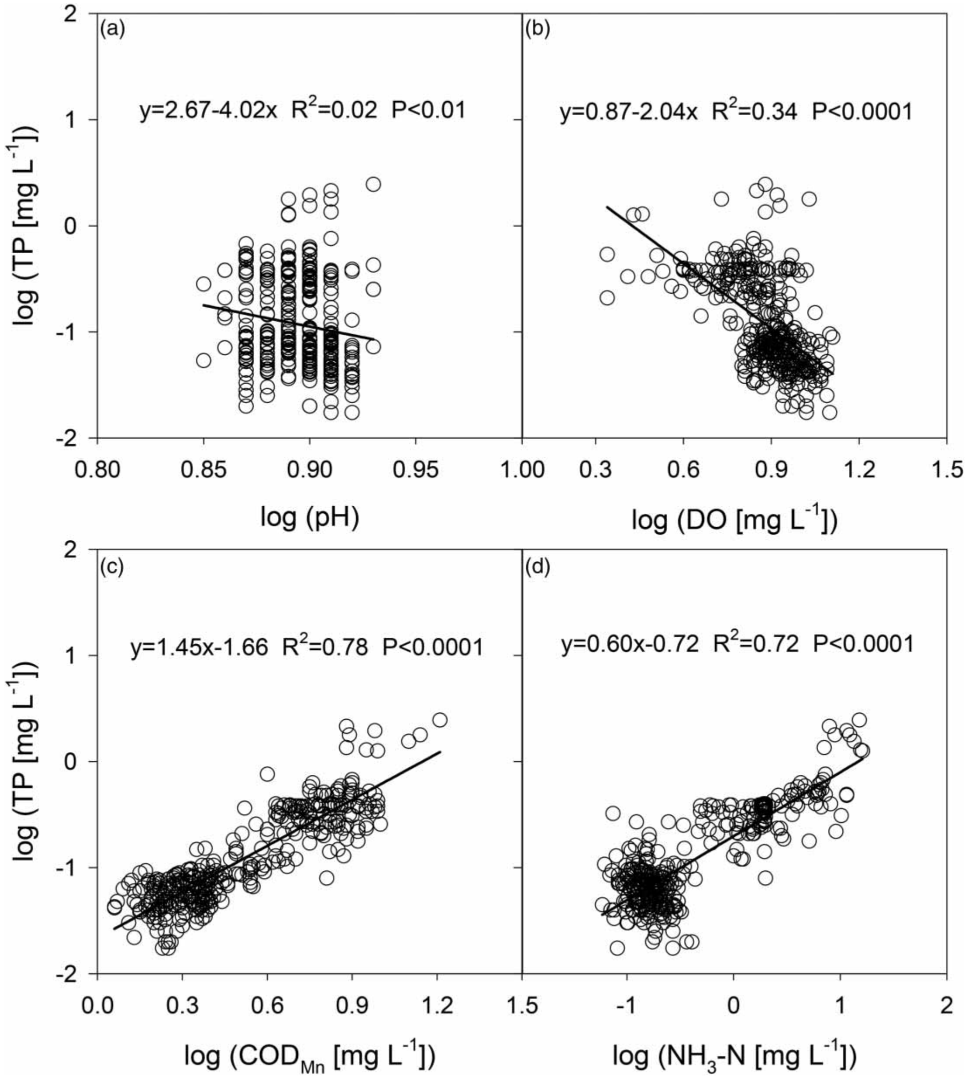


Figure 6 | Relationships between TP concentration and other study water quality variables. (a) TP concentration versus pH, (b) TP concentration versus DO concentration, (c) TP concentration versus COD_{Mn} concentration, (d) TP versus NH_3-N concentration.

Additionally, the river water showed the average NH_3-N concentration of 1.24 mg L^{-1} and TP concentration of 0.21 mg L^{-1}, and significant relationships between NH_3-N and TP concentrations were found in several sampling sites. This result suggested that the potentially consistent sources, such as excess fertilizers and soil erosion occurring in the upper agricultural lands, contributed to the diminished water quality as a result of the heightened human activities and changing climate (Buda *et al.* 2015; Tan *et al.* 2015; Zhang *et al.* 2020). Gong *et al.* (2013) reported that a large tract of flower plantations that had been applied by substantial fertilizers was the pollution source degrading the aquatic ecosystem in the tributary Liangtan River. Similar conditions were also found in the trunk Jialing River (Wu *et al.* 2012a, 2012b). Iida *et al.* (2011), suggesting that ammonium nitrogen and phosphorus could both attach to soil particles and be transported into the downstream river through runoff discharge accompanied by severe soil erosion. Thus, an important way to reduce water quality degradation in rivers is the rational application of fertilizers and controlling soil erosion in the surrounding agricultural lands.

The water quality of Jialing River also presented significant temporal variations. The monthly changes in pH and concentrations of DO, COD_{Mn}, NH_3-N and TP showed similar trends, presenting almost the highest values in February, March and April, and the lowest values in June and August. The seasonal changes also proved these findings, presenting the lower pH and concentrations of DO, NH_3-N and TP in the wet season (May–September) rather than in the dry season (October–April). These findings were further supported by the relationships among these variables in monthly and seasonal scales. The results were partially consistent with the previous findings given by Stevenson *et al.* (2012) who found that DO concentration was lower in summer due to the high algal biomass which could deplete oxygen concentrations by respiration. However, they also found that pH increased with algal biomass owing to the algal uptake of CO_2 and the change in the carbonate equilibrium, which was in contrast with our findings. Parinet *et al.* (2004) found the negative relationship between pH and algal biomass because of the production of acidic compounds in the course of the alga decomposition in a tropical lake system. A similar mechanism was presumably found in river water. The reason for the decline in both pH and DO concentration in the wet season was probably because the relatively high temperature accelerated the decomposition of organic matters by enhancing the microorganism activities (Voutsa *et al.* 2001). This process could not only decrease the pH value of river water through acidification, but also consume a considerable amount of oxygen as a consequence of microbial metabolism, leading to the decline in DO concentration (Gong *et al.* 2013).

The dilution effects resulting from the upstream flow discharge decreased the NH_3-N and TP concentrations in the wet season (Tabari *et al.* 2011; Schliemann *et al.* 2021). This was also in support of the previous findings of Xie *et al.* (2015) who suggested that pollutant concentrations were not necessarily linked to river discharge, and the negative relationship between them was commonly found, resulting in the dilution of pollutants in the wet season. This result indicated that the increase in flow discharge from the upper reach was possibly conducive to ameliorating water quality (Iida *et al.* 2011). However, the COD_{Mn} concentration did not significantly differ by season. This was likely due to the obstinate pollutants originating from the wastewater treatment plants, industrial operations and domestic sewage, regardless of seasonal variability (Li *et al.* 2021; Schliemann *et al.* 2021).

Our results showed that the pH had no inter-annual difference, and DO concentration presented significant inter-annual variability, and concentrations of COD_{Mn}, NH_3-N and TP also had decreased trends from 2010 to 2015. This suggested the potential improvement of water quality due to the launching of controlling measures for the point source pollution in recent years. Gong *et al.* (2013) provided several strategies to improve maximumly the water quality, including reducing rural and urban domestic wastewater loads and industrial pollution loads, and reusing of solid wastes (e.g., municipal solid waste and agricultural residues). These strategies were helpful in preventing point source pollutants from transporting into the rivers, contributing to the reduction in water quality degradation for both the trunk Jialing River and its tributaries. In recent years, the non-point source pollution from overland flow accompanied by soil erosion has been demonstrated to contribute substantial nutrients to the aquatic ecosystem, degrading the water quality worldwide (Fraga *et al.* 2021; Schliemann *et al.* 2021). However, the measures, such as vegetative filter strips (Blanco-Canqui *et al.* 2004), conservation tillage (Issaka *et al.* 2019) and rational fertilization (Du *et al.* 2021), for controlling soil erosion and non-point source pollution are still not adequately assessed. Therefore, more attention should be paid to develop effective strategies for controlling soil erosion and non-point source pollution with the aim of improving downstream water quality in the future.

CONCLUSIONS

The spatiotemporal water quality variations were interpreted in the urbanizing Chongqing reach of Jialing River from January 2010 to December 2015. Relatively lower pH and DO concentration but higher COD_{Mn}, NH_3-N and TP concentrations were found in the tributary river relative to the trunk Jialing River, suggesting the relatively greater dilution effects occurring in the trunk river. Lower pH and concentrations of DO, NH_3-N and TP were found in the wet season (May–September) rather than in the dry season (October–April), and no significant difference in COD_{Mn} concentration was found in the two seasons, implying obstinate pollutants resulting from nature and human activities. The pH presented no pronounced inter-annual variation while DO showed a significant inter-annual difference. Concentrations of COD_{Mn}, NH_3-N and TP showed decreased trends from 2010 to 2015, indicating the potential improvement of water quality attributed to the implementation of point source pollution control measures in the urbanizing Chongqing reach of Jialing River. However, soil erosion and non-point source pollution are the key factors degrading water quality, and effective strategies for minimizing these effects are urgently required to improve river water quality in the near future.

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DECLARATION OF COMPETING INTEREST

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

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

REFERENCES

Ahipathy, M. V. & Puttaiah, E. T. 2006 Ecological characteristics of Vrishabhavathy River in Bangalore (India). *Environmental Geology* **49**, 1217–1222.

Bernhardt, E. S., Blaszczak, J. R., Ficken, C. D., Fork, M. L., Kaiser, K. E. & Seybold, E. C. 2017 Control points in ecosystems: moving beyond the hot spot hot moment concept. *Ecosystems* **20**, 665–682.

Blanco-Canqui, H., Gantzer, C. J., Anderson, S. H., Alberts, E. E. & Thompson, A. L. 2004 Grass barrier and vegetative filter strip effectiveness in reducing runoff, sediment, nitrogen, and phosphorus loss. *Soil Science Society of America Journal* **68** (5), 1670–1678.

Brooks, B. W., Riley, T. M. & Taylor, R. D. 2006 Water quality of effluent-dominated ecosystems: ecotoxicological, hydrological, and management considerations. *Hydrobiologia* **556**, 365–379.

Buda, A. R., Williard, K. W. J., Schoonover, J. E. & Srinivasan, M. S. 2015 Featured collection introduction: agricultural hydrology and water quality. *Journal of American Water Resources Association* **51**, 877–882.

Carpenter, S. R., Caraco, N. F., Correll, D. L., Howarth, R. W., Sharpley, A. N. & Smith, V. H. 1998 Nonpoint pollution of surface waterswith phosphorus and nitrogen. *Ecological Applications* **8**, 559–568.

Clark, E. V., Odhiambo, B. K. & Ricker, M. C. 2014 Comparative analysis of metal concentrations and sediment accumulation rates in two Virginian 39 reservoirs, USA: Lakes Moomaw and Pelham. *Water, Air, & Soil Pollution* **225** (2), 1860.

Dragun, Z., Kapetanović, D., Raspor, B. & Teskeredžić, E. 2011 Water quality of medium size watercourse under baseflow conditions: the case study of River Sutla in Croatia. *Ambio* **40**, 391–407.

Du, Y. N., Li, T. Y. & He, B. H. 2021 Runoff-related nutrient loss affected by fertilization and cultivation in sloping croplands: an 11-year observation under natural rainfall. *Agriculture, Ecosystems and Environment* **319**, 107549.

Dwivedi, D., Arora, B., Steefel, C. I., Dafflon, B. & Versteeg, R. 2018 Hot spots and hot moments of nitrogen in a riparian corridor. *Water Resources Research* **54** (1), 205–222.

Environmental Quality Standards for Water Quality 2002 Ministry of Environmental Protection of the People's Republic of China, Beijing, China.

Fraga, M. D. S., da Silva, D. D., Reis, G. B., Guedes, H. A. S. & Elesbon, A. A. A. 2021 Temporal and spatial trend analysis of surface water quality in the Doce River basin, Minas Gerais, Brazil. *Environment, Development and Sustainability* **23**, 12124–12150.

Gong, D. C., Gao, X., Ntakirutimana, T., Guo, J. S. & Li, K. 2013 Water quality status along the Liangtan River and control planning alternatives. *Polish Journal of Environmental Studies* **22**, 1061–1067.

Grill, G., Lehner, B., Thieme, M., Geenen, B., Tichner, D., Antonelli, F., Babu, S., Borrelli, P., Cheng, L., Crochetiere, H., Macedo, H. E., Filgueiras, R., Goichot, M., Higgins, J., Hogan, Z., Lip, B., McClain, M. E., Meng, J., Mulligan, M., Nilsson, C., Olden, J. D., Opperman, J. J., Petry, P., Liermann, C. R., Sáenz, L., Salinas-Rodríguez, S., Schelle, P., Schmitt, R. J. P., Snider, J., Tan, F., Tockner, K., Valdujo, P. H., van Soesbergen, A. & Zarfl, C. 2019 Mapping the world's free-flowing rivers. *Nature* **569**, 215–221.

Iida, T., Inkhamseng, S., Yoshida, K. & Tanji, H. 2011 Characterization of water quality variation in the Mekong River at Vientiane by frequent observations. *Hydrological Processes* **25** (23), 3590–3601.

Issaka, F., Zhang, Z., Zhao, Z. Q., Asenso, E., Li, J. H., Li, Y. T. & Wang, J. J. 2019 Sustainable conservation tillage improves soil nutrients and reduces nitrogen and phosphorous losses in maize farmland in southern China. *Sustainability* **11**, 2397.

Li, T. Y., Zhang, Y. Q., He, B. H., Yang, B. & Huang, Q. 2021 Periodically hydrologic alterations decouple the relationships between physicochemical variables and chlorophyll-a in a dam-induced urban lake. *Journal of Environmental Sciences* **99**, 187–195.

Long, T. Y., Wu, L., Meng, G. H. & Guo, W. H. 2011 Numerical simulation for impacts of hydrodynamic conditions on algae growth in Chongqing Section of Jiangling River, China. *Ecological Modelling* **222**, 112–119.

Luthy, R. G., Sedlak, D. L., Plumlee, M. H., Austin, D. & Resh, V. H. 2015 Wastewater-effluent-dominated streams as ecosystem-management tools in a drier climate. *Frontiers in Ecology and the Environment* **13**, 477–485.

McClain, M. E., Boyer, E. W., Dent, C. L., Gergel, S. E., Grimm, N. B., Groffman, P. M., Hart, S. C., Harvey, J. W., Jonston, C. A., Mayorga, E., McDowell, W. H. & Pinay, G. 2003 Biogeochemical hot spots and hot moments at the interface of terrestrial and aquatic ecosystems. *Ecosystems* **6**, 301–312.

Moatar, F., Abbott, B. W., Minaudo, C., Curie, F. & Pinay, G. 2017 Elemental properties, hydrology, and biology interact to shape concentration-discharge curves for carbon, nutrients, sediment, and major ions. *Water Resources Research* **53** (2), 1270–1287.

Parinet, B., Lhote, A. & Legube, B. 2004 Principal component analysis: an appropriate tool for water quality evaluation and management-application to a tropical lake system. *Ecological Modelling* **178**, 295–311.

Ramsey, A. B. & Szynkiewicz, A. 2019 Coupled chemical-isotope assessment of potential metal releases to the water column from river sediments impacted by coal ash spill. *Applied Geochemistry* **107**, 34–44.

Ripl, W. 2003 Water: the bloodstream of the biosphere. *Philosophical Transactions of the Royal Society B Biological Sciences* **358**, 1921–1934.

Safari, M., Ahmadfazeli, A., Ghanbari, A., Mokhtari, Z. & Soleimani, Z. 2021 Assessment of the HablehRood River water quality for drinking and irrigation purposes in Garmsar, Iran. *Environmental Earth Sciences* **80**, 336.

Schliemann, S. A., Grevstad, R. N. & Brazeau, I. H. 2021 Water quality and spatio-temporal hot spots in an effluent-dominated urban river. *Hydrological Processes* **35**, e14001.

SEPA, State Environmental Protection Administration 2002 *Monitoring and Analysis Methods for Water and Wastewater*, 4th edn. China Environmental Science Press, China.

Spry, D. J. & Wiener, J. G. 1991 Metal bioavailability and toxicity to fish in low-alkalinity lakes: a critical review. *Environmental Pollution* **71** (24), 243–304.

Stevenson, R. J., Bennett, B. J., Jordan, D. N. & French, R. D. 2012 Phosphorus regulates stream injury by filamentous green algae, DO, and pH with thresholds in responses. *Hydrobiologia* **695** (1), 25–42.

Tabari, H., Marofi, S. & Ahmadi, M. 2011 Long-term variations of water quality parameters in the Maroon River, Iran. *Environmental Monitoring and Assessment* **177** (1), 273–287.

Tan, X., Xia, X. L., Li, S. Y. & Zhang, Q. F. 2015 Water quality characteristics and integrated assessment based on multistep correlation analysis in the Danjiangkou Reservoir, China. *Journal of Environmental Informatics* **25** (1), 60–70.

van Vliet, M. T. H., Florke, M. & Wada, Y. 2017 Quality matters for water scarcity. *Nature Geoscience* **10** (11), 800–802.

Varol, M. 2012 Temporal and spatial dynamics of nitrogen and phosphorus in surface water and sediments of a transboundary river located in the semi-arid region of Turkey. *Catena* **100**, 1–9.

Vega, M., Pardo, R., Barrado, E. & Deban, L. 1998 Assessment of seasonal and polluting effects on the quality of river water by exploratory data analysis. *Water Research* **32** (12), 3581–3592.

Voutsa, D., Manoli, E., Samara, C., Sofoniou, M. & Stratis, I. 2001 A study of surface water quality in Macedonia, Greece: speciation of nitrogen and phosphorus. *Water Air & Soil Pollution* **129**, 13–32.

Walsh, C. J., Roy, A. H., Feminella, J. W., Cottingham, P. D., Groffman, P. M. & Morgan, R. P. 2005 The urban stream syndrome: current knowledge and the search for a cure. *Journal of the North American Benthological Society* **24** (3), 706–723.

Wu, L., Long, T. Y., Liu, X. & Guo, J. S. 2012a Impacts of climate and land-use changes on the migration of non-point source nitrogen and phosphorus during rainfall-runoff in the Jialing River Watershed, China. *Journal of Hydrology* **475**, 26–41.

Wu, L., Long, T. Y., Liu, X. & Mmereki, D. 2012b Simulation of soil loss processes based on rainfall runoff and the time factor of governance in the Jialing River Watershed, China. *Environmental Monitoring and Assessment* **184**, 3731–3748.

Xie, Y., Li, X., Wang, H. & Li, W. 2013 Spatio-temporal variation analysis of hydrochemical characteristics in the Luanhe River Basin, China. *Water Science & Technology* **67** (6), 1332–1338.

Xie, Y., Li, X., Wang, L. & Qu, X. 2015 Seasonal and spatial variation in hydrochemical characteristics of a semi-arid river basin, China. *Human and Ecological Risk Assessment* **21** (3–4), 845–861.

Zhang, S. H., Hou, X. N., Wu, C. S. & Zhang, C. 2020 Impacts of climate and planting structure changes on watershed runoff and nitrogen and phosphorus loss. *Science of the Total Environment* **706**, 134489.

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