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Urban flooding events pose risks of virus spread during the novel coronavirus (COVID-19) pandemic

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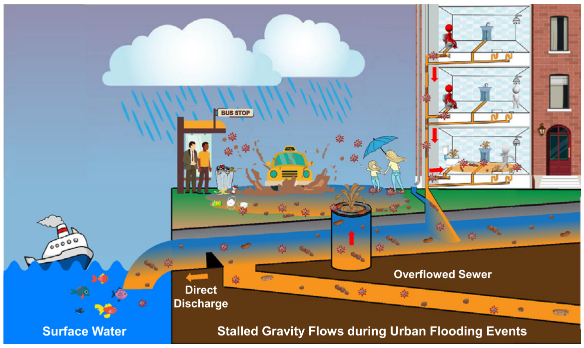
HIGHLIGHTS

- Sewage overflows in urban flooding events pose risk of SARS-CoV-2 virus transmission.
- Communities served by combined sewer systems are particularly prone to such risks.
- Potential shortcut of exposure to overflowed human excreta during flooding events

GRAPHICAL ABSTRACT



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ABSTRACT

Since the first report in December 2019, the novel coronavirus (COVID-19) has spread to most parts of the world, with over 21.5 million people infected and nearly 768,000 deaths to date. Evidence suggests that transmission of the virus is primarily through respiratory droplets and contact routes, and airborne carriers such as atmospheric particulates and aerosols have also been proposed as important vectors for the environmental transmission of COVID-19. Sewage and human excreta have long been recognized as potential routes for transmitting human pathogens. The causative agent of the COVID-19 pandemic, severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), has been detected in human feces and urine, where it could remain viable for days and show infectivity. Urban flooding, a common threat in summer caused by heavy rainfalls, is frequently reported in urban communities along with sewage overflows. With summer already underway and economy re-opening in many parts of the world, urban flooding and the often-accompanied sewage overflows could jeopardize previous mitigation efforts by posing renewed risks of virus spread in affected areas and communities. In this article, we present the up-to-date evidence and discussions on sewage-associated transmission of COVID-19, and highlighted the roles of sewage overflow and sewage-contaminated aerosols in two publicized events of community outbreaks. Further, we collected evidence in real-life environments to demonstrate the shortcuts of exposure to overflowed sewage and non-dispersed human excreta during a local urban flooding event. Given that communities serviced by combined sewer systems are particularly prone to such risks, local municipalities could prioritize wastewater infrastructure upgrades and consider combined sewer separations to minimize the risks of pathogen transmission via sewage overflows during epidemics.

1. Wetter summers

For people living in the Northern Hemisphere, summer is well underway. As part of summer's wonder, heavy rainfalls like thunderstorms

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and drenching downpours become increasingly common. Those bring copious amounts of precipitation, often in the course of few hours in summer. In densely populated urban communities, impervious asphalt and concrete surfaces including roads, pavements, and buildings prevent rainfalls from infiltrating into the ground, and stormwater runoffs can quickly overwhelm the capacity of the urban drainage systems, causing “flash floods”.

Most stormwater infrastructure design codes adopt the “100-year storm events” in sizing urban drainage systems (Wright et al., 2019). But often at times, even those once conservatively sized systems could not cope with the actual events. The increasingly violent weather with intensifying rainfall extremes due to climate change, growing urbanization, and in many places an aging infrastructure with overdued upgrades and maintenance all contribute to this apparent deficiency (ASCE, 2011; Wright et al., 2019). Rainy meteorological summers (June 1 through August 31) with record-ranking precipitations were witnessed across the Northern Hemisphere in the past few years. In particular, January to August 2019 were the wettest eight months on record for the contiguous U.S., with a total precipitation nearly 20% above its historical average (NOAA, 2019).

Global land precipitation monitoring has shown an alerting number of regions receiving record or much higher (>90th percentile) precipitation than their historical averages (NOAA, 2020a). According to the data provided by Global Flood Monitor (de Bruijn et al., 2019), a dedicated site maintained by the Institute for Environmental Studies at University Amsterdam for monitoring global flooding events by analyzing real-time messages on social media, there have been at least 1760 flooding events reported from 1 May 2020 to 10 August 2020 around the globe (Fig. 1). One hundred and nineteen flooding events, including six orange-alert floods (more than 100 dead or 80,000 displaced), have been registered within the same period in the Global Disaster Alert and Coordination System (GDACS), a register for major sudden-onset natural disasters.

In the U.S., incidents of sewage overflows frequently appear in community news headlines, often caused by heavy rainfalls in communities serviced by combined sewer systems (Table 1). The North American country has seen the largest number of COVID-19 infections since 27 March 2020, with over 870,000 active cases on April 30 (Worldometer, 2020) and another 3.9 million cases confirmed between 1 May 2020 and 10 August 2020 (CDC, 2020). More than ten U.S. municipalities reported flooding events during this period, and some reported significant amounts of sewage overflows into public areas (Table 1). In statements issued by local municipalities, most of those incidents were attributed to heavy rainfalls overwhelming their combined sewer systems. Those conveniently designed and often aged systems can be easily overloaded by large stormwater runoffs, causing overflows of untreated or partially treated sewage into habitated areas, as well as water bodies and beaches nearby (Tibbetts, 2005). There are nearly 860 municipalities across the U.S. that still have combined sewer systems (US EPA, 2018). In the event of severe urban flooding, sewages containing untreated human wastes mixed with stormwater runoffs could spread quickly and widely into communities, presenting a nuisance and a threat to public health.

2. A fragile recovery

With all due vigilance, one must keep in mind that those flooding events occurred in the midst of an ongoing, albeit seemingly diminishing, global pandemic. Outbreaks of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) have been reported by countries around the globe since December 2019. Most epicenters of SARS-CoV-2 outbreaks are located in urban areas where there are high population densities and more likelihood of human-to-human transmission. In many urban areas, including the New York city, the largest epicenter emerged in the U.S. so far, numbers are declining (NYC, 2020). People

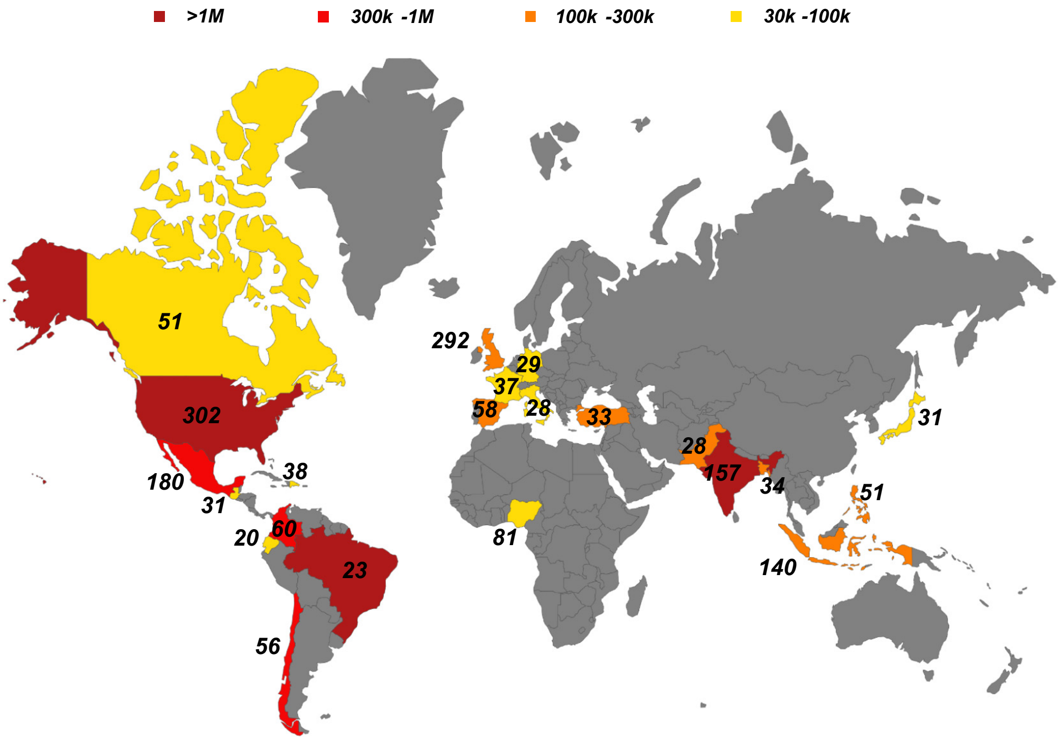

Fig. 1. Flooding events ($n = 1760$) reported around the globe between 1 May 2020 and 10 August 2020. Underlying heat map shows data bands in the cumulative number of confirmed COVID-19 cases within this period. For clarity, only countries reporting over 30,000 new cases and frequent flooding events ($n > 20$) within this period are shown in color in the map. Statistical data on flooding events were provided by Global Flood Monitor, a site maintained by the Institute for Environmental Studies at University of Amsterdam for monitoring global flooding events by analyzing real-time messages on social media (www.globalfloodmonitor.org). Data on cumulative confirmed cases of COVID-19 were provided by Johns Hopkins University Coronavirus Resource Center (coronavirus.jhu.edu/map.html).

Table 1
Precipitation-caused sewage overflows in ten U.S. municipalities between 1 May 2020 and 10 August 2020.

City/state	Date[a]	Precipitation (mm)[b]	Estimated volumes of sewage overflow[c] & affected area size[d]
Chicago, Illinois	May 14–15	114.3 mm (max.) in two days	Several million gallons of human and industrial wastes with runoffs flowed into the city's waterways and Lake Michigan, while flooding the streets and basements at some locations.
Havelock, North Carolina	May 19 & 22	102–127 mm (May 18); 64–76 mm (May 22)	In two separate events, 277,150 gal (ca. 1049 m^3) of untreated sewage overflowed from several manholes on three streets in a school & residential area, and one near a church.
Midland, Michigan	May 19–22	38.0–51.0 mm (max.)	Untreated sewage overflowed from a sewage treatment plant and a chemical manufacturer (volumes unknown) into a creek and a lake nearby, with 10,000 evacuated.
Miami-Dade, Florida	May 25 & 28	152–203 mm (max., on May 25 & 27)	In two separate events, 1.8 million gallons (ca. 6814 m^3) and 10,000 gal (ca. 38 m^3) of sewage spilled from a sewage treatment plant, contaminating a state park and adjacent waters.
Wilmington, North Carolina	June 16	33.5 mm	59,000 gal (ca. 223 m^3) of untreated sewage overflowed from a manhole outside of a sewage pumping station located in a commercial/residential area, and discharged into a creek nearby.
Augusta, Georgia	July 6–7	154 mm (two-day total)	385,625 gal (ca. 1460 m^3) of rainwater mixed with sewage overflowed from several street manholes in commercial/residential areas, and end of the collection system near a park.
Edgewater, Maryland	July 25	83.1 mm	17,000 gal (ca. 64 m^3) of untreated sewage overflowed from a sewer main near a river bank, and spilled to the beach and the river nearby.
Baltimore, Maryland	August 4	54.6 mm[e]	530,000 gal (ca. 2000 m^3) of untreated sewage overflowed from 17 locations (some located in densely populated areas near the city center), and spilled into the city's waterways.
Aberdeen, Maryland	August 4	101.6 mm[e]	178,000 gal (ca. 674 m^3) of untreated sewage overflowed from a cross street in a commercial/residential area, ran a few miles in stormwater drainage ditches, and spilled into a creek.
Orlando, Florida	August 8–9	90.4–123 mm	350,000 gal (ca. 1325 m^3) of untreated sewage overflowed from a pumping station in a park due to power outage caused by thunderstorm and discharged into two nearby lakes.

[a] Based on the local time when sewage overflows occurred. Ranges indicate reoccurring events.
[b] Precipitation data were obtained from public statements issued by local municipalities. When such data were unavailable, quantitative daily precipitation estimates, which were given as bands at half-inch increments by U.S. National Weather Service, were used (https://water.weather.gov/precip/index.php). Precipitation data were converted to metric units.
[c] Most quantities were given as estimates by local municipalities.
[d] Information on surroundings was obtained from Google Maps based on the location of sewage overflows given in public statements.
[e] Rainfalls brought by Tropical Storm Isaias.

are getting back to work, while various mandates are still in place to prevent human-to-human transmission and a possible "second wave" of outbreaks.

The current fragile state of recovery may be easily disrupted by natural disasters such as urban floods or, in the more extreme scenario, hurricanes (NOAA, 2020b). Combined sewer overflows are often inevitable during severe flooding events. This may be exacerbated by the shock loads of wipes, masks, and gloves flushed down the drain or improperly disposed of at roadside during the current pandemic, clogging drainage pipes and sewage pumping stations (Miles, 2020). Although SARS-CoV-2 is primarily transmitted through respiratory droplets and contact routes, infectious SARS-CoV-2 viruses have been found in urine and fecal samples of COVID-19 patients (Jeong et al., 2020; Sun et al., 2020; Xiao et al., 2020; Xu et al., 2020). SARS-CoV-2 viruses could survive for hours to several days in municipal wastewater (Carducci et al., 2020), and have been detected along the wastewater reticulation network (Ahmed et al., 2020) and in both influents and treated effluents of wastewater treatment plants (Haramoto et al., 2020; Randazzo et al., 2020; Rimoldi et al., 2020). While no study has been reported yet confirming the infectivity of SARS-CoV-2 present in municipal sewage, studies have shown the infectivity of SARS-CoV-2 in the urine and feces of COVID-19 patients (Jeong et al., 2020; Sun et al., 2020; Xiao et al., 2020), and postulations have been further made on the infectivity of SARS-CoV-2 in wastewater based on existing evidence on the infectivity of other coronaviruses, including the SARS-CoV-1, in sewage and water (Naddeo and Liu, 2020; Qu et al., 2020; Yeo et al., 2020).

Findings from a recent investigation on a community outbreak of COVID-19 in Guangzhou, China and a "superspreading event" in Hong Kong during the 2003 SARS outbreak supported such postulation. On 12 June 2020, the Guangzhou Center for Disease Control and Prevention (GZCDC) held a news conference where they reported then the first known case of SARS-CoV-2 outbreak via combined sewage overflows from a private rainwater/sewer pipe in a "village-in-the-city" community (Li and Bin, 2020). The virus originated from a household living on the second-floor on a separate building, and later spread to six people in three separate households living in two adjacent buildings located on a lower ground level. Transmission occurred through the exposed combined sewer pipe which had a 10-cm hole at the ground joint. As an alerting case to raise awareness on sewage-associated transmission of COVID-19, the spokesman of GZCDC made specific comments on the important role of heavy rainfalls in the far-ranging transmission later found in the community. Specifically, two days after the infection of the first patient, a heavy rainfall event occurred which spread the sewage from the first household to the two buildings located behind on lower grounds through the hole on the combined sewer pipe. Further, the GZCDC staff were only able to confirm their hypothesized routes of transmission by tracking overflows from the broken pipe during another heavy rainfall event later onsite. SARS-CoV-2 RNAs were detected on the outsoles of shoes and the tire of a bicycle in the homes of four later infected cases. This particular case of community spread of SARS-CoV-2 confirmed recent postulations on sewage-associated transmission of COVID-19 (Naddeo and Liu, 2020; Qu et al., 2020; Yeo et al., 2020). Adding to this evidence, investigations on an early "superspreading event" in a residential apartment complex in Hong Kong during the 2003 SARS epidemic highlighted the risks of virus transmission via sewage-contaminated aerosols, which were generated at large quantities in drainage pipes when flushing toilets. In-building drainage pipes, also called "vertical soil stacks", carry flushed human wastes falling down rapidly by gravity in high-rise apartment buildings. A follow-up study by Yu et al. (2004) found that huge numbers of aerosols were generated by the hydraulic action in vertical soil stacks when toilets were flushed. The authors concluded that "the extremely high concentrations of the SARS-associated coronavirus found in the feces and urine of the index patient, coupled with the aerosolization due to hydraulic action inside the drainage pipes (vertical soil stacks), most likely generated huge numbers of virus-laden aerosols". Investigations by a World Health Organization (WHO) environmental health team also concluded that transmission occurred from bathroom exhaust fans operating with doors closed, drawing sewage-contaminated droplets from drainage pipes via dry-out floor drain traps, then further transporting those droplets to apartments several floors away through the building's light well (Gov HK, 2003).

Overwhelmed sewers and drainage pipes may also create shortcuts of exposure to fresh, non-dispersed human excreta in overflowed sewage. After being flushed down the toilet, human excreta are immediately mixed with water, which would normally flow, further mix, and "age" while travelling through gravity mains and manholes in the municipal wastewater reticulation network. Dispersed human excreta will then be lifted at sewage pumping stations, through force mains (i.e., rising mains) and eventually reach centralized wastewater treatment facilities, where it goes through various stages of treatment before finally being discharged as treated effluents into surface water (Jones et al., 2008). In the events of heavy rainfalls, however, runoff rates greatly exceed the conveyance capacity of sewers in communities served by combined sewers systems. Overwhelmed sewers and drains effectively block gravity flows, forcing them to go upstream in reverse directions and overflow onto lower grounds, including habitated areas and public places with high foot traffic. In these scenarios, flushed human excreta from higher altitudes can quickly overflow into lower areas such as basements, lower levels of buildings, streets, through the nearest outlets and bypassing gravity mains and the aging and mixing process in the wastewater reticulation network. Street manholes, toilets, bathtubs, bathroom drains, and other wastewater outlets in common households located on lower grounds could become "fountains" that continuously pump out fresh, overflowed sewage mixed with flood water. People who live on lower levels of multi-story apartment buildings could have sewage coming down straight into their apartments through toilets and bathroom drains, due to the stalled gravity flows in downstream sewers. In these scenarios, the short residence time of human excreta in sewers prevents their physical disintegration and thorough mixing with water and other types of wastes. Blocks of non-dispersed fecal matter are often visible in sewage overflowed from street manholes near residential buildings (Bolton, 2016; Cilia, 2020). It is particularly worth noting that studies have generally identified high viral loads of SARS-CoV-2 in patients' stools, including asymptomatic individuals (Han et al., 2020; Wölfel et al., 2020; Zhang et al., 2020). Given the substantial viral loads of SARS-CoV-2 in human feces, and that infectivity is dependent on viral RNA load (Han et al., 2020), any contact with non-dispersed fecal matter, or inhalation of aerosols containing fresh human excreta, could pose considerable risks of virus transmission.

Fig. 2 shows the pictures taken during a local flash flooding event on the evening of 30 July 2020, which demonstrate the potential shortcuts of exposure to fresh human excreta in overflowed sewage in real-world environments during such events. Pictures were taken on two overflowing sewage manholes located in a residential/commercial area adjacent to the university campus with high foot traffic, as well as their surrounding environments and affected areas downstream. Sewage mixed with storm runoffs overflowed and splashed onto parking lots, footpaths, streets, where fresh-looking human excreta were visible in the overflows and on adjacent grounds. Several pathways of possible human exposure were identified in this event: 1) direct skin contact (e.g., feet or other exposed skin areas); 2) inhalation of splashes, droplets, or aerosols generated by flow turbulences or driving-through vehicles; 3) touching of contaminated surfaces such as shoes (soles), cars (tires and wheels, exterior), roadside facilities such as bus stops, sharing bicycles (handlebars, brake levers, saddle), and items in open bars and eateries in close proximity to the overflow site. Underground structures such as basements, carparks, and lower part of buildings (e.g., hotel lobby) nearby were also at particular risk of being contaminated by overflowed sewage. In addition to these, recent discussions on the environmental transmission of COVID-19 have proposed other routes of exposure to viruses in human feces and sewage, such as ingestion of contaminated water, contact with surfaces contaminated by mechanical vectors, and contact with surfaces washed by contaminated water (Heller et al., 2020; Cahill and Morris, 2020).

It should be noted that current data and evidence do not yet support a comparative evaluation on the relative significance of flood or sewage associated transmission over other transmission routes including, for instance, human-to-human transmission. However, as commented in an early perspective (Grabow, 2007), exposure to any viable viruses in water constitutes a risk of human infection. Given that the viability of SARS-CoV-2 – and several other coronaviruses – has been well demonstrated in human excreta and sewage, we postulate that risks do exist through the various routes of human exposure outlined in our discussions (Fig. 2). Although in many scenarios such risk may be deemed negligible, under circumstances it may take on catastrophic dimensions, and for that reason, appropriate caution is recommended (Grabow, 2007). One could look at the "superspreading" event at the Amoy Gardens apartment complex in Hong Kong as an example. Although respiratory droplets and contact routes were recognized as the main routes of transmission during the 2003 SARS epidemic, sewage-contaminated aerosols were identified as the main transmitting medium, where one "index patient" caused 321 cases of infections in this private housing estate in 32 days. Urban flooding events, or other natural disasters that are disruptive to the sanitary disposal and treatment of human wastes, also pose risks of spreading infectious pathogens shed at substantial loads in human excreta. This is especially relevant given that an active hurricane season is underway in the Atlantic basin (NOAA, 2020b). In fact, this year has been one of the most active hurricane seasons on record, with 20 tropical storms, including eight hurricanes, observed so far. In a major natural disaster such as the Midland flooding in Michigan, USA, large-scale evacuation is often inevitable in affected areas which results in many people staying in community shelters (Fig. 3). Large indoor gathering, inadequate social distancing, and overwhelming loads of human wastes in shelters could expose people to elevated risks of COVID-19 infection in these environments in the midst of an ongoing pandemic (Shamus, 2020).

3. A possible link to study

As a preliminary analysis, we analyzed the relationship between the reported flood events and possible spikes in cases of local COVID-19 infections in some flood-affected areas. Retrospective analysis was done on selected locations where flooding events were reported, by reviewing the trend of their daily confirmed cases over a three-week timespan after the flood and one-week before the event as reference. To broaden the scope of our analysis, we included both places in the U.S. (with two selected from Table 1) as well as those in other countries where flooding events were reported, during the period from 1 May 2020 to 10 August 2020. Fig. 4 shows the plots of new daily confirmed cases of COVID-19 in seven metropolitan regions. These were selected based on the flooding events registered in the Global Disaster Alert and Coordination System (GDACS), after excluding those reporting daily confirmed cases that accounted for less than 10% of the total daily confirmed cases reported in the greater area. It can be seen that, in the 21-day timespan after the flooding occurred, the daily confirmed cases of COVID-19 reached their maximum levels in Chicago and Mumbai between day 7–11. During the same period, daily confirm cases in the rest of the greater area (after subtracting cases in the target area) either kept at a relatively constant level (Chicago) or decreased (Mumbai). A similar trend was observed in Harris County in Texas, USA, where daily confirmed cases of COVID-19 increased steadily from day 4–8, while a general decrease was observed in the rest of the counties in Texas through this period. The contrasting trends observed in these flood-affected locations versus their greater areas suggest a possible link between the local flooding event and increases in COVID-19 infections, although such contrasts are not clearly seen at other locations. Plots on Miami-Dade County showed that the flood-affected area showed a similar trend with the rest of Florida during the 21-day timespan after the flooding. Other places, such as Porto Alegre, showed large fluctuations in its daily confirmed cases with an abnormal spike on day 9, and no correlation could be drawn. A similar abnormal one-day spike was seen in Muzaffarpur, India.

We wish to point out that, based on the current data, there are significant gaps and uncertainties when performing such analysis, making a conclusive trend analysis difficult to achieve. To offer a point of

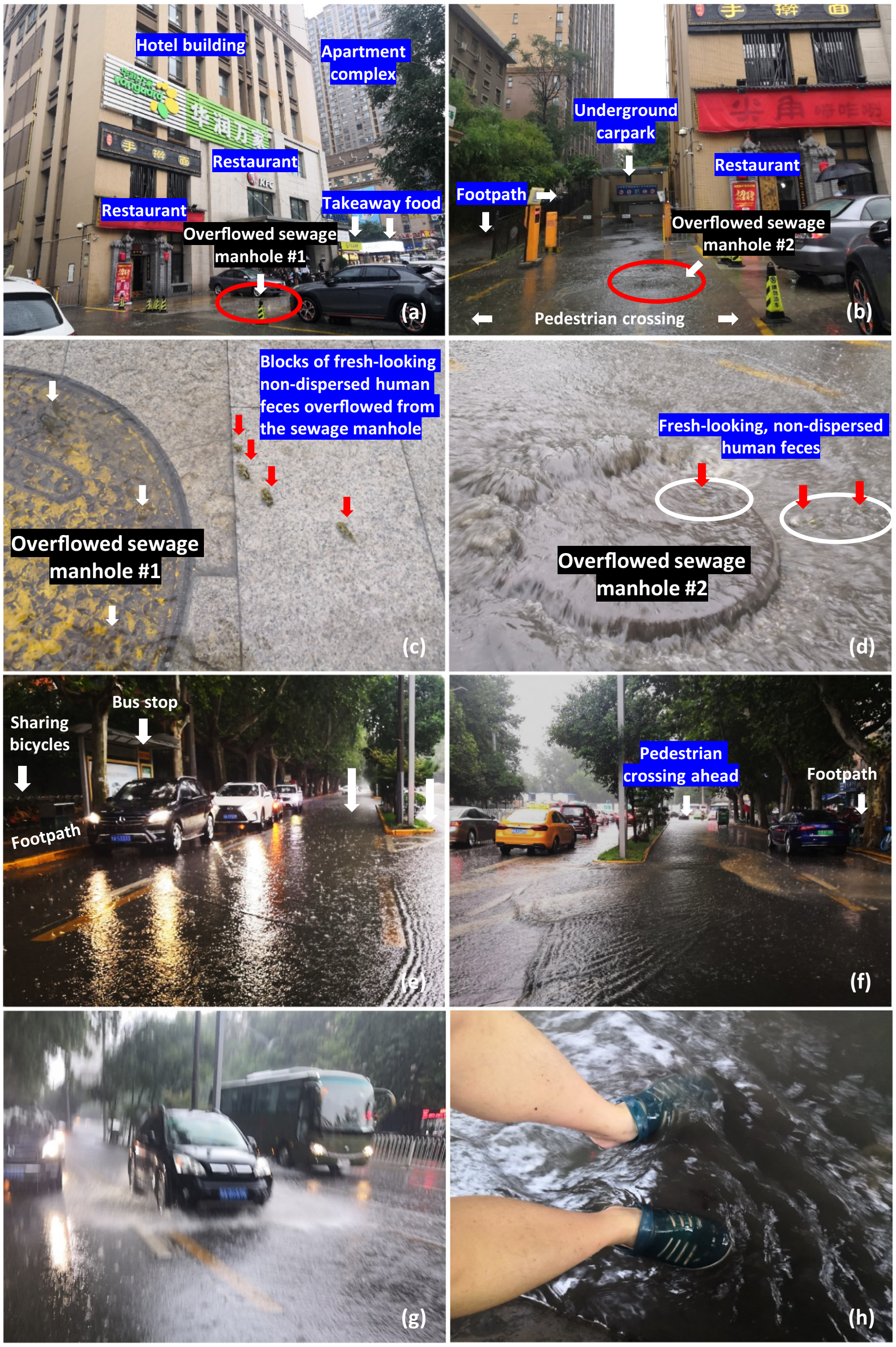

Fig. 2. Combined sewer overflows (CSOs) from manholes during an urban flooding event in Xi'an, China on July 30, 2020. (a) (b) Locations and surrounding environments of two overflowed sewage manholes (red circles); (c) (d) close-up pictures of the manholes, where blocks of fresh-looking, non-dispersed human feces were visible in CSOs and on adjacent ground (red arrows); (e) the CSOs flew to lower grounds, causing flood on an adjacent street; (f) the dark-colored CSOs continued for several hundred meters down the street, and mixed with stormwater runoffs from a nearby construction site; (g) splashes and aerosols of the CSOs generated by vehicles driving through the flooded area; (h) direct skin contact with the CSOs by a pedestrian walking across the street.

reference, here we outline these major gaps and uncertainties, along with some preliminary strategies to mitigate these in future studies. First, with few exceptions, statistics on COVID-19 infections are only available on a national or regional scale. In contrast, flooding often occurs in localized areas and, based on the data from current databases on flooding events, it is not clear what percentage of the habitated area or the local population is affected by the flooding event. Adding to this uncertainty, it is also unknown that whether the flooding events caused any significant sewage overflows in affected areas, especially in locations with high human activities. To our knowledge, there is currently no publicly accessible database providing compiled information on sewage overflow incidents on any level (community, regional, national, or global). Compiling such information would require manual searches and analyses on individual reports from news reports or local utility operators. All incidents in Table 1 were compiled in this way, because a database of this nature does not yet exist. In our preliminary analysis, we attempted to mitigate these uncertainties by focusing on major flooding events in metropolitan areas, which were likely to affect

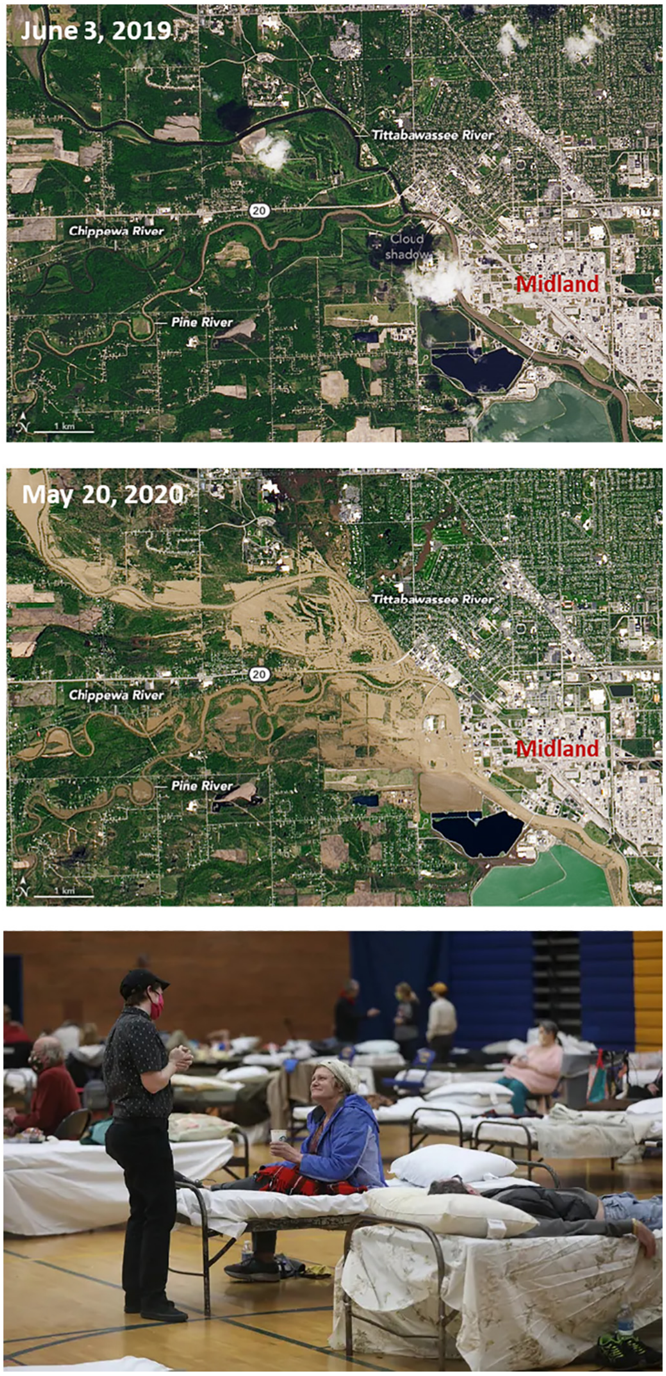

Fig. 3. A major flood occurred in Midland County in Michigan, USA, after the heavy precipitation on May 17, 2020. Accumulating rainfall led to catastrophic dam failures that inundated several nearby communities, with more than 10,000 residents evacuated. Satellite images provided by NASA Earth Observatory show the affected area before (on June 3, 2019) and after the flooding (on May 20, 2020). High-resolution images are available at: https://earthobservatory.nasa.gov/images/146752/muddy-flooding-in-michigan. The photograph was taken inside a community shelter prepared for residents evacuated from their homes in Midland County.
(Photo credit: K.P. Mitchell, Detroit Free Press)

a large geographic area or a large population. For this purpose, we used the Global Disaster Alert and Coordination System (GDACS) as our primary reference, and only selected areas reporting major flooding events between 1 May 2020 and 10 August 2020. However, using this approach, we were limited by the number of locations available for our retrospective analysis, because some countries experiencing major floods (e.g., orange-alert floods) during this period only reported small numbers of COVID-19 infections. Secondly and perhaps more importantly, the number of environmental variables and human factors contributing to the spread of COVID-19 made it difficult to assess the relative significance of one specific transmission route. Transmission of infectious agents is by nature a complex process which involves numerous contributors and processes. Depending on the particular circumstances in a flooded area, other concurrent factors may significantly outweigh sewage overflows or other flooding-associated events as a factor spreading the novel coronavirus in this community. In our preliminary analysis, we attempted to "filter out" the concurrent influence of other human or environmental factors, by comparing trends in the flooded area versus all other areas in the greater region. Although the current analyses do not suggest any conclusive trends, this may be explored as a potentially useful approach in identifying any link between COVID-19 infections and flooding events as a climatic variable during the current pandemic.

4. Combined sewer separation: the costly fix

As a former resident in the Auckland metropolitan area, the author had witnessed then the largest combined sewer separation project in the history of New Zealand. By completing combined sewer separation work for about 1200 dwellings located in two city suburbs, the three-year "Clear Harbour Alliance" project aimed to reduce an estimated 70,000 m^3 annual sewage outflows into the Waitemata harbor in Auckland, the largest coastal city in the country, with a capital expenditure of NZ$50 million (CHA, 2009; Metrowater, 2010). That was, in fact, widely seen as a delayed effort, since many large metropolitan areas in developed nations had begun such work since the late 1990s (US EPA, 2004). The American Society of Civil Engineers projected a $121.7 billion investment through to 2040 for addressing the aging wastewater infrastructure in the U.S., including its combined sewer systems mostly built before 1950 (ASCE, 2011). The substantial capital expenditure required for such work makes it even bigger of a challenge for developing countries, where water and wastewater infrastructures often fall short of the pace of their growing urbanization and industrial activities, yet they face the same climatic challenges.

One could look at China as an example. The work of combined sewer separation is far from complete in most urban areas in mainland China. The world's most populous country proposed a ministerial target of separating about a quarter of its 107,765-km combined sewers in its cities and prefectures (MOHURD, 2016), as part of its 13th Five-Year Plan from 2016 to 2020 (NDRC, 2016). If this target is met, hypothetically, China will need another 15 years to complete the work of combined sewer separation in its urban areas at the current pace. As a temperate and subtropical-zone country, China has endured numerous floods, many of which happened in densely populated urban areas, and this year is no exception. Several major urban flooding events have recently occurred in China. Aerial photographs from Napo County, Baise, a city in Guangxi province in southwest China, showed its streets and buildings inundated in muddy flood water in a high-density residential area on May 24 (Chen and Yue, 2020). On May 21–22, a torrential rainfall caused severe flash flooding in Guangzhou, a megacity and financial hub in southern China. Surveillance and video footages showed the striking depths of floods on streets and residential areas in its three metropolitan districts severely affected by the flood (Newsflare, 2020). The city received an average of 101-mm precipitation overnight, the largest on its record by both the precipitation depth and affected area (Li, 2020). Although few data were reported, those footages indicate that the city's drainage systems were completely overloaded by flood in affected areas. For a megacity with nearly 15 million residents, the good news is that it did not have a significant number of COVID-19 infections ($n = 3$–4) on May 21–22, 2020, when the flooding occurred. In fact, there had not been any large number ($n < 10$) of active cases of COVID-19 in Guangzhou between May 1 and 22, 2020, according to


Chicago, Cook County, Illinois, USA

Mumbai, Maharashtra state, India

Miami-Dade County, Florida, USA

Muzaffarpur, Bihar state, India

Harris County, Texas, USA

Porto Alegre, Rio Grande Do Sul state, Brazil

Veracruz, Veracruz state, Mexico

Fig. 4. Plots of daily confirmed cases of COVID-19 infections in seven metropolitan regions. Blue bars show daily confirmed cases in the target area. Numbers above the data bars show the number of consecutive days after the flooding event. Overlapping zigzag line (shown in orange color) shows daily confirmed cases in the greater area, after subtracting the number of cases in the target area. These were selected from locations reporting significant numbers of new daily confirmed cases of COVID-19 and major flooding events as registered in the Global Disaster Alert and Coordination System (GDACS), after excluding those reporting daily confirmed cases that accounted for less than 10% of the total daily confirmed cases in the greater area. Data on daily confirmed cases of COVID-19 were obtained from official statistics by local municipalities, states, or regions in various countries.

the daily statistics published by the Guangzhou Municipal Health Commission (GMHC, 2020). Should the flooding occur through the peak of its COVID-19 outbreak, the effects could be more disastrous, or even deadly, due to the potential spread of SARS-CoV-2 in those densely populated communities.

An old foe for civil and environmental engineers, combined sewer overflow is a recurring event during urban flooding events. With the SARS-CoV-2 viruses still loom in our communities and governments around the world are bracing for a possible "second wave" of outbreak, it is time for local municipalities to reprioritize their capital expenditure on upgrading aging or poorly functioning wastewater infrastructure, not only for the long-lasting benefits of better wastewater management, but to reduce the immediate risks of pathogen transmission resulting from community-wide sewage overflows during severe flooding events in the midst of a pandemic. Some policymakers are putting those demands into action (Johnson, 2020).

5. Concluding remarks

Human feces and urine have been confirmed as sources of infectious SARS-CoV-2 viruses, which have also been detected by various studies in wastewater treatment plants and along municipal sewage reticulation networks. Evidence on other coronaviruses, including the SARS-CoV-1, showed that they could remain infectious in sewage and water for prolonged periods. With summer already underway, a particular risk arises from the fact that heavy rainfalls often bring large amounts of precipitation which could easily overwhelm combined sewer systems, causing sewage overflows. By reviewing the up-to-date evidence and discussions, including evidence from real-life environments, we propose that transmission may be eventuated through various routes of exposure to overflowed sewage, fresh human excreta, sewage-contaminated surfaces or aerosols, in areas with human activities and receiving sewage overflows during urban flooding events. While a preliminary retrospective analysis on seven locations reporting significant numbers of daily confirmed COVID-19 cases and flooding events during 1 May 2020 to 10 August 2020 did not yield conclusive trends, and that current evidence does not yet support a conclusive link, these should be examined as a potential risk factor as part of an integrated precautionary approach to mitigate the environmental transmission of COVID-19, especially in communities with high infection counts and reoccurring flooding events. The ongoing pandemic presents an unprecedented challenge for local municipalities and utility operators in maintaining the proper functioning of sewer pipelines, pumping stations, and treatment facilities. Local municipalities considering wastewater infrastructure upgrades and particularly combined sewer separations should move forward to safeguard their communities against natural disasters that are disruptive to the sanitary disposal and treatment of human wastes, which may become the transmitting medium of infectious diseases during epidemics and complicating the efforts of risk management.

CRediT authorship contribution statement

Jie Han: Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing, Supervision, Funding acquisition. **Shanshan He:** Investigation, Data curation, Visualization.

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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References

Ahmed, W., Angel, N., Edson, J., Bibby, K., Bivins, A., O'Brien, J.W., Choi, P.M., Kitajima, M., Simpson, S.L., Li, J., Tscharke, B., Verhagen, R., Smith, W.J.M., Zaugg, J., Dierens, L., Hugenholtz, P., Thomas, K.V., Mueller, J.F., 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. Sci. Total Environ. 728, 138764. https://doi.org/10.1016/j.scitotenv.2020.138764.

American Society of Civil Engineers (ASCE), 2011. Failure to Act: The Economic Impact of Current Investment Trends in Water and Wastewater Treatment Infrastructure. Washington, DC.

Bolton, F., 2016. Olive Branch residents angry over sewage overflow. https://www.wmcactionnews5.com/story/31450437/residents-angry-over-sewage-overflow/ (accessed 16 September 2020).

Cahill, N., Morris, D., 2020. Recreational waters – a potential transmission route for SARS-CoV-2 to humans? Sci. Total Environ. 740, 140122. https://doi.org/10.1016/j.scitotenv.2020.140122.

Carducci, A., Federigi, I., Liu, D., Thompson, J.R., Verani, M., 2020. Making waves: coronavirus detection, presence and persistence in the water environment: state of the art and knowledge needs for public health. Water Res. 179, 115907. https://doi.org/10.1016/j.watres.2020.115907.

CDC (Centers for Disease Control and Prevention), 2020. CDC COVID data tracker. https://www.cdc.gov/covid-data-tracker/index.html (accessed 16 September 2020).

CHA (Clear Harbour Alliance), 2009. Project to improve Auckland City's waterways. https://info.scoop.co.nz/Clear_Habour_Alliance.

Chen, Y., Yue, H.B., 2020. City of Baise, Guangxi province: rainstorm causes flood, police officers and soldiers rushed to help. http://military.people.com.cn/n1/2020/0525/c1011-31722451.html (in Chinese) (accessed 16 September 2020).

Cilia, J., 2020. Overflowing drains have turned this buġibba street into a literal shithole. https://lovinmalta.com/news/watch-overflowing-drains-have-turned-this-bugibba-street-into-a-literal-shithole/ (accessed 16 September 2020).

de Bruijn, J.A., de Moel, H., Jongman, B., de Ruiter, M.C., Wagemaker, J., Aerts, J.C.J.H., 2019. A global database of historic and real-time flood events based on social media. Sci. Data 6, 311. https://doi.org/10.1038/s41597-019-0326-9.

GMHC (Guangzhou Municipal Health Commission), 2020. Daily reports of confirmed cases of COVID-19 infection. http://wjw.gz.gov.cn/ztzl/xxfyyqfk/yqtb/index.html (in Chinese) (accessed 16 September 2020).

Gov HK (Government of Hong Kong S.A.R.), 2003. WHO Environmental Health Team reports on Amoy Gardens. https://www.info.gov.hk/gia/general/200305/16/0516114.htm (accessed 16 September 2020).

Grabow, W.O.K., 2007. Overview of health-related water virology. Perspect. Med. Virol. 17, 1–25. https://doi.org/10.1016/S0168-7069(07)17001-4.

Han, M.S., Seong, M.W., Kim, N., Shin, S., Cho, S.I., Park, H., Kim, T.S., Park, S.S., Choi, E.H., 2020. Viral RNA load in mildly symptomatic and asymptomatic children with COVID-19, Seoul. Emerg. Infect. Dis. 26. https://doi.org/10.3201/eid2610.202449.

Haramoto, E., Malla, B., Thakali, O., Kitajima, M., 2020. First environmental surveillance for the presence of SARS-CoV-2 RNA in wastewater and river water in Japan. Sci. Total Environ. 737, 140405. https://doi.org/10.1016/j.scitotenv.2020.140405.

Heller, L., Mota, C.R., Greco, D.B., 2020. COVID-19 faecal-oral transmission: are we asking the right questions? Sci. Total Environ. 729, 138919. https://doi.org/10.1016/j.scitotenv.2020.138919.

Jeong, H.W., Kim, S.M., Kim, H.S., Kim, Y.I., Kim, J.H., Cho, J.Y., Kim, S., Kang, H., Kim, S.G., Park, S.J., Kim, E.H., Choi, Y.K., 2020. Viable SARS-CoV-2 in various specimens from COVID-19 patients. Clin. Microbiol. Infect. https://doi.org/10.1016/j.cmi.2020.07.020.

Johnson, T., 2020. Pandemic pushes back filing date for plans to stop sewage overflow. https://www.njspotlight.com/2020/05/pandemic-pushes-back-filing-date-for-plans-to-stop-sewage-overflow/ (accessed 16 September 2020).

Jones, G.M., Sanks, R.L., Tchobanoglous, G., Bosserman II, B.E., 2008. Pumping Station Design. 3rd ed. Butterworth-Heinemann.

Li, T.Y., 2020. Multi-record-breaking rainstorm. Guangzhou Dailyhttps://gzdaily.dayoo.com/pc/html/2020-05/23/content_130471_700281.htm (in Chinese) (accessed 16 September 2020).

Li, P., Bin, H., 2020. "Solving a case" of COVID-19 outbreak in a village-in-the-city community in Guangzhou: sewage contaminated surrounding environments caused virus infections in residents. http://news.southcn.com/gd/content/2020-06/12/content_191016386.htm (in Chinese) (accessed 16 September 2020).

Metrowater, 2010. Annual Report 2010. Case Study: Clear Harbour Alliance. , pp. 19–20. https://www.watercare.co.nz/About-us/Reports-and-publications (accessed 16 September 2020).

Miles, F., 2020. Coronavirus wipes, masks a nightmare for storm drains, sewers. https://www.foxnews.com/us/coronavirus-wipes-masks-a-nightmare-for-storm-drains-sewers (accessed 16 September 2020).

MOHURD (Ministry of Housing and Urban-Rural Development) of the People''s Republic of China, 2016. Yearly statistics on urban-rural development (2015). http://www.mohurd.gov.cn/xytj/tjzljsxytjgb/jstjnj/ (in Chinese) (accessed 16 September 2020).

Naddeo, V., Liu, H., 2020. Editorial perspectives: 2019 novel coronavirus (SARS-CoV-2): what is its fate in urban water cycle and how can the water research community respond? Environ. Sci.: Water Res. Technol. 6, 1213–1216. https://doi.org/10.1039/d0ew90015j.

NDRC (National Development and Reform Commission) of the People''s Republic of China, 2016. The 13th Five-Year Plan - national urban sewage treatment and recycling facilities construction plan. http://www.gov.cn/xinwen/2017-01/23/content_5162482.htm (in Chinese) (accessed 16 September 2020).

Newsflare, 2020. Heavy rainstorm brings flash floods to Chinese city. https://www.msn.com/en-gb/video/news/heavy-rainstorm-brings-flash-floods-to-chinese-city/vp-BB14sH6V (accessed 16 September 2020).

NOAA (National Oceanic and Atmospheric Administration), 2019. January through August was wettest on record for U.S. https://www.noaa.gov/news/january-through-august-was-wettest-on-record-for-us (accessed 16 September 2020).

NOAA (National Oceanic and Atmospheric Administration), 2020a. Global land precipitation percentile map. https://www.ncdc.noaa.gov/temp-and-precip/global-maps/ (accessed 16 September 2020).

NOAA (National Oceanic and Atmospheric Administration), 2020b. 'Extremely active' hurricane season possible for Atlantic Basin. https://www.noaa.gov/media-release/extremely-active-hurricane-season-possible-for-atlantic-basin (accessed 16 September 2020).

NYC (New York City), 2020. COVID-19 data: daily counts. https://www1.nyc.gov/site/doh/covid/covid-19-data.page (accessed 16 September 2020).

Qu, G., Li, X., Hu, L., Jiang, G., 2020. An imperative need for research on the role of environmental factors in transmission of novel coronavirus (COVID-19). Environ. Sci. Technol. 54, 3730–3732. https://doi.org/10.1021/acs.est.0c01102.

Randazzo, W., Truchado, P., Cuevas-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 Res. 181, 115942. https://doi.org/10.1016/j.watres.2020.115942.

Rimoldi, S.G., Stefani, F., Gigantiello, A., Polesello, S., Comandatore, F., Mileto, D., Maresca, M., Longobardi, C., Mancon, A., Romeri, F., Pagani, C., Cappelli, F., Roscioli, C., Moja, L., Gismondo, M.R., Salerno, F., 2020. Presence and infectivity of SARS-CoV-2 virus in wastewaters and rivers. Sci. Total Environ. 744, 140911. https://doi.org/10.1016/j.scitotenv.2020.140911.

Shamus, K.J., 2020. Health official: 'it's hard to gauge' risk floodwater poses in spreading COVID-19. https://www.freep.com/story/news/local/michigan/2020/05/24/midland-flood-coronavirus-covid-19-spread/5242382002/ (accessed 16 September 2020).

Sun, J., Zhu, A., Li, H., Zheng, K., Zhuang, Z., Chen, Z., Shi, Y., Zhang, Z., Chen, S.B., Liu, X., Dai, J., Li, X., Huang, S., Huang, X., Luo, L., Wen, L., Zhuo, J., Li, Y., Wang, Y., Zhang, L., Zhang, Y., Li, F., Feng, L., Chen, X., Zhong, N., Yang, Z., Huang, J., Zhao, J., Li, Y.M., 2020. Isolation of infectious SARS-CoV-2 from urine of a COVID-19 patient. Emerg. Microbes Infect. 9, 991–993. https://doi.org/10.1080/22221751.2020.1760144.

Tibbetts, J., 2005. Combined sewer systems: down, dirty, and out of date. Environ. Health Perspect. 113, A464–A467. https://doi.org/10.1289/ehp.113-a464.

US EPA (United States Environmental Protection Agency), 2004. National Pollutant Discharge Elimination System (NPDES): 2004 NPDES CSO report to Congress. https://www.epa.gov/npdes/2004-npdes-cso-report-congress (accessed 16 September 2020).

US EPA (United States Environmental Protection Agency), 2018. National Pollutant Discharge Elimination System (NPDES): combined sewer overflows (CSOs). https://www.epa.gov/npdes/combined-sewer-overflows-csos (accessed 16 September 2020).

Wölfel, R., Corman, V.M., Guggemos, W., Seilmaier, M., Zange, S., Müller, M.A., Niemeyer, D., Jones, T.C., Vollmar, P., Rothe, C., Hoelscher, M., Bleicker, T., Brünink, S., Schneider, J., Ehmann, R., Zwirglmaier, K., Drosten, C., Wendtner, C., 2020. Virological assessment of hospitalized patients with COVID-2019. Nature 581, 465–469. https://doi.org/10.1038/s41586-020-2196-x.

Worldometer, 2020. Coronavirus active cases in the United States. https://www.worldometers.info/coronavirus/country/us/ (accessed 16 September 2020).

Wright, D.B., Bosma, C.D., Lopez-Cantu, T., 2019. U.S. hydrologic design standards insufficient due to large increases in frequency of rainfall extremes. Geophys. Res. Lett. 46, 8144–8153. https://doi.org/10.1029/2019GL083235.

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. https://doi.org/10.1053/j.gastro.2020.02.055.

Xu, K., Cai, H., Shen, Y., Ni, Q., Chen, Y., Hu, S., Li, J., Wang, H., Yu, L., Huang, H., Qiu, Y., Wei, G., Fang, Q., Zhou, J., Sheng, J., Liang, T., Li, L., 2020. Management of COVID-19: the Zhejiang experience. J. Zhejiang Univ. (Med. Sci.) 49, 147–157. https://doi.org/10.3785/j.issn.1008-9292.2020.02.02.

Yeo, C., Kaushal, S., Yeo, D., 2020. Enteric involvement of coronaviruses: is faecal – oral transmission of SARS-CoV-2 possible? Lancet Gastroenterol. Hepatol. 5, 335–337. https://doi.org/10.1016/S2468-1253(20)30048-0.

Yu, I.T.S., Li, Y., Wong, T.W., Tam, W., Chan, A.T., Lee, J.H.W., Leung, D.Y.C., Ho, T., 2004. Evidence of airborne transmission of the severe acute respiratory syndrome virus. N. Engl. J. Med. 350, 1731–1739. https://doi.org/10.1056/NEJMoa032867.

Zhang, N., Gong, Y., Meng, F., Shi, Y., Wang, J., Mao, P., Chuai, X., Bi, Y., Yang, P., Wang, F., 2020. Comparative study on virus shedding patterns in nasopharyngeal and fecal specimens of COVID-19 patients. Sci. China Life Sci. https://doi.org/10.1007/s11427-020-1783-9.