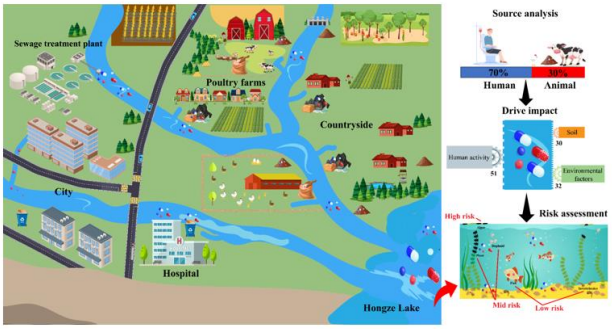
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Occurrence and drivers of antibiotics in the rural-urban river network: a case study of Hongze Lake basin, China

Shanshan Xi[1, 2, 3, 4], Rong He[1, 2, 3, 4], Rongsheng Jiang[1, 2, 3, 4], Jiamei Zhang[1, 2, 3, 4]*, Hua Zhang [1, 3] and Zicheng Shuai[1, 3]
[1]School of Environmental and Energy Engineering, Anhui Jianzhu University, Hefei 230031, Anhui, China
[2]Anhui Institute of Ecological Civilazation, Hefei 230031, Anhui, China
[3]Anhui Provincial Key Laboratory of Environmental Pollution Control and Resource Reuse, Hefei 230031, Anhui, China
[4]Pollution Control and Resource Utilization in Industrial Parks Joint Laboratory of Anhui Province, Hefei 230031, Anhui, China
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*to whom all correspondence should be addressed: e-mail: 575606022@qq.com
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Graphical abstract



Abstract

The massive use of antibiotics and the consequent antibiotic pollution have become a major risk to river ecosystems, water quality, and human health. In this study, 28 antibiotics were analyzed in the rural-urban river water of Suzhou City, the inflow rivers of Hongze Lake. The total concentration of antibiotics in the rural-urban river was nd-85.87 ng L^{-1}, mainly containing veterinary antibiotics, quinolones, and tetracyclines. The distribution of antibiotics was found to be closely related to the population density and the development of the breeding industry along the bank through structural equation model and correlation analysis. Meanwhile, the human activities (70%), livestock and poultry breeding (30%) were the main sources of antibiotics in the study area through the principal component analysis-multiple linear regression (PCA-MLR) source analysis. Finally, the risk assessment was carried out by the Risk Quotient (RQ) method, and indicated that antibiotics pose a low risk to plant and invertebrates, but Ofloxacin, Ciprofloxacin, Erythromycin, Norfloxacin, and Chlortetracycline posed a mid ecological risk to algae. This work provide a valuable data set across the rural-urban river network and revealed the antibiotic contamination profile. Prevention and management to reduce the antibiotic inputs are needed for the rural-urban zones.

Keywords: Antibiotics, rural-urban river network, drivers and sources, risk assessment

1. Introduction

Antibiotics are one class of emerging pollutants with a wide presence in the environment, and widely used to be the medicines of human and veterinary(Wang *et al*. 2021). The global consumption of antibiotics was 4.02 billion defined daily dose (DDD) in 2018, up 45% since 2000, of which 14.3DDD of antibiotics were consumed per 1,000 people daily (Browne *et al*. 2021). China is the largest producer and user of antibiotics in the world and uses more than 25000 tons each year (Ci *et al*. 2021). Antibiotics could enter the aquatic environment through medical waste, animal excreta, and domestic sewage (Ci *et al*. 2021). Residual antibiotics in the water would lead to the reduction of microbial diversity and alteration of bacterial ecology through migration, adsorption, and bioaccumulation (Zhou *et al*. 2020). In addition, antibiotics in water might accumulate in the human body through drinking water and the food chain, causing the human body to develop drug-resistant genes and pose a serious threat to human health (Xiao *et al*. 2023). In summary, antibiotic pollution in water bodies should be widely concerned in the world.

Antibiotics have been widely detected in aquatic environments, including river water, seawater, groundwater and even drinking water (Fu *et al*. 2022; Wang *et al*. 2021). The rural-urban rivers serve as the main source of water supply for rural-urban users (Ci *et al*. 2021), but well known as a hotpot for antibiotics due to the receiving of massive wastes from rural-urban areas (Morina and Franklin 2023). Therefore, to protect human health and ecosystem safety, it is important to investigate the environmental behavior process of antibiotics in the rural-urban rivers. However, there have been only a few studies on antibiotics in the rural-urban river network (Yang *et al*. 2020). Specifically, perhaps due to various factors that affect antibiotic enrichment and migration, researchers have until now known little about antibiotic

drivers in urban and rural river networks (Zainab *et al*. 2021).

Mathematical statistics are the useful tools to identify the drivers of antibiotics in the river water (Wang *et al*. 2024). Recent studies have attempted to utilize the simple linear equation of correlations to study the influence factors of antibiotics in surface water (Wu *et al*. 2023). However, a simple linear equation can only present the relationship between one dependent variable and one independent variable at a time. Structural equation models was developed to identify the potential driving factors and interpret their direct and indirect effects on antibiotic concentrations , and can analyze the relationship between multiple independent and dependent variables at the same time (Tian *et al*. 2021). In short, structural equation models can comprehensive analysis the drivers of antibiotics and more accurate indicate the combined effects of variables, thus the structural equation method will be used to analyze the driving factors of antibiotics in the present study.

Suzhou City in Anhui Province of China, which is located in the upstream of Hongze Lake basin, is the core city of the Huaihai economic cooperation region, an important node of the Yangtze River Delta urban agglomeration, and the Central Plains Economic Zone in China. Lots of industrial and domestic sewage, agriculture and livestock wastewater would inflow into the rural-urban rivers of Suzhou city. In addition, the rural-urban river network in Suzhou has the various river channels, which could also lead to the complex antibiotic pollution situation. Therefore, the objectives of this study are as follows: (1) to investigate the occurrence of commonly used antibiotics (e.g. Quinolones (QNs), Macrolides (MLs), Sulfonamides (SAs), Tetracyclines (TCs)), (2) to study the sources and drives of the antibiotics (3) to estimate the risk assessment of antibiotics in the rural-urban river water of Suzhou City, China.

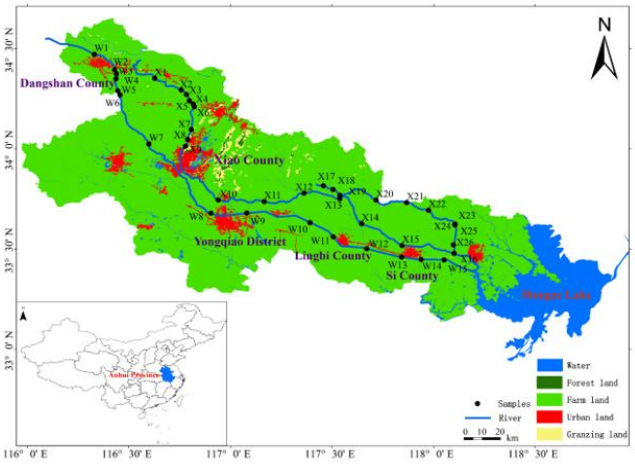


Figure 1. The location of study area and sampling sites in the rural-urban river of Suzhou City, China

2. Materials and methods

2.1. Study area and sample collection

The rural-urban rivers in Suzhou were located in the upstream of Hongze Lake basin (**Figure 1**). At the study area, two rivers (W and X rivers) flow through five counties of Suzhou City (e.g. Dangshan County, Xiao County, Yongqiao District, Lingbi County, Si County). In July 2023, the surface water samples at 41 sampling sites were collected. In detail, the sampling sites of W1-W6 were located in Dangshan County, W7 and X1-X9 were located in Xiao County, W8-W10 and X10-X12 were located in Yongqiao District, W11 and X17-19 were located in Lingbi County, and W12-W15 and X20-X26 were located in Si County.

Approximately 1L of water (0.5m below the river surface) was drawn into a precleaned brown polypropylene bottle at each sampling site and stored at 4-10 °C before analysis. The pH and water temperature (WT) for the surface water were tested at each sampling site using a combo quality meter (HACHDS5X, USA).

2.2. Sample extraction and analysis

For the total nitrogen (TN), nitrate (NO_3-N), and Suspended Solids (SS), all surface water samples were analyzed and determined by the national standards (TN: HJ 636—2012), (NO_3-N : HJ/T 346—2007), (SS : GB/11901—89).

For the antibiotics analysis, 1.0L of water of each sample was filtered through a glass microfiber filter with a pore size of 0.45 μm in the laboratory. The concentrated sulfuric acid was added into each water sample to adjust the pH at 3.0 for the biological activity inhibition, and then 0.5g Na_2EDTA was added to complex the metal ions (Li *et al*. 2019). Afterward, all water samples were extracted by solid phase extraction with Oasis HLB column (KANGZHIDA, 500mg, 6ml), Each water sample flowed through the column at a flow rate of 5 ml min^{-1}. then the column was with 5 ml of deionized water to eliminate impurities and dried for 20 minutes (Deng *et al*. 2016). Subsequently, each HLB column was eluted with 10 ml of methanol. All extracts were concentrated and dissolved into 1 ml methanol.

Concentrations of antibiotics were measured by liquid chromatography - electrospray tandem mass spectrometry (LC-MS / MS) (EXPEC 5210) with a Waters ACQUITY BEH C18 column (2.1×100 mm, 1.7 μm) (Hu *et al*. 2023). The injection volume was 10 μL with a flow rate of 0.3 mL min^{-1}. The mobile phase solvent was 0.1% (v v^{-1}) formic acid (phase A) and methanol (phase B). All extracts were analyzed in positive ion mode and positive ions were collected in multiple reaction monitoring (MRM) mode. The peak area of each compound was obtained from the chromatogram, and the peak area versus concentration was calculated using the standard curve (Zhou *et al*. 2022a).

The solved blanks, program blanks, and standards were analyzed every ten samples to check the analytical precision and accuracy. All experiments were carried out in triplicate, and the limit of detection was from 0.001 to 0.106 depending on the target antibiotics. The surrogates (Sulfamethoxazole-d4, Tetracycline-d6, Ciprofloxacin-d8) were spiked into water samples, and their recoveries ranged from 68% to 83%.

2.3. Composite structural equation model

To determine the drivers of antibiotics in the rural-urban river water, the R4.3.0 analysis software was used to execute the composite structural equation model (SEM) (Tian *et al*. 2021). In the SEM, the data of land type (e.g. River, Water, Forest land, Farm land, Urban land, Grazing land), environment factors (e.g. pH, T, SS, TN, NH_3-N), and human activities (e.g. population density, discharge of livestock breeding wastewater, and manure) were chosen as the influence factors of antibiotics. The data of the land type and human activities were collected from satellite data and local statistical yearbooks (Kim *et al*. 2019), and the environment factors were analyzed in the present study. For livestock and poultry factories were collected as the livestock and poultry factors. Based on the various influence factors, all measured variables in the model were first classified as "complex variables", and then incorporated into the SEM. For the stability of the model relationships, the piecewise SEM was used to rationalize the random effects of the sampling sites and to provide "marginal" and "conditional" contributions of environmental predictors in driving ecosystem stability (Tian *et al*. 2021).

2.4. Source apportionment of Antibiotics

The principal component analysis coupled with multiple linear regression (PCA-MLR) was used to determine the source apportionment of antibiotics in IBM SPSS Statistics 26.0 (Wang *et al*. 2013). PCA aimed to extract principal components (PCs) and suggest potential pollution sources, whereas MLR could select the significant PCs ($p < 0.05$). The determine principal components (PCs) was revealed by using its characteristic antibiotics (loadings on PC_i > 0.5) together with the antibiotic usage in human or animals or their occurrence in wastewater. PCA-MLR analysis was performed for water samples and only the antibiotics with detection frequencies higher than 80% were included.

2.5. Risk assessment of antibiotics

The ecological risk of antibiotics can be assessed by the Risk Quotient (RQ) method (Du *et al*. 2017), which is widely used to assess the risk of various environmental pollutants. The RQ of antibiotics in the aquatic environment was calculated by the following equation:

$$RQ = \frac{MEC}{PNEC} \quad (1)$$

The MEC is the measured environmental concentration and PNEC is the predicted no-effect concentration in water (Zhou *et al*. 2022b). The PNEC in aqueous media was calculated according to the following formula:

$$PNEC = \frac{LC_{50} / EC_{50}}{AF} \quad (2)$$

LC_{50} or EC_{50} is the lowest median effective concentration value (Du *et al*. 2017). In previous studies, AF was represented as an appropriate standardized assessment factor (1000). Risks were categorized as high (RQ >1), medium (0.1 < RQ <1), and low (0.01 < RQ <0.1) (Zhou *et al*. 2022b).

3. Results and discussion

3.1. Occurrence and distribution of antibiotics

The concentration and composition of detected antibiotics in water samples were summarized. Among the 28 target antibiotics, 26 antibiotics were detected at least once in the water samples with concentrations up to 85.87 ng L^{-1}, indicating that antibiotics were widespread along the rural-urban river network. The detection rate of 21 antibiotics in the study area reached more than 80%. The maximum number of detected antibiotics per site was 26 for the surface water, with 61% of target antibiotics. The antibiotics concentration in the surface waters ranged from not detected (ND) to 85.87 ng L^{-1}, with a mean value of 145.78 ng L^{-1} (**Figure 2a, b**). Overall NOR and OTC exhibited the highest mean concentrations of 17.39 ng L^{-1}, and 13.21 ng L^{-1}, with detection frequencies of 98%, and 100%, respectively.

Among the four classes of antibiotics, the antibiotics concentration in the surface water: FQs (46.12 ng L^{-1}) > TCs (44.79 ng L^{-1}) > MLs (38.00 ng L^{-1}) > SAs (16.85 ng L^{-1}) (**Figure 2d**). FQs were considered as the bacteriostatic antimicrobial agents which widely used in human and animal, and the study area was densely populated with towns and cities (Population of Suzhou City:1.94 million), resulting in relatively high usage (Miranda *et al*. 2022). Meanwhile, TCs were widely used in livestock and poultry breeding (Wang *et al*. 2017). According to the statistical yearbook, there were 2280 livestock and poultry farmers in Suzhou City in 2022, with a total of 690,000 tons of wastewater discharges per year, and these discharges contributed to high TCs pollution in the study area. MLs were widely used in the treatment of human bacterial infections, and as feed additives in livestock (Bandell *et al*. 2019). SAs were mainly used in animal treatment in the livestock industry (De Liguoro *et al*. 2018), but they were easily decomposed in sunlight (Hu *et al*. 2022). The abundant light in summer accelerated the decomposition of SAs, which resulted in low concentrations of SAs in water. Thus, it was found that the contents of antibiotics was significantly influenced mainly by human activities around the study area.

The distribution of antibiotic levels in water of the study area was found that Yongqiao District (mean value: 157.49 ng L^{-1}) > Xiao County (mean value: 151.11 ng L^{-1}) > Lingbi County (mean value: 141.96 ng L^{-1}) > Dangshan County (mean value: 141.30 ng L^{-1}) > Si County (mean value: 139.96 ng L^{-1}) (**Figure 2d**). According to the statistical yearbook, Yongqiao District and Xiao County are the two most populous counties in Suzhou, accounting for 58.6% and 12.3% of the population respectively. In addition, there are significant regional differences in the distribution of agricultural and sideline products in Suzhou City. The fruit industry is dominated by Dangshan pear in the northern part of the study area (Dangshan County), while livestock, and poultry breeding are represented by Fuli roasted chicken in the southern part (Yongqiao District and Lingbi County). Based on the distribution of the antibiotics in the five zones, we found that the antibiotics levels in the densely inhabited area and

livestock and poultry breeding area were higher than that in the planting region (Wei *et al*. 2024). The distribution of various antibiotics in each counties were shown that the antibiotics of the human medicinal using were dominant in Xiao County (OFI: 11.7 %, NOR: 11.8 %), Si County (NOR: 12.5 %) while the animal-derived antibiotics were dominant in the Yongqiao District (CTC: 9.0 %), Lingbi County (OTC: 9.4 %, CTC: 9.9 %). OFI and NOR is a common bacterial therapeutic drug which used by humans (Wain *et al*. 2021), CTC and OTC were most used in livestock Sun *et al*. 2017). It is worth noting that in animal excreta, TCs was difficult to remove due to their structural peculiarities and higher concentrations (Yang *et al*. 2022). These antibiotic residues in feces promote the production of ARGs, which might lead to increased drug resistance, making bacterial infections gradually difficult to treat with antibiotics and posing a significant threat to human health (He *et al*. 2020). In summary, the antibiotics contents in water were higher in the densely populated and livestock breeding areas.

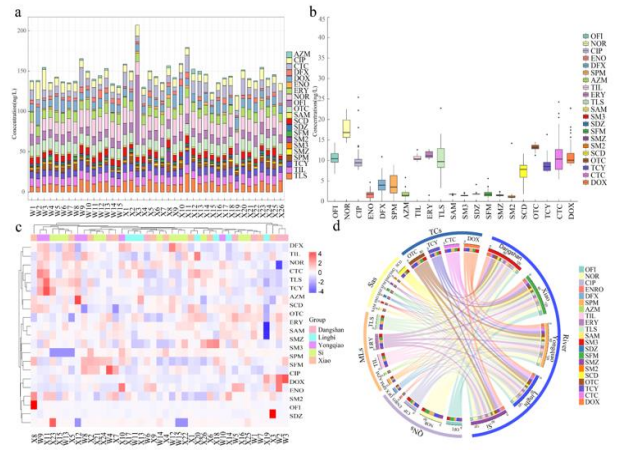


Figure 2. spatial changes of antibiotic in the rural-urban rivers of Suzhou City, China. (a) Antibiotic distribution in study area. (b) Concentration of each antibiotic in present study. (c) Clustered heat map of antibiotic concentrations in all samples, with each cell color representing z-score normalized concentration values. (d) The chordal graph demonstrates the levels of various types of antibiotics in different rivers

3.2. Factors influencing the distribution of antibiotic levels

The driving factors of antibiotic migration and transformation in water bodies were complex (Anthony A *et al*. 2018). The Composite structural equation model, Mantel test, and correlation network model were utilized to analyze the correlation between antibiotics and their drivers in the present study. The structural equation model can be used to determine the degree of influence of individual and global composite variables on antibiotic distribution through multiple regression analysis (Tian *et al*. 2021). The results of the structural equation model indicated that human activities, environmental factors, and land uses were accounted for 69% of the drivers of antibiotics, while the land use had the least driving influence (path coefficient of 0.30) (**Figure 3a**). Among the complex variables of the land use (e.g. farmland, building, water, forest and grassland), all the land uses have non correlation with antibiotics contents.

For the environment factors, the individual environmental factor (pH, T, SS, TN, NH_3-N) did not show a strong correlation with the total amount of antibiotics, but the environmental factors as a whole demonstrated a generally significant driving force of antibiotic distribution (p=0.01) (**Figure 3a**). In the Mantel test (**Figure 3b**), NOR and CIP were affected by the whole environmental factors (p<0.01). In detail, a negative correlation between NOR and pH was identified from the correlation analysis (r=-0.4, **Table S1**) (**Figure 3c**). The result was attributed to the impact of pH on the ionic form of NOR, and the previous study suggested that the degradation of NOR at pH=11 was twice as efficient as at pH=3 (Wang *et al*. 2020). Furthermore, a significant correlation was shown between CIP and SS (r=0.82), due to the high adsorption of CIP to suspended matters and sediments (Dinh *et al*. 2017).

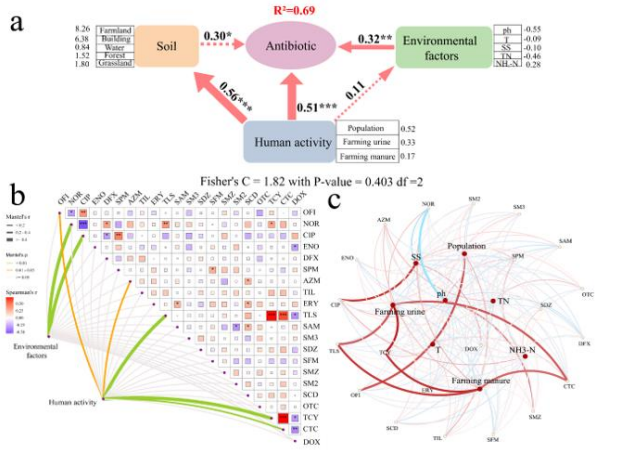


Figure 3. The driving factors of the distribution of antibiotics. (a) The composite structural equation model of antibiotic distribution in the study area. Numbers adjacent to measured variables are their coefficients with composite variables. The numbers next to the arrows are path coefficients showing the direct standardized effect of the relationship. The thickness of the arrows indicates the strength of the relationship. The total standardized effect of the complex variables is shown in marginal, and condition R^2 represents the variance proportion explained by all predictors of the random effect. (b) The correlation between antibiotics and different influencing factor groups by Mantel Test. (c) The correlation between antibiotics and each influencing factors Red lines representing positive feedback effects, blue representing negative feedback effects

The structural equation model revealed that human activities (e.g., population density, discharge of livestock breeding wastewater, and manure) had the highest path coefficient (0.51), as the most direct driving factor (**Figure 3a**). Among the complex variables of human activities, population factor was strongly associated with antibiotics (p<0.001) indicating that population was the main driving factor for antibiotics in the model (**Figure 3a**). In the study area, as the human-derived antibiotics (Norrby and Jonsson 1983), OFI and NOR were the high antibiotics in the rural-urban rivers. In the Mantel test, human activities showed a significant correlation with TLS, TCY, and CTC (p<0.01) (**Figure 3b**), and the correlation analysis revealed that this correlation was primarily influenced by discharges from livestock and poultry breeding (**Figure**

3c). Livestock breeding was booming in the study area, and TCY was widely used for antimicrobial therapy in animals (Amangelsin *et al*. 2023). Besides, CTC and TLS were often added to feeds to promote growth and assist in antimicrobial therapy (Kobashi *et al*. 2008; Thomas *et al*. 2017). These residual antibiotics in urine and feces were flown into the river water. In short, antibiotics were widely used and the main drivers were human activities in the rural-urban rivers.

3.3. Source analysis of antibiotics

To enhance the reliability of the antibiotic source apportionment, the PCA-MLR method was used in the present study (Wang *et al*. 2013). The majority of the variance (84.7%) in the water antibiotics was accounted by four principal components (PCs). PC 1 explained 57.6 % of the total variance, PC 2 accounted for 17.0 %, PC 3 accounted for 6.3 %, and PC 4 accounted for 3.7 %. Along the PC 1 axis, PC 1 had a strong correlation with CTC (0.58), which was commonly used in the livestock and poultry breeding (Kobashi *et al*. 2008; Thomas *et al*. 2017). PC 2 presented significant correlation loading for NOR (0.48), which was closely related to the treatment of urinary tract infections in humans (Norrby and Jonsson 1983). PC 3 had a strong correlations with DOX (0.72), which is often used in the treatment of human skin (Korbi *et al*. 2021). PC 4 presented strong positive loading for OFI (0.996), which was a medication used for treating Typhoid fever in humans (Wain *et al*. 2021).

The contributions of the major inputs of antibiotics in the rural-urban river water were estimated with MLR from the PCA scores. Based on the calculation, the sources of antibiotics were predominated by medicinal use for humans (70%), followed by medicinal use for livestock (30%) in the rural-urban rivers of Suzhou City.

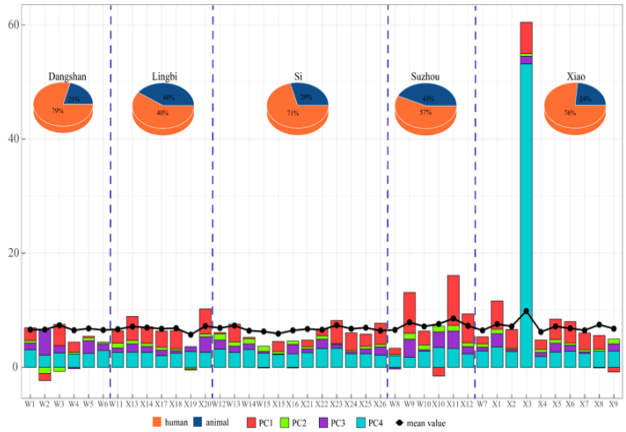


Figure 4. Source contributions of antibiotics by PCA-MLR in stuty area

3.4. Environmental risk assessment

The risk Quotient (RQ) method has been widely used to evaluate the risk assessment of antibiotics (Li *et al*. 2023). However, due to the different hazards of antibiotics to different species (Tian *et al*. 2023), the representative algae, invertebrates, fish, daphnia, and plants were collected for risk assessment in present study. The ecological risk posed by antibiotics was similar in the different counties as shown in **Figure 5**.

For algae, most antibiotics have the medium risk in the rural-urban rivers. In detail, 15.4% of the the antibiotics have the low risk, and 38.5% of the antibiotics have the medium ecological risk. It is noteworthy that the mean RQ values of OFI, CIP, ERY, NOR, and CTC of algae were 0.76, 0.60, 0.57, and 0.44, respectively, indicating OFI, CIP, ERY, NOR, and CTC posed a medium ecological risk to algae. In addition, OFI posed a high risk in the sampling site of X3 at the Xiao county (RQ = 5.37), and CIP posed a high risk in the sampling site of W2, W3 at the Xiao county (RQ = 1.31, 1.35), which induced ARG profiles in algae and allowed more bacteria carrying ARGs to spread from algae to the ecology, cultivating superbugs and posing a threat to the ecology and human health (Xue *et al*. 2023).

For plants, most antibiotics (80 %) have the low risk in the rural-urban rivers. Interestingly, SM2 which belongs to SAs has the lower value in present study (the mean value of 1.44 ng L^{-1}), but has the highest RQ value for pants (RQ = 0.07). Similarly with previous studies, SM2 were potentially significant in causing the ecotoxicological effects (Deng *et al*. 2016; Li *et al*. 2018). The antibiotics have the low risk for animals in the rural-urban rivers, as the least exposing to antibiotics in the study area. In detail, OTC,ERY, and CTC posed low risk to invertebrates and daphnia, but no significant risk to fish in rural-urban rivers (Li *et al*. 2022). In a word, algae was most sensitive to antibiotics in rural-urban rivers of Suzhou City, and the management of antibiotic contamination in the present study is urgent. In recent years, because of the antibiotic pollution in economically developed areas, the ecological risk of antibiotic in rural-urban river network is likely to be more serious (Wu *et al*. 2024). In summary, there is a great need for research on the contamination of the rural-urban river network to prevent the ecological hazards of antibiotic pollution.

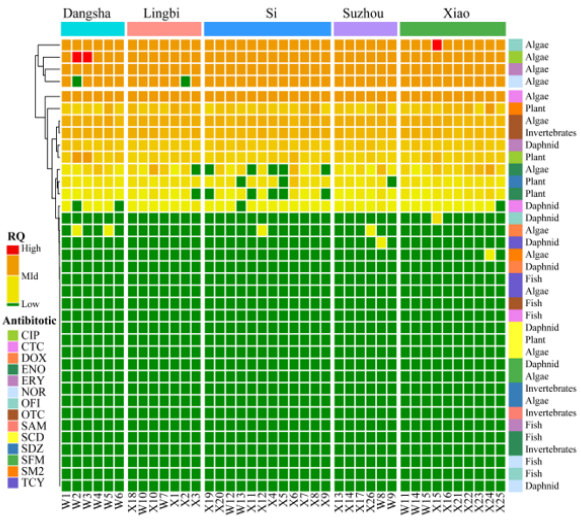


Figure 5. Ecological risk of antibiotics in the study area

4. Discussion

This study presented insights into four antibiotic classes variations throughout the rural-urban river network. Twenty-one antibiotics were detected in the river water with total concentrations in the range of nd-85.87 ng L^{-1}. Antibiotic concentrations in water were following: FQs >

TCs > MLs > SAs, and the antibiotic values were higher in the densely populated and breeding areas. The regional variations of antibiotic profiles in water along the rivers can be explained by the main influence of population, and followed by livestock according on the composite structural equation model, Mantel test, and correlation network model. The PCA-MLR analysis suggests that the antibiotics in river water are mainly from human (70 %) and livestock (30 %) medical using. Finally, antibiotics pose a medium risk to algae, while the risk to plants and Invertebrates is low. The results of the present study will fill the knowledge gap of the antibiotic in the typical rural-urban river network, and also help to provide guidance and suggestions for the management of antibiotic pollution in this study area.

Acknowledgment

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References

Amangelsin Y., Semenova Y., Dadar M., Aljofan M. and Bjørklund G. (2023). The impact of tetracycline pollution on the aquatic environment and removal strategies. *Antibiotics* **12**, 440. https://doi.org/10.3390/antibiotics12030440

Anthony A.A., Adekunle C.F. and Thor A.S. (2018). Residual antibiotics, antibiotic resistant superbugs and antibiotic resistance genes in surface water catchments: Public health impact. *Physics and Chemistry of the Earth* **105**, 177–183. https://doi.org/10.1016/j.pce.2018.03.004

Bandell R.A.M., Dekkers T., Semmekrot B.A., De Wildt S.N., Fleuren H.W.H.A., Warlé-van Herwaarden M.F., Füssenich P., Gerrits G.P. and Kramers C. (2019). Macrolide prescription in Dutch children: compliance with guidelines. *European Journal of Clinical Microbiology & Infectious Diseases*. **38**, 675–681. https://doi.org/10.1007/s10096-019-03473-7

Browne A.J., Chipeta M.G., Haines-Woodhouse G., Kumaran E.P.A., Hamadani B.H.K., Zaraa S., Henry N.J., Deshpande A., Reiner R.C., Day N.P.J., Lopez A.D., Dunachie S., Moore C.E., Stergachis A., Hay S.I. and Dolecek C. (2021). Global antibiotic consumption and usage in humans, 2000–18: a spatial modelling study. *Lancet Planet. Health* **5**, e893–e904. https://doi.org/10.1016/S2542-5196(21)00280-1

Ci M., Zhang G., Yan X., Dong W., Xu W., Wang W. and Fan Y. (2021). Multi-phase distribution, spatiotemporal variation and risk assessment of antibiotics in a typical urban-rural watershe. *Environmental Science and Pollution Research*. **28**, 25241–25254. https://doi.org/10.1007/s11356-020-12202-z

De Liguoro M., Riga A. and Fariselli P. (2018). Synergistic toxicity of some sulfonamide mixtures on Daphnia magna. *Ecotoxicology and Environmental Safety*. **164**, 84–91. https://doi.org/10.1016/j.ecoenv.2018.08.011

Deng W., Li N., Zheng H. and Lin H. (2016). Occurrence and risk assessment of antibiotics in river water in Hong Kong. *Ecotoxicology and Environmental Safety*. **125**, 121–127. https://doi.org/10.1016/j.ecoenv.2015.12.002

Dinh Q.T., Moreau-Guigon E., Labadie P., Alliot F., Teil M.J., Blanchard M. and Chevreuil M. (2017). Occurrence of antibiotics in rural catchments. *Chemosphere* **168**, 483–490. https://doi.org/10.1016/j.chemosphere.2016.10.106

Fu C., Xu B., Chen H., Zhao X., Li G., Zheng Y., Qiu W., Zheng C., Duan L. and Wang W. (2022). Occurrence and distribution of antibiotics in groundwater, surface water, and sediment in Xiong'an New Area, China, and their relationship with antibiotic resistance genes. *Science of the Total Environment*. **807**, 151011. https://doi.org/10.1016/j.scitotenv.2021.151011

Hu J., Li S., Zhang W., Helbling D.E., Xu N., Sun W. and Ni J. (2023). Animal production predominantly contributes to antibiotic profiles in the Yangtze River. *Water Research*. **242**, 120214. https://doi.org/10.1016/j.watres.2023.120214

Hu J., Li X., Liu F., Fu W., Lin L. and Li B. (2022). Comparison of chemical and biological degradation of sulfonamides: Solving the mystery of sulfonamide transformation. *Journal of Hazardous Materials*. **424**, 127661. https://doi.org/10.1016/j.jhazmat.2021.127661

Kim J.H., Lee D.H. and Kang J.H. (2019). Associating the spatial properties of a watershed with downstream Chl-a concentration using spatial analysis and generalized additive models. *Water Research*. **154**, 387–401. https://doi.org/10.1016/j.watres.2019.02.010

Kobashi Y., Ohmori H., Tajima K., Kawashima T. and Uchiyama H. (2008). Reduction of chlortetracycline-resistant Escherichia coli in weaned piglets fed fermented liquid feed. *Anaerobe* **14**, 201–204. https://doi.org/10.1016/j.anaerobe.2008.07.001

Korbi M., Amri F., Njima M., Belhadjali H., Youssef M., Zili J. (2021). Successful treatment of sneddon–wilkinson disease with doxycycline. *Clinical and Experimental Dermatology*. **46**, 1568–1569. https://doi.org/10.1111/ced.14756

Li F., Wen D., Bao Y., Huang B., Mu Q. and Chen L. (2022). Insights into the distribution, partitioning and influencing factors of antibiotics concentration and ecological risk in typical bays of the East China Sea. *Chemosphere*, **288**, 132566. https://doi.org/10.1016/j.chemosphere.2021.132566

Li S., Shi W., Li H., Xu N., Zhang R., Chen X., Sun W., Wen D., He S., Pan J., He Z. and Fan Y. (2018). Antibiotics in water and sediments of rivers and coastal area of Zhuhai City, Pearl River estuary, south China. *Science of the Total Environment*. **636**, 1009–1019. https://doi.org/10.1016/j.scitotenv.2018.04.358

Li S., Shi W., You M., Zhang R., Kuang Y., Dang C., Sun W., Zhou Y., Wang W. and Ni J. (2019). Antibiotics in water and sediments of Danjiangkou Reservoir, China: Spatiotemporal distribution and indicator screening. *Environmental Pollution*. **246**, 435–442. https://doi.org/10.1016/j.envpol.2018.12.038

Li Y., Tong L., Zhang J., Liu H., Li M. and Wen Z. (2023). Distribution and risk assessment of antibiotics under water level fluctuation in the riparian zone of the hanjiang river. *Ecotoxicology and Environmental Safety*. **256**, 114833. https://doi.org/10.1016/j.ecoenv.2023.114833

Miranda C.D., Concha C., Godoy F.A. and Lee M.R. (2022). Aquatic environments as hotspots of transferable low-level quinolone resistance and their potential contribution to

high-level quinolone resistance. *Antibiotics* **11**, 1487. https://doi.org/10.3390/antibiotics11111487

Morina J.C. and Franklin R.B. (2023). Drivers of antibiotic resistance gene abundance in an urban river. *Antibiotics* **12**, 1270. https://doi.org/10.3390/antibiotics12081270

Norrby S.R. and Jonsson M. (1983). Antibacterial activity of norfloxacin. ANTIMICROB AGENTS CHEMOTHER.

Sun J., Zeng Q., Tsang D.C.W., Zhu L.Z. and Li X.D. (2017). Antibiotics in the agricultural soils from the Yangtze River Delta, China. *Chemosphere* **189**, 301–308. https://doi.org/10.1016/j.chemosphere.2017.09.040

Thomas M., Webb M., Ghimire S., Blair A., Olson K., Fenske G.J., Fonder A.T., Christopher-Hennings J., Brake D. and Scaria J. (2017). Metagenomic characterization of the effect of feed additives on the gut microbiome and antibiotic resistome of feedlot cattle. *Scientific Reports*. **7**, 12257. https://doi.org/10.1038/s41598-017-12481-6

Tian L., Xu X., Zhang Z., Ding Y., Zhang K. and Zhi S. (2023). A Comprehensive Contamination Investigation of Bohai Bay Seawater: Antibiotics Occurrence, Distribution, Ecological Risks and Their Interactive Factors. *International Journal of Environmental Research and Public Health* **20**, 1599. https://doi.org/10.3390/ijerph20021599

Tian P., Liu S., Zhao X., Sun Z., Yao X., Niu S., Crowther T.W. and Wang Q. (2021). Past climate conditions predict the influence of nitrogen enrichment on the temperature sensitivity of soil respiration. *Communications Earth and Environment*. **2**, 251. https://doi.org/10.1038/s43247-021-00324-2

Wain J., Simpson J.A., Thi Diem Nga L., Song Diep T., Thanh Duy P., Baker S., Day N.P.J., White N.J. and Parry C.M. (2021). Bactericidal activities and post-antibiotic effects of ofloxacin and ceftriaxone against drug-resistant *Salmonella enterica* serovar Typhi. *Journal of Antimicrobial Chemotherapy*. **76**, 2606–2609. https://doi.org/10.1093/jac/dkab215

Wang D., Feng C., Huang L., Niu J. and Shen Z. (2013). Historical deposition behaviors of PAHs in the Yangtze River Estuary: Role of the sources and water currents. *Chemosphere* **90**, 2020–2026. https://doi.org/10.1016/j.chemosphere.2012.10.079

Wang H., Cheng Z., Zhu N., Yuan H., Lou Z., Otieno P., Li W. (2020). pH-dependent norfloxacin degradation by E+-ozonation: Radical reactivities and intermediates identification. *Journal of Cleaner Production*. **265**, 121722. https://doi.org/10.1016/j.jclepro.2020.121722

Wang L., Li H., Dang J., Guo H., Zhu Y. and Han W. (2021). Occurrence, distribution, and partitioning of antibiotics in surface water and sediment in a typical tributary of Yellow River, China. *Environmental Science and Pollution Research*. **28**, 28207–28221. https://doi.org/10.1007/s11356-021-12634-1

Wang S., Fang L., Sun X. and Lu W. (2024). Occurrence and distribution of antibiotic resistance genes in urban rivers with black-odor water of harbin, China. *Environmental Research*. **259**, 119497. https://doi.org/10.1016/j.envres.2024.119497

Wang Z., Du Y., Yang C., Liu X., Zhang J., Li E., Zhang Q., Wang X. (2017). Occurrence and ecological hazard assessment of selected antibiotics in the surface waters in and around Lake Honghu, China. *Science of the Total Environment*. **609**, 1423–1432. https://doi.org/10.1016/j.scitotenv.2017.08.009

Wei C., Wang Y., Zhang R., Liu F., Zhang Z.E., Wang J., Yu K. (2024). Spatiotemporal distribution and potential risks of antibiotics in coastal water of beibu gulf, south China sea: Livestock and poultry emissions play essential effect. *Journal of Hazardous Materials*. **466**, 133550. https://doi.org/10.1016/j.jhazmat.2024.133550

Wu H., Liu R., Liu G., He M., Arif M., Li F., Si W., Yue Z., Hu H. (2024). Unveiling antibiotic contamination in surface water: A study of the Huaihe River Basin's Huaibei Plain, a significant Chinese herbal medicine planting region. *Science of the Total Environment*. **933**, 173125. https://doi.org/10.1016/j.scitotenv.2024.173125

Wu X., Yuan Z. and Wang S. (2023). Prioritization, sources, and ecological risk of typical antibiotics in the Huai River, a Chinese major river: a warning about aquaculture. *Environmental Science and Pollution Research*. **30**, 64254–64264. https://doi.org/10.1007/s11356-023-27059-1

Xiao R., Huang D., Du L., Song B., Yin L., Chen Y., Gao L., Li R., Huang H. and Zeng G. (2023). Antibiotic resistance in soil-plant systems: A review of the source, dissemination, influence factors, and potential exposure risks. *Science of the Total Environment*. **869**, 161855. https://doi.org/10.1016/j.scitotenv.2023.161855

Xue X., Su X., Zhou L., Ji J., Qin Z., Liu J., Li K., Wang H., Wang Z. (2023). Antibiotic-Induced Recruitment of Specific Algae-Associated Microbiome Enhances the Adaptability of *Chlorella vulgaris* to Antibiotic Stress and Incidence of Antibiotic Resistance. *Environmental Science & Technology*. **57**, 13336–13345. https://doi.org/10.1021/acs.est.3c02801

Yang J., Huang Y., Chen Y., Hassan M., Zhang X., Zhang B., Gin K.Y.H. and He Y. (2020). Multi-phase distribution, spatiotemporal variation and risk assessment of antibiotics in a typical urban-rural watershed. *Ecotoxicology and Environmental Safety*. **206**, 111156. https://doi.org/10.1016/j.ecoenv.2020.111156

Zainab S.M., Junaid M., Rehman M.Y.A., Lv M., Yue L., Xu N., Malik R.N. (2021). First insight into the occurrence, spatial distribution, sources, and risks assessment of antibiotics in groundwater from major urban-rural settings of pakistan. *Science of the Total Environment*. **791**, 148298. https://doi.org/10.1016/j.scitotenv.2021.148298

Zeng Y., Duan L., Xu T., Hou P., Xu J., Li H. and Zhang H. (2024). Occurrence and Risk Assessment of Antibiotics in Urban River–Wetland–Lake Systems in Southwest China. *Water* **16**, 1124. https://doi.org/10.3390/w16081124

Zhou L. J., Wang W. X., Lv Y.J., Mao Z.G., Chen C. and Wu Q.L. (2020). Tissue concentrations, trophic transfer and human risks of antibiotics in freshwater food web in Lake Taihu, China. *Ecotoxicology and Environmental Safety*. **197**, 110626. https://doi.org/10.1016/j.ecoenv.2020.110626

Zhou Q., Liu G., Arif M., Shi X. and Wang S. (2022a). Occurrence and risk assessment of antibiotics in the surface water of Chaohu Lake and its tributaries in China. *Science of the Total Environment*. **807**, 151040. https://doi.org/10.1016/j.scitotenv.2021.151040

Zhou Q., Liu G., Arif M., Shi X. and Wang S. (2022b). Occurrence and distribution of antibiotic resistance genes in urban rivers with black-odor water of Harbin, China. *Science of the Total Environment*. **807**, 151040. https://doi.org/10.1016/j.scitotenv.2021.151040

Supporting information

Table S1. Pearson values of correlation networks

Antibiotic	ph	T	SS	TN	NH3-N	population	Cultured urine	Farming manure
OFI	0.08	0.02	-0.04	-0.19	-0.06	0.7	-0.05	-0.1
NOR	-0.4	0.03	-0.71	0.07	-0.04	-0.06	0.25	0.32
CIP	0.27	-0.03	0.8	0.13	0.33	0.14	-0.09	-0.15
ENO	-0.09	-0.07	-0.07	-0.26	-0.1	0.12	0.09	0.07
DFX	-0.33	0.1	-0.14	-0.33	-0.03	-0.19	0.05	-0.05
SPM	0.26	-0.05	0.23	0.15	0.3	0.1	-0.18	-0.1
AZM	-0.19	0.07	0.04	0.3	0.13	-0.14	0.17	0.27
TIL	-0.16	-0.02	-0.07	-0.03	0.04	0.3	0.16	0.12
ERY	-0.19	-0.17	0.13	-0.03	0.04	0.11	-0.17	-0.07
TLS	-0.09	0.07	-0.21	-0.09	-0.05	-0.07	0.67	0.8
SAM	-0.29	-0.3	0.16	-0.07	0	0.14	-0.18	-0.05
SM3	0.17	0.07	-0.09	0	-0.12	-0.05	-0.04	-0.07
SDZ	0.03	-0.1	0.12	0.05	0.2	0.04	0.04	0.03
SFM	-0.05	-0.2	-0.14	0.09	0.03	-0.05	-0.23	-0.1
SMZ	0.48	0.12	-0.05	0.07	0.06	-0.01	0.06	0.04
SM2	0.01	0.05	-0.06	-0.2	-0.11	0.15	-0.03	-0.04
SCD	-0.1	0.08	0.06	-0.31	-0.23	-0.01	0.15	0.16
OTC	-0.02	0	0.15	0.24	0.1	0.08	-0.1	-0.11
TCY	-0.02	0.25	-0.14	-0.08	-0.05	-0.03	0.9	0.82
CTC	-0.06	0.19	-0.17	-0.06	-0.01	-0.05	0.67	0.61
DOX	0.01	-0.29	0.36	0.06	0.04	-0.13	-0.25	-0.23