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Article

A multimedia fugacity model for assessing the environmental fate of typical antibiotics in Lake Taihu with emphasis on the biomechanical characteristics of drug delivery systems

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Abstract: The extensive use of antibiotics in the Taihu Lake Basin has led to a significant threat to human and environmental health. In this context, the QWASI model is developed to simulate the fate of typical antibiotics in Lake Taihu. Through this model, real-time tracking of the dynamic changes in antibiotic content is possible. The study primarily focuses on evaluating the fate and transfer of antibiotics in the water and sediment phases of the lake. The model results indicate that most of the simulated concentrations and mass fluxes are within the same order of magnitude as the measured values, demonstrating a good simulation effect. However, an underestimation of the simulated output value occurs in some cases. The sediment layer serves as the main accumulation site for antibiotics, and the mass balance equation is a crucial tool for simulating the environmental distribution of antibiotics. Sulfamethoxazole (SMX) exhibits a relatively high concentration in water due to its large model input. The sensitivity analysis reveals that for ATM, SMX, and OFX, the five input parameters with the most significant impact are the half-life in water, sediment-water partition coefficient, sediment solids concentration, sediment particle density, and sediment-water diffusion MTC. For OTC, the impact of lake water depth is more prominent than the sediment-water mass transfer rate. The uncertainty analysis effectively showcases the model's stability, with the water phase concentration showing better stability. In this process, each factor is assigned a correlation coefficient to represent its influence on the original content. The sediment phase antibiotic concentration has a relatively high uncertainty. The source intensity assessment in this study utilizes direct monitoring data of the Taihu Lake water body, ensuring higher accuracy. The major factor contributing to prediction errors is the ambiguity of the sediment phase, which is affected by numerous environmental factors. Importantly, when considering the fate of antibiotics in the lake, the biomechanical characteristics of potential drug delivery systems play a vital role. The movement and dispersion of antibiotics within the water and sediment are influenced by biomechanical forces. In the sediment, the porosity and permeability, which are related to biomechanical properties, can determine the rate at which antibiotics penetrate and accumulate. Understanding these biomechanical aspects of drug delivery systems can help in devising more effective strategies for antibiotic remediation. It can also provide insights into how the physical environment interacts with the chemical behavior of antibiotics, ultimately contributing to a more comprehensive understanding of the environmental fate of antibiotics in Lake Taihu. This is the first study to explore the fate of antibiotics in Lake Taihu and offers valuable recommendations for the restoration of antibiotic-contaminated lakes. It enriches the research perspectives on water management, especially in relation to addressing water pollution caused by antibiotic abuse.

Keywords: QWASI model; antibiotics; environmental fate; Taihu Lake; biomechanical characteristics; drug delivery systems

1. Introduction

Antibiotics are widely used in the prevention and treatment of diseases in humans, livestock and aquatic organisms, and they can also be used to promote the growth in animal husbandry [1]. It is precisely because of the wide use of antibiotics that the problem of antibiotic abuse and pollution in developing countries has become increasingly serious in recent years [2]. Since the human body or animals cannot fully absorb antibiotics after ingestion, most antibiotics will be discharged into the environment in the form of maternal or metabolic products, and the water environment is the main environment for receiving antibiotics [3,4]. As a new type of pollutant, antibiotics are everywhere in the water environment. The environmental problems caused by antibiotics in recent years have been highly valued by countries all over the world [5–7]. As an important subject in the research of water environmental pollutants, the research of antibiotics in lakes has been very extensive, but mainly focused on their residues in lake water and surface sediments [8].

Taihu lake, the third largest freshwater lake in China, is the largest shallow freshwater lake in East China. With the rapid development of urbanization and industrialization in the recent decades, Taihu lake faces increasingly severe water scarcity and serious water pollution problems [9]. Current researches also showed that the antibiotic pollution in Taihu Lake was very serious [5–7]. Researchers not only need a lot of energy to control the pollution, but also need to make accurate prediction of the distribution of antibiotics in the water body of Taihu Lake, so as to facilitate the subsequent pollution control work. The previous articles have discussed that the current researches mainly focus on the residual situation of antibiotics in the lake. There is still no corresponding research on the specific fate of antibiotics in Taihu Lake, which requires building a mathematical model to carry out more accurate simulation [10]. Fugacity model provides us with an important means to simulate the multi-medium fate of pollutants in the environment. In 1983, Mackay et al. [11,12] firstly proposed the QWASI model to simulate the fate of chemical substances in lakes and rivers, which can be directly obtained from the Canadian Environmental Modeling and Chemistry Center (CEMC) as software [13]. At the same time, the QWASI model has been successfully applied to the environmental fate simulation of many compounds. Abbasi et al. [14] have successfully used the QWASI model to simulate and predict the methoxychlorine and other substances in Naiwar Lake (Kenya). Wang et al. [15] have established an improved QWASI model for the new pollutants (ECs) in the urban sewage lagoon system to predict the fate of ECs in the sewage lagoon. Liu et al. [16] used the improved QWASI model to simulate the environmental fate of Zn and Pb in shallow lakes during the glacial period. As Taihu Lake is a shallow freshwater lake, its overall environment is in non-equilibrium and steady state, so the QWASI model can be used to simulate the antibiotics in Taihu Lake. At the same time, no researcher has previously simulated the environmental fate of antibiotics in Taihu Lake, so this study will focus on this.

Therefore, the objective of this study are as follows:

(1) To calculate the source intensity input of four antibiotics in Taihu Lake according to the monitoring data;

(2) To analyze the environmental fate behavior of typical antibiotics in Taihu

Lake and validate the model output;

(3) To analyze the sensitivity of the input parameters, and the uncertainty of the model is further analyzed to validate the stability of the model.

2. Materials and methods

2.1. Study area and sampling points

The Taihu Lake (30.5′–32.8′ N, 119.8′–121.55′ E) is located in East China, which has the best economic development in China. The Taihu Lake spans Jiangsu and Zhejiang provinces, bordering Wuxi City in the north, Huzhou City in the south, Yixing City in the west, and Suzhou City in the east. The water area of Taihu Lake is 2156.16 square kilometers, and the lake shoreline is 393.2 kilometers long. The social economy in Taihu Lake Basin has maintained rapid development, and the population growth trend has slowed down. The per capita water resources in the basin are far below the national average level. The panoramic picture of Tai Lake is shown in **Figure 1**.

The average depth of Taihu Lake is 1.9 m, less than 5 m in general. There are 22 sampling points in Taihu Lake area in this study. 54.5% of the rivers in the whole year mainly enter Taihu Lake (according to the monthly proportion of entering and leaving the lake, the same below), with a total of 12 rivers, including the Taige Canal in Zhushan Lake, Yincun Port, Shedu Port in the western coastal area, Guandu Port, Hongxiang Port, Chengdong Port, Dapu Port, Wuxi Port, and Hexi New Port, Changxing Port, Yangjiapu Port, Maoer Port in the southern coastal area. Among them, the rivers with large amount of water entering the lake are Chengdong Port Bridge and Wuxi Bridge; 18.2% of the watercourses are mainly out of the lake, with a total of 4 watercourses, including Wangyu River, Liangxi River, Tiaoxi River and Daqian Port. The watercourse with a large amount of water out of the lake is Hangchang Bridge; 27.3% of the watercourses are mainly detention, with a total of 6 watercourses, including Daxi Port, Zhihu Port, Wujin Port, Caoqiao River, Dagang River and Jiapu Port.

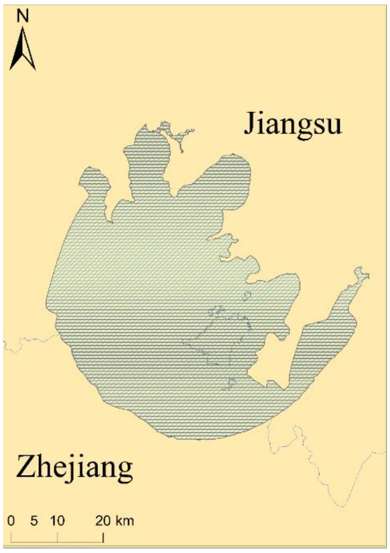

Figure 1. Based on Alber projected panorama of Tai Lake.

2.2. Target antibiotic data collection and source intensity calculation

According to previous research results, 4 antibiotics are selected as target pollutants in Taihu Lake in this study. In this study, a total of 4 typical antibiotics which had been detected widely within Taihu lake were selected as target chemicals. They are belong to four different antibacterial classes: (1) sulfonamides (SAs), including sulfamethoxazole (SMX); (2) tetracyclines (TCs), including oxytetracycline (OTC); (3) fluoroquinolones (FQs), including ofloxacin (OFX); (4) macrolides (MCs), including azithromycin (ATM) [17]. The physiochemical properties of these target antibiotics are presented in **Table 1**.

Table 1. Physical and chemical properties and environmental behavior parameters of target antibiotics.

	ATM	**SMX**	**OTC**	**OFX**
CAS	83905-01-5	723-46-6	79-57-2	82419-36-1
Molecular Formula	$C_{38}H_{72}N_2O_{12}$	$C_{10}H_{11}N_3O_3S$	$C_{22}H_{24}N_2O_9$	$C_{18}H_{20}FN_3O_4$
Molar mass (g/mol)	749	253	460	361
Vapor pressure (Pa)	3.53×10^{-22}	1.73×10^{-5}	4.60×10^{-21}	2.43×10^{-11}
Melting point (℃)	114	170	327	240
$Koc\ (L/kg)$	4293	1530	233	44,100
Henry's law constant ($Pa \cdot m^3 \cdot mol^{-1}$)	5.37×10^{-24}	9.69×10^{-8}	4.79×10^{-22}	1.18×10^{-16}
Solubility (mg/L)	85	400	313	3400
Half-life in water ($hours$)	11	529	216	120
Half-life in sediment ($hours$)	16,776	568	1750	13,000
$log\,K\,ow$	4.02	0.89	−1.22	−0.7
K_{AW}	4.50×10^{-23}	4.42×10^{-9}	2.73×10^{-24}	1.04×10^{-15}

Since the data of water volume in and out of the lake around Taihu Lake are compiled with the hydrological patrol section or single station as the smallest unit, in order to calculate and match, the pollution load in and out of the lake is calculated and counted with the hydrological patrol section or single station as the unit. The hydrological monitoring data of Taihu Lake is presented in **Table 2**. When there is only one water quality monitoring section in the patrol section or single station, the water quality concentration of the section shall be taken as the representative value of the patrol section (station). When multiple water quality monitoring sections are set at the patrol section or single station, the arithmetic mean of water quality concentration is taken as the representative water quality of the same river at multiple sections; The weighted average of water quality concentration is taken as the representative value of the survey section by using the water inflow as the weight for the sections on different rivers. For the inflow pollution load of rivers around Taihu Lake, the method of the product of the instantaneous water quality concentration of rivers entering the lake and the average flow in a representative period is used to calculate the inflow pollution load of a single month (or a single day) of a single patrol section (station), and then the annual inflow pollution load of each patrol section (station) is obtained by quarterly accumulation, and finally the total inflow pollution load of each patrol section (station) is obtained by accumulation.

Table 2. Cross sections of various monitoring rivers in the Taihu Lake.

Order number	River channel name	Administrative district	Control section	Section width (m)	Distance to river mouth (km)
1	Wangyu River	Suzhou, Jiangsu Province	Under Wangting Interchange	110	2.8
2	Daxi Port	Wuxi City, Jiangsu Province	Daxi Port Gate	15	0.1
3	Liangxi River		Jingyiqiao	26	1.6
4	Zhihu Port		Hushan Bridge	54	1.1
5	Wujin Port	Changzhou City, Jiangsu Province	Gongxiangqiao	32	1.3
6	Taige Canal	Yixing City, Jiangsu Province (county-level city, subordinate to Wuxi City)	Fenshui Bridge	30	1.8
7	Caoqiao River		Fenshui Old Bridge	24	1.9
8	Yincun Port		Wuxi Bridge	64	0.1
9	Shedu Port		Shedu Port Bridge	25	1.3
10	Guandu Port		Guandu Port Bridge	24	1
11	Hongxiang Port		Hongxiang Port Bridge	31	1
12	Chengdong Port		Chengdong Port Bridge	74	1
13	Dapu Port		Dapu Port Bridge	47	1.3
14	Wuxi Port		Wuxi Bridge	20	0.8
15	Dagang River		Dongdagang Bridge	16	0.9
16	Jiapu Port	Huzhou City, Zhejiang Province	Jiapu Bridge	18	0.7
17	Hexi New Port		Hexi No.8 Bridge	32	0.2
18	Changxing Port		Xintang Bridge	56	0.3
19	Yangjiapu Port		Yangjiapu Bridge	64	0.1
20	Maoer Port		Jiujiu Bridge	110	12
21	Tiaoxi River		Hangchang Bridge	110	11
22	Daqian Port		Big money gate	40	0.2

The calculation method of pollution load of rivers around Taihu Lake into the lake is calculated according to the following formula:

$$W = \sum_{i=1}^{24} W_i \tag{1}$$

$$W_i = \sum_{n=1}^{4} C_n Q_n \tag{2}$$

where, W is the total amount of pollutants entering the lake in all survey sections (stations); W_i is the amount of pollutants entering the lake in the i^{th} patrol section (station); C_n is the representative value of water quality of pollutants entering the lake in the n^{th} quarter of the survey section (station); Q_n is the water inflow into the lake in the n^{th} quarter of the survey section (station).

2.3. Model framework

The multimedia model based on the concept of fugacity, is a series of models established by the Canadian Modeling Center. The environmental system in this study is a shallow lake, which is characterized by steady state, non-equilibrium and fluidity. The substances are assumed in a non-equilibrium state between phases. And consider the steady state input and output of pollutants and various reactions occur in phases, as well as various diffusion and non-diffusion processes of substances between adjacent phases. Among these, the QWASI model should apply to Taihu Lake system, allowing prediction of the processes of antibiotics migration and transformation between air, water and sediment phases, by assuming a uniform level of water mixing. Based on the description of Taihu Lake, the model in this study was divided into three modules. The transport process of antibiotics in the QWASI model is shown in **Figure 2** and each environmental phase was represented by numbers (air-1; water-2; sediment-4). Based on these, the target antibiotics are not only transported in several major media, but also settled and degraded in each medium. After considering all environmental processes, specific mass balance equations are as follows:

Air:

$$(E_1 + G_{A1}C_{B1} + D_{21}\, f_2 + D_{31}\, f_3) - f_1(D_{12} + D_{13} + D_{R1} + D_{A1}) = 0 \tag{3}$$

Water:

$$(E_2 + G_{A2}C_{B2} + D_{12}\, f_1 + D_{42}\, f_4) - f_2(D_{21} + D_{24} + D_{R2} + D_{A2}) = 0 \tag{4}$$

Sediment:

$$(E_4 + D_{24}f_2) - f_4(D_{42} + D_{R4} + D_{A4}) = 0 \tag{5}$$

where, f: fugacity (Pa); E:Emission rate (mol/h); G_A: Advection velocity (m^3/h); C_B: Background concentration (mol/m^3); D: Transport rate of chemical substances during transport (mol/Pa/h); D_{12}: The D value from media 1 to media 2, and other subscripts also mean the same; Subscript R: represents reaction.

The concentration of antibiotics is calculated as follows:

$$C_x = Z_x \times f_x \tag{6}$$

where, C: Concentration (mol/m^3); Z: Fugacity capacity $(mol/(m^3 \cdot Pa))$. The definition of the fugacity capacity (Z) value is shown in **Table 3**.

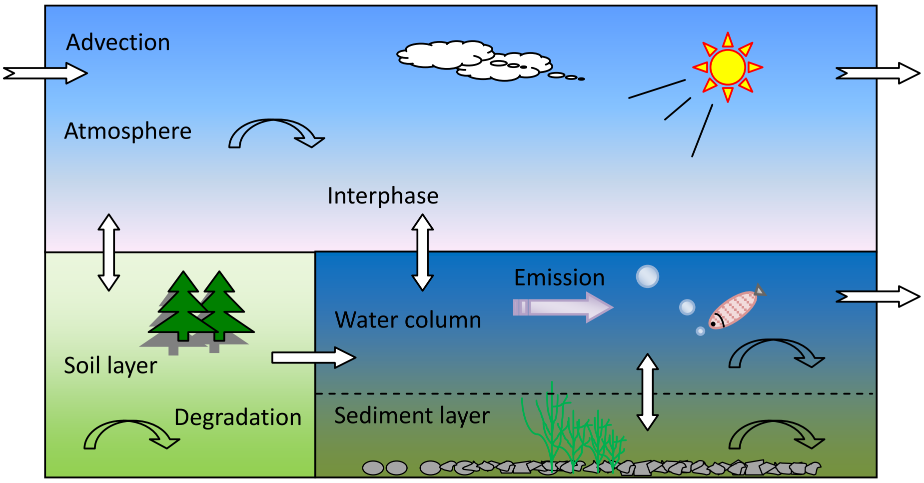

Figure 2. The transport process of antibiotics in various media in the QWASI model.

Table 3. Definition of the fugacity capacity (Z) values (mol/m^3·Pa).

Compartment	Equation	Definition
Air	$Z_a = 1/RT$	R is the gas constant ($8.314 Pa \cdot m^3/(mol \cdot K)$); T is the absolute temperature (K).
Water	$Z_w = 1/H$	H is the Henry's Law constant ($Pa \cdot m^3/mol$).
Solid in water (Z_{2Solid}), and sediment (Z_{4Solid})	$Z_{Solid} = K_{OC} \times \rho_{s(i)} \times Z_w$	K_{OC} is organic carbon normalized partition coefficients (L/kg); $\rho_{s(i)}$ is density of the solid phase (kg/L).
Bulk air	$Z_1 = Z_A \times (1 - X_{1q}) + Z_Q \times X_{1q}$	X_{1q} is the volume fraction of suspended particles in air.
Bulk water	$Z_2 = Z_w \times \left(1 - X_{2sup}\right) + Z_{2Solid} \times X_{2sup}$	X_{2sup} is the volume fraction of suspended particles in water, respectively.
Bulk sediment	$Z_4 = Z_{4Solid} \times (1 - X_{4w}) + Z_w \times X_{4w}$	X_{4w} is the volume fraction of water in sediment.

2.4. Model parameters

The input parameters of the model include environmental attribute parameters and physiochemical properties parameters of typical antibiotics. Environmental attribute parameters include water area (A), water depth (h_2), sediment depth (h_4), solid content in each medium, organic carbon content in water and sediment, and migration rate of environmental media of Taihu Lake. Some environmental attribute parameters used in this study are from Taihu Lake Yearbook, related papers, etc., and some parameters are recommended values. The QWASI model adopted in this study considers the three main media of air, water and sediment. The solution of the QWASI model uses the existing model framework in the Excel developed by the Canadian CEMC Modeling Center. The input parameters of the physiochemical properties of the antibiotics are mainly from the website http://pubchem.ncbi.nlm.nih.gov/ (**Table 1**). As well as literature, environmental parameters mainly come from the measurement and research data of Taihu Lake Basin Hydrology and Water Resources Monitoring Center. And environmental attribute parameters of this study are shown in **Table 4**.

Table 4. Environmental attribute parameters of this study.

Parameter	Character	Numerical value	Unit
Water area	A	2445000000	m^2
Lake depth	h_2	1.9	m
Depth of sediment layer	h_4	0.03	m
Volume fraction of aerosol	Vf_a	40	$\mu g/m^3$
Volume fraction of particulate matter in water	Vf_w	31	mg/L
Volume fraction of particulate matter in sediment	Vf_s	0.47	m^3/m^3
Aerosol density	ρ_a	1500	kg/m^3
Water density	ρ_w	1420	kg/m^3
Sediment density	ρ_s	1420	kg/m^3
Organic carbon content of water body	OC_2	0.01	g/g
Organic carbon content of sediment	OC_4	0.01	g/g
Organic carbon content of resuspended sediment	OC_{40}	0.08	g/g
River flow into the lake	G_{02}	1321978	$m^3 \cdot h^{-1}$
River flow out of the lake	G_{20}	959740	$m^3 \cdot h^{-1}$

Table 4. (*Continued*).

Parameter	Character	Numerical value	Unit
Aerosol deposition rate	Q_1	7.2	$m \cdot h^{-1}$
Rainfall rate	U_R	1.23	$m \cdot year^{-1}$
Air-water mass transfer coefficient at atmospheric side of water column	k_{VA}	1	$m \cdot h^{-1}$
Air-water mass transfer coefficient at water side of water column	k_{VW}	0.01	$m \cdot h^{-1}$
Sediment-water diffusion mass transfer coefficient	k_{SW}	0.004	$m \cdot h^{-1}$

2.5. Sensitivity analysis

This study quantitatively analyzes the sensitivity of the relevant parameters in the model. It is aim to evaluate how each input parameter affects the model outcomes and to identify the most influential inputs [18]. The commonly used local analysis method is to test the influence of the change of a single parameter on the model results (OAT). The OAT method is used to analyze the sensitivity of the environmental attribute parameters and physiochemical property parameters of the model. The five most critical sensitivity parameters are judged according to the results of the sensitivity analysis. The sensitivity coefficient is calculated by the ratio of the change of output value to the change of input parameter. The specific formula is as follows:

$$S = \frac{(Y_{1.01} - Y_{1.0})/Y_{1.0}}{(X_{1.01} - X_{1.0})/X_{1.0}} \tag{7}$$

where, $X_{1.01}$and $X_{1.0}$ represents 1.01 times and 1.0 times of input parameters; $Y_{1.01}$ and $Y_{1.0}$ represents 1.01 times and 1.0 times of the output value corresponding to the input parameter. The sensitivity coefficient quantifies the influence of parameters, and the effective sensitivity parameters will be given in the following specific result analysis.

2.6. Uncertainty analysis

The Monte Carlo method can effectively reflect the range of predicted values of the model and verify the stability of random factors based on the model [19,20]. It can analyze the uncertainty of the model parameters to verify the stability of the model. According to the lognormal distribution characteristics of parameter values, random values were selected from each input parameter distribution. Oracle Crystal ball is used for Monte Carlo analysis. After 10,000 calculations, the average value, minimum value, maximum value, 5th percentile value, median value and 95th percentile value of the simulated concentration is compared. Coefficients of variation (CVs) were used to quantify the differences [15,21].

3. Results and discussion

3.1. Source input estimation results

The estimation of source intensity in this study is based on 22 sampling points. In 2017, each sampling point will be sampled once a month. According to the monthly instantaneous flow monitoring, the river flow velocity and antibiotic concentration at each inlet and outlet of the river can be measured. In the absence of continuous river water quality monitoring data at present, based on the monthly water quality monitoring results, the time flux of pollutants entering the lake in the river or patrol section is estimated by the product of instantaneous concentration and average flow in the representative period. For the algorithm of pollution load out of the lake, according to the monitoring results for many years, the water quality of Taihu Lake is relatively stable, and the change range over time is small. The same calculation method is used for the calculation of pollution load out of the lake. The calculation results are shown in **Table 5**.

Table 5. Source intensity input of 4 antibiotics.

	Annual input load ($kg/year$)	**Annual input concentration (ng/L)**
ATM	9650.695	0.932
SMX	12600.460	5.647
OTC	5501.688	0.498
OFX	9222.290	1.000

According to the calculation results shown in **Table 5**, among all the antibiotics, it can be seen that the distribution of pollution load of antibiotics flowing into Taihu Lake in 2017 is SMX > ATM > OFX > OTC, and the comparison of annual input concentration is SMX > OFX > ATM > OTC. The input of source intensity will directly affect the output of the model and the different fate of different antibiotics in multimedia of Taihu Lake. In addition, the source intensity input method used in this study, which is estimated with actual values, is different from previous studies, and it has greater accuracy. Among previous studies, the source intensity input used by Huang et al. [13] in the study of the environmental fate of polycyclic aromatic hydrocarbons (PAHs) in Shanghai is based on the comprehensive evaluation of the data of previous papers and yearbook data.

3.2. Simulation results and model validation

3.2.1. Predicted antibiotics concentrations in Taihu Lake

The predicted results of the concentration of 4 antibiotics in Taihu Lake are shown in **Figure 3**. After calculated, 4 antibiotics have total concentrations below 0.500 ng/L. In addition, the concentration of 4 antibiotics in the sediment phase is higher than that in the water phase. Since the concentration of SMX in the source intensity input is the highest, the concentration of SMX in the two environmental media is significantly higher than others. And the simulated concentration in the two phases reaches 0.199 ng/L and 0.477 ng/L respectively. In the sediment phase, the predicted concentration of OFX is obviously higher than that of ATM and OTC, reaching 0.166 ng/L. And the concentrations of ATM and OTC in this phase reach 0.014 ng/L and 0.057 ng/L respectively, which may be due to the higher K_{OC} value of OFX compared with ATM and OTC. In the water phase, the predicted concentrations of ATM, OTC and OFX are equivalent, 0.004 ng/L, 0.040 ng/L and 0.038 ng/L respectively. For the prediction of air phase, antibiotics are not shown here because they are not volatile and have low concentration [22].

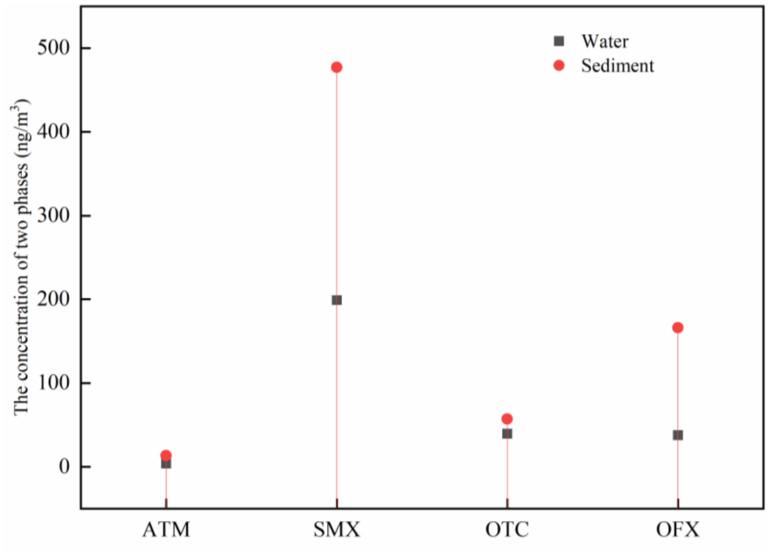

Figure 3. Concentration changes of four antibiotics in various media.

3.2.2. Fate of 4 antibiotics in Taihu Lake

The simulation results of 4 antibiotics are given in the form of mass balance diagram in **Figure 4**, and all transfer fluxes are shown in average. The model output includes all attributes, concentration, fugacity, mass and other complete matrix characteristics of antibiotics in the lake model. Since the K_{AW} values of the 4 antibiotics are relatively low, the mass of their volatilization to the air phase can be ignored. Their degradation half-life is different in the different phases, so their predicted distribution in Taihu Lake is also different. The total mass flux of 4 antibiotics flowing into the lake water has been introduced in 3.1. It is mainly discharged directly. The proportion of 4 antibiotics discharged directly into Taihu Lake accounts for more than 99%, which can basically exclude the advection input of rivers entering the lake. The loss of 4 antibiotics in the aqueous phase is basically through reaction loss. The loss of reaction is 99.3%, 75.8%, 88.5% and 92.9%, respectively. The reaction loss of ATM is the largest, and the advection loss is the smallest. This shows that ATM is easier to react with substances in water, and it also has the lowest solubility. It is worth noting that the proportion of OFX deposited in water is large, which is due to its larger water-sediment exchange coefficient [23–25]. For sediment phase, the loss of four antibiotics is mainly through exchange to the water phase and reaction, and the advection loss can be ignored. Generally, the higher K_{OC} can increase the portion of chemicals in sediments [26]. The K_{OC} value of SMX reached 44,100 L/kg, far higher than the other antibiotics (35.7%), and the simulation results also showed this feature.

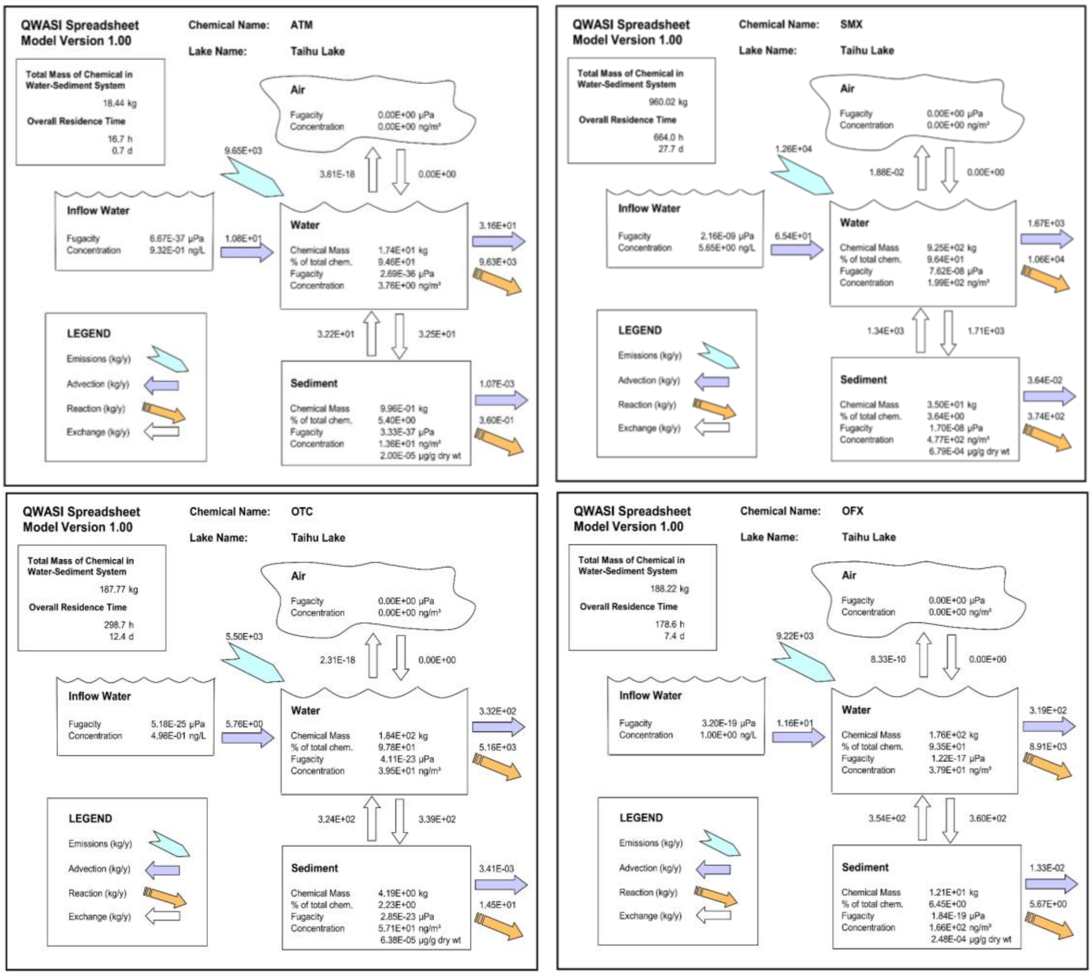

Figure 4. Mass balance diagram of 4 antibiotics in the Taihu Lake.

Figure 5 shows the transfer fluxes of 4 antibiotics across the water sediment interface in Taihu Lake. The transfer fluxes of 4 antibiotics from water to sediment is higher than that from sediment to water, which indicates that sediment can be used as the "sink" of chemicals in Taihu Lake, which is consistent with the research reported by previous scholars [15,27]. It can be concluded that lake sediments are the final destination of most antibiotics. Previous research showed that heavy metals will also accumulate in a large amount in the sediments, but antibiotics, as an organic matter, are more likely to be biotransformed after they flow into the sediments of the stratum, which requires us to add biofacies and make a specific discussion [16]. At the same time, if we want to obtain the time required for the aquatic ecosystem to eliminate these antibiotics in a large amount, we need a IV level model for simulation evaluation [19]. In general, the environmental fate simulation of 4 antibiotics in Taihu Lake requires a complex function, and the mass balance model is a vital means to clarify the impact of plenty of parameters and the ultimate fate of antibiotics.

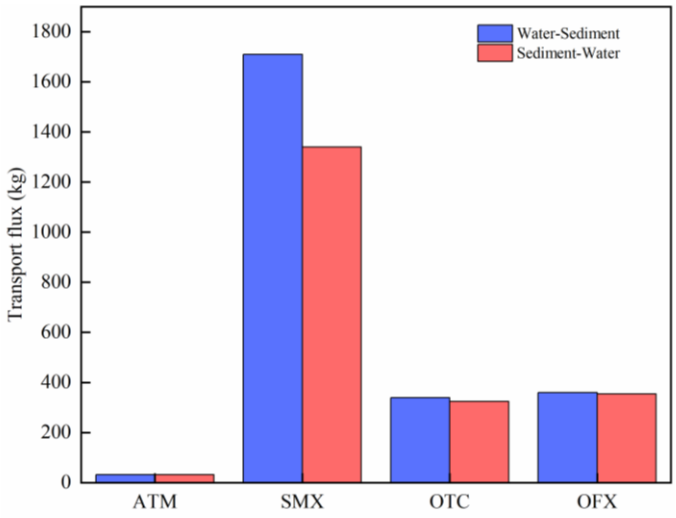

Figure 5. Transport flux of 4 antibiotics at the water sediment interface in Taihu Lake.

3.2.3. Model validation

The most direct way to validate the reliability of the model is to compare the predicting data with monitoring data. The actual outflow of target antibiotics from Taihu Lake is calculated by the method mentioned in Chapter 2. The actual outflow flux of antibiotics is calculated according to the lake water velocity and antibiotic concentration measured at several outflow points of Taihu Lake. According to **Figure 6**, the actual outflow and predicted outflow of the 4 antibiotics are within a level of magnitude, which shows that the prediction effect of the model is good. The possible reasons for the deviation between the model prediction and the actual situation are as follows: the input parameters of the model are partly from the literature or empirical values, which cannot represent the actual environmental attribute characteristics. Overall, the simulation results are comparable with the prediction results, validating the potential use of this modeling system.

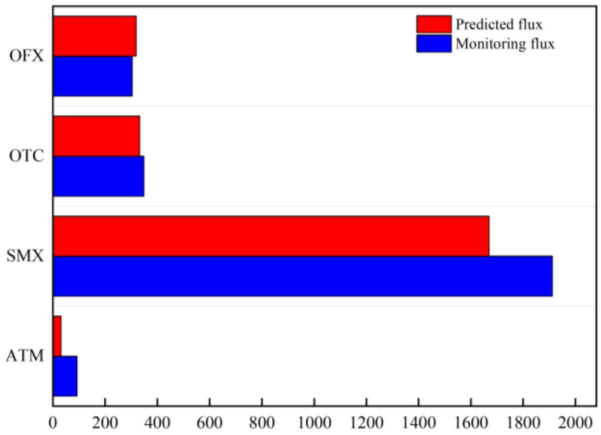

Figure 6. Comparison between simulated flux and actual flux.

3.3. Sensitivity analysis and uncertainty analysis

3.3.1. Sensitivity analysis

The sensitivity analysis of the 17 most important input parameters of the model through the OAT method is shown in **Figure 7**. The influence of each parameter on each antibiotic is different. The five input parameters that have the most significant impact on ATM, SMX and OFX are half-life in water, partition Coefficient of sediment-water, concentration of solids in sediment, density of particles in sediment and diffusion of sediment-water MTC, the sensitivity coefficient (*S*) exceeds 0.2. Significantly, the most influential factor on typical antibiotics is almost the half-life of antibiotics in water. This is because most half-lives are estimated by chance (not the result of experiments), and the uncertainty may exceed 10 times [28]. For OTC, the impact of lake water depth is obviously more important than the sediment-water mass transfer rate, which may be due to its low sediment-water exchange coefficient. At the same time, the river flow into the lake is positively correlated with the concentration of 4 antibiotics, while the river flow out of the lake is negatively correlated with the concentration of 4 antibiotics.

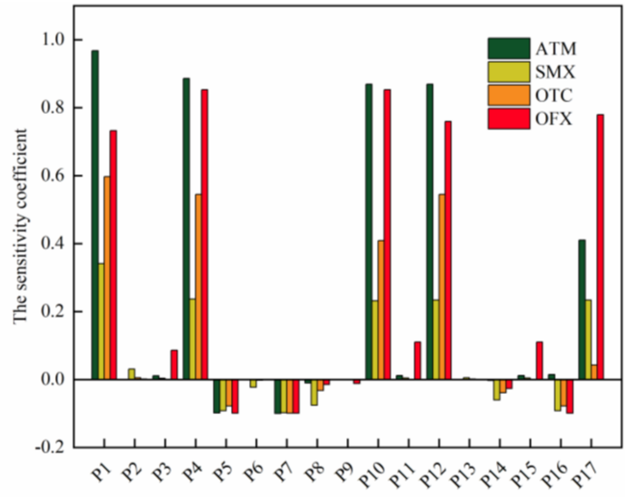

Figure 7. Parameter sensitivity analysis results. P1: Half-lives in water; P2: Half-lives in sediment; P3: Partition Coefficient of suspended particles-water; P4: Partition Coefficient of sediment-water; P5: Partition Coefficient of resuspended sediment-water; P6: Water surface area; P7: Water layer depth; P8: Sediment layer depth; P9: Concentration of solids in water; P10: Concentration of solids in sediment; P11: Density of particles in water; P12: Density of particles in sediment; P13: Water inflow rates; P14: Water outflow rates; P15: Sedimentation rate; P16: Sediment resuspension rate; P17: Diffusion of sediment-water MTC.

3.3.2. Uncertainty analysis

The values of predicted antibiotics concentrations in water and sediment phases after 10,000 simulations, are shown in **Figure 8**. The coefficient of variation (CV) of the predicted concentrations are employed to quantify the uncertainties. The CV values of the simulated concentrations of antibiotics in the two phases are between 8.35% and 21.73%, indicating that the model has good stability (**Figure 9**). In addition, the concentration in water phase shows better stability. According to the model output concentration obtained by Monte Carlo analysis, the average and median values of the predicted concentrations of the model fall between the 5% and 95% places, also indicating that the model has good stability. The predicted concentrations of ATM, SMX and OFX in water have low uncertainty (CV < 0.1), while the predicted concentrations of ATM and OFX in sediment have high uncertainty (CV > 0.2). Hence the higher uncertainty is the antibiotics concentration of sediment phase, and is related to the parameters in sensitivity analysis. This indicated that parameters involving sediment phase are vital to the model output.

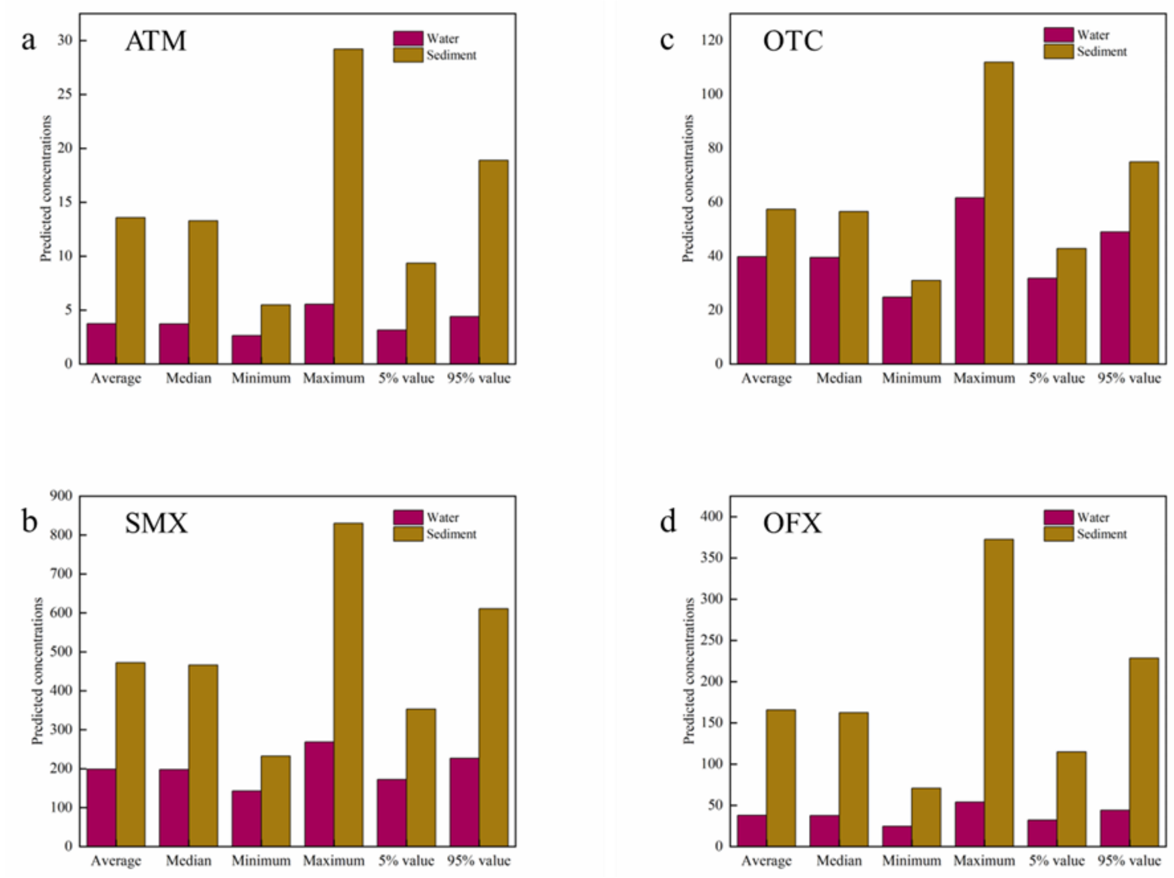

Figure 8. Statistical value of concentrations uncertainty analysis of the model.

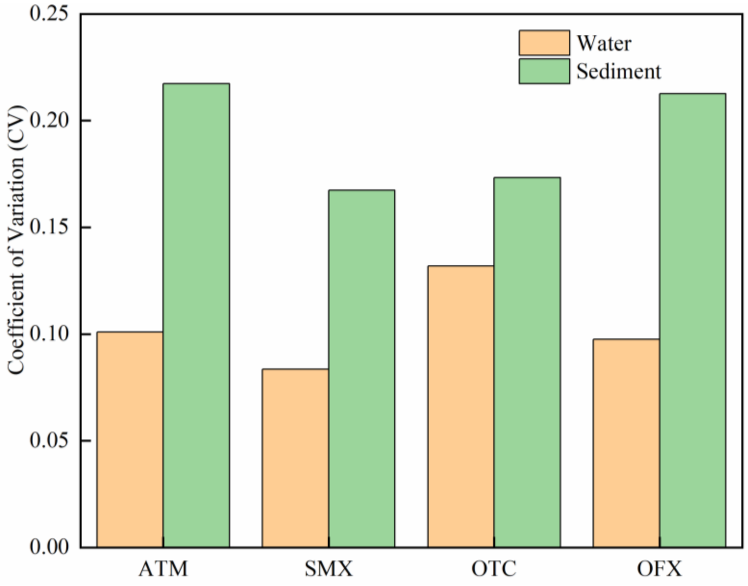

Figure 9. Summary of CV values of the output concentration of four antibiotics in the two-phase.

3.4. Discussion

(1) A new method is used to estimate the antibiotic source intensity input in Taihu Lake. The hydrology and water resources monitoring center of Taihu Lake basin is used to measure the flow of rivers entering and leaving Taihu Lake at 22 monitoring points. The corresponding input value of source intensity is obtained by calculating the mass fluxes and concentrations of target antibiotics into the lake through reasonable calculation methods. The method effectively avoids the large deviation between the model output and the actual result caused by the large difference in the source intensity assessment level. However, due to the fact that the sampling is conducted once a month, there may also be corresponding problems. It is recommended to increase the sampling frequency in the future, and consider it comprehensively in combination with the yearbook data.

(2) The concentrations of ATM, SMX, OTC and OFX simulated by the model in the sediment phase are higher than those in the water phase. The concentration of SMX in the two phases is the highest, reaching 0.199 ng/L and 0.477 ng/L respectively. The mass balance diagram of 4 antibiotics in Taihu Lake is also given. The main way for antibiotics to enter Taihu Lake is direct discharge (99%), and the proportion of advection input is very low. Antibiotics in the aqueous phase mainly pass through reaction loss, and ATM advection loss accounts for the smallest proportion, which indicates that ATM is easier to combine with substances in water, and also verifies that its solubility is smaller. OFX has a higher water-sediment exchange coefficient, so the loss of antibiotics in the sediment phase with a larger proportion of deposition is mainly through exchange to the water phase and reaction, and the advection loss can be ignored. The antibiotic transfer fluxes across the water-sediment interface are very interesting, and the results show that the sediment is a “sink” of antibiotics.

(3) Through sensitivity analysis, the most important factors affecting the fate of antibiotics in the environment can be obtained. Monte Carlo analysis is used to analyze the uncertainty of the model, and CV value is used to quantify the uncertainty. The results show that the model has good stability. In response to the sensitivity analysis, the CV value of antibiotic concentration in sediment phase is larger, so the concentration of antibiotic in sediment phase has higher uncertainty.

4. Conclusions

This study systematically calculated and simulated the emissions and fate of 4 antibiotics in Taihu Lake, which can provide guidance for antibiotic management in the lake. The comparison between the predicted values and measured values showed that QWASI model had a good simulation effect on the environmental fate of typical antibiotics in Taihu Lake. Since the SMX, as a sulfonamide antibiotic, is the most used in medicine, the results show that the source intensity input of SMX is the highest, and the source intensity input of OTC is the lowest. The mass balance diagrams of 4 antibiotics show that the migration process of antibiotics in the lake is a complex functional process, and the concentration on sediment layer is higher. The model validation results show that the model simulation effect is good, which also proves that the QAWSI model is suitable for simulating shallow lakes. Several vital influence parameters obtained from the sensitivity analysis also provide a better context for the uncertainty analysis of the model. Meanwhile, the statistical value given by the uncertainty analysis shows that the model is stable. The environmental fate simulation of antibiotics in Taihu Lake by QWASI model provides a better scientific understanding for the sustainable development of the lake.

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References

1. Zhou, L.-J., Wu, Q.L., Zhang, B.-B., Zhao, Y.-G., Zhao, B.-Y., 2016. Occurrence, spatiotemporal distribution, mass balance and ecological risks of antibiotics in subtropical shallow Lake Taihu, China. Environ. Sci. Process. Impacts 18, 500–513. https://doi.org/10.1039/C6EM00062B
2. Zhang, Q.-Q., Ying, G.-G., Pan, C.-G., Liu, Y.-S., Zhao, J.-L., 2015. Comprehensive Evaluation of Antibiotics Emission and Fate in the River Basins of China: Source Analysis, Multimedia Modeling, and Linkage to Bacterial Resistance. Environ. Sci. Technol. 49, 6772–6782. https://doi.org/10.1021/acs.est.5b00729
3. Wang, J., Zhuan, R., Chu, L., 2019. The occurrence, distribution and degradation of antibiotics by ionizing radiation: An overview. Sci. Total Environ. 646, 1385–1397. https://doi.org/10.1016/j.scitotenv.2018.07.415
4. Cai, Y.-Y., Zhang, Q.-Q., Yan, X.-T., Zhai, Y.-Q., Guo, Z., Li, N., Ying, G.-G., 2022. Antibiotic pollution in lakes in China: Emission estimation and fate modeling using a temperature-dependent multimedia model. Sci. Total Environ. 842, 156633. https://doi.org/10.1016/j.scitotenv.2022.156633
5. Chen, Y., Zhou, J.L., Cheng, L., Zheng, Y.Y., Xu, J., 2017. Sediment and salinity effects on the bioaccumulation of sulfamethoxazole in zebrafish (Danio rerio). Chemosphere 180, 467–475. https://doi.org/10.1016/j.chemosphere.2017.04.055
6. Gupta, S., Graham, D.W., Sreekrishnan, T.R., Ahammad, S.Z., 2023. Heavy metal and antibiotic resistance in four Indian and UK rivers with different levels and types of water pollution. Sci. Total Environ. 857, 159059. https://doi.org/10.1016/j.scitotenv.2022.159059
7. Li, C., Xu, Y., Song, W., 2023. Pollution Characteristics and Risk Assessment of Typical Antibiotics and Persistent Organic Pollutants in Reservoir Water Sources. Water 15, 259. https://doi.org/10.3390/w15020259
8. Ma, N., Tong, L., Li, Y., Yang, C., Tan, Q., He, J., 2022. Distribution of antibiotics in lake water-groundwater - Sediment system in Chenhu Lake area. Environ. Res. 204, 112343. https://doi.org/10.1016/j.envres.2021.112343
9. Xu, J., Zhang, Y., Zhou, C., Guo, C., Wang, D., Du, P., Luo, Y., Wan, J., Meng, W., 2014. Distribution, sources and composition of antibiotics in sediment, overlying water and pore water from Taihu Lake, China. Sci. Total Environ. 497–498, 267–273. https://doi.org/10.1016/j.scitotenv.2014.07.114
10. Lin, H., Dyar, O.J., Rosales-Klintz, S., Zhang, J., Tomson, G., Hao, M., Stålsby Lundborg, C., 2016. Trends and patterns of antibiotic consumption in Shanghai municipality, China: a 6 year surveillance with sales records, 2009–14. J. Antimicrob. Chemother. 71, 1723–1729. https://doi.org/10.1093/jac/dkw013
11. Mackay, D., Joy, M., Paterson, S., 1983a. A quantitative water, air, sediment interaction (QWASI) fugacity model for describing the fate of chemicals in lakes. Chemosphere 12, 981–997. https://doi.org/10.1016/0045-6535(83)90251-5
12. Mackay, D., Paterson, S., Joy, M., 1983b. A quantitative water, air, sediment interaction (QWASI) fugacity model for describing the fate of chemicals in rivers. Chemosphere 12, 1193–1208. https://doi.org/10.1016/0045-6535(83)90125-X
13. Huang, Y., Sun, X., Liu, M., Zhu, J., Yang, J., Du, W., Zhang, X., Gao, D., Qadeer, A., Xie, Y., Nie, N., 2019. A multimedia fugacity model to estimate the fate and transport of polycyclic aromatic hydrocarbons (PAHs) in a largely urbanized area, Shanghai, China. Chemosphere 217, 298–307. https://doi.org/10.1016/j.chemosphere.2018.10.172
14. Abbasi, Y., Mannaerts, C.M., 2020. Exploring the Environmental Exposure to Methoxychlor, α-HCH and Endosulfan–sulfate

Residues in Lake Naivasha (Kenya) Using a Multimedia Fate Modeling Approach. Int. J. Environ. Res. Public. Health 17, 2727. https://doi.org/10.3390/ijerph17082727

15. Wang, Y., Khan, S.J., Fan, L., Roddick, F., 2020. Application of a QWASI model to produce validated insights into the fate and transport of six emerging contaminants in a wastewater lagoon system. Sci. Total Environ. 721, 137676. https://doi.org/10.1016/j.scitotenv.2020.137676
16. Liu, Y., Zhang, S., Li, C., Shi, X., Zhao, S., Sun, B., Zhu, Y., 2019. A modified QWASI model for fate and transport modeling of Zn and Pb in a shallow lake during the ice-free period. Sci. Total Environ. 657, 577–584. https://doi.org/10.1016/j.scitotenv.2018.12.003
17. Nkoom, M., Lu, G., Liu, J., 2018. Occurrence and ecological risk assessment of pharmaceuticals and personal care products in Taihu Lake, China: a review. Environ. Sci. Process. Impacts 20, 1640–1648. https://doi.org/10.1039/C8EM00327K
18. Zhu, Y., Price, O.R., Kilgallon, J., Rendal, C., Tao, S., Sweetman, A.J., n.d. 1 A multimedia fate model to support chemical management in China: 2 a case study for selected trace organics.
19. Kong, X., He, W., Qin, N., He, Q., Yang, B., Ouyang, H., Wang, Q., Yang, C., Jiang, Y., Xu, F., 2014. Modeling the multimedia fate dynamics of γ-hexachlorocyclohexane in a large Chinese lake. Ecol. Indic. 41, 65–74. https://doi.org/10.1016/j.ecolind.2014.01.024
20. Liu, C., Bennett, D.H., Kastenberg, W.E., McKone, T.E., Browne, D., 1999. A multimedia, multiple pathway exposure assessment of atrazine: fate, transport and uncertainty analysis. Reliab. Eng. Syst. Saf. 63, 169–184. https://doi.org/10.1016/S0951-8320(98)00045-3
21. Luo, Y., Yang, X., 2007. A multimedia environmental model of chemical distribution: Fate, transport, and uncertainty analysis. Chemosphere 66, 1396–1407. https://doi.org/10.1016/j.chemosphere.2006.09.026
22. Zhang, Z.-B., Duan, Y.-P., Zhang, Z.-J., Tu, Y.-J., Luo, P.-C., Gao, J., Dai, C.-M., Zhou, L., 2022. Multimedia fate model and risk assessment of typical antibiotics in the integrated demonstration zone of the Yangtze River Delta, China. Sci. Total Environ. 805, 150258. https://doi.org/10.1016/j.scitotenv.2021.150258
23. Chen, Q., Dong, J., Zhang, T., Yi, Q., Zhang, J., Hu, L., 2019. A method to study antibiotic emission and fate for data-scarce rural catchments. Environ. Int. 127, 514–521. https://doi.org/10.1016/j.envint.2019.04.014
24. Dai, C., Han, Y., Li, Y., Duan, Y., Liu, S., Zhang, Y., Tu, Y., 2022. Simulation and risk assessment of typical antibiotics in the multi-media environment of the Yangtze River Estuary under tidal effect. Environ. Sci. Pollut. Res. 29, 81875–81891. https://doi.org/10.1007/s11356-022-21519-w
25. Yu, X., Zhang, X., Chen, J., Li, Y., Liu, X., Feng, Y., Sun, Y., 2022. Source, occurrence and risks of twenty antibiotics in vegetables and soils from facility agriculture through fixed-point monitoring and numerical simulation. J. Environ. Manage. 319, 115652. https://doi.org/10.1016/j.jenvman.2022.115652
26. Chen, H., Jing, L., Teng, Y., Wang, J., 2018. Multimedia fate modeling and risk assessment of antibiotics in a water-scarce megacity. J. Hazard. Mater. 348, 75–83. https://doi.org/10.1016/j.jhazmat.2018.01.033
27. Liu, Y., Li, C., Anderson, B., Zhang, S., Shi, X., Zhao, S., 2017. A modified QWASI model for fate and transport modeling of mercury between the water-ice-sediment in Lake Ulansuhai. Chemosphere 176, 117–124. https://doi.org/10.1016/j.chemosphere.2017.02.111
28. Gouin, T., Cousins, I., Mackay, D., 2004. Comparison of two methods for obtaining degradation half-lives. Chemosphere 56, 531–535. https://doi.org/10.1016/j.chemosphere.2004.04.018