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.
Original Research Article

Water-sanitation-health nexus in the Indus-Ganga-Brahmaputra River Basin: need for wastewater surveillance of SARS-CoV-2 for preparedness during the future waves of pandemic

Paromita Chakraborty 1,*, P.G. Vinod 2,3, Jabir Hussain Syed 4, Balram Pokhrel 5, Girija K Bharat 6, Avanti Roy Basu 6, Tama Fouzder 7, Mukesh Pasupuleti 8, Magdalena Urbaniak 9, Vladimir P. Beskoski 10

1 Environmental Science and Technology Laboratory, Department of Chemical Engineering, SRM Institute of Science and Technology, Kattankulathur, Tamil Nadu 603203, India
2 Department of Computer Science, SRM Institute of Science and Technology, Kancheepuram district, Tamil Nadu 603203, India
3 Nuevo Chakra (OPC) Pvt Ltd, Mumbai, Maharashtra
4 Department of Meteorology, COMSATS University Islamabad Tarlai Kalan Park Road 45550, Islamabad, Pakistan
5 Department of Chemical Sciences and Engineering, Kathmandu University, Dhulikhel, Nepal
6 Mu Gamma Consultants Pvt. Ltd, Gurgaon, India
7 Department of Electrical and Electronic Engineering, University of Liberal Arts Bangladesh (ULAB), Bangladesh
8 Central Drug Research Institute, B.S. 10/1, Sector 10, Jankipuram Extension, Sitapur Road, Lucknow 226031, India
9 European Regional Centre for Ecohydrology of the Polish Academy of Sciences, Tylna 3, 90-364 Lodz, Poland
10 University of Belgrade-Faculty of Chemistry, Studentski trg 12–16, 110 00 Belgrade, Serbia

A R T I C L E   I N F O

Article history:
Received 3 August 2021
Revised 15 October 2021
Accepted 3 November 2021
Available online 15 November 2021

Keywords:
Indus Ganga Brahmaputra River Basin
SARS-CoV-2
Sustainable Development Goals
Sanitation
Health and Hygiene

A B S T R A C T

The Indus–Ganga-Brahmaputra River Basin (IGBRB) is a trans-boundary river basin flowing through four major countries in South Asia viz., India, Pakistan, Bangladesh, and Nepal. Contamination of surface water by untreated or inadequately treated wastewater has been a huge problem for pathogenic microorganisms in economies in transition. Recent studies have reported that sewage surveillance can provide prior information of the outbreak data, because faeces can contain the novel coronavirus (SARS-CoV-2) shed by infected humans. Hence, in this study we geo-spatially mapped the COVID-19 hotspots during the peak time in the first and second wave of pandemic to demonstrate the need and usefulness of wastewater surveillance strategy in IGBRB during ongoing pandemic.

Further, we discussed the status of sanitation, health and hand-hygiene in the IGBRB along with characterization of the challenges posed by the pandemic in achieving the United Nations Sustainable Development Goals (UN-SDGs).

Monthly Geographical Information System (GIS) mapping of COVID-19 hotspots in the IGBRB showed an increase in the spread along the direct sewage discharge points. The social inequalities expose the vulnerabilities of the urban poor in terms of the burden, risks, and access to Water, Sanitation, and Hygiene (WASH) needs. Such an evidence-based image of the actual SARS-CoV-2 viral load in the community along the IGBRB can provide valu-

* Corresponding author: Tel: +91-44-27417909; Fax: +91-44-27456702.
E-mail address: paromite@srmist.edu.in (P. Chakraborty).

https://doi.org/10.1016/j.ecohyd.2021.11.001
1642-3593/© 2021 European Regional Centre for Ecohydrology of the Polish Academy of Sciences. Published by Elsevier B.V. All rights reserved.
1. Introduction

Southeast Asia is in the midst of a resurgence of Coronavirus disease 2019 (COVID-19), with alarming outbreaks now consuming serious attention in the region. The first and second waves of the pandemic caused drastic reduction in the availability and use of essential public health services in South Asia. Moreover, lesser degree of vaccination in South Asia can further magnify the likelihood of the virus spiralling in the economies in transition. Urgent action and steadfast leadership are needed to combat this catastrophe. As of May 12, 2021, a total of 1,264,164,553 vaccine doses have been administered (WHO, 2021). The disease induced by this novel virus has been impacting global, ongoing efforts towards achieving United Nations Sustainable Development Goals (UN-SDGs).

Atmospheric transmission via aerosol is reported to be the predominant pathway of the SARS-CoV-2 spread (Van Doremalen et al., 2020). However, latest studies confirmed that SARS-CoV-2 is excreted in faeces (stool) of infected individuals. The presence of SARS-CoV-2 in the stool of infected people was reported worldwide e.g. in the USA, Australia, France, Netherlands, China (Gao et al., 2020; Holshue et al., 2020; Kitajima et al., 2020; Wu et al., 2020; Wurtzer et al., 2020; Xiao et al., 2020). Studies indicate that 48% (Cheung et al., 2020) to 53% (Xiao et al., 2020) of the infected individuals were tested positive for SARS-CoV-2 RNA in stool. About 23% of patients continued to show positive results in stool samples despite showing negative results in their respiratory samples (Xiao et al., 2020), and only 18% exhibited gastrointestinal symptoms (Cheung et al., 2020). Post negative respiratory swabs, the duration for viral shedding in faeces were observed to range from 7 days (Chen et al., 2020), to 10 (Cheung et al., 2020), 20 days (Xing et al., 2020), up to 33 days (Wu et al., 2020). Other researchers demonstrated 18–31% asymptomatic infection of COVID-19 (Mizumoto et al., 2020; Nishiura et al., 2020; Treibel et al., 2020).

The rising circulation of SARS-CoV-2 in communities increases the viral load in the sewer systems, and thus, increases the viral concentration in sewer water. Subsequently, the potential transmission of SARS-CoV-2 by faecal-oral route has gained attention of scientists (Gormley et al., 2020; Yuen et al., 2020), mostly from the perspective of the possibility for application of wastewater-based epidemiology (WBE) approach for monitoring of the spread of COVID-19 among the population. WBE is an effective way to provide inexpensive, real-time and large-scale monitoring of community wastewater, to understand the infectious disease and resistance spread, and to examine the emergence of new disease outbreak at the community level (Sims and Kasprzyk-Hordern, 2020). In term of SARS-CoV-2, several research groups have reported detection of this novel coronavirus in wastewater in the USA, Australia, Japan, France, Italy, Spain and the Netherlands (Ahmed et al., 2020; Haramoto et al., 2020; La Rosa et al., 2020; Medema et al., 2020; Randazzo et al., 2020; Wu et al., 2020; Wurtzer et al., 2020). The pattern of COVID-19 outbreak in Paris (France) was reflected in the sewage samples collected in the region (Wurtzer et al., 2020). In Spain, in the Region of Murcia, the presence of SARS-CoV-2 in the wastewater was observed before the first cases were reported by local or national authorities, highlighting the relevance of WBE as an early warning indicator of the circulation of SARS-CoV-2 within the served population (Randazzo et al., 2020). In southern India, the first surveillance of SARS-CoV-2 and organic tracers (OTs) in community wastewater was conducted during partial and post lockdown phases (August–September 2020) in Chennai city, Tamil Nadu (Chakraborty et al., 2021a).

In this context, it may be underlined that WBE approach is especially important in developing countries of South Asia, wherein passive forms of surveillance have disadvantages that led to underestimation of real risks related to the pandemic. One of such vulnerable regions is the Indus-Ganga-Brahmaputra River Basin (IGBRB), wherein about 300 million people live. About 60% and 48.2% of the people have no access to improved sanitation in the Ganga-Brahmaputra and Indus River basins, respectively (UNEP, 2008). Release of wastewater from treatment plants and other discharge points directly into the riverine environment occur in the entire stretch of River Ganga (Chakraborty et al., 2021b). In addition, this region is subject to significant fluctuations in the amount of water due to cyclic monsoons. Consequently, the annual floods of IGBRB delta can collect SARS-CoV-2 from untreated sewage outlets and could spread them to larger areas. Hence, it is especially important to track the spread of SARS-CoV-2 during monsoonal shower, through logged water, uncontrolled flow through sewer outlets and wastewater discharge points particularly along the riverine catchment, and in the slums or congested areas of the urban and peri-urban regions in the IGBRB.

In view of the above, and owing to the importance of detecting SARS-CoV-2 not only in symptomatic and asymptomatic patients but also in the municipal wastewater, the aim of our study was to map the COVID-19 hotspots in the IGBRB in relation to the sewer outlets and wastewater discharge points as well, to chart an overall wastewater management strategy in IGBRB countries. Based on our knowledge and available literature, this is the first report oriented towards the distribution of the novel coronavirus, SARS-CoV-2 in the IGBRB (in relation to wastewater discharge hotspots) as either the potential source of the spread of epidemic or a useful tool to monitor and manage the epidemic propagation. Our objective is not to focus
only on SARS-CoV-2, but to make a good basis for future pandemic proofing of this area due to inadequate monitoring and management of wastewater.

2. Materials and Method

2.1. Study Area

The IGBRB is a densely populated, trans-boundary river basin in South Asia. The IGBRB map is presented in Figure 1 with locations of various sewage treatment plants (STPs) and wastewater treatment plants (WWTPs) along the entire basin. The IGBRB covers an area of 1.12 million km² supporting 300 million people in Pakistan (47%), India (39%), China (8%), and Afghanistan (6%). The Brahmaputra River Basin consists of the rivers Ganga and Brahmaputra, and flows through parts of India, Tibet, Bhutan, Nepal, and Bangladesh. The Ganga forms the world's largest river delta and is known for its unique biodiversity and highest population density. The River Ganga bifurcates into two branches: the eastern branch flowing through Bangladesh as River Padma and the western branch flowing through the state of West Bengal in India as the Bhagirathi.

Regarding wastewater management approaches, in India, there are 193 common effluent treatment plants (CETPs) and 920 STPs. Discharge of untreated sewage into rivers is a major pollution source, because out of 38000 million litres daily (MLD) of sewage, only about 12000 MLD is treated, indicating a big gap between wastewater generation and treatment capacity (ENVIS, 2019). In Nepal, the Kathmandu Valley has five WWTPs: an activated sludge plant at Guheshwori (the only functional one), non-aerated lagoons at Kodku and Dhobighat, and aerated lagoons at Sallaghari and Hanumanghat (ADB 2021; Green et al., 2003). In an ongoing project funded by the Asian Development Bank, the wastewater network and treatment facilities in the populous Kathmandu Valley are being modernized, the sewerage network is being rehabilitated, and the wastewater management institutions are being strengthened. Also, the capacity of five WWTPs is being expanded from around 16 MLD to 90.5 MLD (ADB, 2021). Decentralized wastewater treatment systems like constructed wetlands are also used to treat wastewater in Nepal (Jha and Bajracharya, 2014). In Pakistan, eight WWTPs (primary) cater to 388 cities, out of which three are in Islamabad (one is functional). Karachi has two trickling filters (for screening and sedimentation), Lahore has screening and grit removal systems (but not functional), and Faisalabad has one WWTP (primary). Wastewater treatment is absent in rural Pakistan leading to surface water and groundwater pollution (Murtaza and Zia, 2012). In Bangladesh, the capital city of Dhaka has only one WWTP with 120,000 m³/day capacity covering 30% of households while the rest use their own septic tanks (Sharmin, 2016). Faridpur has one faecal sludge treatment plant which was commissioned in 2017 (Jahan, 2019).

2.2. Geo-spatial Mapping

The spatial distribution maps of wastewater discharge points, WWTPs and STPs were prepared in GIS platform using ArcGIS software version 10.5. The tabular data on the
wastewater discharge points, WWTPs and STPs was converted to a shape file. The major rivers of the IGBRB were delineated using arc hydro tool of ArcGIS software. The spatial pattern of population of the study area has been mapped with the latest data for the year 2020. The source of data for mapping was taken from the Global High-Resolution Population Denominators project funded by the Bill and Melinda Gates Foundation. The resolution of data was 3 arc seconds (90m). The projection was Geographic Coordinate System, WGS84. The units were number of people per pixel. The mapping approach was Random Forest-based dasymetric redistribution (WorldPop, 2018; Lloyd et al., 2019). The base map was prepared using ESRI world imagery. The COVID-19 hotspots areas have been mapped geospatially for the months of March, April, May, June, July, August 2020 and April 2021. The coordinates for COVID-19 hotspots in India region as of April 2021 is given in Supporting Information (SI) Table S1.

2.3. Data sources

Information, statistics, specific evidences taken from various web-based sources apart from scientific articles, is given in Table S2. Summary of water quality parameters in inlet and outlet of STPs in COVID-19 hotspots regions are given in Table S3-S12.

2.4. Spatial Autocorrelation

Spatial autocorrelation was applied to assess the spatial correlation between variables through matching location similarity and attribute similarity (Hu et al., 2012). Global Moran’s I, an index of spatial autocorrelation based on cross products is mathematically expressed as follows:

\[ I = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} (x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^{n} (x_i - \bar{x})^2} \]

where \( n \) is the number of regions; \( x_i \) the attribute value at area \( i \); \( \bar{x} \) the mean value of the attribute in the study region; and \( w_{ij} \) elements of a spatial lag operator \( W \) (spatial weights of matrix \( W \)). The significance of the index is usually tested in a situation of normal distribution (Mazzulla et al., 2012). Global Moran’s \( I \) varies between -1 and 1 with a positive value meaning that a point in question is prone to be clustered by adjacent points, while a negative value means the opposite. Values close to 0 indicate that the data are randomly distributed.

4. Results & Discussion

3.1. SARS-CoV-2 in wastewater

The extended time of incubation and shedding of SARS-CoV-2 from asymptomatic individuals have been observed to be the two main influential parameters for the pandemic spread. Based on the computer simulation of wastewater from Wuhan (China), Milan (Italy), Madrid (Spain), Tehran (Iran), and the US cities such as New York, Seattle, Detroit, Tempe, and New Orleans, Hart and Halden (2020) revealed that, depending on local conditions, one symptomatic/asymptomatic infected individual can be detected per 100 to 2,000,000 non-infected persons. Based on the obtained results, the authors identified WBE as a potential tool for assessing and managing the novel coronavirus pandemic, which needs to be followed by clinical testing. They predicted that to monitor approximately 30% of the world’s population in terms of coronavirus spread, wastewater from 105,600 STPs need to be tested.

Unlike SARS-CoV-2, most infectious viruses are transmitted through waterborne routes. Studies indicate that the waterborne route of infection is relevant for Hepatitis E virus (HEV), a positive-sense, and single-stranded RNA virus that cause infection in pregnant women and in children with high mortality. The HEV was detected in untreated wastewater and river water (Kamar et al., 2014). Molecular analysis also revealed the prevalence of enterovirus and Hepatitis A virus in sewage polluted river water and in drinking water of the three main cities of Pakistan (Lahore, Islamabad and Rawalpindi) (Ahmad et al., 2018). Another example of water transmitted virus is norovirus - a causal agent of several outbreaks in many countries (Tryfinopoulou et al., 2019; Hellmér et al., 2014). Wastewater samples obtained 2 to 3 weeks prior to the actual human infection showed an increased amount of norovirus GII (Genogroup II). Two surrogate coronaviruses (transmissible gastroenteritis -TGEV and mouse hepatitis - MHV) were found to remain infectious for days to weeks in water and pasteurized settled sewage (Gundy et al., 2008; Casanova et al., 2009). During the first wave of COVID-19 pandemic, a study by Wurzner et al (2020) demonstrated the presence of SARS-CoV-2 in the wastewater of Paris. The authors demonstrated the time-course of viral load in wastewater with an average 2-log increase of genome units that was reflected in the peak in the number of new cases.

In western India, presence of three genes specific for SARS-CoV-2 (ORF1ab, Nucleocapsid (N) and Spike (S)) have been reported during the earlier phase after the outbreak of pandemic in the wastewater from WWTP of Ahmedabad city, Gujarat (Kumar et al., 2020). The number of gene copies increased ten-fold between 8 and 27 May 2020 (i.e. 0.78 \( \times \) 10^2 copies L^{-1} and 8.05 \( \times \) 10 copies L^{-1}, respectively), which corresponded to more than the doubling in the number of active COVID-19 cases in Ahmedabad city (i.e. 4912 and 10674 individuals on 8 and 27 May, respectively). Number of gene copies in this study were found comparable to that reported in the untreated wastewaters of Australia, China, and Turkey and lower than that of the USA, France, and Spain. A similar study was conducted in hospital wastewater samples as well as from WWTPs of Jaipur (Rajasthan), which has been a pandemic hotspot (red zone) since April 2020 (Arora et al., 2020). In this study, authors further reported that the presence of SARS-CoV-2 viral genome, correlated with the increased number of reported COVID-19 positive patients. This study reported the presence of SARS-CoV-2 viral genome in wastewater at higher ambient temperature of above 40°C. In southern India, the first surveillance of SARS-CoV-2 and organic tracers (OTs) in community wastewater showed that caffeine can act as a potential indicator for removal of SARS-CoV-2 in STPs, and as an effective marker to understand the efficacy of the STPs (Chakraborty et al., 2021a).
Untreated sewage containing SARS-CoV-2 excreted from symptomatic and asymptomatic individuals can end up in a catchment (Sinclair et al., 2008; Xagoraraki and O’Brien, 2020). In Pakistan, about 27% of wastewater samples collected from the drainage of COVID-19 patient quarantine centre in 13 districts, showed the presence of SARS-CoV-2 by RT-PCR (Sharif 2020). Similarly, sequencing data revealed the presence of partial ORF-1a of SARS-CoV-2 in the same wastewater from the above-mentioned COVID-19 quarantine centres (Sharif, 2020). Infected individuals may continue to shed SARS-CoV-2 through the faecal matter (Hindson, 2020). With this in mind, the informations associated with wastewater direct discharge points or sewage outlets need to be observed and studied in the wider perspective.

3.2. COVID-19 pandemic vs. wastewater management in the IGBRB

In the IGBRB countries (India, Nepal, Pakistan and Bangladesh), there are 27354433 people with confirmed cases of the novel coronavirus and 315732 deaths as on date 18 May 2021, with the most in India followed by Pakistan, Bangladesh, and Nepal. As of May 2021, a total of 190,742,964 vaccine doses have been administered in the four IGBRB countries. India has administered the highest number of vaccine doses followed by Bangladesh, Pakistan, and Nepal (WHO, 2021). In terms of testing, India conducted the maximum number of viral detection tests in the IGBRB followed by Pakistan, Bangladesh, and Nepal. The number of people who were tested positive or the “positive rate” is a very important metric for understanding the pandemic. In the IGBRB region, as of May 2021, the highest positive rate was found in Nepal (44%) followed by India (19%), Bangladesh (8.7%) and Pakistan (7.5%). However, in a country as vast and densely populated as India, many infected people have been reported to go undetected. Reports suggest that the actual numbers may be much higher due to inadequate testing or vaccination, and many unreported cases in the countries. In the IGBRB region, a large number of SARS-CoV-2 patients are asymptomatic (with no symptoms) and oligosymptomatic (with few/minor symptoms), most of whom are not clinically tested and hence contribute to an inaccurate estimation of the disease burden of COVID-19 (Bhattacharya et al., 2021; Jahan et al., 2020). Additionally, the wastewater treatment capacity of these four countries are also very dismal with 8% in Pakistan (Murtaza and Zia, 2012), 5% in Nepal, 17% in Bangladesh, and 33% in India. Moreover, open defecation contributes to water pollution along the river banks in the IGBRB region, due to which the situation worsens during monsoons. At the same time, settlements along the IGBRB extensively use the river water as the freshwater source for various purposes like irrigation, consumption, and other domestic needs, mostly without any prior treatment. Consequently, wastewater monitoring to track the spread of SARS-CoV-2 through logged water and uncontrolled flow through sewer outlets and wastewater discharge points along the riverine catchment (including slum areas) of IGBRB is, at the same time, an opportunity and a big challenge.

Wastewater surveillance not just facilitates the early prevention of the viral spread but can also help to identify areas where current vaccination efforts are inadequate. There are several barriers to COVID-19 vaccination at present. Wastewater surveillance may reveal the anthropogeography of unvaccinated communities and help in informed decision making, in terms of facilitating interventions like enhancing public awareness, generating resources, or creating convenient vaccination access points. This can speed up the process of achieving mass vaccination goals to attain herd immunity.

The surveillance study of SARS-CoV-2 of community wastewater in Chennai (Chakraborty et al., 2021a) offered some interesting insights on the importance of wastewater monitoring. The predicted estimated number of COVID-19 cases from the study was found to be in line with the available clinical data from the catchments. For instance, during the post lockdown phase, the estimated number of infected persons found for a given catchment was in line with the number of actual active COVID-19 cases. Further, the study highlighted that the number of infected persons were higher in the densely populated regions especially where sanitation conditions were poor. Such studies have indicated that wastewater monitoring is an effective tool to monitor and manage the spread of pandemic. Such wastewater surveillance initiatives can go a long way in controlling the pandemic in the vast and densely populated IGBRB region.

3.3. Geo-spatial mapping of pandemic hotspots in the IGBRB

Genetic material can be detected in both viable (“infec-

tious”) and non-viable or inactivated (“killed”) viruses, so its detection does not mean the individual is necessarily infected or that the faeces are infectious. Although SARS-CoV-2 genetic material has been detected in untreated wastewater (Ahmed et al., 2020; Medema et al., 2020; Wu et al., 2020), there are no reports of the detection or persistence of viable, infectious SARS-CoV-2 in the treated wastewater.

The COVID-19 hotspots areas in the IGBRB have been mapped geospatially from March to August 2020 during the first wave and April 2021 after the hit of the second wave of the pandemic (Figure 2). Monthly mapping of COVID-19 hotspots in the IGBRB showed maximum spread in the highly populated regions from June 2020 onwards with the maximum spread in August 2020 after the post lockdown during the first wave (Figure 2), mainly along the Indus and Ganga River Basins. In the Indus River Basin (Pakistan), the number of COVID-19 cases had spiked in June 2020, followed by the flattening of the curve in August/September 2020, and then spiked again in April 2021. Figure 3 shows the increasing number of COVID-19 hotspots in the IGBRB during 2021 after the hit of second wave of pandemic. The incidence of COVID-19 in the 216 administrative regions around the basin is illustrated in Figure 4 depicting the situation as on 30th April 2021 (Table S13). In the Ganga River Basin (India), the number of COVID-19 cases spiked dramatically in September 2020 and again during the gigantic second wave during April/May 2021. During the second wave, about 216
districts, geospatially spread around the basin has been severely affected. Overall, there is an exponential growth of COVID-19 cases in hotspot regions (during lockdown/post-lockdown phases and beyond) from March 2020 to August 2020 in the IGBRB (Figure S1). Figure S2 shows the STPs located in the COVID-19 hotspot regions along the Ganga River.

The spatial correlations of COVID-19 epidemics between the 216 administrative regions for COVID-19 according to Global Moran's I calculations is given in Figure S3. Moran's I and the z-score were 0.0833 (p=0.00002 < 0.05), 4.229312, respectively, indicating that the pattern expressed is randomly distributed.

**Indus River Basin:** The Indus River system and its tributaries (the Jhelum, the Chenab, the Ravi, the Sutlej, the Beas, and the Kabul rivers) act as the main source of freshwater for the population of Pakistan (Sohail et al., 2014). Local areas along the Indus river bank are facing water challenges due to poor sanitation system. In slum areas, almost everyone is dependent on public toilets which are poorly maintained. Only a few cities along the river bank have treatment plants but these treatment plants are inappropriately located and receive little or no sewage. Indiscriminate discharges of wastewater from seven identified discharge points (Himmat, Kokaar, Thoyal Faazal, Shami Road, Army Camp, Ghafar Tee, and Darya Khan) have been observed to pose a major challenge. The sewage drains at Shami Road are considered as major point sources of pollution in D.I. Khan, southern region of Khyber Pakhtunkhwa, Pakistan. Southeast of the Indus River, muddy water ac-
cumulates in agricultural fields. There are 22 wastewater discharge locations along the banks of River Indus. A total of 20 districts of Pakistan, which belong to the hotspot zone lies at par with these wastewater discharge locations (Figure 1).

**Ganga River Basin:** According to an assessment by the Central Pollution Control Board, the main source of pollution in River Ganga is untreated domestic sewage contributing to approximately three-fourth of discharged wastewater followed by industrial effluents. Furthermore, along the main stem of the river, there are 30 million toilets with tanks of mostly inadequate faecal sludge disposal and management systems. There are 32 STPs along the banks of River Ganga (Figure S2). The Ganga River basin generates around 12,000 MLD of sewage with a treatment capacity of 4,000 MLD. In India, cities and towns are divided based on population densities: class I cities have the highest population density including all the metropolitan cities followed by class II or ‘developing’ cities with a rapid growth rate in industrial and allied sectors. A total of 36 class I cities and 14 class II cities discharge their wastewater directly into River Ganga, 113 class I cities and 18 class II cities discharge the wastewater into its tributaries, while 30 class I cities and 115 class II cities have land disposal. The 179 class I and 147 class II cities generate about 11000 MLD and 1000 MLD of wastewater, respectively (NMCG, 2020).

A rapid growth of COVID-19 cases was observed in hotspot regions from March to August 2020, as illustrated in Figure 2. About 75% of the COVID-19 hotspot regions are on the river bank. There are 138 drains discharging 6087 MLD of wastewater into River Ganga with 14 drains in Uttarakhand (440 MLD), 45 drains in Uttar Pradesh (3289 MLD), 25 drains in Bihar (579 MLD) and 54 in West Bengal (1779 MLD) discharging industrial and domestic wastewater directly or indirectly to the river. In most cases, in absence of sewerage systems, drains are turned into open sewers to carry storm water and sewage into the Ganga River basin. About 50% of the COVID-19 cases in the hotspots are reported from the embankment of River Ganga. Haridwar district has 122 slums out of which 23 are from Roorkee. It was noticed that the slum regions of Roorkee remained under the hotspot category throughout the pandemic months. Times of India (TOI, 2019) reported that despite Haridwar being declared as an open-defecation-free district, the slum colonies near Har Ki Pauri defecate in the open along the banks of River Ganga. This area also was among the COVID-19 hotspots during March to May 2020 (Figure 2a-2c). A slum located on the riverbed of Rispana in Dehradun falls in the COVID-19 hotspot region. Rajapurwaslum of Kanpur district located along the bank of Ganga also belongs to vulnerable zone as far as COVID-19 is concerned. Slum areas of Rajendra Nagar area, Ramakrishna Nagar, Kankarbagh, Boring Road, Nala Road, Gandhi Maidan are among the COVID-19 hotspots locales of Patna district during March to August 2020. In West Bengal, the main source of pollution of River Ganga is from four districts (Hooghly, Howrah, North 24 Parganas and Kolkata). Several non-functional STPs have been previously identified in these districts and were responsible for the

![Figure 3. Geo-spatial mapping of COVID-19 spread along the Indus-Ganga-Brahmaputra River Basin for the month of April 2021 after the hit of second wave of pandemic](image)

*P. Chakraborty et al. Ecolhydrology & Hydrobiology 22 (2022) 283–294*
release of various organic micropollutants into the river (Chakraborty et al., 2019). The North 24 Parganas district has emerged as a COVID-19 hotspot recording a greater number of deaths. Around 10 STPs are spatially distributed in North 24 Parganas district. In Hooghly district, death toll was high, and it remains a vulnerable region. A particular slum in Howrah district has accounted for numerous COVID-19 cases and the area has been marked as a COVID-19 risk zone. The slum areas are highly vulnerable to COVID-19. The open defecation-free report by National Family Health Survey (NFHS, 2015), revealed that the sanitation facilities were not up to the mark in the cities along the bank of River Ganga in the states of Uttar Pradesh, Bihar and West Bengal.

According to a recent report by the Central Pollution Control Board (CPCB, 2020), there has been no improvement in water quality of River Ganga during the lockdown period. The water quality showed reduced compliance to the criteria limits from 64.6% to 46.2%, which may be attributed to factors such as discharge of untreated or partially treated sewage, higher concentrations of pollutants due to negligible dry season flow, and lack of freshwater discharges from upstream.

**Brahmaputra River Basin:** The key environmental issues of River Brahmaputra in Assam (India) are oil pollution, lack of STPs and disposal of waste directly into the river. The town of Dibrugarh (Assam, India) generates about 75 to 80 metric tons of garbage every day, much of which ends up into the river. During monsoon, garbage flows into River Brahmaputra. India has planned to dredge the Brahmaputra to prevent high flows from inundating its banks, which result in floods.

With an estimated population of about 1.7 million, Guwahati, the biggest city of Assam is one of the smart cities under the Indian government’s Smart Cities Mission, neither has sewerage (network of pipelines to carry sewage), nor any municipal STP to treat the wastewater. About 39 drains empty into Bahini-Bharalu River, of which 17 are major drains. The sewage generation is expected to increase to around 280 MLD by 2025. Presently, there is no sewerage system in Guwahati city. Untreated or semi-treated sewage is disposed of into the storm water drains, which again ends up into River Brahmaputra.

There are eight WWTPs along the border line of River Brahmaputra. All the COVID-19 hotspots in this region surround these WWTPs. Although no death case has been reported in the region, the number of confirmed cases stands high in Dhubri district located along the bank of Brahmaputra. Kamrup Metro district in Assam is witnessing an alarming spike in COVID-19 spread with the highest death toll in Assam being reported from this district. The area remained to be a COVID-19 hotspot zone all throughout during the period.
the months of March to July 2020 (Figure 2a-e). According to the CPCB, an overall improvement in water quality was observed in Brahmaputra River basin during lockdown period for the criteria parameters (DO, BOD and FC) and it showed 100% compliance for all monitored locations for outdoor bathing criteria parameters (CPCB, 2020).

3.4. Sanitation, Health and Hygiene in the IGBRB in light of the COVID-19 pandemic

Globally, around 2.2 billion people lack safe drinking water, 4.2 billion people live without access to adequate sanitation, and 3 billion people lack basic handwashing facilities at home, according to the Joint Monitoring Programme (JMP) report (JMP, 2019). The practice of frequent hand washing has been suggested for breaking human transmissibility of SARS-CoV-2. However, a large number of people out of the 3 billion lacking handwashing facilities, live in South Asia and sub-Saharan Africa (whose population together accounts for 85% of the world’s poor) (WSSCC, 2020). Nearly 40% households, 50% schools (900 million children) and 40% healthcare facilities worldwide do not have access to soap and water which are the basic hand-hygiene services needed during the COVID-19 crisis (JMP, 2019). According to the World Health Organization and United Nations Children’s Fund (WHO/UNICEF) Joint Monitoring Programme for Water Supply, Sanitation and Hygiene (JMP), in 2020, the national population with basic hygiene facilities (with availability of handwashing facility with soap and water at home) in IGBRB countries were: 68% in India (60% urban and 82% rural), 62% in Nepal (59% urban and 75% rural), 58% in Bangladesh (54% urban and 66% rural), and 80% in Pakistan (74% urban and 90% rural). Between 2015 and 2020, the proportion of the global population with basic handwashing facilities (with soap and water at home) increased from 67% to 71%. However, in 2020, 2.3 billion people still lacked basic hygiene, and 670 million lacked any form of handwashing facility (JMP, 2021).

The hygiene scenario in the four IGBRB countries (Bangladesh, India, Nepal and Pakistan), in terms of availability and access to handwashing facilities, have been presented in Figure S4. The risks posed to those living in urban slums is higher compared to others, considering their workplace exposure, lack of access to running water for handwashing, inability to maintain social distancing and isolation while living in cramped habitations. Such social inequalities expose the vulnerabilities of the urban poor in terms of the burden, risks and access to Water, Sanitation, and Hygiene (WASH) needs (Figure S5). As expected, the richest quintile of population has better access to drinking water, sanitation, and hygiene. However, the inequity in access to drinking water between the richest and the poorest is lesser compared to sanitation and hygiene. There have been no reports yet of faeco–oral transmission of the SARS-CoV-2 (WHO, 2020). It could, however, remain infectious in water contaminated with faeces for days to weeks. Safely managed WASH services are also critical during the recovery phase of a disease outbreak to mitigate secondary impacts on community health, livelihood, and wellbeing.

The COVID-19 situation in the IGBRB countries (ECDC, 2020) is depicted in Figures S6 and S7. In Pakistan, the highest number of deaths was reported in the month of June 2020. The month of August 2020 recorded the highest death toll as far as India is concerned. A total of 96,351 deaths have been reported during mid last year in India, 6482 in Pakistan, 481 in Nepal and 5193 in Bangladesh. However, there is a need to use the data with caution due to different inclusion criteria and variability in underestimation and delays by various organizations. COVID-19 pandemic reiterates the need for improvement of WASH infrastructure in the low-economic settlements in the densely populated South Asian countries.

5. Challenges for the UN SDGs for the COVID-19 pandemic in the IGBRB– the water-sanitation-health nexus

The United Nations Sustainable Development Goals have been introduced to call for action by all countries – poor, rich and middle-income – to promote prosperity while protecting the planet. The SDGs through addressing the global challenges constitute a proposal to achieve a better and more sustainable future for all before 2030. At the same time, the outbreak of the COVID-19 pandemic has posed a significant threat to the healthy lives and well-being of billions of people worldwide, especially in highly vulnerable developing countries (Ahmed et al., 2020, Sumner et al., 2020). From the perspective of water-sanitation-health nexus, the current COVID-19 pandemic in the IGBRB influences mostly the following SDGs: GOAL 3: Good Health and Well-being; GOAL 6: Clean Water and Sanitation; GOAL 10: Reduced inequalities; GOAL 11: Sustainable Cities and Communities.

The progress of Goal 3 (Good Health and Well-Being) has been hindered by COVID-19 as it poses a global health risk and has shown the critical need for preparedness. In the face of COVID-19 pandemic, the developing countries, such as those located in the IGBRB, struggle with far greater problems than developed countries. During pandemic, the limited availability of medical services in the IGBRB countries seriously affects the health of citizens and may lead to significant delay in achieving the SDG 3 in that area. Therefore, the wastewater surveillance for early detection of SARS-CoV-2 and maintenance of WASH infrastructure, especially mobile hand washing and sanitation facilities as provided by some governments of IGBRB during the current pandemic, are crucial to achieve and maintain good health and well-being for the people of the region.

The importance of sanitation, hygiene, and adequate access to clean water (Goal 6: Clean Water & Sanitation) is crucial in fighting with diseases including COVID-19 pandemic. WHO indicates handwashing as one of the most effective actions to reduce the spread of pathogens and viruses, including the SARS-CoV-2 virus, and in this way, minimize spread of the disease. At the same time, worldwide, one in three people do not have access to safe drinking water, two out of five people do not have a basic hand-washing facility with soap and water (United Nations 2020). In the IGBRB, the wastewater treatment capacity ranged from 5% in Nepal to 33% in India. Only
about 50% and 40% of people in the Indus and Ganga-Brahmapura-Meghna Basins, respectively have access to improved sanitation facilities (UNEP, 2008), indicating the need for further investments, but also demonstrating the risk for development and spread of diseases, including COVID-19, among people living there. The implementation of wastewater monitoring could provide a decision platform for countries to adjust their WASH services to prevent the spread of SARS-CoV-2. This would include continued support to affected, high-risk, and vulnerable communities to secure WASH services and infection control. The results of wastewater surveillance can help governments in mobilizing resources and implementing innovative and context-appropriate solutions to take timely decisions. Such wastewater surveillance efforts would not only control the spread of SARS-CoV-2, but will prevent other “true” waterborne pathogens, including bacteria and viruses causing severe gastrointestinal diseases (e.g. Shigella, Salmonella, Vibrio, Norovirus).

Also, achieving the SDG Goal 10 (Reduced inequalities) has been seriously hindered by the COVID-19. As far as inequality within and among countries is a persistent cause for concern for the UN, the COVID-19 has deepened existing inequalities, hitting the poorest and most vulnerable communities the hardest. SARS-CoV-2 does not discriminate, but its impacts have exposed deep weaknesses in the delivery of public services and structural inequalities that impede access to them (United Nations 2020). Thus, deepening the economic and societal inequities among 300 million people living in the IGBRB inhabitants will constitute another challenge for sustainable development in the post-pandemic world.

In term of Goal 11 (Sustainable Cities and Communities), it may be underlined that by 2030, about 60% of the global population will live in the cities and 95% of urban expansion will take place in developing countries. Such rapid urbanization results in a growing number of slum inhabitants, inadequate and overburdened infrastructure, and services, including waste collection and water and sewage systems. The effects of COVID-19 are most devastating in poor and densely populated urban areas, especially for the 883 million people that live in slums today (most of them are found in Eastern and South-Eastern Asia), where overpopulation hampers not only social distancing and self-isolation but also reduced the access to clean water and sanitation, endangering public health (United Nations 2020).

It needs to be highlighted that the actual impacts of COVID-19 on SDG achievement will be known in the future. However, as some countries are moving towards recovery, coherent actions can put them on a strong trajectory towards achieving many of these SDGs. In July 2020, in order to continue achieving the targets of SDGs in the time of COVID-19 pandemic, the United Nations developed the SDG 6 Global Acceleration Framework outlining a better coordinated support to countries to ensure global sustainable management of water and sanitation for all. Building upon this insight, the strategic idea suggested in the following section can contribute during the response and recovery and set a course for achieving the SDGs.

6. Urgent need for wastewater surveillance

The spread of SARS-CoV-2 in highly populated countries in South Asia can be curbed only through continuous surveillance to arrest hotspots. WBE can be very effective tool in arresting the “further waves” of the pandemic by way of detecting the coronavirus in sewage long before manifestations of reinfection are witnessed in the community. Identification of potential chemical and biological markers present in faeces and urine of infected individuals that are released in the wastewater could provide an efficient and prompt way to predict the efficacy of STPs in removal of SARS-CoV-2. At this point, wastewater treatment using various approaches are analysed and optimized, but chlorination, ultraviolet (UV) radiation light and ozone treatment of water are the most promising ones.

The increasing number of COVID-19 cases during the post lockdown phase emphasizes the fact that there is a need to understand the situation in a catchment to prevent other waves of pandemic. WBE is a cost-effective tool to manage the spread of coronavirus pandemic.

Although we are still not close to finding a fast remedy for COVID-19, it can be pragmatic to make a significant contribution, which will offer key benefits in areas of critical importance for people and the environment. By establishing a system for monitoring of SARS-CoV-2 in the sewage and wastewater treatment plants or discharge points in the Indus-Ganga-Brahmaputra River Basin, we will get closer towards the path of fulfilling SDGs. This could be of tremendous importance for South Asia, as it may lead to positive impacts on the water-sanitation-health nexus. Further, the results of the study are applicable to monitor the spread of other pathogenic microorganisms including antibiotic-resistant bacteria and related diseases and epidemics that may be a potential threat to human health in the future.

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.

Acknowledgement

PC and GB would like to acknowledge the support of the Swiss Confederation acting through the Federal Department of Foreign Affairs (FDFA), acting through the Swiss Agency for Development and Cooperation (SDC), Swiss Cooperation Office India, Embassy of Switzerland, Nyaya Marg, Chanakyapuri, New Delhi (Proposal no. 7F-09271.04.01). VPB was supported by the Ministry of Education, Science and Technological Development of Republic of Serbia (Contract number: 451-03-68/2020-14/200168).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ecohyd.2021.11.001.
References

Ahmad, T., Adnan, F., Nadeem, M., Kakar, S.J., Anjum, S., Saad, A., Waheed, A., Arshad, N. 2018. Assessment of the risk for human health of Enterovirus and Hepatitis A virus in clinical and water sources from three metropolitan cities of Pakistan. Annals of Agricultural and Environmental Medicine 25, 708–713.

Ahmed, W., Angel, N., Edson, J., Bibby, K., Bivins, A., O’Brien, J.W., Choi, P.M., Kitajima, M., Simpson, S.L., Li, J. 2020. First confirmed detection of SARS-CoV-2 in untreated wastewater in Australia: A proof of concept for the wastewater surveillance of COVID-19 in the community. Science of The Total Environment, 138764.

Arora, S., Nag, A., Sethi, J., Rajvanshi, J., Saxena, S., Shrivastava, S.K., Gupta, A.B. 2020. Sewage surveillance for the presence of SARS-CoV-2 genome as a useful wastewater based epidemiology (WBE) tracking tool in India. medRxiv.

Asian Development Bank (ADB). 2021. Nepal: Kathmandu Valley Wastewater Management Project. Sovereign Project 43524-01A. Accessed on 6th October 2021; Available at: https://www.adb.org/projects/43524-014/main

Bhattacharya, P., Kumar, M., Islam, M.T., et al. 2021. Prevalence of SARS-CoV-2 in Committed Wastewater Through Wastewater Surveillance—A Potential Approach for Estimation of Disease Burden. Current Pollution Reports 7, 160–166. doi:10.1007/s40726-021-00178-4.

Casanova, L., Rutala, W.A., Weber, D.J., Sobsey, M.D. 2009. Survival of surrogates coronaviruses in water. Water Research 43, 1893–1908.

Chakraborty, Paromito, Mukhopadhyay, S., Moitrajee, Satmita, Srimurali, Ramaswamy, Babu Rajendran, Katsiyannis, Athanasios, Cincinelli, Alessandra, Snow, Daniel, et al. 2019. Organic micropollutants in the surface riverine sediment along the lower stretch of the transboundary river Ganga: Occurrences, sources and ecological risk assessment. Environmental Pollution 249, 1071–1080. doi:10.1016/j.envpol.2018.10.115.

Chakraborty, P., Pasupuleti, M., Shankar, M.J., Bhartik, K.G., Krishnasaamy, S., Dasgupta, S.C., Sarkar, S., Jones, K.C., 2021a. First surveillance of SARS-CoV-2 and organic tracers in community wastewater during post lockdown in Chennai, South India: Methods, occurrence and concurrence. Sci Total Environ. 778, 146225.

Chakraborty, P., Shappell, N.W., Mukhopadhyay, M., Onanong, S., Rex, K.R., Snow, D., 2021b. Surveillance of plasticizers, bisphenol A, steroids and caffeine in surface water of River Ganga and Sundarbhan wetland along the Bay of Bengal: occurrence, sources, estrogenicity screening and ecotoxicological risk assessment. Water Research 190, 116668.

Chen, Y., Chen, L., Deng, Q., Zhang, G., Wu, K., Ni, L., Yang, Y., Liu, B., Wang, W., Wei, C. 2020. The presence of SARS-CoV-2 RNA in the feces of COVID-19 patients. Journal of Medical Virology.

Cheung, K.S., Hung, I.F., Chan, P.P., Lung, K., Tso, E., Liu, R., Ng, Y., Chu, M.Y., Chung, T.W., Tam, A.R., 2020. Gastrointestinal manifestations of SARS-CoV-2 infection and virus load in fecal samples from the Hong Kong cohort and systematic review and meta-analysis. Gastroenterology.

ENVS, 2019: Centre for Environmental Forensics, Sanitation, Sewage Treatment Systems and Technology; Accessed on: 6th October 2021; Available at: http://www.sulabhenvis.nic.in/database/stdt_wastewater_2090.aspx.

CPCB, 2020. Central Pollution Control Board 2020: A report on the impact on lockdown on water quality of River Ganga; Available at: https://www.cpcb.nic.in/watersurvey/2020/pdf/133597.pdf?fbclid=IwAR312ztoEueyFwX2y8yOTNwM4uZ3x03DjUWq9Z2WRyXh38b3NvMyT3D8yGcRMsJ35Dhc=<url>http://www.cpcb.nic.inendirudda/fileupload/11_Environment%20Analysis%20and%20Management%20Framework%20Annexure%201%20Baseline%2020%20202.pdf</url>.

MacManus, G., Hejnen, L., Elsinga, G., Iuliander, R., Brouwer, A., 2020. Presence of SARS-CoV-2 in sewage. MedRxiv.

Mizumoto, K., Kagaya, K., Zarebski, A., Chowell, G. 2020. Estimating the asymptomatic proportion of coronavirus disease 2019 (COVID-19) cases on board the Diamond Princess cruise ship, Yokohama, Japan. 2020. Eurosurveillance 25, 2000180.

Muzzalla, G., Forciniti, C. 2012. Spatial association techniques for analysing trio distributions in an urban area. European Transport Research Review 4, 217–233 2012.

Medema, G., Hejnen, L., Elsinga, G., Iuliander, R., Brouwer, A., 2020. Presence of SARS-CoV-2 in sewage. MedRxiv.

Mizumoto, K., Kagaya, K., Zarebski, A., Chowell, G. 2020. Estimating the asymptomatic proportion of coronavirus disease 2019 (COVID-19) cases on board the Diamond Princess cruise ship, Yokohama, Japan. 2020. Eurosurveillance 25, 2000180.

Murtaza, G., Zia, M.H. 2012. Wastewater production, treatment and use in Pakistan. Second regional workshop of the project Safe use of wastewater in agriculture and health.

NFHS, 2015. National Family Health Survey, Available at: http://chrisplus.org/nfhs/NFHS-4report.shtml; Accessed on 9th July 2020.

National Mission for Clean Ganga (NMCG), Ministry of Jal Shakti Department of Water Resources, River Development & Ganga Rejuvenation, Government of India. 2020. Environmental and Social Management Framework (ESMF) Annex-I - Environmental and Social Baseline. Accessed on: last viewed on October 5, 2021; Available at: https://nmcg.nic.in/writeradda/fileupload/11_Environmental%20Analysis%20and%20Management%20Framework%20Annexure%201%20Baseline%2020%20Ganga%20202.pdf.

Nishiura, H., Kobayashi, T., Suzuki, A., Jung, S., Hayashi, K., Kinoshita, R., Yang, Y., Yuan, B., Akhmetzhanov, A., Linton, N., 2020. Estimating clinical severity of COVID-19 from the transmission dynamics in Wuhan, China. Estimation of the asymptomatic ratio of novel coronavirus infections (COVID-19). International Journal of Infectious Disease.

Ranadze, W., Truchado, P., Cuenas-Ferrando, E., Simón, P., Allende, A., Sánchez, G., 2020. SARS-CoV-2 RNA in wastewater anticipated COVID-19 occurrence in a low prevalence area. Water Research, 115044.

Sharif, S. 2020. Detection of SARS-CoV-2 in wastewater, using the existing environmental surveillance network: An epidemiological gateway to an early warning for COVID-19 in communities.

Sharrin, A., 2016. Water and wastewater in Bangladesh, current status and a design of a decentralized solution.
Sims, N., Kasprzyk-Hordern, B., 2020. Future perspectives of wastewater-based epidemiology: monitoring infectious disease spread and resistance to the community level. Environment International, 105689.

Sinclair, R.G., Choi, C.Y., Riley, M.R., Gerba, C.P., 2008. Pathogen surveillance through monitoring of sewer systems. Advances in Applied Microbiology 65, 249.

Sohail, M.T., Delin, H., Siddiq, A., 2014. Indus Basin Waters A Main Resource of Water in Pakistan: An Analytical Approach. Current World Environment 9, 670.

Sumner, A., Hoy, C., Ortiz-Juarez, E., 2020. Estimates of the Impact of COVID-19 on Global Poverty. WIDER; UNU-WIDER, Helsinki, Finland.

TOI, 2019. Open Defecation continues along Ganga in Haridwar; https://timesofindia.indiatimes.com/city/dehradun/open-defecation-continues-along-ganga-in-haridwar/articleshow/71653289.cms; Accessed on 16th July 2020.

Treibel, T.A., Manisty, C., Burton, M., McKnight, A., Lambourne, J., Augusto, J.B., Couto-Parada, X., Cutino-Moguel, T., Noursadeghi, M., Moon, J.C., 2020. COVID-19: PCR screening of asymptomatic healthcare workers at London hospital. The Lancet 395, 1608–1610.

Tryfinopoulou, K., Kyritsi, M., Mellou, K., Kolokythopoulou, F., Mouchodzą, V., Potamits-Komi, M., Lamprou, A., Georgakopoulou, T., Hadjichristodoulou, C., 2019. Norovirus waterborne outbreak in Chalkidiki, Greece, 2015: detection of GI P2, GI 2 and GI P16, GI 13 unusual strains. Epidemiology & Infection 147.

UNEP, 2008. Freshwater under Threat; South Asia; http://wedocs.unep.org/handle/20.500.11822/7715; Accessed on 16th July 2020.

UnitedNations, 2020. COVID-19: water and sanitation-related information; https://www.unwater.org/covid-19-water-and-sanitation-related-information/; Accessed on 16th July 2020.

Van Doremalen, N., Bushmaker, T., Morris, D.H., Holbrook, M.G., Gamble, A., Williamson, B.N., Tamin, A., Harcourt, J.L., Thornburg, N.J., Gerber, S.I., 2020. Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1. New England Journal of Medicine 382, 1564–1567.

WHO, 2020. https://www.who.int/; Accessed on 16th July 2020.

WorldPop, 2018. https://dx.doi.org/10.5258/SOTON/WP00647; Accessed on 16th July 2020.

WSSCC, 2020. Coronavirus is a hygiene crisis; https://www.wsscc.org/media/resources/coronavirus-hygiene-crisis; Accessed on 22nd July 2020.

Wu, Y., Guo, C., Tang, L., Hong, Z., Zhou, J., Dong, X., Yin, H., Xiao, Q., Tang, Y., Qu, X., 2020. Prolonged presence of SARS-CoV-2 viral RNA in faecal samples. The lancet Gastroenterology & Hepatology 5, 434–435.

Wurtzer, S., Marechal, V., Mouchel, J.-M., Moulin, L., 2020. Time course quantitative detection of SARS-CoV-2 in Parisian wastewaters correlates with COVID-19 confirmed cases. MedRxiv.

Xagoraraki, I., O’Brien, E., 2020. Wastewater-based epidemiology for early detection of viral outbreaks. Women in Water Quality. Springer, pp. 75–97.

Xiao, F., Tang, M., Zheng, X., Liu, Y., Li, X., Shan, H., 2020. Evidence for gastrointestinal infection of SARS-CoV-2. Gastroenterology 158 1831–1833. e1813.

Xing, Y., Ni, W., Wu, Q., Li, W., Li, G., Tong, J., Song, X., Xing, Q., 2020. Prolonged presence of SARS-CoV-2 in feces of pediatric patients during the convalescent phase. medRxiv.

Yuen, K.-S., Ye, Z.-W., Fung, S.-Y., Chan, C.-P., Jin, D.-Y., 2020. SARS-CoV-2 and COVID-19: The most important research questions. Cell & Biology 10, 1–5.