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Occurrence, spatiotemporal distribution and potential ecological risks of antibiotics in Dongting Lake, China

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Abstract We investigated the occurrence and distribution of 18 antibiotics in surface water from Dongting Lake, as well as in influents and effluents from a municipal wastewater treatment plant (WWTP) and a swine farm. The total concentrations of target antibiotics in surface water ranged from limit of quantification to 3107 and 5.32–107 ng L^{-1} in the dry season and wet season, respectively. Among these studied antibiotics, ciprofloxacin (CIP) and lomefloxacin were as the main components in the dry season, while CIP, oxytetracycline, and chlortetracycline were the main components in the wet season. The concentrations of target compounds exhibited obvious temporal-spatial variation characteristic in the studied region, suggesting their different emission sources related to pig breeding, aquaculture, and human activities, as well as possible degradation in the aquatic system. We estimated that the daily total input and output masses of antibiotics in the influent and effluent from the swine farm were 12.1 mg d^{-1} pig^{-1} and 7.49 μg d^{-1} pig^{-1}, while they were 103 μg d^{-1} $inhabitant^{-1}$ and 22.9 μg d^{-1} $inhabitant^{-1}$ in the WWTP. The risk assessment results indicated that CIP posed a moderate or high risk to algae in most locations in Dongting Lake.

Keywords Dongting Lake · Antibiotics · Spatial-temporal distribution · Risk assessment

Introduction

Antibiotics are pharmaceuticals that are commonly used to cure human and animal diseases, to prevent bacterial infections, and as feed additives to promote animal growth (Merve and Nursen 2019). After consumption, antibiotics are metabolized partially in vivo, and then the metabolites and residual parent compounds are excreted into sewer systems via feces and urine (Hirsch et al. 1999; Kummerer et al. 2000; Levison and Levison 2009; Dinh et al. 2017a). However, conventional municipal wastewater treatment plants (WWTPs), which are designed to eliminate traditional pollutants, such as total suspended particles, chemical oxygen demand, and biochemical oxygen demand, exhibit limited removal efficiencies for emerging micro-pollutants such as antibiotics and their corresponding metabolites (Liu et al. 2017; Zhang et al. 2018). Thus, a large amount of antibiotics and metabolites are being discharged into

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receiving water directly or indirectly through wastewater, causing their widespread distribution and elevated concentrations in aquatic systems, as well as the resultant antibiotic resistance genes (ARGs)(Danner et al. 2019; Li et al. 2018b). It has been reported that antibiotics can induce accumulation and propagation of ARGs and antibiotic-resistant bacteria even at low concentration(Gullberg et al. 2011; Sandegren 2014), which can then stay and spread in the aquatic system and thus pose long-term impact on non-target organisms (Marti et al. 2014; Nnadozie and Odume 2019). Consequently, there has been increasing concern in recent years about the occurrence and distribution of antibiotics in the environment, as well as their potential adverse effects on the human body and ecosystem mainly derived from the possibility of resistance genes.

China is one of the largest consumers of antibiotics in the world, most of which are used in commercial livestock production and fisheries aquaculture (Yin et al. 2013; Zhang et al. 2015). Dongting Lake basin is one of the largest bases for livestock, poultry breeding, and fishery in China (Liu et al. 2018). According to the Hunan Statistical Yearbook (http://222.240.193.190/18tjnj/indexch.htm), about 61.1 million pigs were raised in Hunan Province, and the total output of aquatic products was 1258 thousand tons in the Dongting Lake Basin in 2017. Consequently, a large amount of antibiotics was used, this then led to residual antibiotics being discharged into Dongting Lake via livestock wastewater. For example, it has been assessed that up to 3440 tons of antibiotics were discharged into Dongting Lake in 2013, including FF, CAP, FLE, LOM, CIP, and TCs (Zhang et al. 2015). However, limited data were available for the presence and distribution of antibiotics in surface water in Dongting Lake.

Dongting Lake, which is located in the northern part of Hunan Province, receives inflows from the tributaries of Yuanjiang River, Zishui River, Xiangjiang River, and Lishui River, and then discharges into Yangtze River at Chenglingji (Fig.1). Inhabitants in cities surrounding the Dongting Lake have a population of approximately 14.2 million, accounting for 19.4% of the total population in Hunan Province in 2017. These include the cities of Yueyang, Changde, and Yiyang. From these cities, a large amount of domestic wastewater was also discharged indirectly or directly into Dongting Lake (Lin et al. 2018), from which water is sourced for the surrounding inhabitants. There is great concern about water pollution, especially in relation to antibiotic pollution in the region. To the best of our knowledge, only one work has reported the occurrence of 12 antibiotics in surface water from East Dongting Lake (Liu et al. 2018).

In the present study, 18 antibiotics were chosen as target compounds and investigated for their presence in surface water covering Dongting Lake. These target antibiotics included 11 fluoroquinolones (FQs), four tetracyclines (TCs), and three chloramphenicols (CPs). The main objectives of this study were 1) to determine the concentrations, distribution, and spatial-temporal variations of 18 antibiotics in surface water from Dongting Lake; 2) to trace their possible emission sources by investigating their occurrence in a representative WWTP and wastewater related to a swine (*Youkshire*) farm; and 3) to assess the potential ecosystem risk based on the measured concentrations of antibiotics in the surface water of Dongting Lake.

Materials and methods

Materials and chemical standards

Eighteen antibiotics selected in this study can be classified into three groups: FQs, TCs, and CPs. The 11 FQs target compounds were ciprofloxacin (CIP), enrofloxacin (ENR), lomefloxacin (LOM), marbofloxacin (MAB), norfloxacin (NOR), ofloxacin (OFL), enoxacin (ENO), difloxacin (DIF), fleroxacin (FLE), sarafloxacin (SAR), and gatifloxacin (GAT). The four TCs consisted of oxytetracycline (OTC), tetracycline (TTC), chlortetracycline (CTC), and doxycycline (DC). The three CPs were chloramphenicol (CAP), florfenicol (FF), and thiamphenicol (TAP). Four isotope-labeled standards, enrofloxacin-D5 (ENR-D5), ciprofloxacin-D8 (CIP-D8), carbamazepine-D10 (CBZ-D10), and fluconazole-D4 (FCZ-D4), were used as internal standards. Detailed information and specific physicochemical properties of the target antibiotics are given in the Supporting Information (Table S1). Individual stock solutions in methanol (1 mg/mL) were prepared. Calibration solutions at 2–500 ng/mL were prepared by mixing and diluting individual stock solutions in methanol–water (50:50, *v*/v) and stored in amber glass vials at −20 °C in the dark.

Methanol and formic acid of HPLC grade were obtained from Merck (Darmstadt, Germany). Hydrochloric acid was from Guangzhou Chemical Reagent Factory

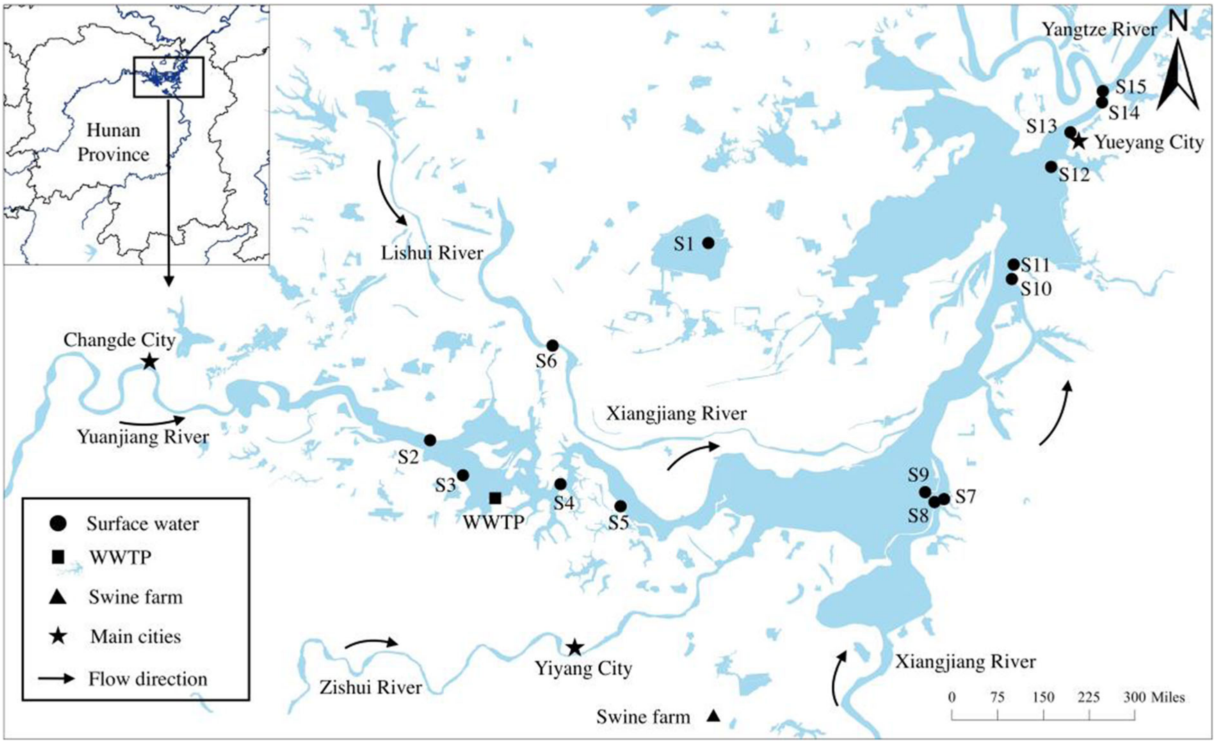


Fig. 1 Maps of the sampling sites in Dongting Lake, China

(Guangzhou, China). Disodium ethylenediamine tetraacetate (Na_2EDTA) and Oasis HLB cartridges (6 mL, 500 mg) were purchased from Waters (Milford, MA, USA). Glass microfiber filters (GF/F, pore size 0.7 μm) were purchased from Whatmann (Maidstone, England) and furnaced at 450 °C for 4 h prior to use. Milli-Q water (>18.2 MΩ) was produced by an FBZ2002-UP-P ultrapure water purification system.

Sample collection and pretreatment

According to the Hunan Statistical Yearbooks, in dry season in 2017 the average temperature were 12.6–13.6 °C in the three cities (Yueyang, Changde and Yiyang) surrounding the Dongting Lake, and precipitation were about 52.9–67 mm and sunshine were 72–93 h (http://222.240.193.190/18tjnj/ indexch.htm). While in wet season in 2018, the average temperature were 29–30.6 °C, precipitation were about 115.7–159.3 mm with longer sunshine time (198–251 h) (http://222.240.193.190/19tjnj/indexch. htm). Geographically, Dongting Lake can be grouped into four water bodies, namely, Datong Lake, West Dongting Lake, South Dongting Lake, and East Dongting Lake.

In November 2017 (dry season), 10 sampling locations were selected from Datong Lake (S1), West Dongting Lake (S2–S5), South Dongting Lake (S6), and East Dongting Lake (S11–13 and S15), and 1 L of surface water was collected at a depth of 0.2 m from each sampling location. In July 2018 (wet season), five additional sampling sites were added (S7–9 in South Dongting Lake, S10 and S14 in East Dongting Lake), and then 15 surface water samples were collected. The sampling locations are illustrated in Fig. 1, and detailed information of the sampling sites is given in the Supporting Information in Table S2.

To trace the possible emission of human antibiotics, influent and effluent wastewater were simultaneously collected in a municipal WWTP located in Hanshou County in Changde City, from which the effluent was discharged into West Dongting Lake. The WWTP mainly treated domestic wastewater from 230,000 inhabitants. It had 40,000 $m^3 \cdot d^{-1}$ capacity and used an improved anaerobic/anoxic/oxic treatment technology (A^2O). Meanwhile, a swine farm situated in Yiyang City was chosen to discriminate the possible usage and resultant emission of veterinary antibiotics. The swine farm raised up to about 1000 pigs. The swine houses were flushed daily with tap water, and then the mixed wastewater (HS-1) was treated by two continuous oxidation ponds followed by a lagoon. Finally, the effluent (HS-2) from the lagoon was directly discharged into a receiving stream connecting South Dongting Lake.

One liter of surface water was collected from Dongting Lake using a stainless-steel barrel and was placed into precleaned amber glass bottles; 200 mL instantaneous wastewater samples from municipal WWTP and swine farm were collected into precleaned amber glass bottles. Sodium azide (1 g/10 L) was added immediately to the water samples to inhibit microbial activity. The samples were transported to the laboratory in an ice bath and were filtered through GF/Fs. The resultant aqueous samples were treated within two days. Antibiotics in aqueous samples was extracted and enriched using Oasis HLB cartridges according to EPA method 1694 developed by the US Environmental Protection Agency with minor modification. While freeze-dried particles was extracted by ultrasonic-assistance three times with 10 mL acetonitrile and 10 mL citric buffer at pH 3. The combined extract was subjected to SPE as aqueous sample after removing organic solvent via rotary evaporation. Detailed descriptions are given in the Supporting Information in Text 1.

In the present study, limited particle was obtained from all surface water samples, and trace level (<LOQ) of DC and CTC was found in aqueous phases, consequently the reported concentrations of antibiotics in surface water in Dongting Lake were actually the aqueous concentrations. Concerning the wastewater from municipal WWTP and swine farm, the reported concentrations were sum of aqueous phase and the corresponding particles.

Determination and quantification of target antibiotics

The target antibiotics were analyzed using liquid chromatography–tandem mass spectrometry (LC-MS/MS; Agilent Liquid Chromatography 1100 series LC system coupled to a Biosystems/Sciex API 4000 triple quadrupole mass spectrometer (MS/MS) with an electrospray ionization (ESI) source in multiple-reaction monitoring mode. A Zorbax Eclipse Plus C18 column (4.6 × 250 mm. i.d., 5 μm; Agilent Technology) was used with column temperature maintained at 30 °C. Ultrapure water with 0.05% (*v*/v) formic acid (A) and methanol with 0.05% (v/v) formic acid (B) was used as the mobile phase; the injection volume was 10 μL. The FQs and TCs were determined using ESI positive ion mode at flow rate of 0.6 ml min^{-1}, while CPs using ESI negative ion mode at flow rate of 0.5 ml min^{-1}. Because ofloxacin and levofloxacin are isomers that were indistinguishable under the current LC-MS/MS conditions, the total concentrations were reported in this study. Detailed information about instrumental analyses is given in the Supporting Information in Table S3. Mass parameters of the target antibiotics and internal standards were optimized by declustering potential, entrance potential, collision energy, and collision cell exit potential, specific mass parameters are shown in Table S4.

Quality assurance and quality control

For quality assurance and quality control, procedural blanks ($n = 3$), spiked matrix ($n = 3$ for each matrix, e.g., surface water, influent, effluent, and swine wastewater), and replicate samples (n = 3 for surface water, influent, effluent, and swine wastewater, respectively) were pretreated with real samples in each batch of 10 samples. Isotope-labeled internal standards were added to all samples before pretreatment. Intra-day and inter-day precisions were determined from five repeated injections using 50 ng L^{-1} standards during the same day (repeatability) and in five successive days (reproducibility), which were lower than 10% and 15%, respectively. The limits of detections (LODs) and limits of quantifications (LOQs) of the antibiotics were calculated with signal/noise (S/N) ratios of 3 and 10, respectively (Jelic et al. 2009). The LODs of the target antibiotics were 0.170–1.95 ng L^{-1}, and LOQs were 0.510–5.84 ng L^{-1} (Table S5).

No target antibiotic was detected in any of the procedural blanks. The recoveries of ENR-D5, CIP-D8, CBZ-D10, and FCZ-D4 in three water samples were 87.4 ± 25.2%, 94.9 ± 35.4%, 95.8 ± 35.1%, and 99.5 ± 19.3%, respectively, and recoveries of the target antibiotics at three concentrations (20, 50, and 100 ng L^{-1}) in surface water were 50%–150% for most antibiotics, except for OTC and CTC (detailed information is given in Table S5).

Mass loads of antibiotics in wastewater from the swine farm and WWTP

Mass loads of the antibiotics per pig / per capita in the influent and effluent can be used to indicate the daily excretion from pigs and humans, as well as the output of the WWTP to the receiving water bodies (Zhou et al. 2013b). Detailed calculations and related parameters used in this study are given in the Supporting Information in Text 2 and Text 3. For those target compounds measured below the LOQs, 1/2 LOQ was used for calculation of mass loads of target antibiotics in wastewater from the swine farm and WWTP.

Risk assessment

In this study, the potential ecological risks of antibiotics in surface water were assessed using risk quotients (RQs)(Sun et al. 2016). Risk quotients were obtained by dividing the measured environmental concentration by the predicted no-effect concentration (PNEC) of the antibiotics. The PNEC values for algae, invertebrates, and aquatic plants of different target antibiotics were obtained from literature and are shown in Table S6. The potential risks as evaluated on the basis of commonly used criteria were low risk ($0.01 \leq RQ < 0.1$), medium risk ($0.1 \leq RQ < 1.0$), and high risk ($RQ \geq 1.0$) (Hernando et al. 2006).

Results and discussion

Concentrations and distribution of antibiotics in surface water in Dongting Lake

The concentrations and detection frequencies (DFs) of the 18 antibiotics in surface water of Dongting Lake are summarized in Table 1, and detailed information of their concentrations in the dry season and wet season are listed in Tables S7 and S8, respectively. The occurrence of human antibiotics and veterinary antibiotics in surface water may indicate that domestic sewage and livestock wastewater were discharged directly or led indirectly into Dongting Lake.

As indicated in the table, all target antibiotics were detected in water samples with different DFs. The total concentrations of the 18 antibiotics ($\sum 18_{\text{antibiotics}}$) ranged from <LOQ to 3107 ng L^{-1}, exhibiting obvious temporal variation in the studied region. In dry season, the $\sum 18_{\text{antibiotics}}$ ranged from <LOQ to 3107 ng L^{-1}, and the highest load was observed in Wanzi Lake (S6, 3107 ng L^{-1}), follow by Lujiao River (S11, 149 ng/L) and Jiangjiazui River (S3, 59.3 ng L^{-1}). While in wet season, the $\sum 18_{\text{antibiotics}}$ ranged from <LOQ to 107 ng L^{-1}, the highest level was found at Nanzui River (S5, 107 ng L^{-1}), followed by Xiaohezui (S4, 39.4 ng L^{-1}) and Chenglingji port (S14, 46.6 ng L^{-1}). The results may be ascribed to the fact that different antibiotics at different doses were consumed in the dry and wet seasons, resulting in their different discharge into the receiving water. In addition, antibiotics might undergo various environmental processes (particle-water-sediment partitioning, degradation and transformation, etc.) depending on their specific physicochemical properties (Kummerer 2009; Li et al. 2018a; Doorslaer et al. 2014). It has been reported that the target antibiotics exhibited markedly different half-lives, in the range of 2.05 min (NOR) to 20.8 days (CAP), suggesting their different ultimate fates and persistence in fresh water (Yi et al. 2019), which could affect significantly their occurrence and distribution in fresh water after emission. Detailed information about the half-lives of antibiotics is listed in Table S9.

As can be seen from Table 1, there occurred different temporal characteristics for specific antibiotics in wet season and dry season. Generally, the four FQs, i.e., CIP (1.81–90.6 ng L^{-1}, mean of 13.1 ng L^{-1}), NOR (ND–4.47 ng L^{-1}, mean of 3.96 ng L^{-1}), ENO (ND–11.3 ng L^{-1}, mean of 8.32 ng L^{-1}), and FLE (ND–4.20 ng L^{-1}, mean of 3.40 ng L^{-1}), were detected with DFs higher than 50% in wet season. However, DIF (ND–4.75 ng L^{-1}, mean of 3.02 ng L^{-1}) and SAR (ND–6.09 ng L^{-1}, mean of 5.92 ng L^{-1}) were measured with DFs higher than 50% in the dry season. Generally, antibiotics could be easily transformed / degraded under UV irradiation, higher transformation / degradation efficiencies could be expected in summer because of higher temperature (29.0–30.6 °C) and longer sunshine time (198-255 h) than those in winter (12.6–13.6 °C and 72–93 h sunshine). In addition, much more precipitation in summer (115.7–159.3 mm) might result in obvious dilution of organic pollutants in the Dongting Lake. It seems likely that lower levels of antibiotics should being presence in the water. However, our results disclosed higher levels of FQs in Dongting Lake, which might suggest their higher usage frequencies in the wet season than in the dry season in the studied region. The results agreed to those published work (Liu et al. 2018; Zhou et al. 2012).

It was notable that LOM, which showed a lower half-life of about 3 min (Zhang et al. 2019), was detected at 3075 ng L^{-1} in Wanzi Lake (S6) in dry season. Because of its potentially adverse effect, LOM was banned as additive to animal feed in December 31, 2016

Table 1 Summary of the concentrations and detection frequencies of antibiotics in surface water in wet season and dry season of Dongting Lake (ng L^{-1})

Compounds	Dry season				Wet season			
	Frequency	Min	Max	Mean	Frequency	Min	Max	Mean
FQs								
ENR	20%	ND	4.82	4.82	27%	ND	2.40	2.40
CIP	40%	ND	134	46.7	100%	1.81	90.6	13.1
LOM	40%	ND	3075	776	13%	ND	<LOQ	NA
MAB	40%	ND	0.870	0.800	20%	ND	1.01	1.01
NOR	20%	ND	6.22	5.07	60%	ND	4.47	3.96
OFL	20%	ND	<LOQ	NA	20%	ND	<LOQ	NA
ENO	30%	ND	13.7	13.6	53%	ND	11.3	8.32
DIF	70%	ND	4.75	3.02	20%	ND	<LOQ	NA
FLE	40%	ND	8.88	6.17	53%	ND	4.20	3.40
SAR	60%	ND	6.09	5.92	40%	ND	7.94	5.09
GAT	40%	ND	<LOQ	NA	7%	ND	<LOQ	NA
TCs								
OTC	20%	ND	10.2	8.56	53%	ND	20.9	10.6
TTC	10%	ND	25.0	25.0	53%	ND	7.69	6.46
CTC	10%	ND	<LOQ	NA	33%	ND	13.7	9.32
DC	0%	ND	ND	NA	60%	ND	9.69	7.90
CPs								
CAP	0%	ND	ND	ND	7%	ND	<LOQ	NA
TAP	30%	ND	<LOQ	NA	40%	ND	<LOQ	NA
FF	100%	<LOQ	2.48	1.49	93%	ND	1.88	1.71

ND: not detected; NA: the mean value do not calculated; LOQ: the limit of quantification; Min: minimum concentration; Max: maximum concentration; Mean: mean concentration. ENR, Enrofloxacin; CIP, Ciprofloxacin; LOM, Lomefloxacin; MAB, Marbofloxacin; NOR, Norfloxacin; OFL, Ofloxacin; ENO, Enoxacin; DIF, Difloxacin; FLE, Fleroxacin; SAR, Sarafloxacin; GAT, Gatifloxacin; OTC, Oxytetracycline; TTC, Tetracycline; CTC, Chlortetracycline; DC, Doxycycline; CAP, Chloramphenicol; TAP, Thiamphenicol; FF, Florfenicol

(http://www.moa.gov.cn/nybgb/2015/jiuqi/201712/t20171219_6103873.htm). However, it still being used to treat human diseases. Consequently, we speculated that high concentrations of LOM in S6 suggested a possible but unidentified emission source adjacent to the sampling site. A further study should be carried out to discriminate its possible emission source. The concentrations of CIP in Dongting Lake were comparable to those of Bosten Lake (17.3–112 ng L^{-1}) (Lei et al. 2015) and Jianghan Plain (45.9–93.9 ng L^{-1}) (Yao et al. 2015), but higher than those of 139 streams in the United States (ND–30.0 ng L^{-1}) (Kolpin et al. 2002). The mean concentrations of LOM (with the exception of S6) in Dongting Lake was comparable to that of the rural catchments in Paris (3.60–6.70 ng L^{-1}) (Dinh et al. 2017b) and Chaohu Lake (ND–5.50 ng L^{-1}) (Tang et al. 2015), but lower than that of the Jianghan Plain (16.0–30.4 ng L^{-1}), which is one of the agriculture and aquaculture production areas in central China (Yao et al. 2015). The concentrations of ENO in the present study were comparable to those of the Seine River (ND–11.0 ng L^{-1}; Dinh et al. 2017a), but much lower than those of Jianghan Plain (ND–109 ng L^{-1}; Yao et al. 2015) and rural catchments in Paris (ND–1310 ng L^{-1}; Dinh et al. 2017b). For most of the FQs, the half-lives were from 2.05 min (NOR) to 771 ± 8.40 min (GAT) in the simulation environment (except ENO and FLE), which may explain the lower DFs and pollution levels of FQs in surface water (Ge et al. 2010; Merve and Nursen 2019). It was noted that CIP has a half-life of about 19.3 min (Ge et al. 2010); however, it was detected in all samples in the wet season, in contrast to the 40% DFs in the dry season. The results therefore suggested that CIP was widely used in the studied region in the wet season.

As for the TCs, OTC (ND–20.9 ng L^{-1}), TTC (ND–7.69 ng L^{-1}), and DC (ND–9.69 ng L^{-1}) were found with DFs higher than 50% in the wet season. However, in the dry season DC was not found, the other three TCs, OTC (ND–8.56 ng L^{-1}), TTC (ND–25.0 ng L^{-1}), and CTC (<LOQ) were seldom detected with DFs of <20%. The results suggested that these antibiotics had high usage rates in swine farms in the wet season (Zhou et al. 2013a; Cheng et al. 2014). Generally, livestock, poultry, and fish are in a period of rapid growth and disease outbreak in the warmer season; hence, TCs are widely used to prevent or treat disease and as additives to increase feed conversion efficiencies in livestock and poultry breeding and aquaculture (Zhou et al. 2013a). Therefore, we observed higher detection frequencies and concentrations of TCs in the wet season, but there was no obvious difference in concentration levels in the two campaigns, probably because of the higher temperature and dilution factors in the rainy season (Cheng et al. 2014).

Compared to those in published work, the OTC concentrations (ND–20.9 ng L^{-1}, mean of 10.0 ng L^{-1},) in Dongting Lake was comparable to those in Poyang Lake (ND–8.90 ng L^{-1}; Ding et al. 2017), Bosten Lake (ND–6.60 ng L^{-1}; Lei et al. 2015), and Chaohu Lake (ND–4.00 ng L^{-1}; Tang et al. 2015). The concentrations of TTC (ND–25.0 ng L^{-1}) in the present study were at the same levels as those of the Ghana Stream (11.0–30.0 ng L^{-1}; Azanu et al. 2017), Jianghan Plain (10.2–14.5 ng L^{-1}; Yao et al. 2015), Taihu Lake (10.3–40.9 ng L^{-1}; Xiong et al. 2017), streams in the United States (ND–110 ng L^{-1}; Kolpin et al. 2002), and rural catchments in France (ND–68.0 ng L^{-1}; Dinh et al. 2017b). In general, CTC (9.32 ng L^{-1}, ND–13.7 ng L^{-1}) and DC (7.90 ng L^{-1}, ND–9.69 ng L^{-1}) in Dongting Lake were low compared to rivers in other parts of the world (Yang et al. 2018).

Three CPs were investigated in the present study. We detected FF with DFs higher than 90% in two sampling campaigns, and lower concentrations ranged within LOQ–2.48 ng L^{-1} in dry season and ND–1.88 ng L^{-1} in wet season from measurements of surface water. CAP and TAP could not be quantified in any sample in both seasons in Dongting Lake (Table 1). CAP has been banned in China in 2002 for food-producing animals because of its high toxicity (http://jiuban.moa.gov.cn/zwllm/zcfg/qtbmgz/ 200,601/t20060123_ 540,873.htm). As a derivative of CAP, FF has less toxicity and higher antibacterial activity; it is used as a substitute for preventing or treating bacterial diseases in livestock breeding and aquaculture in various countries (Fabiano et al. 2016; Ge et al. 2009). This might explain the wide detection of FF and the absence of CAP in Dongting Lake. It was observed that FF has a longer half-life(4.8 days, Ge et al. 2009) than FQs and TCs (Please see Table S9); this might be one reason why FF exhibited DFs higher than those of the other compounds. The concentration of FF was comparable to those in Taihu Lake (ND–2.60 ng L^{-1}) (Xiong et al. 2017), but lower than that in Huangpu River (ND–241 ng L^{-1}, mean of 116 ng L^{-1}) (Chen and Zhou 2014).

Antibiotics in wastewater of a swine farm

The antibiotic residue and daily mass loads in the influent and effluent in swine wastewater are listed in Table 2. In the influent (HS-1) of swine wastewater, seven FQs, i.e., ENR, LOM, MAB, NOR, ENO, DIF, and SAR, were not detected. However, we detected significantly high levels of TCs as main antibiotic components, which accounted for 99.9% of the total concentration of antibiotics. Specifically, concentrations of OTC, DC, CTC, and TTC were 739517, 148928, 81223 and 34546 ng L^{-1}, respectively (Table 2). Similar results have been reported that high levels of TCs were detected in swine farm samples; these indicated that TCs were used in high dosages in swine breeding (Zhou et al. 2013a; Zhang et al. 2018; Wang et al. 2019; Chen et al. 2017; Sim et al. 2011).

In effluent (HS-2), four TCs were present in effluent, accounting for 91.9% of the total antibiotics, with OTC being the main antibiotic at a concentration of 459 ng L^{-1}. The results were similar to those of swine wastewater in Guangxi Province (586 ± 95.8 ng L^{-1}) (Zhou et al. 2013a), but lower than those from Guangdong Province (1820 ± 1390 ng L^{-1}) (Zhang et al. 2018).

From the measured concentrations, the daily excretion mass loads per swine were calculated as 8874, 1787, 975, and 415 μg day^{-1} pig^{-1} (Table 2). OTC, TTC, and CTC are commonly used feed additives in swine farms, while DC is mainly used for disease prevention or treatment, and it is allowed to be used as feed additive in livestock and poultry breeding. These commonly used feeding additives accounted for 99.9% of the total daily excretion mass loads of antibiotics; similar results were observed in some swine farms in China (Zhou et al. 2013a; Zhang et al. 2018). These results indicated that antibiotics excreted by swine mainly originated from the feeds (Zhou et al. 2013a). It was reported that about 61.1 million pigs were raised in Hunan Province in 2017 (http://222.240.193.190/18tjnj/indexch.htm). By reference to the daily mass loads of antibiotics in influent and effluent in this swine farm, we assessed roughly that total excretion mass loads of antibiotics via influent from swine farms and the total output mass loads discharged from swine farms via effluent into the receiving water in Hunan Province were about 269,243 kg year^{-1} and 174 kg year^{-1}, respectively.

Antibiotics in municipal WWTP

The occurrence of target antibiotics, as well as daily mass loads in influent and effluent in the municipal WWTP, are summarized in Table 2. In the influent of the WWTP, seven FQs (ENR, MAB, NOR, ENO, DIF, FLE, and GAT) and CTC were not detected. The other four FQs, three TCs, and three CPs were found, with LOM (113 ng L^{-1}), CIP (84.5 ng L^{-1}), OFL (71.5 ng L^{-1}), OTC (117 ng L^{-1}), TTC (92.1 ng L^{-1}), and CAP (70.2 ng L^{-1}) detected as the main components, which accounted for 89% of the total antibiotics. Generally, the concentrations of these detected antibiotics in this study were similar to those measured in China (Lin et al. 2018; Liu et al. 2017; Wu et al. 2016; Gao et al. 2012; Minh et al. 2009), and different from those reported outside China. For example, LOM concentration was much higher than in Paris (ND–29.0 ng L^{-1}; Dinh et al. 2017b), CIP concentration was much lower than that from Croatia (2610 ng L^{-1}; Senta et al. 2013), OFL concentration (64.7 ng L^{-1}) was much lower than those detected in Paris (1074–20,200 ng L^{-1}; Dinh et al. 2017b) and Italy (450–2200 ng L^{-1}; Verlicchi et al. 2012), and OTC (109 ng L^{-1}) was much lower than that in Korea (ND–8660 ng L^{-1}; Sim et al. 2011).

In the effluent, the concentrations of OFL, OTC, and TTC were 93.7, 12.1 and 11.7 ng L^{-1}, respectively; these were the main antibiotics and accounted for 91% of the total antibiotic concentration. Similar to the results for the influent, the residual antibiotics in influent in this study were comparable to those detected in China (Wu et al. 2016; Lin et al. 2018) and Australia (70.0 ng L^{-1}) (Watkinson et al. 2009), while being much lower than those from Spain (Gros et al. 2010).

In this study, the total mass loads of antibiotics per capita in the influent and effluent of WWTP were 107 μg d^{-1} inhabitant^{-1} and 22.9 μg d^{-1} inhabitant^{-1}, respectively. By reference to the calculated mass loads of antibiotics per capita in the studied WWTP, the total excretion mass loads from 65.7 million inhabitants and the total mass loads discharged from WWTPs via effluent into the receiving water in Hunan Province were approximately 2561 kg year^{-1} and 549 kg year^{-1}, respectively.

Spatial distribution of antibiotics in Dongting Lake

As mentioned above, five additional sampling sites in the wet season were added. The concentrations in these sampling sites (10 sites) in both seasons were selected to study the seasonal variation of the target antibiotics. Consequently, we investigated the spatial distributions of the target antibiotics in the wet season because of higher DFs and higher levels for most of the target analytes (Table 2). In general, higher loads of antibiotics were found in West Dongting Lake (mean of 42.1 ng L^{-1}), followed by Datong Lake (30.6 ng L^{-1}) and East Dongting Lake (23.7 ng L^{-1}); lowest levels were found in South Dongting Lake (11.9 ng L^{-1}). As for the specified sampling location, the highest concentration of antibiotics was observed in Nanzui River (S5, 107 ng L^{-1}), followed by Xiaohezui (S4, 39.4 ng L^{-1}) and Chenglingji port (S14, 46.6 ng L^{-1}) in Dongting Lake (Fig.2). It was found that CIP was the main antibiotic in S5 (90.6 ng L^{-1}), accounting for 84% of the total concentration. CIP is commonly used to treat bacterial infections and is applied to animal husbandry and human-related diseases. In this study, we have detected CIP in swine wastewater at one order of magnitude higher than in domestic wastewater in this region (Table 2). It could be speculated that CIP in S5 might be ascribed to discharge from livestock wastewater and domestic wastewater. Datong Lake is a small closed lake with neither discharge from industrial wastewater nor domestic sewage, where fishery is well developed. For the sampling site (S1) situated in middle of the lake, ENO (13.4 ng L^{-1}), FLE (5.38 ng L^{-1}), and DIF (3.25 ng L^{-1}) were measured in the dry season (Table S7); while CIP (4.71 ng L^{-1}), NOR (4.47 ng L^{-1}), ENO (11.3 ng L^{-1}), and OTC (10.1 ng L^{-1}) were measured in the wet season (Table S8). These results indicate that these antibiotics were used in fisheries aquaculture within this closed

Table 2 Summary of the concentrations and mass loads of target antibiotics in swine wastewater treatment system and municipal wastewater treatment plant

Compounds	Swine wastewater treatment system				Wastewater treatment plant			
	Concentrations (ng/L)		Mass load (μg/d/pig)		Concentrations (ng/L)		Mass load (μg/d/human)	
	HS-1	HS-2	HS-1	HS-2	Influent	Effluent	Influent	Effluent
FQs								
ENR	1.06	ND	0.0100	ND	ND	2.69	ND	0.470
CIP	589	12.6	7.07	0.150	84.5	ND	14.7	ND
LOM	ND	10.9	ND	0.130	113	ND	19.6	ND
MAB	ND	ND	ND	ND	ND	ND	ND	ND
NOR	ND	ND	ND	ND	ND	ND	ND	ND
OFL	116	ND	1.39	ND	71.5	93.7	12.4	16.3
ENO	ND	ND	ND	ND	ND	ND	ND	ND
DIF	ND	<LOQ	ND	0.0200	ND	ND	ND	ND
FLE	11.0	<LOQ	0.130	0.0100	ND	6.98	ND	1.21
SAR	ND	ND	ND	ND	27.1	ND	4.70	ND
GAT	52.5	<LOQ	0.630	0.0100	ND	ND	ND	ND
TCs								
OTC	739517	459	8874	5.51	117	12.1	20.4	2.10
TTC	34546	17.2	415	0.210	92.1	11.7	16.0	2.04
CTC	81223	53.2	975	0.640	ND	<LOQ	ND	0.310
DC	148928	67.6	1787	0.810	7.32	ND	1.27	ND
CPs								
CAP	6.70	0.260	0.0800	ND	70.2	0.800	12.2	0.140
TAP	7.69	2.96	0.0900	0.0400	26.5	ND	4.62	ND
FF	38.8	25.7	0.470	0.310	4.91	1.79	0.850	0.310

Note: NOR, MAB and ENO were not found in municipal WWTP and swine farm, then not included in the Table

ND: not detection; LOQ: the limit of quantification

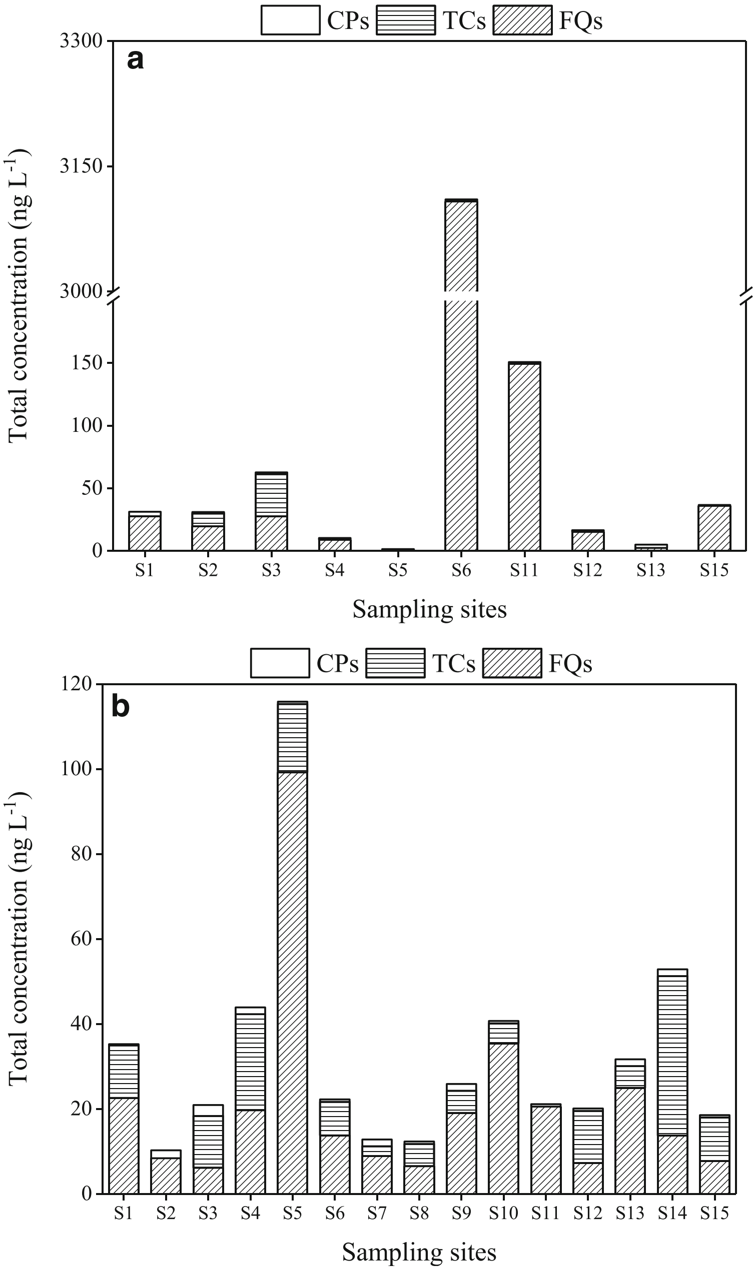
HS-1: influent in the swine farm; HS-2: effluent in the swine farm

lake. In addition, S4 is located in a well-developed aquaculture area in West Dongting Lake, receiving discharge from the Yuanjiang River, which is impacted by livestock wastewater. In this location, CIP, ENO, SAR, OTC, and DC were detected in the wet season; however, a higher level of LOM was found in the dry season. We speculated that these residual antibiotics in the wet season were mainly from input from river discharge containing livestock wastewater; LOM might be ascribed to local usage in aquaculture in the dry season. OTC and CTC were the main antibiotics in S14, accounting for 74% of the total concentration (Fig. 3). The sampling site is located in East Dongting, another well-developed area with livestock and poultry breeding (Liu et al. 2018). We also have noted that some TCs were detected in the studied region in the wet season. For example, OTC was found at S9 (5.20 ng L^{-1}L), S12 (7.03 ng L^{-1}), and S14 (20.3 ng L^{-1}); TTC was found at S3 (7.69 ng L^{-1}) and S5 (5.22 ng L^{-1}); and CTC was found at S6 (6.11 ng L^{-1}). As mentioned above, TCs were the main antibiotics widely used in livestock (please see Section 3.2). The occurrence of TCs in surface water in Dongting Lake suggested that Dongting Lake was impacted by livestock.

Potential risk

The box plots of RQs for algae, invertebrates, and aquatic plants of different antibiotics in Dongting Lake are shown in Fig.4. The results indicated that CIP (RQ =

Fig. 2 Spatial distribution of target antibiotics in Dry season (**a**) and Wet season (**b**) of Dongting Lake



0.360–27.2) might pose medium or high risk to algae in most areas in Dongting Lake. Because of the higher concentration of LOM in S6 in the dry season and the lower PNEC values, the RQs was higher than 1, suggesting the significantly high risk it poses to organisms in this aquatic system (Fig. 4). ENO posed moderate risk to algae in some aquaculture areas (S1, S3, S4, and S10; RQ = 0.290–0.480). OTC might pose a medium risk to algae, invertebrate and plants in S14 (RQs > 0.1) in the wet season; and CTC could cause moderate risk to algae in S5, S14, and S15 sampling areas in the wet season (RQ = 0.130–0.270). Because of the lower concentrations and higher PNEC values of CPs, the RQs were much lower than 0.01, indicating limited ecological risk to aquatic organisms. On the basis of the above discussion, much attention should be paid to the antibiotic pollution and ecological risks in the adjacent water bodies of the livestock and poultry breeding area (e.g.,

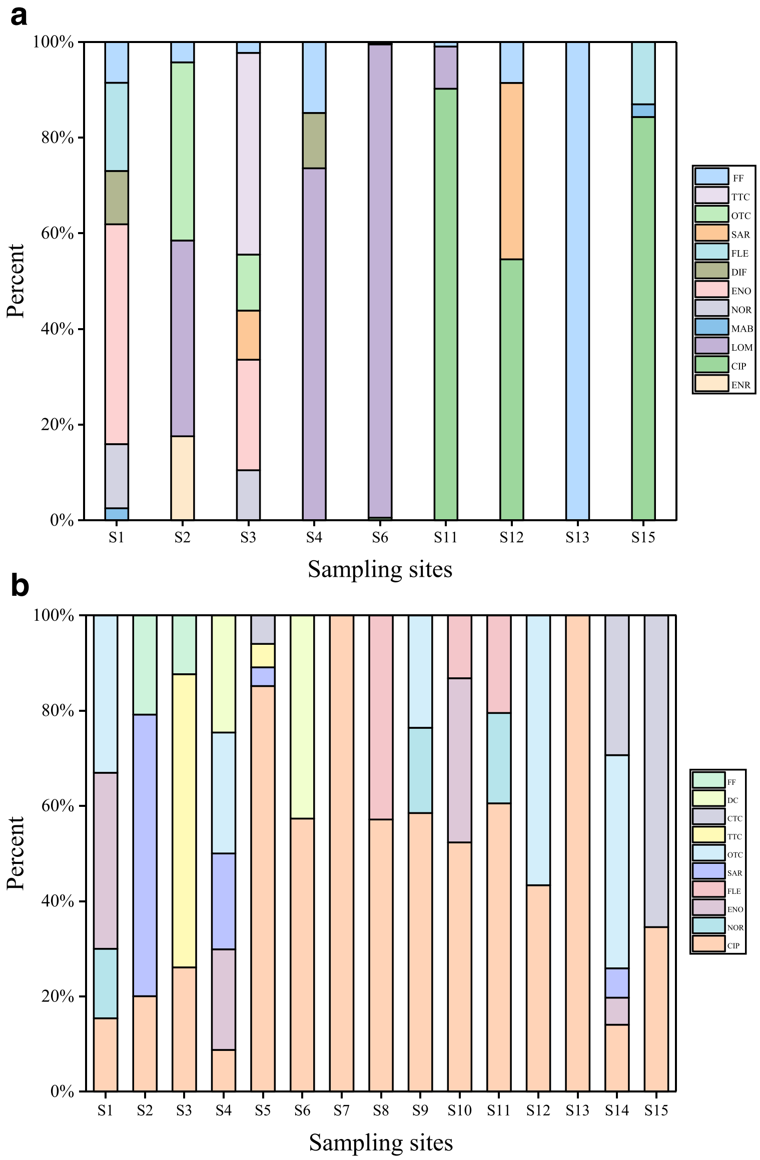


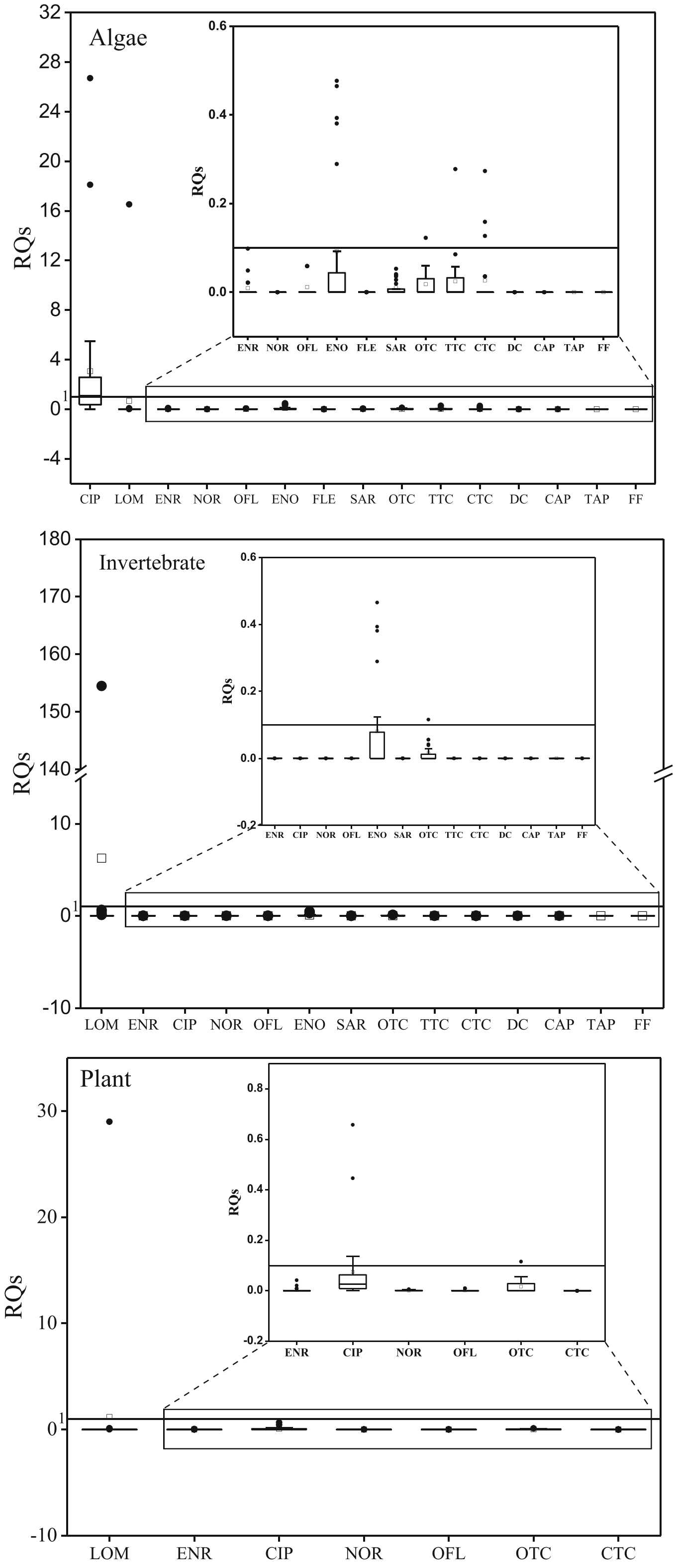
Fig. 3 Composition profiles of antibiotics in Dry season (**a**) and Wet season (**b**) of Dongting Lake

Yueyang, Changde, and Yiyang) and aquaculture area (e.g., Hanshou County and Xiangyin County) of Dongting Lake basin (Liu et al. 2018).

Conclusions

We assessed that approximately 716 kg/year antibiotics was discharged from swine farms and WWTPs into the environment in Hunan Province based on the measured concentrations of antibiotics in wastewater in the present study. This resulted in wide distribution of antibiotics in Dongting Lake. TCs were the main antibiotics in swine wastewater and might be mainly derived from additives in livestock feed. In addition, ENO might also be used in aquaculture activity. Different anthropogenic activities and the environment behavior of specific antibiotics resulted in their different concentration and distribution in surface water in Dongting Lake. Risk assessment revealed that CIP was the main antibiotic that has a potentially adverse effect on algae in surface water. Further studies should be carried out on their degradation or transformation and the ARGs in the region, especially in drinking-water sources of Dongting Lake, as well as the potential health risk posed to human inhabitants surrounding the lake.

Fig. 4 The box plots of risk quotients (RQs) for algae, invertebrate and aquatic plants of different antibiotics in Dongting Lake



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