Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Hospital sewage treatment facilities witness the fighting against the COVID-19 pandemic

Zhi-Hua Li, a,b,*, Jia-Xing Wang, a,b, Meng Lu, a,b, Tianyu Zhang c, Xiaochang C. Wang, a,b, Wen-Wei Li d, Han-Qing Yu d

a Key Laboratory of Northwest Water Resource, Environment and Ecology, MOE, Xi’an University of Architecture and Technology, Xi’an, 710055, China
b Shaanxi Key Laboratory of Environmental Engineering, Xi’an University of Architecture and Technology, Xi’an, 710055, China
c Department of Mathematical Sciences, Montana State University, Bozeman, MT, 59717-2400, USA
d CAS Key Laboratory of Urban Pollutant Conversion, Department of Applied Chemistry, University of Science & Technology of China, Hefei, 230026, China

* Corresponding author. Key Laboratory of Northwest Water Resource, Environment and Ecology, MOE, Xi’an University of Architecture and Technology, Xi’an, 710055, China.
E-mail address: lizhihua@xauat.edu.cn (Z.-H. Li).

https://doi.org/10.1016/j.jenvman.2022.114728
Received 31 October 2021; Received in revised form 22 January 2022; Accepted 13 February 2022
Available online 15 February 2022
0301-4797/ © 2022 Elsevier Ltd. All rights reserved.

ABSTRACT

Real-time evaluation of the fighting activities during a sudden unknown disaster like the COVID-19 pandemic is a critical challenge for control. This study demonstrates that the temporal variations of effluents from hospital sewage treatment facilities can be used as an effective indicator for such evaluation. Taking a typical infection-suffering city in China as an example, we found that there was an obvious decrease in effluent ammonia and COD concentrations in line with the start of city lockdown, and its temporal variations well indicated the major events happened during the pandemic control. Notably, the lagging period between the change point of effluent residual chlorine and the change points of COD and ammonia concentration coincided with a period in which there was a deficiency in local medical resources. In addition, the diurnal behavior of effluents from designated hospitals has varied significantly at different stages of the pandemic development. The effluent ammonia peaks shifted from daytime to nighttime after the outbreak of the COVID-19 pandemic, suggesting a high workload of the designated hospitals in fighting the rapidly emerging pandemic. This work well demonstrates the necessary for data integration at the wastewater–medical service nexus and highlights an unusual role of the effluents from hospital sewage treatment facilities in revealing the status of fighting the pandemic, which helps to control the pandemic.

1. Introduction

The recent novel coronavirus disease 2019 (COVID-19) pandemic, caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) infection, has led to more than 200 countries and regions had been affected. Globally, as of 31 October 2021, the total confirmed number of cases of COVID-19 has reached 244 million, and more than 4.9 million deaths were reported (WHO, 2021). SARS-CoV-2 is primarily transmitted between humans via respiratory droplets and close contact (Thakur et al., 2021). Therefore, many regions and countries took strict control measures, which proved effective in restraining the spread of the virus, such as city lockdowns (or shelter-in-place), isolation of infected individuals, enhanced disinfection, improvement of medical resources, and construction of temporary hospitals (Ahmad et al., 2021; Kraemer et al., 2020).

As the main battlefield to fight against the epidemic, operation stably and efficiently of the hospital could ensure the treatment of infections. However, with the outbreak of COVID-19, the healthcare personnel and emergency supply system faces unprecedented pressure. The fast increase of infections has brought difficult challenges to managers, who need to evaluate the operating conditions of the hospital to achieve a reasonable allocation of resources. In the early period of the pandemic, most countries in the world face problems such as the unbalanced and inadequate supply of medical services, which would lead to higher mortality (Chai et al., 2020; Haldane et al., 2021). However, the medical data used to evaluate the operation of the hospital was not collected in time due to the sudden and large-scale spread of the virus (Miller et al., 2020; Peiffer-Smadja et al., 2020). The large-scale increase of infected people in the different regions leads to the decentralized distribution of medical resources, which aggravates the restriction of the scarcity of medical resources to control the spread of the epidemic (Emanuel et al., 2020; Feng et al., 2020). To solve the aforementioned problems, the
local hospitals were reorganized and categorized as general hospitals, designated hospitals, fever clinics, and temporary medical centers. The treated patients of the general hospitals were non-infected people, while suspected cases of infection with symptoms including fever, cough, and shortness of breath were requested to the fever clinics. Confirmed cases of COVID-19 patients were placed in designated hospitals for treatment. Temporary medical centers, also known as mobile cabin hospitals, these medical centers were reconstructed using existing public buildings such as schools and exhibition centers and were used as a supplement to designated hospitals (Chen et al., 2020).

Generally, wastewater is a mirror of society, which provides useful information for exploring human lifestyle and behavior (Reinstadler et al., 2021). Considering that all hospitals are equipped with sewage treatment facilities for sewage treatment, and sewage properties are usually correlated with the number of patients (Brewer et al., 2012), we hypothesize that these sewage treatment facilities might provide a window for us to look into the hospital operating status, where the effluent quality of the treatment facilities might reveal valuable information on fighting the COVID-19 pandemic, which is very important to control the pandemic (Lundy et al., 2021).

This study took a typical infected city in Hubei, China (the center of the COVID-19 pandemic outbreak in China) as an example, analyzed the discharge characteristics of sewage from different hospitals to reveal the operating status of hospitals during the epidemic. It was found that there was an apparent change in the effluent from these hospital sewage treatment facilities during different stages of fighting the COVID-19 pandemic infection control in the hospitals and different types of hospital exhibited different characteristics. By analyzing the effluent data from these facilities, valuable information was obtained, such as the availability and deficiency of medical resources in local hospitals to fight the COVID-19 pandemic, which provides a new window to observe the control of the pandemics. Such real-time information can provide helpful guidance for policymakers and city governors to optimize resource allocation and policy implementation towards effective pandemic control.

2. Methods and materials

2.1. Data source

According to the code of China, effluent in terms of COD, ammonia and residual chlorine from hospitals is required monitored online, and these data were collected from various hospitals in H city, a prefecture-level city in southeastern Hubei province, with a resident population of 2.47 million and approximately 90 km away from Wuhan. The peak value of daily confirmed cases was reached on Feb 14, 2020 in this city (Fig. 1a). Lockdown of the city was implemented on Jan 23, 2020 and lifted on Mar 25, 2020. The effluent concentrations of sewage treatment facilities, including ammonia nitrogen, chemical oxygen demand (COD), residual chlorine, and influent flow rate, were collected hourly from 10 hospitals and 6 municipal wastewater treatment plants from 2019 to 01-01 to 2020-05-20. All hospitals included 3 designated hospitals, 5 fever clinics, and 2 general hospitals.

2.2. Data analysis

Statistical analysis of the data set was analyzed using the pandas' package in Python programming language, including the hourly and daily average sampling of the time series data (McKinney, 2011). The change point of the effluent concentrations dataset was determined using the Pettitt test, which was implemented in the pyHomogeneity package of python, and the mean values before and after the change point were simultaneously calculated in this package (Shourov, 2020). The Pettitt test is a non-parametric method used for determining the
time and direction of the change points in the time series (Pettitt, 1979). According to the Pettitt test, the point change point is identified, and the time series is divided into two parts change point with specific statistical characteristics. The detailed calculation method of the Pettitt test appears in Pettitt (1979). In this study, the primary change point is calculated using the data from 2019 to 12-01 to 2020-05-20, and the secondary change point is calculated based on the data from 2019 to 12-01 to the date of the primary change point to probe the event that happened in the early period of the COVID-19 pandemic.

3. Results and discussion

3.1. Response of effluent quality from hospital treatment facilities to the COVID-19 pandemic

Both ammonia and COD concentrations in the effluent of hospital sewage treatment facilities dropped drastically when the city lockdown started (around Jan 23, 2020): from 15.35 to 8.03 mg/L for ammonia ($p = 2.26 \times 10^{-17}$), and from 43.86 to 38.47 mg/L for COD ($p = 1.32 \times 10^{-4}$) (Fig. 1b and c). The good effluent quality indicates that the activated sludge in these wastewater treatment facilities maintained high activity despite possibly increased use of disinfection agents in hospitals. The improved effluent quality might be mainly due to the decreased supply of non-essential medical services due to shelter-in-place, in which case those patients with non-emergent diseases not being accepted by hospitals. The decrease in the number of patients, together with the decrease in the number of caregivers due to high risks of COVID-19 infection, significantly lowered the pollutant loading of the sewage treatment plants (Atinkpahoun et al., 2018; Chen et al., 2021), as verified by the decreased influent flow rate (Fig. S1). The increased use of disinfectant in hospitals for therapy and increased dosage of chloride in the treatment facilities for effluent disinfection might also partially contribute to the removal of pollutants (Liu et al., 2012; Song et al., 2021), as evidenced by the slightly increased content of total residual chlorine in the effluent from 5.11 to 7.21 mg/L ($p = 5.10 \times 10^{-27}$) (Fig. 1d). Notably, the change point of residual chlorine was approximately one month later than that of effluent COD and of ammonia (Fig. 1), and coincided with an increase in the supply of medical resources to this region (ECNS, 2020).

Therefore, while the variations of effluent COD and ammonia concentrations are mainly a result of city lockdown, the effluent residual chlorine is more indicative of the availability of local medical resources. The lag time between the decrease in COD and ammonia and the increase in residual chlorine could reflect the duration of the deficiency in public medical resources as chlorine is one of the most essential chemicals for hospitals.

3.2. Variations of effluent COD and ammonia in different types of hospitals

Targeted at different types of patients, different hospitals also showed different changing trends in effluent pollutant concentrations. For the designated hospitals, the effluent ammonia and COD decreasing by 54.79% and 23.32% respectively upon city lockdown, in spite of the increased confirmed infection cases (Figs. 2a and b, S2a and S2b). Similar results are shown by the fever clinics, with effluent ammonia and COD concentrations decreased by 55.23% and 13.56% respectively (Figs. 2c and d, S2c and S2d). The improved effluent quality is likely due to the decreased number of ordinary patients in these hospitals, where non-essential medical service was not provided. The construction of temporary treatment centers that accepted a considerable number of patients with mild symptoms further alleviated the load of designated hospitals and fever clinics (Liu et al., 2020a). As a consequence, when all the temporary treatment centers were closed (on Mar 10), and the diagnosed patients were transferred to the traditional hospitals, the effluent pollutant concentrations in both the designated hospitals and fever clinics rose again (Figs. 2a and b, S2a and S2b) (Dong et al., 2020; Liu et al., 2020a).

Fig. 2. Effluent ammonia and COD concentrations in the different types of hospitals with large scales.
The general hospitals, which are not targeted specifically at the confirmed or suspected COVID-19 patients, also showed a slight decrease in the effluent ammonia and COD concentrations during the lockdown period (Figs. 2e, f, S2e and S2f), suggesting that the non-essential medical services were also suppressed (Sreide et al., 2020). Furthermore, the lockdowns also resulted in a decrease in COD concentration of municipal effluent during this period (Fig. S3a), while the variation of ammonia concentration was negligible since it was already at a very low level (Fig. S3b).

3.3. Insightful information from diurnal variations of effluent

In hospitals, the activities of medical services and daily lives generate a considerable amount of sewage. Thus, the diurnal behavior of effluent COD and ammonia could provide insightful information on the operating status of the hospitals. Effluents from designated hospitals varied more significantly than those from fever and general hospitals, as the peak time swapped in these hospitals (Fig. 3). For designated hospitals, before the outbreak of the COVID-19 pandemic, the peak and valley of ammonia concentrations occurred in the daytime and at night, with a clear changing trend during the day-night shift (blue lines in Fig. 4). This could be explained by the fact that most caregivers for patients stay in the hospital only in the daytime. However, during the serious stage of the COVID-19 pandemic, lower peak values of both ammonia and COD concentrations were observed (red lines in Fig. 4), suggesting a reduced number of patients and caregivers for the sake of effective quarantine (Liu et al., 2020b). In addition, frequent fluctuations in effluent ammonia and COD were observed, signifying the beginning of around-the-clock services in the designated hospitals to fight the rapidly emerging pandemic (Liu et al., 2020b). When the pandemic became more severe and a clear protocol for caring for COVID-19 patients came out (pandemic being kept under well control), the effluent concentrations from the designated hospitals showed a clear peak and valley again, but the time-course variation pattern differed drastically from that before the pandemic (green lines in Fig. 4). The peak values for both ammonia and COD increased and occurred at night, suggesting a high degree of deficiency in medical resources at this stage.

The peak time of ammonia and COD generally occurred in the morning before the pandemic, at between approximately 5:00 and 10:00 (Fig. 4). With the gradual increase in confirmed patients, the peak time began to change, eventually extending to evening, occurring between approximately 19:00 and 20:00 (Fig. 4). Meanwhile, the valley time shifted from between 19:00 and 20:00 to between 9:00 and 11:00 in the next day (Figs. 3a and S4a). It is worth noting that since Jan 15 several sub-peaks and sub-valleys of effluent ammonia in the designated hospitals occurred within 24-h over two consecutive days (Fig. S5), implying long working hours in the hospitals during this period. Thus, the service strength of the designated hospitals was at a very high level, which could be attributed to the rapid increase in the number of confirmed and suspected cases (Mo et al., 2020).

3.4. Potential application of the insightful information from effluent profiles

The variations of effluent COD and ammonia in hospitals coincided well with the major events of local COVID-19 pandemic development and control (Fig. 5), suggesting that the effluent of local hospital sewage treatment facilities could reveal valuable information about the local efforts in fighting the pandemic. Comprehensive decision-making on medical resources allocation and community management for controlling the pandemic requires efficient tools to estimate the development of the pandemic and the efficiency of the measures taken. Wastewater-based epidemiology (WBE) is a promising approach to determining the scale of the pandemic and providing guidance for its control (Hillary et al., 2021; Suthar et al., 2021). Unlike the conventional WBE approach, with direct probing of the molecular component of the virus from wastewater (Wurtzer et al., 2021), this study proposes the novel and promising approach of using the indirect parameters of wastewater effluent quality as an indicator, making it possible for real-time monitoring of the pandemic. Indirect digital epidemiology based on a search engine, such as Google Flu Trends received much attention for early prediction of seasonal epidemics, which could quickly identify the trend of the epidemic through a search of keywords related to the epidemic (Arslan and Benke, 2021; Ginsberg et al., 2009). However, considering the existence of some false reports, the epidemic method based on online effluent data from treatment plant facilities could be more reliable (He et al., 2020).

Measures, including lockdowns or shelter-in-place orders, not only caused considerable decreases in effluent ammonia and COD concentrations in hospitals, but also caused a significant delay in the increase of
residual chlorine due to a deficiency in the supply of medical resources, in a similar way to the global supply chains under the global trade modeling framework (Guan et al., 2020). Therefore, the lag time of residual chlorine response offers an effective indicator for evaluating the availability and deficiency of medical resources. These effluent data could be conveniently obtained from the various sewage treatment facilities, implying a great potential for this strategy to be extended to evaluate the medical resources deficiency at the city, national or even global levels.

The online effluent data could not only reveal information about the operating status of designated hospitals during different stages of the COVID-19 development and control, but also provide meaningful information for WBE analysis. Severe acute respiratory syndrome (SARS) viruses could be easily inactivated in 30 min at 20 °C with more than 0.5 mg/L residual free chlorine or 2.19 mg/L residual chlorine dioxide (Wang et al., 2020). Sewage with a much higher residual chlorine concentration from hospitals may affect the WBE results (Fig. 1d). To reduce this impact of residual chlorine on virus monitoring, we suggest the optimal time for sewage sampling at the early stage of a pandemic should be approximately between 10:00 and 18:00, when the effluent with residual chlorine concentration in the effluent is lowest (Fig. S6). The presence of organic matter and suspended solids in water could
provide protection for viruses adsorbed on these particles and provide a way for virus transmission (Dhama et al., 2021; Hillary et al., 2021). During the most stringent period of the pandemic, the optimal sample time should be adjusted to 14:00, when the minimal concentration of residual chlorine and the high concentration of COD occurred (Figs. S4 and S6).

4. Conclusion

The variations of effluent COD and ammonia in hospitals coincided well with the major events of local COVID-19 pandemic development and control and well reflected the fighting activities of the pandemic. For example, the lag period between the change points of COD and ammonia and the change point of residual chlorine could reflect the duration of the deficiency in public medical resources and the diurnal variations show the workload of designated hospitals. Due to the necessarily presence of hospital sewage treatment facilities and the regular monitoring of the effluent pollutant concentrations, information discovered from here without extra cost offers opportunities for better understanding and controlling the development of pandemics at the city or national level. Therefore, more study on the data integration at the wastewater–medical service nexus is highly demanded.

Author statement

Zhi-Hua Li, Jia-Xing Wang, Meng Lu, Tianyu Zhang, Xiaochang C. Wang, Wen-Wei Li, Han-Qing Yu all were ranked by contribution for the Author statement interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (52070149, 51878539).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.114728.

References

Ahmad, J., Ahmad, M., Usman, A.R.A., Al-Wabel, M.I., 2021. Prevalence of human pathogenic viruses in wastewater: a potential transmission risk as well as an effective tool for early outbreak detection for COVID-19. J. Environ. Manag. 298, 113486.

Arslan, J., Benke, K.K., 2021. Artificial intelligence and telehealth may provide an early warning of epidemics. Front. Artif. Intell. 4, 556848.

Atinkpahoun, C.N.H., Le, N.D., Pontvianne, S., Poirot, H., Leclerc, J.-P., Pons, M.-N., Atinkpahoun, C.N.H., Le, N.D., Pontvianne, S., Poirot, H., Leclerc, J.-P., Pons, M.-N., 2021. Data-driven forecast of COVID-19 transmission characteristics and SARS-CoV-2 detection in wastewater: a case study. Chemosphere 286, 131680.

Brewer, A.J., Ort, C., Banta-Green, C.J., Berset, J.D., Field, J.A., 2012. Normalized difference between-day trends in illicit and legal drug loads that account for changes in population. Environ. Sci. Technol. 46 (15), 8305-8314.

Chai, K.C., Zhang, Y.B., Chang, K.C., 2020. Regional disparity of medical resources and its effect on mortality rates in China. Front. Public Health 8, 288.

Chen, S., Zhang, Y., Wang, J., Zhai, X., Barnighausen, T., Wang, C., 2020. Fangcang shelter hospitals: a novel concept for responding to public health emergencies. Lancet 395 (10232), 1305-1314.

Chen, Y., Wang, L., Cui, X., Xu, J., Xu, Y., Yang, Z., Jin, C., 2021. COVID-19 as an opportunity to reveal the impact of large hospital expansion on the healthcare delivery system: evidence from Shanghai, China. Ana. Transl. Med. 9, 1297-1297.

Dhama, K., Patel, S.K., Yatoo, M.I., Tiwari, R., Sharan, K., Dhama, J., Natesan, S., Malik, Y.S., Singh, K.P., Harapan, H., 2021. SARS-CoV-2 existence in sewage and wastewater: a global public health concern? J. Environ. Manag. 280, 111852.
suggestions for disinfection strategy during coronavirus Disease 2019 (COVID-19) pandemic in China. Environ. Pollut. 262, 114665.

WHO, 2021. WHO Coronavirus Disease (COVID-19) Dashboard. https://covid19.who.int/. (Accessed 31 October 2021).

Wurtzer, S., Waldman, P., Ferrier-Rembert, A., Frenois-Veyrat, G., Mouchel, J.M., Boni, M., Mauy, Y., Marechal, V., Moulin, L., 2021. Several forms of SARS-CoV-2 RNA can be detected in wastewaters: implication for wastewater-based epidemiology and risk assessment. Water Res. 198, 117183.