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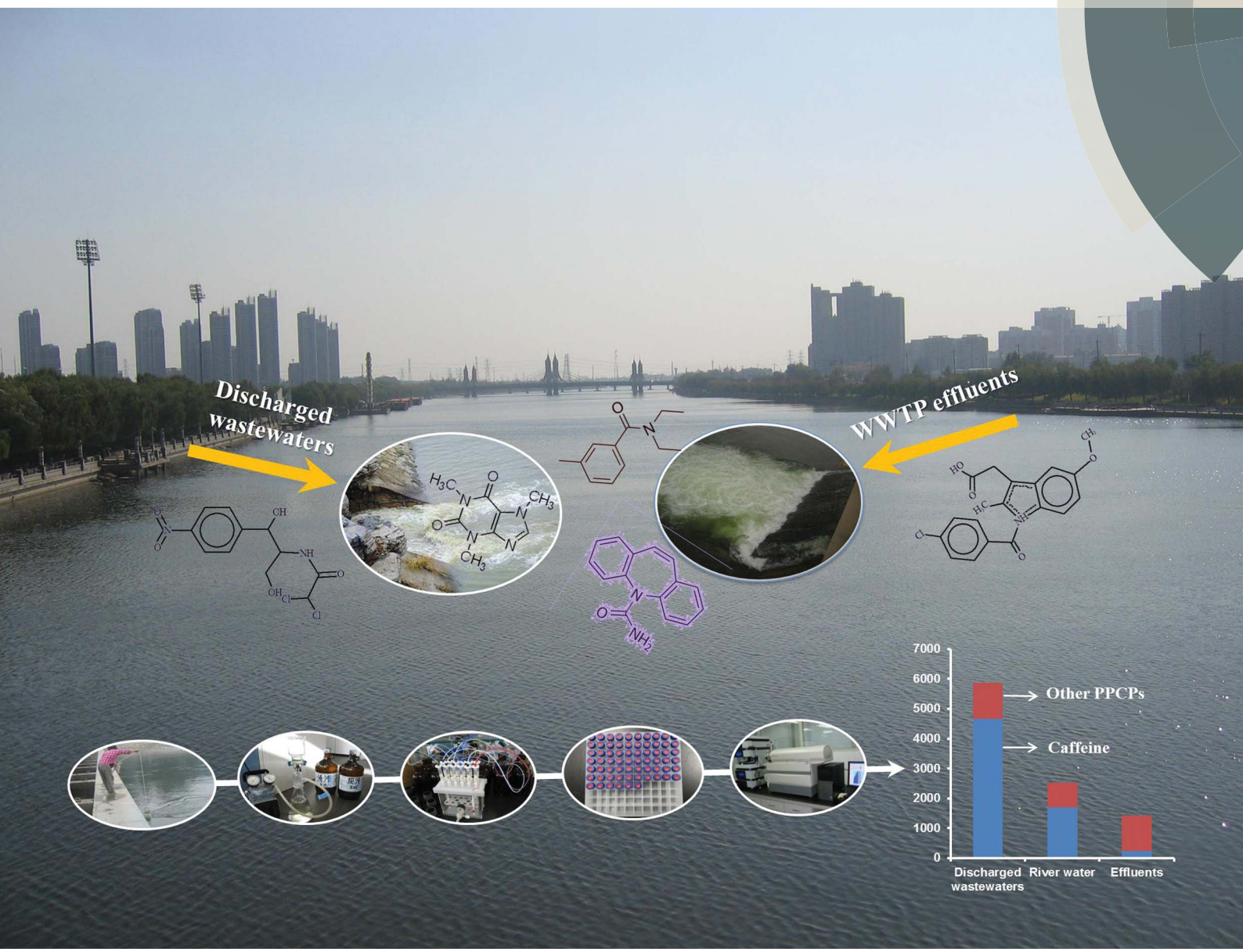

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Pharmaceuticals and personal care products (PPCPs) in urban and suburban rivers of Beijing, China: occurrence, source apportionment and potential ecological risk†

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This study analyzed 15 pharmaceuticals and personal care products (PPCPs) in two rivers with different urbanization levels in the surrounding watershed (urban and suburb) in Beijing, China. Along the rivers, effluent samples from wastewater treatment plants (WWTPs) and wastewater samples from direct discharge outlets were also collected to reveal their possible contribution to the occurrence of PPCPs in these two rivers. Among the 15 PPCPs, 14 compounds were detected with caffeine (maximum 11 900 ng L^{-1}) being the dominant compound. The total concentration of the detected PPCPs in direct discharge outlets (median 4706 ng L^{-1}) was much higher than that in river waters (2780 ng L^{-1}) and WWTP effluents (1971 ng L^{-1}). The suburban-influenced Liangshui River had significantly higher PPCP concentrations compared to the urban-influenced Qing River due to more input of untreated wastewater from direct discharge outlets. Source apportionment showed that approximately 55% of the total PPCPs were contributed by untreated wastewater in the suburban-influenced river. Finally, ecological risk assessment has been regarded as a necessary part of general research. According to the environmental risk assessment results, caffeine, trimethoprim and metoprolol were found to be the most critical compounds, due to their high risk quotient values. The results of the present study can provide useful information for future PPCP pollution control and sustainable water management in Beijing, China.

Environmental impact

PPCP pollution has been generally thought to be positively correlated with the regional urbanization level and population density. However, the situation may differ in developing countries, *e.g.* China, due to poor infrastructure development. Our study on the urban-influenced Qing River and suburban-influenced Liangshui River in Beijing shows that, rather than the Qing River influenced by the larger population density, the Liangshui River is more polluted by PPCPs due to a much larger contribution from untreated wastewater. Poor infrastructure development leads to higher PPCP pollution. The study helps readers better understand the relationship between PPCP pollution and urbanization levels and contributes to PPCP source and pollution management.

1. Introduction

Pharmaceuticals and personal care products (PPCPs), which contain diverse organic groups, such as antibiotics, hormones, antimicrobial agents, synthetic musks, *etc.*, have raised significant concerns in recent years for their continuous input and potential threats to the aquatic environment and human health.[1–3] As an important group of organic pollutants with intensive studies in recent years, PPCPs have been found to be ubiquitous in the aquatic environment throughout the world.[2,4–10] China is the largest producer and consumer of PPCPs in the world. The pharmaceutical production can account for more than 20% of the total production volume of the world,[11] and the average usage of antibiotics by Chinese is 10 times more than the usage by Americans.[12] China is also among the top three countries with the largest personal care product consumption, together with America and Japan.[11,13] PPCPs have become pervasive in surface water of China, with levels varying from ng L^{-1} to μg L^{-1}.[14]

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PPCPs can enter the aquatic environment *via* multiple sources including treated and untreated wastewater, industrial discharge, leaching of municipal landfills, leaking of septic systems, *etc.*[1] Previous studies have reported that higher PPCP concentrations are generally associated with higher population densities in urban areas, because of the presence of a PPCP major source, *i.e.* WWTP effluents.[15–17] However, the situation seems to be different in some other regions. For example, Bunch and Bernot[18] found that higher pharmaceutical concentrations were measured in streams with more than 90% agricultural land use in central Indiana due to the higher contribution of nonpoint sources such as septic tanks. Our recent study found that raw sewage significantly contributed to PPCP pollution in the surface water of Beijing, China.[19,20] However, the abundance and sources of PPCPs have not been well compared in between urban- and suburban-influenced rivers in Beijing. The objective of this study was to investigate the occurrence and sources of PPCPs in the urban- and suburban-influenced rivers in Beijing, as well as to evaluate the potential ecological risks of PPCPs in these rivers. The results of the present study can provide useful information for future PPCP pollution control and sustainable water management in Beijing, China.

2. Materials and methods

2.1 Study area and sampling

Beijing, the capital of China, is one of the most densely populated cities in the world. Beijing spans an area of over 16 800 km^2 (with an urban area of 1040 km^2), and the population has exceeded 20 million by the end of 2011. Beijing city consists of eight urban districts and ten suburban districts. The Qing River and Liangshui River selected in this study are two major tributaries of the Beiyun River in Beijing (Fig. 1). Detailed information on the Beiyun River basin has been provided in our previous study.[19] The Qing River is mainly situated in Haidian and Chaoyang Districts and predominantly influenced by urban inputs, whereas the Liangshui River is mainly situated in Tongzhou and Daxing Districts and predominantly influenced by suburban inputs. The Qing River is 23.6 km long, with a watershed area of 210 km^2, and has a population of 3.0 million. The land use within the Qing River basin consists of ~6% agricultural cultivation and 70% developed land. The Liangshui River is 56.8 km long, with a watershed area of 624 km^2, and has a population of 4.5 million. The land use within the Liangshui River basin consists of 55% agricultural cultivation and ~10% developed land.

The sampling campaign was conducted between April and May, 2014. River samples were collected from 8 sites (QR1-QR8) in the Qing River and 15 sites (LSR1-LSR15) in the Liangshui River (Fig. 1). Meanwhile, 5 effluent samples were taken as grab samples from five WWTPs (QWTP, XJHWTP, XHMWTP, BSWTP and YJWTP), whose effluents are directly discharged into the two rivers. Detailed information on each WWTP investigated is shown in Table S1 (ESI†). 12 wastewater samples (QD1-QD3 and LD1-LD9) were taken from direct discharge outlets occasionally found along the investigated two rivers, where water was directly discharged into the two rivers; their sources were not very clear but thought to be mainly from residential areas. For all sampling sites, replicate samples were collected. No rain event occurred in the previous week of the campaign or during sampling days. All water samples were stored in pre-cleaned amber glass bottles and maintained at 4 °C. Water samples were extracted within 2 days after collection.

2.2 Chemicals

15 target PPCPs including bezafibrate (BF), carbamazepine (CBZ), caffeine (CF), chloramphenicol (CP), diclofenac (DF), gemfibrozil (GF), indometacin (IM), ketoprofen (KP), mefenamic acid (MA), metoprolol (MTP), nalidixic acid (NA), propranolol (PPN), sulpiride (SP), trimethoprim (TP), and *N*,*N*-diethyl-*meta*-toluamide (DEET) were purchased from Sigma-Aldrich (Steinheim, Germany) (Table S2 in the ESI†). ^{13}C-phenacetin obtained from Sigma-Aldrich, gemfibrozil-d_6 from Toronto Research Chemicals Inc. (Toronto, Canada), and mecoprop-d_3, chloramphenicol-d_5, and DEET-d_7 from Dr. Ehrenstorfer (Augsburg, Germany) were used as internal standards. All standard solutions were stored at −18 °C in the dark

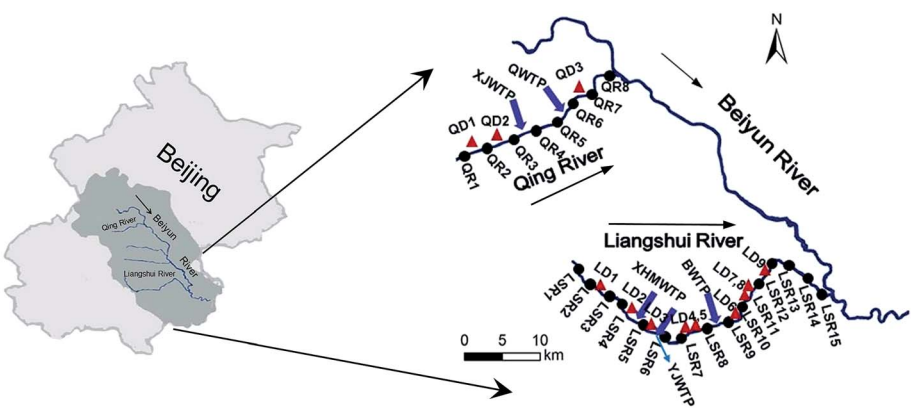

Fig. 1 Map of sampling sites in two rivers of Beijing (arrow indicates the flow direction). The dots, blue arrows and red triangles indicate the river water, WWTP effluent and discharged wastewater sampling sites, respectively.

prior to use. All solvents used were of HPLC grade from Dikma, USA, and ultrapure water was produced by using a Milli-Q unit (Millipore, USA).

2.3 Sample extraction and analysis

PPCPs were extracted and analyzed following the methods described in our previous studies with minor modifications.[19,21] Briefly, the collected samples (500 mL) were first filtered through pre-baked glass-fiber filters (GF/F, 0.7 μm; Whatman) and were subsequently spiked with 50 ng internal standards before solid phase extraction (SPE) using Oasis HLB cartridges (200 mg, 6 mL, Waters). The SPE cartridges were first conditioned with 10 mL of methanol and 10 mL of ultrapure water, before the water samples were percolated at a flow rate of 6 mL min^{-1}. After loading the samples, the cartridges were washed with 10 mL of ultrapure water and vacuum dried for 15–20 min to remove excess water. The target compounds were eluted from the SPE cartridges using 8 mL of methanol, which were evaporated to near dryness under a gentle stream of N_2. Finally, the extracts were reconstituted with 500 μL methanol–water (25 : 75, v/v) before being analyzed.

PPCPs were analyzed using high-performance liquid chromatography (Ultimate3000 HPLC system, Dionex, USA) followed by electrospray ionization and tandem mass spectrometry (ESI-MS/MS, API3200, AB Sciex, USA). PPCPs were separated by using two chromatographic columns. An Agilent XDB C18 column (150 mm × 3.0 mm, particle size of 3.5 μm) was used to separate CBZ, CF, DEET, MTP, NA, PPN, TP, SP, DEET-d_7 and ^{13}C-phenacetin in positive ion mode (ESI^+), while a Capcell PAK C18 column (100 mm × 3.0 mm, particle size of 3.0 μm) was used for BF, CP, DF, GF, KP, IM, MA, mecoprop-d_3, chloramphenicol-d_5 and gemfibrozil-d_6 in negative ion mode (ESI^-). The injection volume was 10 μL, and the column temperature was 30 °C. A mobile phase of 0.1% (v/v) formic acid in ultrapure water (mobile phase A) and methanol (mobile phase B) was used for ESI^+ at a flow rate of 0.30 mL min^{-1}, and the mobile phase gradient was ramped from 15% to 40% B in 4 min and 40–100% B in 14 min, maintained at 100% B for 7 min, and then ramped down again to 15% B and kept for 10 min. A mobile phase of 2 mM ammonium acetate in ultrapure water (mobile phase A) and methanol (mobile phase B) was used for ESI^- at a flow rate of 0.35 mL min^{-1}, and the gradient was ramped from 20% to 40% B in 8 min and 40% to 100% B in 7 min, maintained at 100% B for 7 min, and then ramped down again to 20% B and kept for 10 min. Multiple reaction monitoring (MRM) mode was applied for detection and quantification. The MRM parameters of the target analytes and the internal standards were optimized by direct infusion of the pure analytes into the MS/MS compartment. Detailed information concerning optimized MRM conditions is presented in Table S2 (ESI†).

2.4 Quality assurance and quality control

Calibration of the compounds was done from 0.5 to 1500 ng mL^{-1}. Recoveries of target PPCPs and matrix effects (MEs) were assessed according to our previous study.[21] Among the 15 target compounds, the recoveries ranged from 45–117% and MEs were less than 30% for most target compounds. Recoveries and MEs were reproducible with the relative standard deviation below 20% for each compound. Calculations of the limit of quantification (LOQ) were based on the variability of seven times analyses of Milli-Q water fortified at 10 ng L^{-1} of the analytes. The LOQ was determined by multiplying the sample standard deviation calculated from each group of fortified solutions by the Student's t-variate for a one-sided t-test at the 99% confidence level with $n - 1$ degrees of freedom.[22] The LOQs for the target analytes were in the range of 1.78–11.0 ng L^{-1}. Detailed method performance parameters are described in Table S3 (ESI†). Field control, procedural blanks and solvent blanks were run for each batch of samples to check background pollution. PPCPs were not detected in any of these extraction blanks.

2.5 Source apportionment of PPCPs

Source apportionment analysis was conducted using principal component analysis followed by multiple linear regression (PCA-MLR) based on the profiles of all detected compounds to interpret the contribution from different sources to total PPCPs. In PCA with Kaiser Normalization and varimax rotation, only factors with eigen values >1 were used for identification of the possible sources. MLR analysis of the PCA factor scores is used to quantify the source contribution.[23] Using the PCA factor scores as independent variables, MLR was run with the standard normal deviate of the SumPPCP values as the dependent variables as shown in eqn (1). Stepwise MLR modeling was used to remove any insignificant parameters, and only parameters that were significant at the 0.10 significance level were retained as eqn (1). After normalization, the multiple regression model is represented by the simple formula:

$$\hat{Z}_{\mathrm{SumPPCP}} = \sum B_k t_k \quad (1)$$

where SumPPCP is the total concentrations of the detected PPCPs in the present study, $\hat{Z}$ is the standard normalized deviate of the SumPPCP values, B_k is the modeled regression coefficient, and t_k is the factor score calculated by PCA.

The mean percentage contributions of each factor are calculated by eqn (2):

$$\text{Mean contribution of source } k\ (\%) = 100 \times (B_k/\textstyle\sum B_k) \quad (2)$$

The contribution of each source k to the SumPPCP is calculated by eqn (3).

$$\text{Contribution of source } k\ (\text{ng L}^{-1}) = \mathrm{mean}_{\mathrm{SumPPCP}} \times (B_k/\textstyle\sum B_k) + B_k \sigma_{\mathrm{SumPPCP}} t_k \quad (3)$$

where $\mathrm{mean}_{\mathrm{SumPPCP}}$ is the mean concentration of SumPPCP, and $\sigma_{\mathrm{SumPPCP}}$ is the standard deviation of SumPPCP for all samples.

2.6 Potential ecological risks

The potential risk posed by each PPCP was assessed based on the risk quotient (RQ) value, which is expressed as the ratio between the maximum measured environmental concentration

(MEC) and the predicted no-effect concentration (PNEC) of an individual compound, as suggested by the EMEA.[24] PNEC values used in the risk analysis are 1000 times lower than the lowest ecotoxicity concentration values found for three representative trophic levels of the ecosystem, fish, daphnia and algae. Data from the literature about the toxicity of the detected PPCPs to tested organisms are given in Tables S4 and S5 (ESI†). The potential environmental adverse effect on aquatic organisms fell into three levels: RQ < 0.1, low risk; 0.1 ≤ RQ ≤ 1, medium risk; RQ ≥ 1, high risk.[25]

3. Results and discussion

3.1 PPCPs in river water and wastewater

The concentration ranges of the selected PPCPs in river water and wastewater are shown in Fig. 2 and Table S3 (ESI†). Among the 15 PPCPs, 12 PPCPs (including CF, DEET, CBZ, MA, SP, IM, CP, GF, BF, MTP, KP and DF) were detected in 100% of the river water samples. NA (91%) and TP (69%) also exhibited high frequencies of detection, whereas PPN, a β-blocker, was not detected in any river sample (Table S3†). The total concentrations of the 14 detected PPCPs ranged from 276 to 6109 ng L^{-1} (median, 2780 ng L^{-1}) in river samples. The highest concentration was observed for CF, with a median concentration of 1870 ng L^{-1}. MTP (median, 115 ng L^{-1}), SP (90.0 ng L^{-1}), NA (89.7 ng L^{-1}), DEET (83.4 ng L^{-1}), KP (77.6 ng L^{-1}), DF (71.5 ng L^{-1}) and TP (51.5 ng L^{-1}) were also found in higher concentrations (Fig. 2). Other frequently detected PPCP compounds, including CBZ, IM, BF, GF, CP, and MA, showed relatively lower concentrations, with median concentrations below 50 ng L^{-1} in river samples (Fig. 2). Compared with our previous study on the surface water of Beijing, the concentration levels of all detected PPCPs in the present study were similar to those found in 2013 (Table 1).[19] CF showed the highest concentration in most river samples likely due to the universal use of caffeine, such as coffee, tea, cakes, chocolates and soft drinks.[15] The maximum concentration of CF (4720 ng L^{-1}) in the present study is higher than that observed in the Tennessee River, USA (175.7 ng L^{-1}),[26] Tone River, Japan (2100 ng L^{-1})[4] and Han River, Korea (250 ng L^{-1}),[7] but lower than that in the rivers in the USA (10 000 ng L^{-1})[27] and Costa Rica (1121446 ng L^{-1}).[9] In comparison, the median concentrations of CF, CP, NA, BF, DF, IM, MTP and SP in the present study were relatively higher than those observed in other water bodies, such as those in the USA, UK, Spain and Costa Rica and some rivers in Asia, while the median concentrations of DEET, TP, KP, GF, PPN, MA and CBZ were at middle levels compared to those of other water bodies, as shown in Table 1.

In addition to the river samples, we also analyzed 5 WWTP effluents and 12 wastewater samples collected from direct discharge outlets along the investigated rivers, which might contribute to the PPCP pollution in rivers (Fig. 2). Overall, the total PPCP concentrations in 12 wastewater samples from discharge outlets ranged from 219 ng L^{-1} (site QD2) to 13 805 ng L^{-1} (site QD3), with a median concentration of 4706 ng L^{-1}, 2 times higher than that in river samples (Fig. 3). CF (median 3570 ng L^{-1}) was found to be the compound with the highest concentration, followed by SP (median 173 ng L^{-1}), MTP (165 ng L^{-1}), DEET (127 ng L^{-1}) and KP (124 ng L^{-1}) (Table S3†). Analysis of the WWTP effluents showed that the

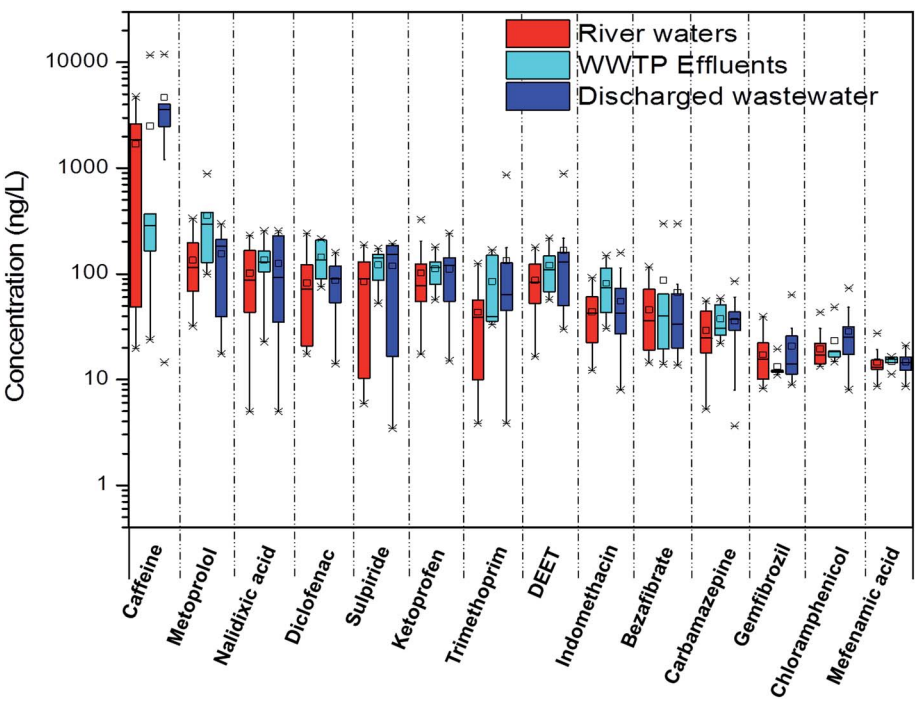

Fig. 2 Concentration ranges of PPCPs in river waters and wastewaters from WWTP effluents and direct discharge outlets. The solid bar in box marks the median, and the square in box marks the mean. The box denotes the 0.25 and 0.75 percentiles.

Table 1 Median concentrations (ng L^{-1}) of 15 target pharmaceuticals and personal care products (PPCPs) in river waters around the world[a]

	PPCP concentrations (ng L^{-1})															
Sampling locations	CP	NA	TP	GF	BF	DF	IM	MA	KP	MTP	PPN	CBZ	SP	DEET	CF	References
Tennessee River, USA	—	—	5.6	—	—	—	—	—	—	—	—	5.0	—	—	28.2	26
Rivers, UK	4	—	73	—	32	41	—	20	3	9	31	184	—	—	—	5
Tone River, Japan	nq	3.8	nq	—	35	2.6	16	nq	24	nq	nq	5.6	30	18	420	4
Rivers, Costa Rica	—	—	<7	<41	—	<14	<7	—	<7	—	—	<1	—	—	<24	9
Bangkok, Thailand[b]	—	—	18.4	—	—	—	—	291	—	—	—	—	—	—	763.8	10
Han River, Korea	—	—	50	27	—	67	—	—	—	—	—	132	—	160	111	7
Madrid, Spain	—	—	12.0	—	13.6	20	—	—	143	7.0	2.1	24.9	—	—	59.9	6
Pearl River, China	9.1	—	39.4	9.1	—	39.4	—	10.3	—	—	—	27.2	—	—	10.3	28
Hai River, China	—	—	—	64.4	—	23.4	—	nq	—	—	—	—	—	—	—	29
Liao River, China	—	—	—	nq	—	9.9	—	nq	—	—	—	—	—	—	—	
Yellow River, China	—	—	—	9.0	—	5.7	—	42.2	—	—	—	—	—	—	—	
Hai River, China	—	—	60	—	21	35	—	5	—	36	—	50	—	140	320	30
Beiyun River, China	8.2	36.7	54.2	9.1	22.6	65.3	32.6	4.2	67.6	91.4	nq	56.4	117.0	169.5	2130	19
Qing River and Liangshui River	17.0	89.7	51.5	15.5	36.3	71.5	42.3	13.1	77.6	115	nq	24.7	90.0	83.4	1870	This study

[a] nd, not quantified (<LOQ). [b] Mean values.

total PPCP concentrations ranged from 685 ng L^{-1} (QWTP) to 13 560 ng L^{-1} (YJWTP) (Fig. 3), with a median concentration of 1971 ng L^{-1}. MTP was the most abundant compound with the highest median concentration of 296 ng L^{-1}, followed by CF with a median concentration of 285 ng L^{-1}, and these two compounds accounted for more than 50% of total PPCPs in WWTP effluents. The exception is the YJWTP effluent, where CF was measured at the highest concentration of 11 700 ng L^{-1}, which was about 40–160 times higher than those in the other four WWTP effluents, and comparable to the levels at direct discharge outlets QD3 and LD5 (Fig. 3). In fact, YJWTP is a simple WWTP built in 2013 with only primary treatment equipment to remove particles to avoid a large amount of untreated sewage discharged directly into the Liangshui River, while obviously the elimination of PPCPs in YJWTP was very poor as shown in Fig. 3.

3.2 Comparison between the Qing River and Liangshui River

Generally, the most contaminated surface water samples from the Qing River and Liangshui River were collected at sampling sites adjacent to the direct discharge outlets or WWTP effluent outfalls. In the Qing River, the most contaminated water samples were found at sites QR7 and QR8. These two sites were situated downstream of direct discharge outlet QD3, where a huge amount of untreated wastewater was discharged into the Qing River, explaining the very high concentrations of PPCPs at these two sites (Fig. 3). Samples collected at site QR6 were also found to contain high PPCP concentrations, maybe due to the influence of WWTP effluents from XJHWTP and QWTP. In the Liangshui River, levels of PPCPs in the YJWTP effluent and wastewater collected from most of the direct discharge outlets were higher than those detected in their upstream and downstream river water samples (Fig. 3), showing that wastewater from direct discharge outlets and the YJWTP effluent should be the most important sources of PPCPs in the Liangshui River.

The total PPCP concentrations in the urban-influenced Qing River ranged from 276 (QR3) to 2921 ng L^{-1} (QR8), with a median concentration of 393 ng L^{-1}. The total PPCP concentrations in the suburban-influenced Liangshui River ranged from 284 (LSR2) to 6109 ng L^{-1} (LSR7), with a median concentration of 3325 ng L^{-1}. The Mann–Whitney U test showed that the total PPCP concentrations in the Liangshui River were significantly higher than those in the Qing River ($p < 0.01$). The differences in concentrations in these two rivers should be attributed to the differences in source inputs within the respective area. As shown in Fig. 3, the PPCP concentrations in wastewaters from direct discharge outlets and WWTP effluents along the Liangshui River were higher than those along the Qing River. The input of untreated wastewaters with higher PPCP concentrations should contribute to the higher PPCP levels in the Liangshui River.

3.3 Source apportionment of PPCPs in rivers

Caffeine has been shown to be a suitable marker for untreated domestic wastewater because it has high removal efficiencies (>90%) in WWTPs.[31–33] Among the 14 PPCPs quantified in this study, CF was the predominant compound in the suburban-influenced Liangshui River, with an average contribution of 69%. The fraction pattern of PPCP individuals in the surface water of the Liangshui River was very similar to that in the discharged wastewaters input into the Liangshui River (Fig. S1†), indicating the great influence of untreated wastewater. To further identify the source apportionment based on the profiles of all detected compounds, the PCA-MLR model was employed, which has been successfully used for source identification of polycyclic aromatic hydrocarbons in the atmosphere and sediment,[23,34] perfluoroalkyl acids in urban groundwater,[35] and PPCPs in surface water.[19] The compounds used for multivariate analysis are shown in Table 2 and undetected PPN was not included. Four principal components (PC1, PC2, PC3 and PC4) were identified after varimax rotation for the Liangshui

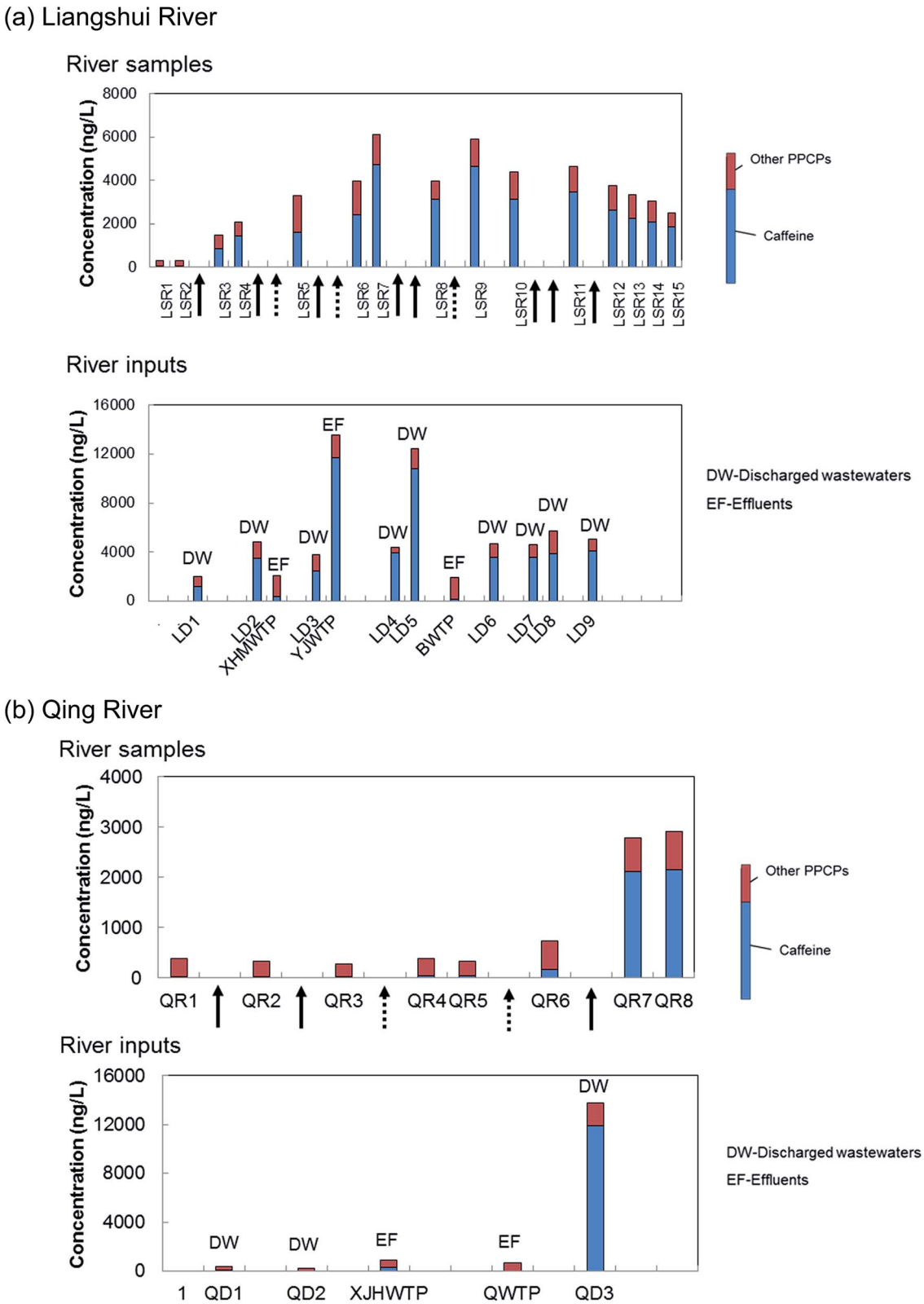

Fig. 3 Distribution of detected pharmaceuticals and personal care products (PPCPs) in the (a) Liangshui River and (b) Qing River with the data for the river samples on the top, and the data for the sources put on the bottom. Sampling sites are shown in order from upstream on the left to downstream on the right, as shown in Fig. 1. Solid arrow, direct discharge outlets. Dotted arrow, WWTP effluents.

Table 2 Varimax-rotated component matrix following principal component analysis of all water samples. Bold values denote PCA loading higher than 0.6

	Components for the Liangshui River				Components for the Qing River	
Variable	1	2	3	4	1	2
Mefenamic acid	**0.719**	0.256	0.024	0.231	**0.799**	0.312
Chloramphenicol	0.482	**0.766**	0.152	0.299	0.540	**0.722**
Gemfibrozil	0.017	0.562	−0.161	**0.756**	0.373	**0.713**
Bezafibrate	0.334	**0.743**	0.571	0.567	0.375	**0.920**
Nalidixic acid	0.282	0.473	**0.615**	−0.162	**0.674**	**0.641**
Indomethacin	0.227	0.198	**0.653**	0.107	**0.690**	**0.693**
Carbamazepine	0.512	−0.011	**0.645**	−0.068	**0.689**	0.572
Trimethoprim	0.008	**0.890**	−0.104	−0.266	**0.896**	0.500
Diclofenac	**0.873**	0.015	0.261	−0.052	**0.714**	0.542
Sulpiride	0.405	0.143	0.412	**0.604**	**0.682**	0.583
Metoprolol	**0.600**	−0.288	0.163	−0.043	**0.703**	**0.690**
Ketoprofen	0.891	0.069	−0.156	0.019	**0.721**	0.215
DEET	−0.184	−0.128	**0.736**	−0.127	0.456	**0.822**
Caffeine	0.066	**0.863**	0.243	0.303	0.490	**0.926**
Variance explained (%)	23.3	16.8	14.3	11.2	52.3	36.8

River, and these components accounted for 23.3%, 18.8%, 14.3% and 11.2% of the total variance, respectively. PC1 is highly associated with DF, KP, MA and MTP, which have low removal efficiencies (5–55%) in WWTPs.[33,36,37] Thus, high proportions of these compounds in this component suggest a source from treated wastewater. PC2 is characterized by the high loading of CF, CP, BF and TP. These compounds usually have high removal efficiencies (80–100%) in WWTPs.[31–33] Thus, PC2 can be highly indicative of the untreated wastewater source. PC3 and PC4 are correlated with GF, DEET, CBZ, IM, NA and SP. GF and DEET usually have high removal efficiencies (~80%), while CBZ, IM, NA and SP show low or even negative removal efficiencies (<50%) in WWTPs.[31–33] This profile for PC3 and PC4 might suggest nonpoint sources, such as leachates from random dumped garbage along the Liangshui River bank. This speculation can be confirmed by the high levels of GF and DEET in garbage leachates.[38,39]

In the Qing River, two principal components (PC1 and PC2) were identified, which accounted for 52.3% and 36.8% of the total variance, respectively. PC1 has high loadings of MA, NA, IM, CBZ, TP, SP, MTP, KP and DF, which suggests a source from treated sewage due to their moderate or low removal efficiencies in WWTPs.[33,38,39] PC2 is highly associated with CF, CP, DEET, BF and GF, which suggests an untreated wastewater input as mentioned above.

MLR analysis with the factor scores (t_k) against the standard normal deviate of the SumPPCP values ($\hat{Z}$) was performed to determine the mass apportionment of the four and two components in the Liangshui River and Qing River, respectively, according to eqn (1). The resulting equations were

$$\hat{Z}_{\mathrm{SumPPCP}} = 0.161t_{\mathrm{L1}} + 0.889t_{\mathrm{L2}} + 0.302t_{\mathrm{L3}} + 0.269t_{\mathrm{L4}} \ (R^2 = 0.895,\ p < 0.001) \quad (4)$$

$$\hat{Z}_{\mathrm{SumPPCP}} = 0.855t_{\mathrm{Q1}} + 0.431t_{\mathrm{Q2}} \ (R^2 = 0.975,\ p < 0.001) \quad (5)$$

for the Liangshui River and Qing River, respectively. Then, the percentage contributions calculated by using eqn (2) were 55% for untreated wastewater (t_{L2}), 10% for treated wastewater (t_{L1}), and 35% for nonpoint sources (t_{L3} and t_{L4}), respectively, in the Liangshui River. In the Qing River, the percentage contributions calculated by eqn (2) were 66% for treated wastewater (t_{Q1}) and 33% for untreated wastewater (t_{Q2}).

The contribution of each source k to the SumPPCP can be calculated by eqn (3). In this study, $\mathrm{mean}_{\mathrm{SumPPCP}}$ is 4205 ng L^{-1} and 1859 ng L^{-1}, and $\sigma_{\mathrm{SumPPCP}}$ is 2955 ng L^{-1} and 3703 ng L^{-1} for the Liangshui River and Qing River, respectively. Fig. 4 shows the estimated contributions for each source in all samples. The positive contributions explain the variations of the source contributions in all samples, and the negative contributions indicate the outcome of improper variable scaling inherent in PCA methods as described previously.[23] The contributions from untreated wastewater (t_{L2}) are very high at most of the sampling sites in the Liangshui River (Fig. 4a). In addition, the contributions from nonpoint sources ($t_{\mathrm{L3}}/t_{\mathrm{L4}}$) were high at some locations, especially at direct discharge outlet LD3 of the Liangshui River, possibly due to the leachates from quite a few open garbage dumps on the bank of the Liangshui River.[40] In the Qing River, PPCP concentrations at most of the sampling sites were contributed by treated sewage from WWTPs (t_{Q1}), while at sites QR7 and QR8 in the downstream of the Qing River, PPCP pollution might be mainly attributed to untreated wastewater (t_{Q2}) due to the large input of untreated domestic wastewater from direct discharge outlet QD3 (Fig. 4b). The quantities that the different sources (*e.g.*, hospitals, industries and institutions) contribute were not discussed, because wastewaters from these sources were not collected in the present study.

Overall, the PPCP concentration in the suburban-influenced Liangshui River was significantly higher than that in the urban-influenced Qing River ($p < 0.05$). This result can be explained by

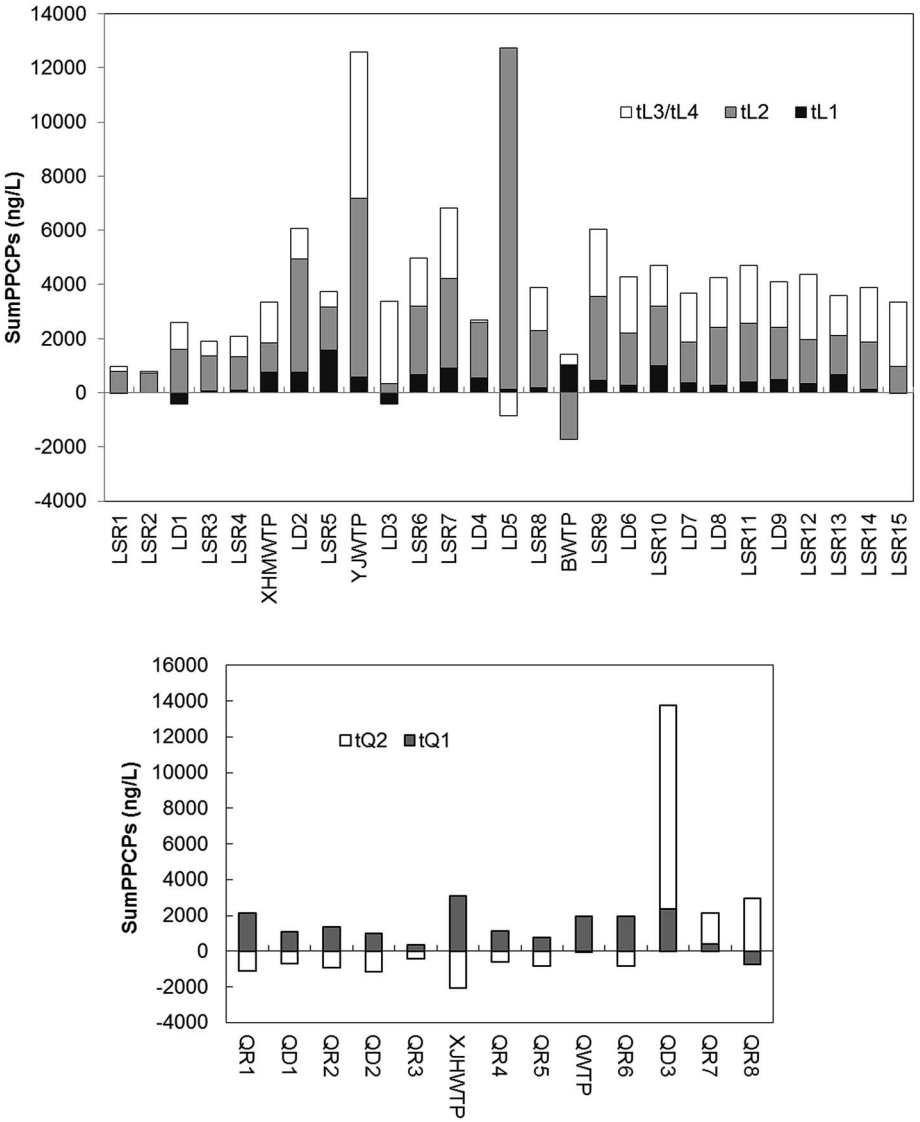

Fig. 4 PCA-MLR source contribution plots for all water samples including river, directly discharged wastewaters, and WWTP effluents. Sampling sites are shown in Fig. 1.

the following facts: firstly, the sewage collection rate is around 50% in suburb areas of Beijing, and a large amount of untreated sewage is directly discharged into the receiving river. For example, it was reported that a huge amount of untreated wastewater (60 000 m^3 per day) from seven direct discharge outlets was discharged directly into the Liangshui River in 2013.[41] Secondly, suburb areas tend to use more septic tanks and less advanced sewer systems that can leak untreated sewage into rivers, suggesting that these sources may be contributing to PPCP contamination in the Liangshui River. For example, Bunch and Bernot[18] found that higher pharmaceutical concentrations were measured in streams with >90% agricultural land use due to nonpoint sources such as septic tanks. Thirdly, it is apparent that large quantities of pharmaceuticals are not consumed for various reasons and end up with domestic garbage in China. Quite a few open garbage dumps located on the bank of the Liangshui River should be an important source of PPCPs in the Liangshui River,[40] while, in urban areas of Beijing, the sewage collection rate is more than 80%, and also the urban areas usually have better sewage systems which carry wastewater to treatment facilities, making PPCP contamination in the urban-influenced Qing River less apparent than that in the suburban-influenced Liangshui River. These results highlight the importance of infrastructure development in predicting PPCP levels in receiving waters in developing countries, such as China. In rural and suburb areas of China, the infrastructure development is relatively poor. The PCA analysis indicated the more complicated PPCP sources for the suburban-influenced Liangshui River, surely due to the lack of wastewater treatment in the surrounding area. Regions with higher urbanization levels usually have more advanced infrastructure in China, which can offset the influence by the larger population densities, thus leading to less environmental pollution.

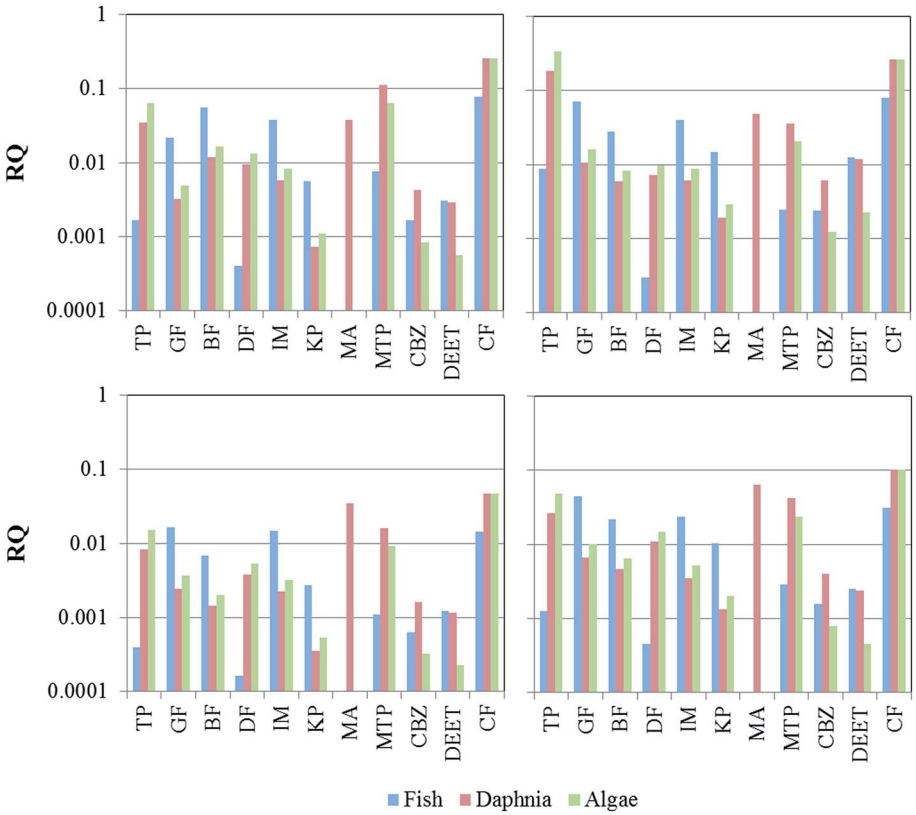

Fig. 5 RQs of the investigated compounds. TP, trimethoprim; GF, gemfibrozil; BF, bezafibrate; DF, diclofenac; IM, indomethacin; KP, ketoprofen; MA, mefenamic acid; MTP, metoprolol; CBZ, carbamazepine; DEET, *N*,*N*-diethyl-*meta*-toluamide; CF, caffeine.

3.4 Potential ecological risk assessment

Occurrence of PPCPs in the freshwater ecosystem at environmentally relevant trace concentrations potentially elicits the ecotoxicological effects on various aquatic species under chronic and/or acute exposure. Based on the EMEA guidelines,[24] the RQs were calculated for the target PPCPs to estimate their potential adverse effects on three different representative trophic levels of the ecosystem, fish, daphnia and algae in WWTP effluents, directly discharged wastewater and river waters. RQs of each compound for the three different endpoints tested are shown in Fig. 5 and Table S4 (ESI†). According to the risk ranking system proposed by Hernando *et al.*,[25] CF could pose a medium risk to daphnia and algae in effluents (RQ = 0.3, Fig. 3 shows the extremely high CF concentration in YJWTP effluents), directly discharged wastewaters (RQ = 0.3), and the Liangshui River (RQ = 0.1) (Fig. 5 and Table S4†). MTP could pose a medium risk to daphnia (RQ = 0.1) in effluents, and TP could pose a medium risk to daphnia (RQ = 0.2) and algae (RQ = 0.3) in directly discharged wastewaters (Fig. 5 and Table S4†). CF, TP and MTP were found to be the most critical compounds, due to their high RQ values. For all the other PPCPs, the calculated RQs were consistently <0.1, corresponding to a minimal risk. Compared with fish, daphnia and algae were more sensitive to the PPCPs' exposure in the aquatic environment. In the case of the Qing River, RQs were obviously lower than those in the Liangshui River (Fig. 5).

Some previous studies have also reported potential risks in surface water of other regions around the world due to the presence of PPCPs. You *et al.*[42] reported the potential ecological risk of CF (RQ in the range of 0.1–0.6) in urban surface waters of Singapore. Potential high risks of DF, TP and MA were suggested in urban rivers of Taiwan and Thailand.[10,43] At the maximum occurrence values, KP, CBZ, PPN and DF were reported to be of high risk to aquatic organisms in surface waters of Spain.[25] Zhao *et al.*[28] also reported a high RQ of DF in the Pearl River system, South China. Overall, such a risk assessment approach provides useful guidance about which chemicals to target for control based on those with high RQ values. However, it should be mentioned that the environmental risk analysis conducted in this study was based on the acute toxicity of single compounds, not taking into account the synergistic effects of a mixture of PPCPs, which are likely to be even more harmful even at lower single concentrations.[28] The present study clearly showed that medium risks were mostly associated with the effluents, directly discharged wastewaters and the Liangshui River. Therefore, risk reduction could be achieved through application of appropriate sewage treatment technologies in WWTPs as well as improving the collection rate of domestic wastewater in the suburban areas of Beijing.

4. Conclusions

The occurrence and sources of 15 PPCPs were investigated in two rivers of Beijing with different urbanization levels in the

surrounding areas (urban and suburb). Among the 14 detected PPCPs, CF was the predominant compound, with the maximum concentration of 11 900 ng L^{-1} in directly discharged wastewater samples. PPCP concentrations in the suburban-influenced Liangshui River were significantly higher than those in the urban-influenced Qing River due to the direct input of a large amount of untreated wastewater and nonpoint sources such as leachates from garbage dumps. Source apportionment showed that untreated wastewater contributed much (55%) to the PPCP levels in the suburban-influenced Liangshui River, which indicates that it is very urgent to improve the wastewater collection system and treatment capacity and cut down illegal discharge of untreated wastewater into surface water to reduce the potential ecological risks from PPCPs in the suburb area of Beijing, China. Finally, according to environmental risk assessment data, CF, TP and MTP exhibited RQ > 0.1, demonstrating that they are potentially dangerous to the aquatic ecosystem and therefore they should be included in targeted monitoring campaigns on a regular basis to provide further information on possible risks.

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