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Impact of hydrological factors on the dynamic of COVID-19 epidemic: A multi-region study in China

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ABSTRACT

Considering the live SARS-CoV-2 was detected and isolated from the excrement and urine of infected patients, the potential public health risk of its waterborne transmission should be paid broad and close attention. The purpose of the current study is to investigate the associations between COVID-19 incidences and hydrological factors such as lake area, river length, precipitation and volume of water resources in 30 regions of China. All confirmed cases for each areas were divided into two clusters including first cases cluster driven by imported cases during the period of January 20th to January 29th, 2020 and second cases cluster driven by local cases during the period of January 30th to March 1st, 2020. Based on the results of descriptive analysis and nonlinear regression analysis, positive associations with COVID-19 confirmed numbers were observed for migration scale index (MSI), river length, precipitation and volume of water resources, but negative associations for population density. The correlation coefficient in the second stage cases cluster is apparently higher than that in the first stage cases cluster. Then, the negative binomial-generalized linear model (NB-GLM) was fitted to estimate area-specific effects of hydrological variables on relative risk (RR) with the incorporation of additional variables (e.g., MSI) and the effects of exposure-lag-response. The statistically significant associations between RR and river length, the volume of water resources, precipitation were obtained by meta-analysis as 1.24 (95% CI: 1.22, 1.27), 2.56 (95% CI: 2.50, 2.61) and 1.59 (95% CI: 1.56, 1.62), respectively. The possible water transmission routes of SARS-CoV-2 and the potential capacity of long-distance transmission of SARS-CoV-2 in water environment was also discussed. Our results could provide a better guidance for local and global authorities to broaden the mind for understanding the natural-social system or intervening measures for COVID-19 control at the current or futural stage.

1. Introduction

In December 2019, an outbreak of COVID-19 emerged in Wuhan city, Hubei province of China, where its widespread transmission had presented a tremendous threat to public health (Wu et al., 2020b). Similar to the other virus belonging to genus of beta-coronavirus (e.g., SARS-CoV and MERS-CoV), SARS-CoV-2, the virus that causes COVID-19, was identified as a new member of zoonotic viruses with the risk of animal-to-human transmission (Corman et al., 2018). The main symptoms of COVID-19 include fever, cough, sputum, pneumonia and dyspnea associated with multiple organ diseases such as myocardial damage, coagulation dysfunction, kidney injury and liver damage (Zheng et al., 2020). As of 15 May 2020, there had been 4,347,935 global infected cases including 297,241 deaths in 214 countries and territories (WTO, 2020a), in which United States and Europe have gradually becoming the epicenter of the pandemic (WTO, 2020b).

Previous studies suggested that when the patients exhale, sneeze or cough, the droplets containing large amounts of pathogens enter the environments, while smaller respiratory droplets stay in the air temporarily and large droplets would deposit on the surface of the objects (e.g., lift buttons, door knob and grips) (Lei et al., 2018; Lu et al., 2020). Moreover, aerosols could also mediate SARS-CoV-2 for the long-distances via air movement, particular in a relatively closed environment such as bus and surgery (Qu et al., 2020).

Water transmission routes of SARS-CoV-2 should also be taken into account. Recent study reported that live SARS-CoV-2 can be isolated from the excrement and urine of COVID-19 patients (Holshue et al., 2020), and viral nucleic acid of more than 20% of patients remained

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positive in stool samples even after viral clearance in respiratory tract, indicating the risk of fecal-oral transmission of SARS-CoV-2 should be of concern (Xiao et al., 2020). Remarkably, a point-source outbreak of SARS involving 321 patients occurred in a high-rise apartment in Hong Kong in 2003 was attributed to the contaminated sewage system (Peiris et al., 2003). In addition, as the terminal units of sewerage system, wastewater treatment plant (WWTP) should also establish effective measures to prevent COVID-19 transmission through aerosols transmission which are associated with the performance of bubble-busting, hydraulic drop and turbulence of wastewater particular in aeration process (Wigginton and Boehm, 2020). Therefore, appropriate personal protective equipment should be considered including gloves, goggles, protective suit and surgical masks when employees are exposed to wastewater. On the other hand, SARS-CoV-2 deposited on the surface of objects can be washed by rainfall into surface runoff and then migrate for a certain distance with infections. Some studies have shown that SARS-CoV-2 could survive several hours in aerosols or even days on the surface of the objects when the air temperature is 21–23 °C and relative humidity is 40%–65%, such as 10–16 h for steel and 13–19 h for plastic (Neeltje et al., 2020). Therefore, regarding the risk of water transmission of SARS-CoV-2, studies should not be neglected to answer that whether the hydrological conditions (e.g., river length, lake area, precipitation and volume of water resources) could associate to the outbreak of COVID-19.

Generalized linear model (GLM), a linear combination expansion model, proposed by Nelder in 1972 is conducted to investigate the effect of hydrological parameters on COVID-19 incidence rate (Nelder and Wedderburn, 1972). In this study, assuming that the probability model depends on the exponential distribution family, the GLM can be constructed and decomposed into standard linear prediction variables (e.g., hydrological factors and migration scale index (MSI)) which can be mapped into the relation function of the expected value of daily confirmed COVID-19 cases.

In order to examine the effect of hydrological factors on the dynamics of COVID-19 epidemic in China, and formulate necessary preventive measure in advance in other places, the objectives of this study entail the following three key steps: (1) To identify the area-specific effects of hydrological variables on COVID-19 incidences via descriptive analysis and nonlinear regression analysis; (2) To assess the associations between hydrological variables and daily confirmed case numbers of COVID-19 based on the negative binomial-generalized linear model (NB-GLM) with the incorporation of additional variables and controls (e.g., MSI) and effects of exposure-lag-response for each areas; (3) To explain the possible water transmission routes of SARS-CoV-2 and the potential capacity of long-distance transmission of SARS-CoV-2 in water environment.

2. Methods

2.1. Data collection

30 areas including 21 provinces, 5 autonomous regions and 4 municipalities of China with serious epidemic situation were chosen except for Hubei province with complicated COVID-condition such as Wuhan lockdown and mass screening. Daily confirmed case counts of COVID-19 were obtained from the official websites of the health commission of 30 areas during the periods from January 20th to March 1st, 2020 (see details in Supporting Information (SI) Table. S1). Regional hydrological data such as lake area, river length, precipitation and volume of water resources was collected from *China Water Statistical Yearbook* (2019). Based on a great number of data obtained from geographic location service, the impact on the epidemic situation of large-scale population migration can be analyzed accurately. Daily MSI and population density of 30 areas were obtained from the website of Baidu Migration (https://qianxi.baidu.com/) and *China Statistical Yearbook* (2019), respectively. MSI reflecting timeliness and continuity represents the population scale of moving in. Since the data on hydrological variables and confirmed case numbers were reported officially, ethical review was not required.

2.2. Statistical analysis

China covers a vast geographic area associated with imbalanced regional spatial distribution, in which three autonomous regions involving Xinjiang, Inner Mongoria and Tibet account for around a quarter of the total areas of China. To eliminate the imbalance acting of uneven spatial distribution, hydrological variables data of these 30 regions except for precipitation were analyzed as follows:

$$x' = \frac{x}{A} \tag{1}$$

where x and x' present the value of regional hydrological factors on whole area and unit area, respectively; A presents the regional area. All area-specific features data was analyzed by descriptive study. In addition, a second order polynomial nonlinear regression analysis were conducted between COVID-19 confirmed case counts and hydrological factors.

The negative binomial-generalized linear model (NB-GLM) was further employed to explore the associations between hydrological factors and confirmed case counts for the clustering features of COVID-19. Firstly, the basic models for confirmed case counts were built concentrating on the effect of MSI, in which incorporated smoothed spline functions of time was performed to mediate nonmonotonic and nonlinear models between infections and time (Ma et al., 2020). Then, hydrological factors such as lake area, river length, precipitation, surface water resources, groundwater resources and total volume of water resources were introduced into NB-GLM to explore their effects on infections. The fitness between practical data and non-linear regression patterns was appraised by Akaike's information criterion and the fitted equations were shown as follows:

$$logE(Y_t) = \alpha + \beta X + \gamma MSI \tag{2}$$

where E (Y_t) represents the expected number of daily confirmed cases on day t; α represents the intercepts; β and γ represent the regression coefficient; X represents the hydrological variables such as lake area, river length, precipitation and volume of water resources. In addition, associations in single day lag (from lag 0 to lag 5) between daily confirmed case numbers and these hydrological variables for each regions were examined to assess the lag effects of MSI on COVID-19 incidences.

All the statistical analysis was performed with R software version 3.5.0 using "MASS" package, and the results were represented as the relative risk (RR) in daily confirmed cases of COVID-19 with 95% confidence intervals (95% CIs) associated with per unit increase of each factor (Liu et al., 2020).

3. Results

On January 23rd, 2020, Wuhan, the capital city of Hubei province, was locked down to control the spread of the virus by closing its airports, rail stations and all main roads out of town, as well as suspended public buses and subways. After that, each province of China has activated first-level public health emergency response to reduce imported cases from Wuhan and the scale of population mobility. Therefore, January 23rd is considered as the time node for division. However, considering the median latency of COVID-19 is 4.8 days (Li et al., 2020), cumulative confirmed cases before January 29th are defined as the first stage cases cluster dominated by imported cases. After that, cumulative confirmed cases from January 30th to March 1st, 2020 are taken as the second stage cases cluster dominated by secondary cases related to close contacting with imported cases.

Fig. 1 presented the regional pattern of confirmed COVID-19 cases

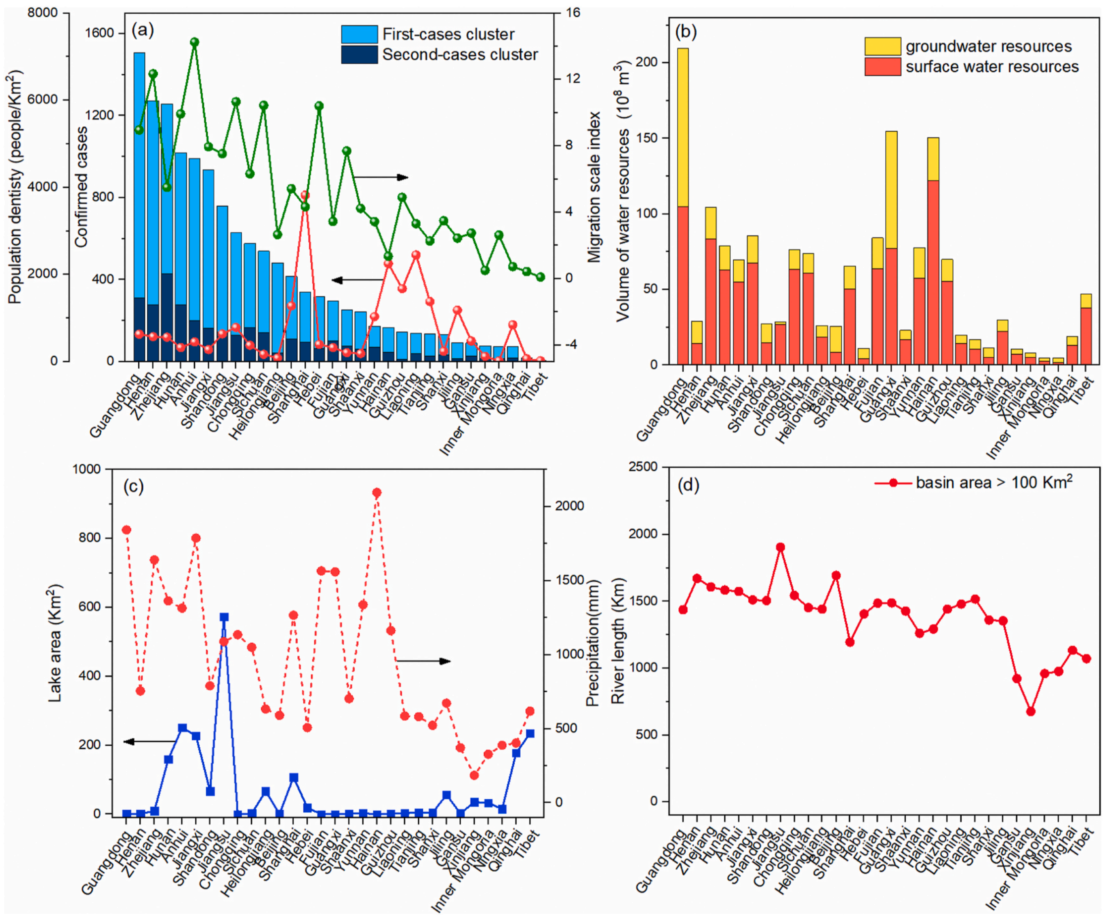

Fig. 1. Regional patterns of (a) COVID-19 daily confirmed cases and hydrological factor levels including (b) volume of water resources, (c) lake area, precipitation and (d) river length in 30 typical regions of China, from January 20th to March 1st, 2020.

and related impact factors, indicating that spatial distribution of infections had a similar pattern with population density, MSI and hydrological factors. During the study period from January 20th, 2020 to March 1st, 2020, 30 typical regions in China were suffering from COVID-19 as the total number of confirmed cases increased from zero to 12,179. Besides, confirmed COVID-19 cases of these regions displayed a pyramid style, in which 10 regions with more than 500 confirmed cases occupy the majority accounting for 72.1% of all cases. Among the 10 regions that have more than 500 cases, 8 regions located in the south of China with sufficient surface water resources ($1.2 \pm 0.7 \times 10^{11}$ m^3) and plentiful rainfall (1402.8 ± 440.3 mm). Besides, the population density and MSI in these 10 regions were relatively higher than the other 10 regions that have cases less than 500.

The results of nonlinear regression analysis shown in Fig. S1and Fig. 2 indicated the brief distribution characters between COVID-19 incidences and related impact factors in 30 typical areas of China, in which the confirmed case counts increased with the increasing of MSI, river length, volume of water resources and precipitation. Besides, the negative associations were found between confirmed case counts and population dentistry in the range of 0–4000 people/Km^2. As depicted in Fig. 2d, confirmed case counts of COVID-19 present strong positive correlation with river length, moderate relationship with MSI and precipitation, and weak correlation with the volume of water resources. Furthermore, the correlation coefficient in the second stage cases cluster is apparently higher than that in the first stage cases cluster.

Since the small sample size of second stage case cluster in 10 regions with less than 100 cases, the fitted area-specific GLM and meta-analysis were only performed for the 20 regions with 100 and more cases from January 30th to March 1st, 2020 to assess the relationship between COVID-19 case numbers and hydrological variables (shown in Fig. 3). The relative results of area-specific study suggested that significant positive associations were found in all regions, after controlling the effects of MSI. Meanwhile, the statistically significant associations between relative risk (RR) and river length, the volume of water resources, precipitation were obtained by meta-analysis as 1.24 (95% CI: 1.22, 1.27), 2.56 (95% CI: 2.50, 2.61) and 1.59 (95% CI: 1.56, 1.62), respectively. 0–5 days lag were employed to examine the effect of exposure-lag-response on the confirmed cases of COVID-19, and the results suggested that RR gradually increased with the number of lag days increasing, and then reached a peak when lagging by 3 days (shown in Fig. 3d and Fig. S2).

4. Discussion

4.1. *The possible water transmission routes of SARS-CoV-2*

COVID-19 transmission can be influenced by several factors, including environmental factors, medical care and population density (Wang et al., 2020). This study is intended to associate COVID-19 incidences with hydrological variables. SARS-CoV-2 fragment was detected in sewage at several sites in the Netherlands using reverse transcription-polymerase chain reaction technology, while no SARS-CoV-2 was detected in these sites during a period before the first COVID case confirmed in this region. (Medema et al., 2020). SARS-CoV-2 genetic material was also detected in river water in Milan, Italy (Rimoldi et al., 2020). Moreover, according to quantitative assessment of SARS-CoV-2 in sewage from wastewater treatment facility, the detected concentration of virus in Massachusetts (USA) was 3–4

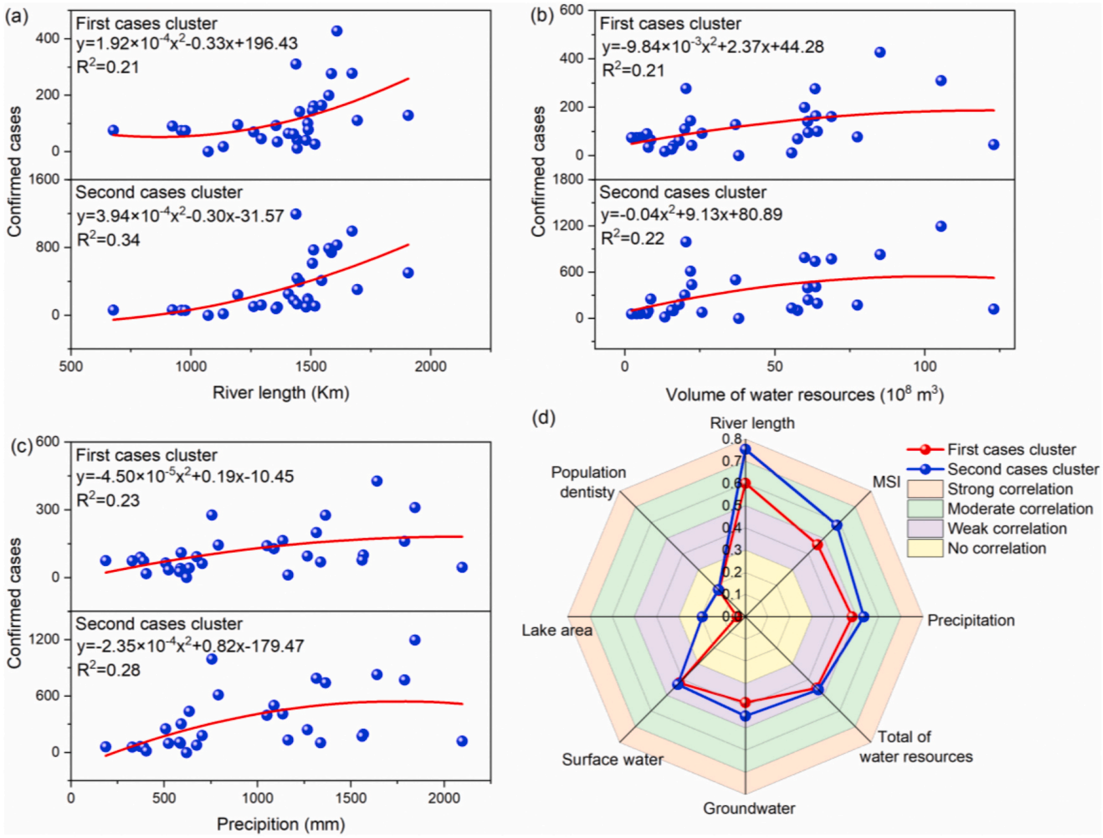

Fig. 2. Associations between COVID-19 confirmed case counts and hydrological factors including (a) river length, (b) total volume of water resources, (c) precipitation in 30 regions of China. (Solid points represent actual values of 30 regions; red lines represent second order polynomial curves.) (d) Correlation coefficient between COVID-19 daily confirmed cases and various factors in 30 typical regions of China. Note: first cases cluster represents cumulative confirmed cases before January 29th; second cases cluster represents cumulative confirmed cases from January 30th to March 1st, 2020). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

orders of magnitude compared to that in Queensland (Australia), ascribed to the higher number of COVID-19 confirmed cases in the former region (Ahmed et al., 2020; Wu et al., 2020a). Therefore, considering of the existence of SARS-CoV-2 in the wastewater and river, more attention might be paid to for its waterborne transmission routes in order to better control the potential risk for public.

The impacts of hydrological characteristics such as precipitation over the COVID-19 transmission are in accordance with the results of previous research on the transmission of dengue fever and other infectious disease, which might be ascribe to the water transmission routes of viruses (Lenaker et al., 2017; Tsai et al., 2018). The possible migration trajectory of SARS-CoV-2 in the whole hydrologic cycle is depicted in Fig. 4, in which locations of potential human exposure are classified into five types including living areas and treatment regions, wastewater pipe network, wastewater treatment system, surface water and water supply system (see more details about the fate of SARS-CoV-2 in the water environment and locations of potential human exposure in SI Text. S1). Although physical, chemical and biological processes in wastewater treatment plant (WWTP) can efficiently remove SARS-CoV-2 with at least 4.0-log reduction (see details in SI Text. S2), a portion of viruses would be released to surface waters on account of malfunction, particular during major wet weather events. Besides, SARS-CoV-2 could access into surface water via rainwater or runoff contaminated by domestic garbage (e.g. masks and kitchen waste) of COVID-19 patients. Due to the performance of flow disturbance and high drop height, viruses that settled on the bottom of the river might form virus aerosol and pose a potential public health threat (Wigginton and Boehm, 2020). Some current literature suggested that precipitation influences the global transmission of SARS-CoV-2, displaying that each additional increase (1 mm) in precipitation per day was associated with 2.21 increase in COVID-19 daily confirmed cases (Sobral et al., 2020).

4.2. The potential capacity of long-distance transmission of SARS-CoV-2

Based on the results of the nonlinear regression analysis and NB-GLM, positive associations are observed between COVID-19 and river length, volume of water resources, implying that SARS-CoV-2 in the water environment might travel long distances and poses threat to the local people who is exposed to infective viruses. The capacity of long-distance transmission of SARS-CoV-2 is ascribed to its survival ability and tolerance ability in the water environment. Some studies have shown that the transmissibility of coronavirus (such as SARS-CoV) in the water environment is less than that of enterovirus because coronavirus is vulnerable and inactivate fast in the wastewater with a 99.9% reduction within two days (Gundy et al., 2008; Wang et al., 2005).

Coronavirus could prolong survival time through alleviating the extent of damage produced by intimidating environment. Previous studies indicated that the virus particle in water environment could improve its resistance to adversity via aggregating (Chen et al., 2015). However, the protective effects of aggregation can be ignored in nature water environment due to the low concentration and rapid inactivation of virus. Furthermore, virus aggregates are easy to be scattered by the interference of external environmental factors, such as acoustic wave, ultrasonic treatment and proteolytic enzyme (Labelle and Gerba, 1980; Malina et al., 1975). For example, poliovirus aggregates are completely dispersed in the diluent of secondary sewage treatment plant effluent (Hejkal et al., 1981). Some studies have reported that virus has a tendency to adsorb on the surfaces of suspended solids in natural

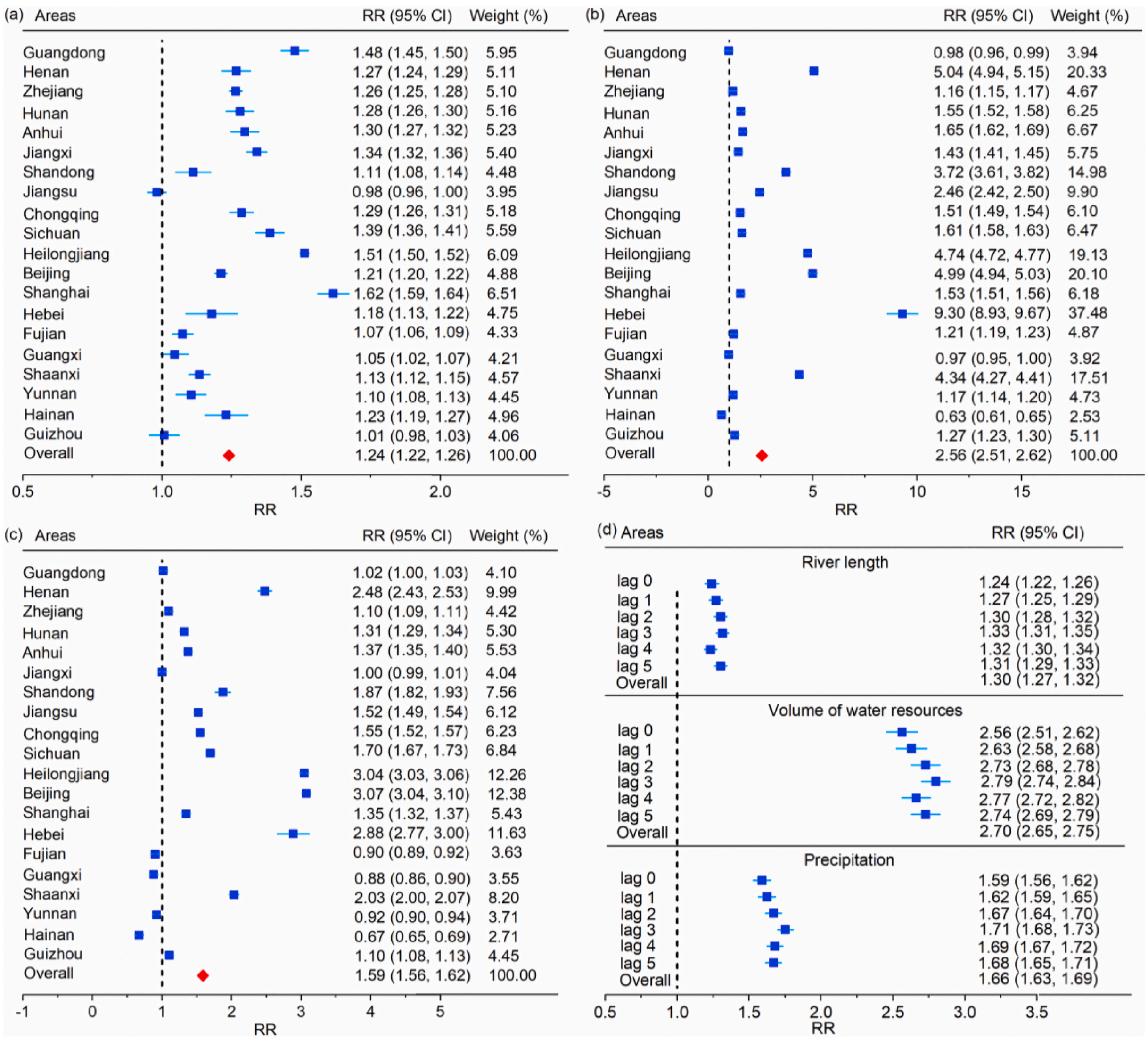

Fig. 3. Meta-analysis for effects of hydrological variables on COVID-19 incidences across 20 regions in China during the second stage (from January 30th to March 1st, 2020). Note: (a) river length; (b) volume of water resources; (c) precipitation; (d) pooled estimates in lag 0 to lag 5. The associations of COVID-19 case numbers with river length, volume of water resources and precipitation in each areas were assessed by fitting NB-GLM (lag 0).

environments or wastewater, and consequently concentrates in sludge (Karim et al., 2004). Sludge, as a major, integral and dynamic components of the water environment system, was also an important product of wastewater treatment mainly derived from the primary sedimentation tank and secondary clarifier. Untreated sludge contains a great number of parasitic ovum and pathogenic microorganisms, such as coxsackie virus, reovirus and echovirus (Fields, 1981; Wommack et al., 2009). Untreated sludge might be a source of viral pollution in natural water environment, when it is employed as landfills or fertilizer in farming land (Sano et al., 2003). It is generally considered that the concentration of virus adhered in sediment of constructed wetland was more than 1 $\log_{10}$ unit higher than those in overlaying water (Karim et al., 2004). Besides, the virus concentrated in sludge inactivated more slowly than those in water environment (Martin-Diaz et al., 2020) because the clay contained in sludge could embed and protect virus from the interferences of external inactivation factors (Labelle and Gerba, 1980; Malina et al., 1975). Organic materials abundant in sludge could also reduce the inactivation of oxidants to virus by keeping survival environment stable at a low redox potential (Martin-Diaz et al., 2020), which could prolong the survival time of SARS-CoV-2 in water environment and responsible for the long distance transmission of COVID-19.

Moreover, river biofilm could also play an important role in reservoirs of microbial pathogens (Mackowiak et al., 2018). When virus adheres to soluble organic substances, organic compounds would stimulate microbial cells to secrete polysaccharides and form matrix around cells, enhancing the resistance of the virus to an adverse environment (Gutierrez et al., 2009). The surface hydrophobicity of the virus is a significant factor to evaluate the adsorption and distribution characteristics of microorganisms in the water environment. Previous studies suggested that weak surface hydrophobicity is conducive to improving the suspension stability of the virus, while strong surface hydrophobicity is conducive to the occurrence of adsorption process with low affinity to the water environment (Popovici et al., 2014). Sediment and biofilm settled on the bottom of the river might be responsible for a public health risk on account of the mobilization of pathogens from the riverbed during extreme precipitation events or floods. Therefore, hydrological conditions with high precipitation, long river length and high volume of water resources likely favor the waterborne transmission of SARS-CoV-2.

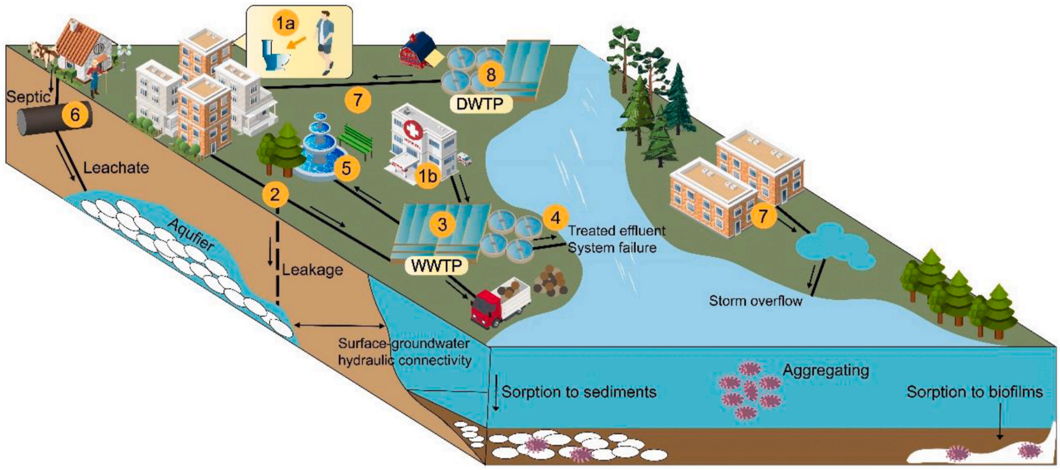

Fig. 4. The possible water transmission routes and the migration mechanism of viruses. Viruses excreted in 1) feces and urine of patients are collected and transported by 2) sewage pipe network, and subsequently enter the 3) wastewater treatment plant (WWTP). Viruses may be discharged with 4) sewage effluent to surface water in case of malfunction. 5) Reclaimed water applied in spray irrigation, cooling towers and toilet flushing may carry viruses. Viruses excreted in feces and urine are treated by 6) septic and transported into groundwater. Viruses adsorbed on 7) domestic garbage (e.g. masks and kitchen waste) enter the runoff via rainwater. Viruses survived in intake water would be treated with a range of physical, biological, and chemical processes in 8) drinking water treatment plants (DWTP) and transported to residential area by 9) water distribution system.

4.3. Different roles of lake area and river length on COVID-19 epidemic

Lake area, one of the important hydrological characteristics, present no correlation for COVID-19 incidences (R < 0.3). Rather than river supplied by surface water and groundwater flowing along the narrow and long depression frequently or intermittently, lakes are considered as the natural depressions with relatively closed water storage. The distinctive characteristics of lakes are conducive to the adsorption of virus on the lake bottom sediment and biofilm, which could make against the formation of aerosols. Meanwhile, virus releasing in lakes is exposed to a variety of physical, chemical and biological environmental factors. For example, bacteria can inactivate the virus via secreting protease to destroy the capsid of virus protein or prey on the virus as their own growth matrix (JR et al., 1997). Similarly, polysaccharides, polypeptides and small molecule metabolites produced by algae can also inactivate the virus. Furthermore, ultraviolet radiation (UV) derived from sun light can directly destroy the protein coat and nucleic acid of the virus or generate active oxidants to inactivate the virus via oxidizing compounds (e.g., nitrate, nitrite and chromophoric dissolved organic matter) in water environments (Fusco et al., 2020). Current literature has shown that compared to river waters, lake waters were characterized by higher hydroxyl radical photogeneration rate ($1.10–1.82 \times 10^{-10}$ M s^{-1} vs. $5.10–11.69 \times 10^{-11}$ M s^{-1}) and steady-state hydroxyl radical concentration ($2.50–10.33 \times 10^{-17}$ M vs. $1.76–3.11 \times 10^{-17}$ M), in which hydroxyl radical with strong standard oxidation-reduction potential can inactivate virus efficiently (Xu et al., 2020).

All confirmed cases for each provinces were divided into two clusters including first stage cases cluster dominated by imported cases and second stage cases cluster driven by local cases. As expected, the correlation coefficient between the confirmed case number and hydrological factors in the first stage was considerably lower than that in the second stage, which is consistent with the behavioral evidence on SARS-CoV-2 transmission in water environment. However, various boundary limitations should not be neglected. Firstly, the dynamics of COVID-19 infections in China may be influenced by some other significant variables, including virus characteristics, population immunity levels, operating situation of the WWTP and government intervention. However, although previous studies have shown that population density can influence SARS-CoV-2 transmission (Wang et al., 2020), population density presented no obvious correlation on COVID-19 transmission (shown in Fig. S1) in this study based on the conclusion of the nonlinear regression analysis and NB-GLM analysis, which may be contributed to the effect of government intervention such as curbing population flow, canceling mass gatherings and reducing the frequency of bus services in the city. These factors should be further evaluated in the future research. Besides, ecologic time-series analysis was adopted in this study, which might be associated with the fallacy caused by other ecological variables that also changed over time.

5. Conclusion

This is the first study to evaluate the effect of hydrological factors including river length, lake area, precipitation and volume of water resources on the epidemic of COVID-19. According to the results of descriptive analysis and nonlinear regression analysis, confirmed COVID-19 case counts present significant correlation to MSI, moderate relationship to river length and precipitation, weak correlation to the volume of water resources. The correlation coefficient in the second stage cases cluster is apparently higher than that in the first stage cases cluster. Moreover, this study reported that hydrological variables as important correlation coefficients in the predication of COVID-19 incidences, implying that the waterborne transmission of SARS-CoV-2 could pose a threat to the public health. The NB-GLM presented the statistically significant associations between RR and river length, the volume of water resources, precipitation as 1.24 (95% CI: 1.22, 1.27), 2.56 (95% CI: 2.50, 2.61) and 1.59 (95% CI: 1.56, 1.62), respectively. Furthermore, RR gradually increased with the number of lag days increasing, and then reached a peak when lagging by 3 days. These results provided better introductions for local and global authorities to strengthen intervention activities that target COVID-19.

Credit author statement

Jingquan Wang: Conceptualization, Formal analysis, Investigation, Writing - original draft. Wei Li: Formal analysis, Writing - review & editing. Bo Yang: Writing - review & editing. Xin Cheng: Formal analysis. Zixin Tian: Writing - review & editing. Hongguang Guo: Conceptualization, Methodology, Writing - review & editing, Supervision.

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.

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Appendix A

Supporting Information

Text S1, the fate of SARS-CoV-2 in the water environment and locations of potential human exposure; Text S2, evaluation of removal efficiency of virus in WWTP; Table S1, the summary of the official website of Health Commission of 30 areas; Figure S1, associations between COVID-19 confirmed case counts and MSI, population dentistry, lake area, volume of surface water, volume of ground water in 30 regions of China; Figure S2, meta-analysis for effects of exposure-lag-response on COVID-19 incidences across 20 regions in China during the second stage.

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