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Distribution and impacts on the geological environment of antiviral drugs in major waters of Wuhan, China

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Abstract

This study investigated water samples collected from the surface water and groundwater in Wuhan City, Hubei Province, China in different stages of the outbreak of the coronavirus disease 2019 (hereinafter referred to as COVID-19) in the city, aiming to determine the distribution characteristics of antiviral drugs in the city’s waters. The results are as follows. The main hydrochemical type of surface water and groundwater in Wuhan was Ca-HCO₃. The major chemical components in the groundwater had higher concentrations and spatial variability than those in the surface water. Two antiviral drugs and two glucocorticoids were detected in the surface water, groundwater, and sewage during the COVID-19 outbreak. Among them, chloroquine phosphate and cortisone had higher detection rates of 32.26% and 25.80%, respectively in all samples. The concentrations of residual drugs in East Lake were higher than those in other waters. The main drug detected in the waters in the later stage of the COVID-19 outbreak in Wuhan was chloroquine phosphate, whose detection rates in the surface water and the groundwater were 53.85% and 28.57%, respectively. Moreover, the detection rate and concentration of chloroquine phosphate were higher in East Lake than in Huangji Lake. The groundwater containing chloroquine phosphate was mainly distributed along the river areas where the groundwater was highly vulnerable. The residual drugs in the surface water and the groundwater had lower concentrations in the late stage of the COVID-19 outbreak than in the middle of the outbreak, and they have not yet caused any negative impacts on the ecological environment.

Keywords: Water environment, Antiviral drugs, COVID-19, Groundwater, Urban geological survey engineering, Environment geological survey engineering, Wuhan, Hubei Province, China

1. Introduction

In the process of protecting life and health, human beings inevitably administer medicine to fight diseases. The high or even excessive usage of drugs has increased drug substances entering the ecological environment, resulting in environmental pollution. Previous studies have found various levels of drug residues in environmental media, such as wastewater, surface water, drinking water, groundwater, atmosphere, and soil (Pal R et al., 2013). Since the start of COVID-19, which first broke out in Wuhan in December 2019, the environmental pollution from antiviral drugs has drawn widespread attention (Chen S et al., 2020). In particular, drug residues in surface water and wastewater have been the most widely studied (Hu P et al., 2017). As stated in the Diagnosis and Treatment Protocol for COVID-19 (trial version 7) issued by the National Health Commission of the People’s Republic of China on March 3, 2020, antiviral drugs (α-interferon, lopinavir, ritonavir, ribavirin, chloroquine phosphate, and arbidol) play an important role in the general treatment of COVID-19 patients. Antibiotic therapy is also needed as an assist to fight infections in critically ill patients (Guan WJ et al., 2020). Urban wastewater treatment plants (WWTPs) are not equipped with units used to treat process residual drugs in China (Wang XH et al., 2022). As a result, drugs enter the environment media along with disposed medical wastewater and medical solid waste and subsequently...
migrate among waters, soil, and, to a lesser degree, sediments and the atmosphere (Jiang KW et al., 2015). These residues in receiving environmental waters raise ecotoxicological concerns (Godoy AA and Kummrow F, 2017). In particular, large amounts of antiviral drugs and their metabolites are released into environmental waters during the COVID-19 pandemic, likely posing high risks to aquatic ecosystems (Nannou C et al., 2020). Therefore, it is necessary to address the potential negative consequences of the increased levels of anti-epidemic chemicals (Chen XP et al., 2021).

The COVID-19 pandemic first broke out in Wuhan, which thereby is a typical city for this study. Previous studies on the drugs in water environments in Wuhan have mainly focused on concentrations of antibiotics. With several lakes in Wuhan as the research objects, Tan F et al. (2017) detected the residues of antibiotic sulfamethoxazole in six representative lakes in Wuchang District in the city center. Ma NJ et al. (2022) studied the distribution characteristics of antibiotics in the surface water, sediments, and groundwater at various depths in the shore zones of the Chenhui Wetlands in the outer suburbs of the city. Yin W et al. (2020) revealed that the residues from the massive usage of disinfectants during the COVID-19 outbreak could bring potential impacts on the water quality of rivers and lakes as well as on the health of the water ecosystem in the city.

Despite previous studies of the residual antibiotics and disinfectants in environmental media in Wuhan, there is a lack of research on the distribution of antiviral drugs used for the treatment of COVID-19 in the city’s water environments. Chen XP et al. (2021) investigated the concentrations and the spatial and seasonal distributions of pharmaceuticals and personal care products (PPCPs) and evaluated the post-pandemic ecological risks of the PPCPs detected in aquatic environments in surface waters and the sediments in lakes and the river estuary systems of WWTPs around hospitals in Wuhan. Furthermore, the presence and impacts of residual antiviral drugs in the groundwater system have been scarcely studied. Since it is difficult to remove antiviral drugs in WWTPs, these substances constantly enter water environments (Wang XH et al., 2022). This study analyzed water samples taken from representative lakes and groundwater monitoring wells around designated hospitals in Wuhan, aiming to determine the distribution characteristics of major COVID-19 drugs in the surface water and groundwater in Wuhan. The results of this study will provide a theoretical basis for the scientific prevention and control of COVID-19 outbreaks.

2. Materials and methods

2.1. The study area

Wuhan City is located near the northeastern edge of the Jianghan Plain, where the Yangtze River and the Hanjiang River converge at a Y-shaped juncture. Wuhan is generally high in the south and low in the north (Fig. 1). The margins of basins in northern Wuhan mainly consist of hill-shaped plains, with an elevation of 35–60 m and a relative height difference of 10–20 m (Tian WX et al., 2011). The landforms in Hankou, Hanyang, and Wuchang (parts along the rivers) in the north are dominated by the first and second terraces of the Yangtze River that are interspersed with the ridge plains, forming undulating terrain. The alluvial plains along the river are flat and have distinct binary structures consisting of Holocene clays in the upper part and sandy soils and pebble gravel layers in the lower part. The southern part of Wuhan mainly consists of ridge plains, which have a relative height difference of 10–30 m and are mainly composed of Pleistocene loam, sandy loam, and clay. The middle part of Wuhan consists of a few banded hills and monadnocks, which primarily comprise Devonian and Silurian quartz sandstones, sandy shales, and limestones. Wuhan has many rivers, lakes, and reservoirs, including 166 lakes on the lake protection list, which have a blue-line stream area of 867.07 km² and a volume of 270.7 × 10⁶ m³. The current water surface area in the city is 2117.6 km², which accounts for about 24.7% of the city’s total area (Wuhan Municipal Water Authority, 2021).

The groundwater in Wuhan mainly occurs in pores of Quaternary sands and gravels along the Yangtze River and is confined except for the phreatic water on both sides of the river center and in the third-grade rivers. The roof of the aquifer has a burial depth of 9–27 m, and the aquifer is mostly thin, with a thickness of 6–22 m (Fig. 2). The terrain along the rivers is low-lying and wide, and some of the groundwater is close to the surface. Overall, the groundwater level is high and varies annually by approximately 1 m. Because of the weak water permeability of the upper covering layer, the groundwater has a slightly varying water level, minimal potential energy, and extremely limited vertical replenishment and discharge. The lateral discharge of the groundwater along the river mainly occurs in narrow banded areas and is controlled by the water permeability of the riverside deposits.

2.2. Sample collection, analysis and testing

To conduct a comparative study of the changes in the concentrations of antiviral drugs in the water environments in Wuhan, samples were collected in the middle and late stages of the COVID-19 outbreak in Wuhan. In the middle of the COVID-19 outbreak, emergency investigations were highlighted and samples were collected on April 8–13 and May 10–11, 2020. As a result, 13 groundwater samples were collected around the designated COVID-19 hospitals and mobile cabin hospitals. Meanwhile, 11 surface water samples were collected from the wastewater treatment system of Leishenshan Hospital, its matching Huangjiahu wastewater treatment plant, and rivers and lakes around the wastewater treatment plant (Fig. 1). The main detection indicators of these samples were antiviral drugs. In the late stage of the COVID-19 outbreak, samples were systematically collected from surface water and groundwater on July 22–25 and September 18–23, 2020. Besides antiviral drugs, the test indicators included conventional anions and cations at this...
stage. A total of 21 groundwater samples were collected from 10 more boreholes than those in which water was sampled in the middle of the COVID-19 outbreak (samples could not be obtained from the groundwater in two boreholes sampled in the middle of the outbreak). Moreover, 19 surface water samples were obtained from East Lake, and seven surface water samples were taken from Huangjia Lake.

The surface water samples from lakes were the mixture of water collected at multiple depths from the shores and centers (accessed by manned boat) of major lakes in Wuhan using a surface water sampling device. The boreholes where the groundwater was sampled were hydrogeological monitoring boreholes used by a certain national geological water monitoring project. Groundwater samples were collected using submersible pumps or portable peristaltic pumps after the groundwater was pumped out from the boreholes for a set amount of time. The water temperature, pH, electrical conductivity (EC), redox potential (Eh) and dissolved oxygen (DO) of the water samples were tested on site using a YSI multi-parameter water quality analyzer. The concentrations of bicarbonate ions and carbonate ions in the water samples were determined through acid-base titrations on the day of sampling, and the concentrations of cations such as K⁺, Na⁺, Ca²⁺, and Mg²⁺ were tested using an inductively coupled plasma mass spectrometer (PE OPTIMA8000) with an accuracy of 0.01 mg/L. The concentrations of anions such as Cl⁻, SO₄²⁻, and NO₃⁻ were determined using an ion chromatography system (ICS-1100, produced by Thermo Fisher Scientific) with an accuracy of 0.01 mg/L. The mass concentration of HCO₃⁻ was determined using the acid standard solution titration method (standard No.: F-HZ-DZ-DXS-0023) on the day of sampling, with a lower limit of detection of 5 mg/L.

Water samples were processed as follows. A certain volume of samples (100 mL of sewage, 200 mL of surface water, and 500 mL of groundwater samples) were taken and
filtered using a glass sand core suction filter (0.45 μm filter membrane) to remove particulate impurities. Subsequently, the samples were cleaned and enriched. Then, 4 mL of methanol and 6 mL of ultrapure water were pipetted to activate the HLB extraction cartridge (500 mg, 6 cc Vac Cartridge, produced by Waters, USA). Afterward, the samples were loaded into the cartridge, which was then continuously dried for 20 mins. Then, the residuals were eluted with 6 mL of methanol solution in a 10 mL glass vial. The eluent was blown nearly dry with mild nitrogen at room temperature. Then, the residues were dissolved in methanol, achieving a volume of up to 0.5 mL. The residues were then passed through a 0.22 μm microporous membrane, put into a 1.5 mL brown injection vial, and tested using a liquid chromatography tandem high-resolution mass spectrometer (Q Exactive, Thermofisher), of which the parameters were stated in the literature (Asghar MA et al., 2018). All the six drugs were quantified using the external standard method. Satisfactory linearity testing results were obtained, with a coefficient of determination of 0.99. Satisfactory precision results (inter- and intra-day) were also gained, with relative standard deviation (RSD) below 10% in all the cases. The liquid chromatography tandem high-resolution mass spectrometer used in this study had a limit of detection (LOD) of 0.50–1.00 μg/L and a limit of quantification (LOQ) of 1.67–3.33 μg/L. The recovery ranged from 63.81% to 97.54% for all the compounds. All the above tests were conducted in the laboratory of the School of Environmental Studies, the China University of Geosciences in Wuhan, and the State Key Laboratory of Biogeology and Environmental Geology of the university.

3. Results and discussion

3.1. Antiviral drugs in the water environments during the COVID-19 outbreak in Wuhan

Six antiviral drugs and five glucocorticoids were predominantly used in the treatment of COVID-19 patients. In this study, quantitative tests were conducted to determine the presence of six different drugs, i.e., lopinavir, ritonavir, chloroquine phosphate, cortisone, prednisone, and prednisolone, in water environments in Wuhan. In addition, qualitative screenings were performed to determine the presence of three drugs, i.e., arbidol, tocilizumab and methylprednisolone. As a result, two antiviral drugs (chloroquine phosphate and lopinavir) and two glucocorticoid drugs (cortisone and prednisone) were detected in the water samples. The detected drug residues in the samples and their concentrations are shown in Fig. 3. According to this figure, the concentrations and detection rates of chloroquine phosphate and cortisone were found high in both the surface water samples and the groundwater samples. The higher detection rate of chloroquine phosphate is mainly because this drug has antiviral effects in vivo and in vitro. Since it may be more efficient than other drugs (Mo LQ and Zheng P, 2020), chloroquine phosphate was used in larger quantities and subsequently entered water environments (Li Y et al., 2022). The highest concentrations of chloroquine phosphate and cortisone in surface water were found in East Lake. The concentration of chloroquine phosphate was up to 19 μg/L,

![Fig. 3. Concentration of drug for COVID-19 in water environment of Wuhan City during the COVID-19 outbreak.](image-url)
and the highest concentration of cortisone was almost the same. East Lake is located in the main urban area, where the urban sewage network is old and riven with problems (Gao XH et al., 2009). In addition, the Zhongnan Hospital and the Health Commission of Hubei Province are located nearby, and thus drug residues may have come from the wastewater of the hospital or from leaks from municipal sewage pipes. By contrast, no chloroquine phosphate and cortisone were detected in the surface water of rivers and lakes near Leishenshan Hospital. This is possibly because Leishenshan Hospital was built according to the requirements of an infectious disease hospital, for which strict measures were taken to prevent medical wastewater from leaking. Moreover, Leishenshan Hospital only operated from February 8, 2020, to April 15, 2020, and residual drugs from the hospital had probably not yet reached its surrounding surface water when this study was conducted.

Chloroquine phosphate was detected in six of the 13 groundwater samples (GW06, GW08, GW09, GW10, GW11, and GW12), prednisone was found in one groundwater sample (GW08), and cortisone was also found in only one groundwater sample (GW09). The detection rate and concentration of chloroquine phosphate were high, with the concentration up to a maximum of 276 ng/L (Fig. 3). These groundwater samples were all collected in the riverine zones of the main urban area, where the groundwater mainly occurs in loose rock pores and the surface is mostly silty sands and contains a small amount of clay locally. These zones have low-lying terrain and high groundwater level, which is quite close to the ground surface sometimes and has an annual variation of approximately 1 m (He J et al., 2016). These zones are highly sensitive to groundwater pollution (Wang YX et al., 2002), and the residual drugs in the surface water are prone to vertically migrate to groundwater.

Cortisone was detected in only three of the seven wastewater samples collected from the wastewater treatment system of Leishenshan Hospital and the Huangjiahu wastewater treatment plant. Other antiviral drugs and glucocorticoids were not detected in any of the wastewater samples. Cortisone had a low detected concentration of 3–30 ng/L. These results may be attributed to the fact that the samples were collected at the end of the COVID-19 outbreak in Wuhan, when the number of patients, drug use, and the production of wastewater decreased. Therefore, the detected residual drugs had low concentrations.

3.2. Antiviral drugs in water environments in the later stage of the COVID-19 outbreak in Wuhan

3.2.1. Hydrochemical characteristics

As indicated by the statistics of major ions in the surface water and groundwater samples (Table 1), both the surface water and the groundwater in Wuhan were predominantly weak alkaline, with the surface water being slightly more alkaline. The major cations in the surface water and the groundwater had similar characteristics and were dominated by Ca$^{2+}$ and Na$^+$. The anions in the two types of water samples mainly included HCO$_3^−$. Moreover, the surface water had a higher concentration of SO$_4^{2−}$ than the groundwater, whereas the groundwater had a slightly higher concentration of Cl$^−$ than the concentration of SO$_4^{2−}$. Overall, the groundwater had higher concentrations of major ions than the surface water. This is mainly caused by the complex water-rock interactions in the aquifer media in the underground water, which cause the groundwater to absorb more chemical components through leaching. Furthermore, regarding spatial variability, the major chemical components in the groundwater have significantly higher coefficients of variation than those in the surface water. This finding further confirms that the chemical components of the groundwater are related to the aquifer conditions where they are reserved.

The hydrochemical types were determined using the Shukarev classification method. As shown in the Piper trilinear diagram (Fig. 4), the hydrochemical types of the surface water samples were relatively concentrated. All the surface water samples fell in the lower left corner of the diagram, indicating that all of them were Ca-HCO$_3$-type water. Although the groundwater samples had less concentrated hydrochemical types than the surface water samples, most of them still fell in the lower left corner of the Piper trilinear diagram. The ions of most of the samples were dominated by Ca$^{2+}$ and HCO$_3^−$, indicating that the main hydrochemical type of the groundwater was Ca-HCO$_3$. Besides, some samples had hydrochemical types of Ca-HCO$_3$,

| Table 1. Statistical characteristic of hydrochemical parameters in water samples. |
|-----------------------------|---|---|---|---|---|---|---|---|---|---|
| Water sample type | pH | Eh (mV) | EC (μS/cm) | DO (mg/L) | K$^+$ (mg/L) | Na$^+$ (mg/L) | Ca$^{2+}$ (mg/L) | Mg$^{2+}$ (mg/L) | Cl$^−$ (mg/L) | SO$_4^{2−}$ (μS/cm) | HCO$_3^−$ (mg/L) |
|-----------------------------|---|---------|-------------|-----------|-------------|--------------|----------------|----------------|-------------|----------------|---------------|
| Surface water | Max | 9.46 | −8.10 | 432.50 | 11.24 | 6.41 | 18.50 | 47.30 | 10.20 | 19.90 | 50.63 |
| Min | 7.64 | −47.60 | 279.10 | 1.29 | 2.46 | 9.10 | 23.60 | 5.98 | 7.93 | 24.97 | 47.60 |
| Avg | 8.72 | −33.56 | 328.98 | 7.76 | 4.68 | 14.41 | 32.78 | 7.76 | 14.01 | 30.80 | 94.39 |
| Sv | 6.52 | 10.62 | 37.38 | 2.64 | 0.84 | 3.91 | 7.01 | 1.23 | 4.91 | 6.04 | 31.09 |
| Cv | 0.07 | 0.32 | 0.11 | 0.34 | 0.18 | 0.27 | 0.21 | 0.16 | 0.35 | 0.20 | 0.33 |
| Groundwater | Max | 8.08 | 61.40 | 2539.00 | 3.81 | 13.34 | 261.40 | 263.72 | 84.85 | 566.72 | 615.08 |
| Min | 6.53 | −261.10 | 289.60 | 0.43 | 0.33 | 3.62 | 29.60 | 29.97 | 0.77 | 0.21 | 51.30 |
| Avg | 7.12 | −130.85 | 1032.16 | 1.92 | 2.38 | 46.42 | 116.77 | 29.95 | 81.90 | 86.55 | 395.33 |
| Sv | 0.34 | 110.82 | 545.22 | 0.91 | 2.77 | 55.64 | 54.56 | 14.89 | 134.26 | 132.46 | 184.93 |
| Cv | 0.05 | −0.85 | 0.53 | 0.47 | 1.16 | 1.20 | 0.47 | 0.50 | 1.64 | 1.53 | 0.47 |

Max—maximum; Min—minimum; Avg—average; Sd—standard deviation; Cv—coefficient of variation.
Ca-SO$_4$, and Ca-Cl. The hydrochemical type of one karst confined water sample collected separately was Ca-HCO$_3$. Moreover, the water samples with detected antiviral drugs were all Ca-HCO$_3$ type water.

3.2.2. Distribution characteristics of antiviral drugs

Three drugs used during the COVID-19 outbreak, i.e., chloroquine phosphate, lopinavir, and ritonavir, were mainly detected in the 26 surface water samples collected in the late stage of the outbreak. Among them, chloroquine phosphate had a detection rate of 53.85%. It was mainly detected in East Lake but was also found in a few samples collected from Huangjia Lake (Figs. 5a, b). It had a high concentration of 22.28‒166.74 ng/L (average: 67.72 ng/L) in East Lake and a concentration of 22.24‒39.35 ng/L (average: 32.36 ng/L) in Huangjia Lake. Chloroquine phosphate was also detected in all four samples collected from East Lake Port, which connects East Lake and the Yangtze River, with a concentration of 25.05‒32.05 ng/L (average: 28.64 ng/L). The hydraulic connection between East Lake and the Yangtze River through East Lake Port indicates that chloroquine phosphate may also have been discharged into the Yangtze River during the COVID-19 outbreak. Ritonavir and lopinavir had detection rates of 24% and 16%, respectively. They were found in East Lake, East Lake Port, and Huangjia Lake, where, however, the concentrations of the two drugs were below the LOQ. The other three antiviral drugs were not detected.

The spatial distribution patterns of antiviral drugs in surface water indicate the presence of chloroquine phosphate residues in East Lake near Liyuan Hospital and in the East Lake Port area (samples DH05–DH09). However, no chloroquine phosphate was detected near the Moshan Hill area. In Huangjia Lake, chloroquine phosphate was detected in a water body near Leishenshan Hospital (samples HJH05 and HJH06). The concentrations of COVID-19 drugs in surface water were low and were even below the LOQ for some of the drugs. In addition, precipitation and floodwater drainage presented a large disturbance to the water bodies of the lakes, leading to different distributions of the three COVID-19 drugs in the water bodies. However, the detection rates of residual drugs in places closer to medical institutions were generally higher than those in places further from these institutions.

As mentioned above, 21 groundwater samples were collected in the late stage of the COVID-19 outbreak. Among them, 11 samples were taken from boreholes in which water was sampled in the middle of the outbreak, except boreholes GW05 and GW08, where samples could not be obtained at the late stage. The remaining 10 groundwater samples were collected from 10 new boreholes. The test results showed that chloroquine phosphate was detected in six samples, with a detection rate of 28.57% and a maximum concentration of 105 ng/L (Fig. 6). Lopinavir had a detection rate of 38.10% but had a low concentration less than the LOD. Ritonavir had a detection rate of 19.48% and a low concentration with a maximum of approximately 0.5 ng/L. From the angle of spatial distribution characteristics, besides low-lying areas along the underground terrain of rivers, drug residues were also detected in monitoring boreholes GW17 and GW19 in the terrace or hillock areas at a high elevation and in the karst confined water (GW09). This finding indicates that the drugs had entered several aquifer systems in Wuhan.

3.3. Comparison of the distribution characteristics of antiviral drugs in the water environments in different stages of the COVID-19 outbreak in Wuhan

As indicated by the comparative analysis of the antiviral
drug residues in the water samples collected at the same sampling points in different stages of the COVID-19 outbreak, the concentrations of chloroquine phosphate in the three surface water samples collected from East Lake all significantly decreased in the late stage of the outbreak (Fig. 7). The reduction in the concentrations may have resulted from the adsorption of the residual drugs in the water environments onto both sediments and suspended particulate matters or from their dissipation through biodegradation, hydrolytic degradation, and photodegradation (Jiang KW et al. 2015). Alternatively, it may have been the result of the dilution of residual drugs due to the large amount of precipitation that...
entered the lake during the flood season in September. However, the results of five surface water samples collected from Huangjia Lake near Leishenshan Hospital showed that drug residues were not detected in April but were detected in two samples (HJH03 and HJH05) in September. This change may be related to the wastewater treatment plant since HJH03 was collected near the Huangjiahu wastewater treatment plant and HJH05 was collected from the lower reaches of the discharge outlet of the wastewater treatment plant.

The 11 groundwater samples collected from the same sampling points where the water was sampled in the middle of the COVID-19 outbreak showed a decrease in the concentration of chloroquine phosphate, except for sample GW07, which showed a slight increase in the concentration (Fig. 8). Similar to the decrease in the residual drug concentration in the surface water, the decrease in the concentration of chloroquine phosphate in the groundwater may be also due to the recharge from a large amount of precipitation and surrounding surface water during the flood season. By contrast, the increase in the concentration of individual samples may be due to the lag effect caused by the existence of the clay layer in local areas, the low water conductivity coefficient of the vadose zone, and the slow transfer of seepage and harmful substances (Wang YX et al., 2002).

3.4. Impacts on the ecological environment

As indicated by the comparison of the concentrations of residual drugs in different stages of the COVID-19 outbreak in Wuhan, these concentrations were significantly reduced in the late stage of the outbreak. Each drug itself may have a certain biological activity that allows it to be naturally attenuated through adsorption, hydrolysis, photodegradation, and biodegradation (Jiang KW et al. 2015). Moreover, the change in the concentrations might be related to the recharge of water environments during flood season. The samples were collected in April and September. June-August is the flood season in Wuhan, and the precipitation intensity increased significantly (Fig. 9), recharging surface water and groundwater in large quantities. The concentrations of residual drugs likely decreased accordingly by dilution. The impacts of these drugs on the environment were thus further reduced.

4. Conclusions

The key findings of this study are as follows:

(i) The major surface water and the groundwater in Wuhan related to the COVID-19 outbreak in the city mainly contained cations Ca$^{2+}$ and Na$^+$ and anions HCO$_3^-$ . Their main hydrochemical type was Ca-HCO$_3$. The concentrations of the main ions in the groundwater were higher than those in the surface water, and the spatial variability of the main chemical components was significantly higher in the groundwater than in the surface water.

(ii) Two antiviral drugs, i.e., chloroquine phosphate and lopinavir, and two glucocorticoid drugs, i.e., cortisone and prednisone, were detected in the surface water, groundwater, and wastewater during the outbreak in Wuhan. Among them, chloroquine phosphate and cortisone had higher detection rates of 32.26% and 25.80%, respectively. The water samples collected from East Lake had higher concentrations of residual drugs than those collected from other water environments.

(iii) In the late stage of the COVID-19 outbreak in Wuhan, the main residual drug in surface water was chloroquine phosphate, which had a detection rate of 53.85%. The water samples collected from East Lake yielded higher detection rates and concentrations of chloroquine phosphate than those taken from Huangjia Lake. The detection rate of chloroquine phosphate in the groundwater was 28.57%, which was lower than that in the surface water. Moreover, chloroquine phosphate was mainly distributed in the low-lying areas along the rivers in the main urban area where the groundwater was
highly vulnerable.

(iv) As revealed by the comparison of the concentrations of residual drugs in the surface water and the groundwater in different stages of the COVID-19 outbreak, the concentrations in the late stage of the outbreak were lower than those in the middle of the outbreak. The possible reason for this was the increase in water volume during the flood season, which may have been caused by the adsorption of the residual drugs. A slight increase in the concentrations at a few sampling points may have resulted from the lag effect of the transfer of the residual drugs into the water environments.

CRediT authorship contribution statement

Jun He and Tong Feng took the lead in writing the manuscript. Yue-e Peng, Lei Tong and Xin-wen Zhao conceived of the presented idea. Xin Shao, Lin-ya Xu, Yan-lin Yang and Yong-bo Zhao contributed to sample preparation and experiment. All authors discussed the results and contributed to the final manuscript.

Declaration of competing interest

The authors declare no conflicts of interest.

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