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Post Covid-19 water and waste water management to protect public health and geoenvironment

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The coronavirus disease 2019 pandemic has posed severe threats to humans and the geoenvironment. The findings of severe acute respiratory syndrome coronavirus 2 (Sars-CoV-2) traces in waste water and the practice of disinfecting outdoor spaces in several cities in the world, which can result into the entry of disinfectants and their by-products into storm drainage systems and their subsequent discharge into rivers and coastal waters, raise the issue of environmental, ecological and public health effects. The aims of the current paper are to investigate the potential of water and waste water to operate as transmission routes for Sars-CoV-2 and the risks of this to public health and the geoenvironment. Additionally, several developing countries are characterised by low water-related disaster resilience and low household water security, with measures for protection of water resources and technologies for clean water and sanitation being substandard or not in place. To mitigate the impact of the pandemic in such cases, practical recommendations are provided herein. The paper calls for the enhancement of research into the migration mechanisms of viruses in various media, as well as in the formation of trihalomethanes and other disinfectant by-products in the geoenvironment, in order to develop robust solutions to combat the effects of the current and future pandemics.

Introduction

Humanity is facing the most demanding challenge of the twenty-first century to date, a global pandemic caused by a new kind of coronavirus, severe acute respiratory syndrome coronavirus 2 (Sars-CoV-2). Historically, humankind has faced several infectious diseases, which, in almost all cases, had a zoonotic origin – that is, the infectious agent was transmitted from an animal to a human. This zoonotic origin is just the initial transmission step, the spread of a pandemic requires the confluence of several factors, such as international travel and trade, globalisation of food supplies, changes in food processing, use of antibiotics, environmental changes and adaptation of microorganisms (Manivannan, 2008; Morens and Fauci, 2007; Taubenberg *et al*., 2007; Yang *et al*., 2007).

Transmission routes of infectious diseases are varied and include direct contact with respiratory droplets from infected persons, mosquito bites and consumption or contact with polluted water or food. Water is a major vehicle of transmission of pathogenic germs, such as bacteria, protozoa and helminths (Mosteo *et al*., 2013). Most of these microorganisms inhabit the gastrointestinal tract of humans and animals and are discharged through faeces to the geoenvironment, from where they may pollute surface water and/or groundwater (Mosteo *et al*., 2013). For example, Corsi *et al*. (2014) reported that human and bovine viruses were present in 63 and 46%, respectively, of run-off samples in the Milwaukee River in Wisconsin, USA.

The main pathway of pathogens to a person is through direct intake of contaminated water or consumption of a raw vegetable or fruit that has come into contact with such water (Marín-Galvín, 2003). Additional routes can be inhalation of polluted water droplets (this is the case of *Legionella* spp. and the meningoencephalitis caused by amoeba *Naegleria fowleri*) or dermal contact with polluted water (such as with *Pseudomonas aeruginosa*, *Klebsiella* and *Aeromonas*).

The presence of Sars-CoV-2 has been detected in untreated waste water in the Netherlands (Lodder and de Roda Husman, 2020; Medema *et al*., 2020), Australia (Ahmed *et al*., 2020), Greece (N. Papaioannou, personal communication, 4 April 2020) and the USA (Wu *et al*., 2020). Sars-CoV-2 macromolecules were found in the saliva, blood and anal swabs of patients (Guo *et al*., 2020; Xiao *et al*., 2020; Zhang *et al*., 2020), raising the question of viral gastrointestinal infection and of oral and faecal transmission routes for the virus.

Gundy *et al*. (2008) conducted a study on the survival of coronaviruses and polioviruses in tap water and waste water. They observed that coronaviruses survived for up to 100 days in tap water at 4°C, whereas they were inactivated within 10 days in room-temperature water. Temperature appeared to be the main factor for survival of these viruses, which also persisted in unfiltered water, a fact that was attributed to the presence of suspended solids. Based on these results, the survival of Sars-CoV-2 may be favoured by unfiltered tap water and waste water with high levels of suspended solids. Casanova *et al*. (2009) showed that coronaviruses can be infectious for long periods of time while in water and waste water (17–22 days at room temperature and more than 4 weeks at 4°C). Casanova and Weaver (2015) suggested that enveloped viruses could survive in sewage for 6–7 days, while van Doremalen *et al*. (2020) reported that Sars-CoV-2 may live from 4 to 72 h on environmental surfaces, depending on the nature of the surface material. A recent report from the US Centers for Disease Control and Prevention (CDC) suggested that the virus can survive for up to 17 days in the environment (Moriarty, 2020). Slater *et al*. (2011) had found that the use of antivirals and antibiotics during the 2009–2010 influenza affected the bacterial communities of waste-water-treatment plants (WWTPs), raising the question of WWTP performance during a pandemic.

In order to minimise disease transmission from hospital waste waters that may have a high load of pathogens during a pandemic, Sozzi *et al*. (2015) suggested that these be first treated in situ, before being discharged into the municipal sewerage network. Two protocols were tested, combining coagulation with disinfection at various pH levels, and both proved to be successful in disinfecting hospital waste waters and sludge. Bibby *et al*. (2015) investigated the survival of the Ebola virus in waste water and suggested containing virus-contaminated waste water for at least 1 week before allowing it to enter the sewerage system, as well as applying higher-level protective measures for WWTP staff. Benschop *et al*. (2017) detected polioviruses, enteroviruses and the measles virus in sewage samples from refugee centres in the Netherlands. Ivanova *et al*. (2019) summarised the sampling campaigns at four WWTPs in Moscow, Russia, from 2004 to 2017 and found that 20% from a total of 5450 samples tested positive for various viruses. Wigginton *et al*. (2015) reviewed the effects on drinking water and waste water of enveloped viruses, particularly of coronaviruses, which had caused the severe acute respiratory syndrome (Sars) in 2003 and the Middle East respiratory syndrome (Mers) in 2012. The current virus, Sars-CoV-2, is also an enveloped virus – that is, it is surrounded by an outer lipid membrane. These authors mentioned that 'survivability studies show that many enveloped viruses are capable of retaining infectivity for days to months in aqueous environments' (Wigginton *et al*., 2015). Recently, Nghiem *et al*. (2020) referred to a potential Sars-CoV-2 viral transmission from aerosols from waste water systems.

Because of the risk of transmission by way of water, disinfection of drinking water is vital in order to prevent waterborne diseases. Disinfection is the destruction of viable, potentially infectious pathogens by different treatment methods, the most common being by chlorine, chlorine dioxide, ozone and ultraviolet (UV) radiation (Gerardi and Zimmerman, 2005; López *et al*., 2019). More recent developments include the application of advanced oxidation processes (AOPs) that combine high-oxidation chemical compounds with elements capable of activating them for the generation of highly reactive radicals (Guerra-Rodríguez *et al*., 2018; Rodriguez-Chueca *et al*., 2015). All these treatments present a series of advantages and disadvantages, but chlorination stands out as the most widely used method all over the world.

Although all disinfection techniques can inactivate pathogenic microorganisms, not all of them have the same efficacy in the elimination of viruses, with the efficacy decreasing, in general, in the following order: ozone > chlorine dioxide > chlorine (USEPA, 1999a; Watts *et al*., 1995), but also depending on species and water characteristics. Chlorine dioxide is equivalent to chlorine as bactericidal and superior to it as virucidal in a wider range of pH values and does not form halogenated by-products. However, Wang *et al*. (2005a), in a study of the inactivation of Sars-CoV in waste water, found that free chlorine required a lower concentration than chlorine dioxide to inactivate this virus.

During the coronavirus disease 2019 (Covid-19) pandemic, the World Health Organization (WHO) has advised handwashing with sanitiser/soap for mitigating the transmission of Sars-CoV-2. However, more than 3 billion people worldwide lack sanitisers/soap and water to maintain proper hygiene. In addition, in rural areas, particularly in developing countries, people use untreated water from rivers, ponds, springs and wells, which are sometimes located at considerable distances from their residences and of which the quality of water may be questionable. Hence, transmission of Sars-CoV-2 in these areas is possible with the congregation of people at water sources and their exposure to infected persons. In addition, the existence of Sars-CoV-2 traces in the waste water stream of several cities raises concerns about the rudimentary and scantly controlled sanitary systems of several developing countries.

Given that in large parts of the world, measures for the protection of water resources, controls on the treatment and supply of drinking water and the treatment and discharge of waste water may be substandard by the guidelines by the WHO (2017) or not in place, the current paper has the following three major aims: firstly, to investigate the potential of water and waste water to operate as transmission routes for the Sars-CoV-2; secondly, to assess the risks and threats to both public health and the geoenvironment posed by a potential entry of the virus in water and waste-water-treatment systems; and thirdly, to raise the issue of disinfectant application on outdoor public spaces in many cities in the world, which on entering storm drainage systems find their way to surface and coastal waters.

Geoenvironmental engineering's role in pandemics and public health issues

Pandemics such as Covid-19 and their health, financial and social implications are not new. The plague of ancient Athens in 430 BC is perhaps the first famous case of an epidemic, recorded in the *History of the Peloponnesian War* by Thucydides (2020), with the agent being the salmonella or typhoid bacteria or even the Ebola virus (Papagrikorakis *et al*., 2008; Smith, 1996). The Plague of Justinian (AD 541–542, but with recurrences until AD 750) was the first known major pandemic, and it was caused by the Gram-negative bacterium *Yersinia pestis*. It was the first time, perhaps, that the practice of massively disposing bodies into burial pits (reportedly holding up to 70 000 corpses) was recorded.

The Black Death (1347–1352) was a bubonic plague pandemic in Europe whose agent was the same bacterium responsible for Justinian's Plague. Estimates of its deaths are in several tens of millions, and its aftermath was rebellions and the complete transformation of the European medieval society (Cartwright, 2020). This was the first time that official patient isolation was enforced in Venice, with returning sailors put under a 40-day '*quarantino*'.

In North and South America, some of the worst epidemics were caused by smallpox, which in the fifteenth century killed 90–95% of the indigenous people in Mexico (Roos, 2020) and in the 1600s about 70% of the native American population in the north-east of the USA (Robinson and Battenfield, 2020).

The association between water resource contamination and public health became obvious during the cholera (a bacterial infection) outbreaks of the nineteenth century. For example, in imperial Paris in the mid-nineteenth century, there were no public water supply or sewerage systems. 'The citizens of Paris took their water supplies … from the River Seine … [which] … was both the source and the sink for the Parisian water system' (Freeze, 1994: p. 29). As a result, Paris developed a citywide drinking water and sewerage system by the mid-1860s. Henry Darcy, who was the chief engineer of the Côte-d'Or (one of the 83 administrative departments in France), conducted his famous experiments during construction of the water distribution system at Dijon, France, which he concluded 25 years earlier than Paris did.

The city of London faced four major cholera outbreaks, in 1831, in 1848–1849, in 1853–1854 and again in 1866. The tracing of the 1854 cholera deaths to a popular drinking water well established the connection between the disease and water (Ball, 2009; Smith, 1999). This public health crisis was resolved by Joseph Bazalgette, chief engineer of London's Metropolitan Board of Works, who supervised the creation of a series of sewers (finalised in 1875), moving the waste water away from the River Thames (Mohamed and Paleologos, 2017).

The water supply system of the city of New York City (NYC) had relied on wells until the mid-nineteenth century. Following several cholera outbreaks, fresh water was brought to the city in 1842 by way of reservoirs and aqueducts were constructed under Chief Engineer John B. Jervis (Pierce, 2018). NYC started constructing its sewerage system in 1849, connecting almost all of the city by 1902 and finalising it in the 1930s in order to address the pollution problems from raw sewage entering the NYC harbour. These major public infrastructure projects in three of the most famous cities of the world and the names of the prominent engineers associated with them constitute proof of the indispensable role that geoenvironmental engineering plays in safeguarding public health. It is fair therefore to state that although the analysis and understanding of disease vectors belong to the health disciplines, the solution to several of the major epidemics and pandemics was ultimately given by civil, environmental and sanitary engineers (Wigginton and Boehm, 2020).

In recognition of the threat to public water supplies, chlorination has been commonly performed since the mid-twentieth century in most developed countries, both for the treatment of drinking water and for the sanitisation of waste water prior to its discharge from WWTPs. These measures have largely eliminated disease outbreaks arising from drinking water (USEPA, 2000). Maximum levels of pathogens and of other contents in drinking water have been established by WHO (2018), the EU (EC, 1998) and national governments (e.g. Health Canada, 2019). Water bodies have to be monitored regularly to ensure that their water meets quality regulatory requirements with remedial actions to be taken in the opposite case (e.g. EC, 2000; Papapetridis and Paleologos, 2011, 2012). Despite these improvements, WHO reported that more than 3.4 million people die each year from waterborne diseases, making it the leading cause of illness and death in the world (Berman, 2009).

In addition to the high mortality rate and the toll on the population's general physical and mental well-being, other serious aspects to ponder from epidemics/pandemics are the huge financial instability that they create, followed by an equally troubling decline in the social order and the morality and ethics of the societies afflicted. The lessons from past cases are relevant for the present times because successful reaction from, among others, the civil, environmental, geotechnical and municipal engineering communities depends strongly on both the maintenance of social consensus regarding public health measures and safeguarding an economic order. Together these would allow critical public health-related civil and geoenvironmental infrastructure upgrades, as those proposed in the following sections of the current paper and in the companion paper by Tang *et al*. (2020).

Challenges and risks of Sars-CoV-2 in waters

Pathways of the virus to enter water bodies

Sars-CoV-2 can enter the soil and water by a range of pathways originating from solid and liquid waste by infected people (Xu *et al*., 2020b). Leaking water and sewerage networks, as a result of prolonged underinvestment in maintenance, upgrade and modernisation. can lead to cross-contamination of soil and water, endangering the geoenvironment and public health. Thus, the fate, transport and interaction of pathogens, such as of Sars-CoV-2, with surface water and groundwater and the soil must be assessed.

In some parts of the world, faeces constitute an important organic fertiliser that is poured onto farmland to promote crop growth. In rainy days, virus-contaminated run-off may enter surface waters or the groundwater by infiltration, causing their contamination. The appearance of Sars-CoV-2 in wells, streams, rivers and lakes will likely be more prevalent in developing countries and poor rural areas of Asia, Africa and South America where sewerage systems are either rudimentary, ageing or non-existent (WHO and Unicef, 2019). In 2013 the *Asian Water Development Outlook* (AWDO) (ADB, 2013: Table 7) reported that about 45% of the rivers in Asia were polluted and classified them under a bad or poor river health index. The situation slightly worsened in 2016 (ADB, 2016) as a result of intensified agricultural and other economic activities.

Various guidelines for the disposal of pathogen-contaminated substances have been developed internationally (e.g. CDPH, 2020; WHO, 2005). For instance, if leakage of pathogen-laden waste water occurs, contaminated groundwater should be remediated. This emphasises the need for research into the fate and transport of Sars-CoV-2 and other pathogens in soil and surface water/groundwater (Bender *et al*., 2017). This is critical for rural areas where groundwater is used for agriculture and as a source of drinking water and where there may exist less uniform controls on water treatment or quality. This can be achieved by a systematic disposal approach for contaminated substances that is aimed at isolating them from the hydrologic cycle, such as disposing downstream of water resources, locating appropriate geologic formations for disposal and minimising leakage of infected leachate.

Sars-CoV-2 in fresh and bathing waters

There have not been any studies, to date, that reported infection from the Sars-CoV-2 arising from water bodies. The US CDC (2020) has stated that standard disinfection methods used in municipal water-treatment plants (WTPs) should be sufficient to inactivate the virus. The CDC (2020) has also mentioned that recreational waters in swimming pools, hot tubs and spas should pose no risk to public health if proper operation and maintenance are maintained. International standards for water chlorination recommend both a specific concentration and a contact time (C_t), the time needed for chlorine to act so that pathogens are killed SDWF (2017). For drinking water, this is at least 15 mg min/l (i.e. exposure of 1 litre of water to 1 mg of free chlorine for at least 15 min). For swimming pools, 'current recommendations/best practice' stipulates a free chlorine residual of at least 1.0 mg/l (depending on the pool type and disinfectant used) (HPSC, 2020). Higher doses are mandated in the UK for spa pools with free chlorine at 5 mg/l before emptying them and 50 mg/l for at least 1 h on refilling them (PWTAG, 2016, 2020).

International bodies have relied on experience dealing with other viruses, such as Sars and Mers, which belong to the same coronavirus family as Sars-CoV-2, in order to analyse the risks posed by the new virus (HPSC, 2020; PWTAG, 2020; WEF, 2020; WHO and Unicef, 2020). Coxsackie virus, poliovirus and rotavirus, which all plot within the bottom left box of Figure 1, are all examples of non-enveloped viruses, for which the 15 mg min/l chlorination dose works. Sars-CoV-2 is an enveloped virus and according to the Health Protection Surveillance Centre of Ireland (HPSC, 2020: p. 2) it 'will be inactivated at lower C_t values'.

However, it should be noted that the C_t of water subvolumes that pass through a disinfection contact tank may not be the same for all, as some 'water may short-circuit the tank and thus have a

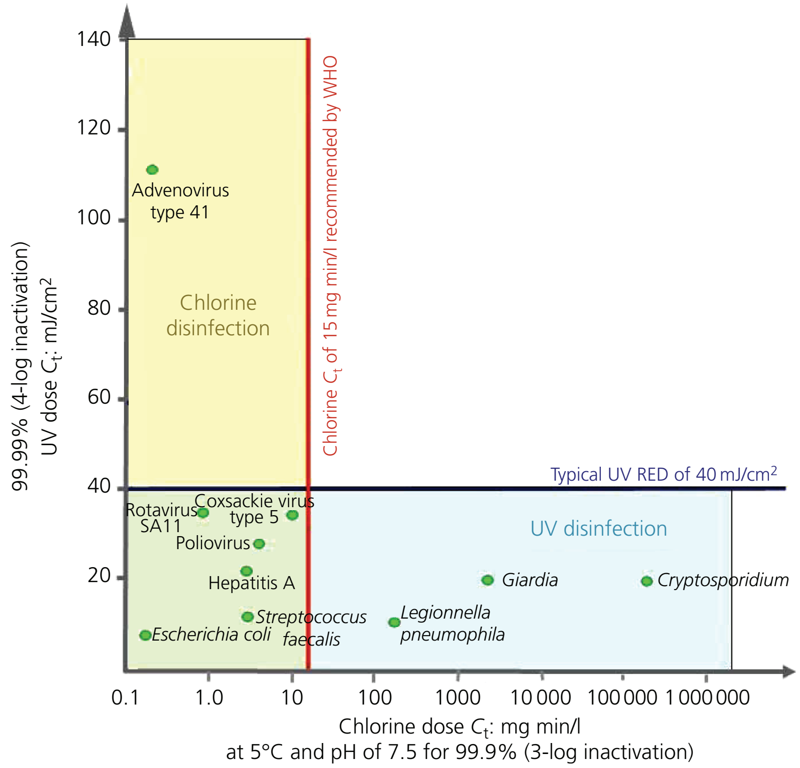

Figure 1. Chlorine and UV doses required for the inactivation of various viruses in drinking water (HPSC, 2020; Irish EPA, 2011). RED, reduction equivalent dose

residence time [that is] less than τ', where τ is the average global residence time of water based on plug flow (Irish EPA, 2011: p. 45). In order to account for non-ideal flow conditions, a time t_x is considered for disinfection, defined as the time needed for the fastest flowing x% of water to exit from the outlet of the tank (based on tracer tests). The guidelines by the US Environmental Protection Agency (USEPA, 1999b, 2003a) for disinfection are based on a corrected residence time t_{10} (of the fastest 10% of the tracer passing through the outlet after a 'spike' test), and they provide recommended correction residence times τ of disinfection for different baffling arrangements. For the poor flow conditions shown in Figure 2, residence times of more than 300% of the t_{10} may be required. It is clear from the above that although the probability may be exceedingly small, there does exist a risk, at least for some pockets of the drinking water body, not to be disinfected fully and hence potentially to pose a drinking health risk in terms of Sars-CoV-2.

Despite reassurances about the effect of disinfection in swimming pools, the need for social distancing and the seriousness of the risk have led many countries to issue orders for the closure of swimming pools and other recreational water bodies

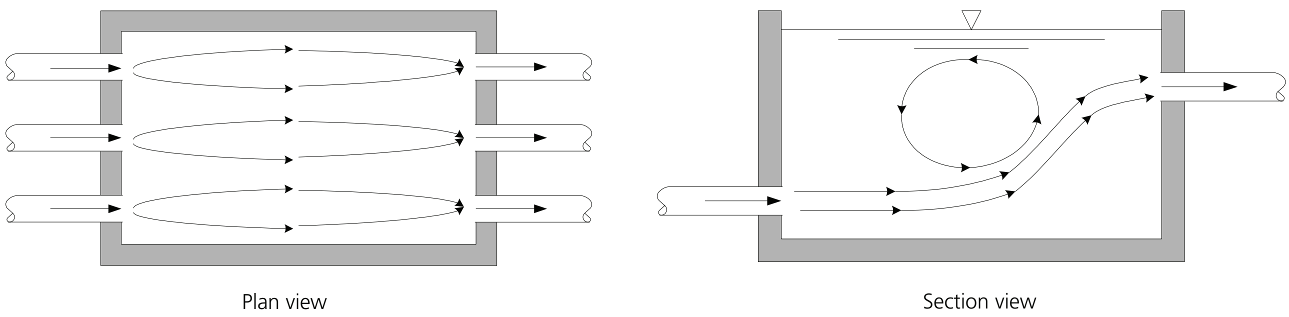

Figure 2. Poor baffling conditions in a disinfection tank (USEPA, 2003a)

(PWTAG, 2020). In the USA, the CDC (2020) has delegated the decision on the operation of recreational water venues to local and state authorities.

Potential contamination of surface and coastal waters and groundwater by disinfectants and disinfection by-products

The Covid-19 pandemic has changed drastically the extent of disinfectant use. This has expanded beyond medical settings with much higher hygienic standards currently required in everyday activities. Some countries, such as Italy, South Korea, the UAE and China, have imposed night curfews in order to clean the streets in major cities with a weak disinfectant solution. The USEPA (2020a) has listed 392 disinfectant products (List N) that are effective against Sars-CoV-2. These disinfectants can be broadly divided into alcohol, bleach, hydrogen peroxide and quaternary ammonium compounds. For residential use, the list of active ingredients together with the contact time needed to inactivate coronaviruses is given in Table 1.

Most of the disinfectants used in medical centres are sodium hypochlorite-based (ESR, 2015; Fukuzaki, 2006; Rutala and Weber, 1997). During the Covid-19 pandemic, heavy usage of these disinfectant products was also done in households. Thus, the percentage of waste that would contain traces of sodium hypochlorite is expected to increase during the pandemic, resulting in this chemical becoming part of the landfill leachate. In addition, the practice to spray outdoor public spaces, including roads, schools and buildings that had hosted infected persons, has directly inserted disinfectants into the storm drainage systems of many cities, thus discharging them into rivers, streams and coastal waters.

Rook (1974) found that hypochlorous acid is formed when sodium hypochlorite is added to water, and in the presence of bromine, hypobromous acid is formed. These two acids react with natural organic matter to produce many water disinfection by-products, including the four primary trihalomethanes (THMs), which are chloroform, bromodichloromethane, dibromochloromethane and bromoform, referred to as total THMs (TTHMs). Medeiros *et al.* (2019) reviewed the toxicological aspects of THMs and concluded that they pose potential genotoxic and carcinogenic health risks, particularly for the liver and kidney.

Table 1. Active ingredients and their working concentrations effective against coronaviruses (NEA, 2020)

Active ingredient	Contact time: min
Accelerated hydrogen peroxide (0.5%)	1
Benzalkonium chloride (0.05%)	10
Chloroxylenol (0.12%)	10
Ethyl alcohol (70%)	10
Iodine in iodophor (50 ppm)	10
Isopropanol (50%)	10
Povidone-iodine (1% iodine)	1
Sodium hypochlorite (0.05–0.50%)	5
Sodium chlorite (0.23%)	10

TTHMs are limited to 80 parts per billion, or 0.080 mg/l, in treated drinking water in the USA (USEPA, 2010). The Australian Drinking Water Guidelines (ADWG, 2004) recommends that THM levels in drinking water not exceed 0.25 mg/l. The guidelines for drinking water by WHO (2017), shown in Table 2, specify the upper limits of THM concentrations in drinking water.

Landfill leachate is a complex liquid the chemical composition of which is controlled by waste type and nature, among other factors (Iskander *et al.*, 2018; Renou *et al.*, 2008). During the pandemic, the impact of excess sodium hypochlorite on leachate chemistry should be monitored. Although the composition of leachate is site-specific, the organic content of leachate is generally a few tens to thousands times higher than that of sewage (Li and Deng, 2012). The presence of organic matter and hypochlorite in landfill leachate could trigger the formation of THM. This could be troubling, particularly for landfills that have not been designed with leachate collection systems (Li and Deng, 2012), such as several smaller regional landfills in Australia (Australian National Waste Report, 2016). Stuart *et al.* (2001) investigated the potential for THM formation in aquifers contaminated by leaking landfills in Mexico, Jordan and Thailand and detected THM concentrations up to 4.551 mg/l at several monitoring wells of the study sites.

There is a need to conduct more studies to assess the potential for THM formation in landfill leachate, as well as the retention and diffusion properties of THM through landfill clay liners. Finally, given the injection of disinfectants into the storm drainage systems of cities practicing public space disinfection, the effect on the ecosystems of rivers, streams and coastal waters where these systems are discharging must be urgently studied.

Threats and risks to rural areas and developing countries

The Covid-19 pandemic presents an acute threat for developing countries, in particular those that are densely populated and struggling with the impact of other health and social problems. For Sars-CoV-2, which is easily transmitted, mass congregation in places that also have poor infrastructure can favour disease transmission. Management of the pandemic in such areas can be accomplished with safe and readily available drinking water, sanitation and hygiene (Wash) (Unicef, 2020). Figure 3, which shows for Asia and the Pacific the relation between per capita gross domestic product (GDP) and household water security (HWS), indicates that countries with low GDP have low HWS, thus raising the issue of the effect of the pandemic on low-GDP and low-HWS countries (ADB, 2016).

Table 2. Guideline values for THMs in drinking water (WHO, 2017)

THM	Guideline value: mg/l
Chloroform	0.30
Bromoform	0.10
Dibromochloromethane	0.10
Bromodichloromethane	0.06

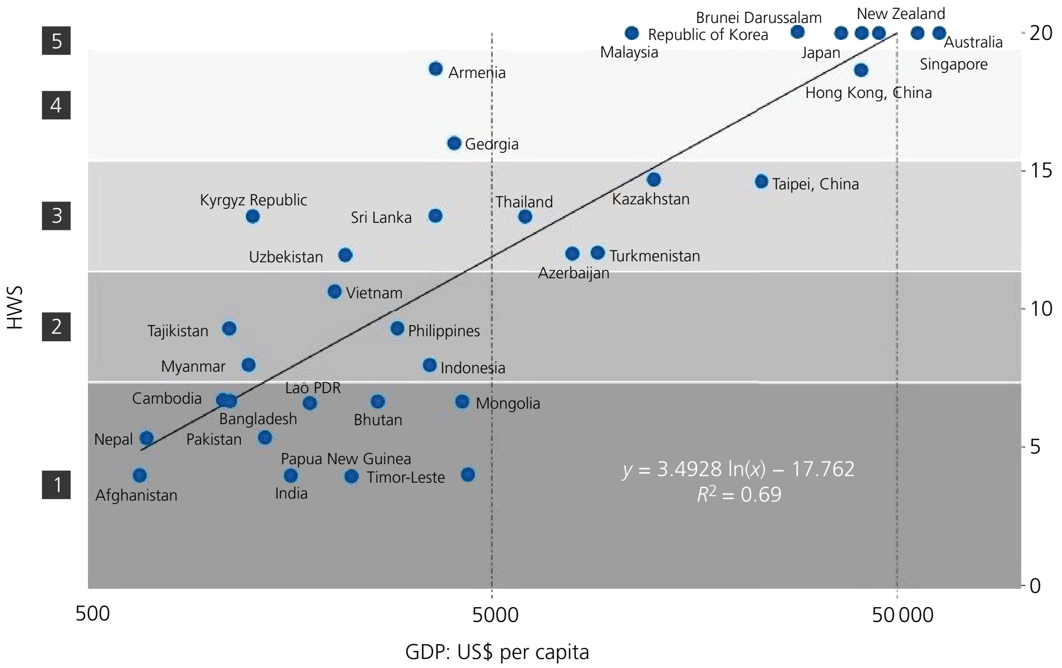

Figure 3. Relation between per capita GDP and HWS in Asia and the Pacific (ADB, 2016: Figure 12)

Concerns are growing regarding the potential impact of a Covid-19 outbreak in overcrowded settlements (including refugee camps) with little or no public services and where dwellings may be packed close together and often housing several family members in one room. Such settings can become the nexus for water and sanitation-related infectious disease transmission, leaving little opportunity to follow social distancing guidelines and self-isolation when required. In such cases, sanitation measures may include provision of handwashing stations and distributing soap, detergent and hygiene kits. For example, in 2017, only 60% of the global population had a basic handwashing facility with soap and water available at home (Concern Worldwide, 2020). Where water is not readily available, people may decide that handwashing is not a priority, thereby adding to the likelihood of Covid-19 and other disease infections.

A major issue in rural areas is the lack of adequate public water supply systems. Hence, a large portion of the rural population in several countries find it difficult to access properly disinfected water (Gall *et al.*, 2015; Unicef, 2020). According to the 2016 AWDO (ADB, 2016), Asia accounts for half of the world's poorest people, where irrigation and agricultural practices consume 80% of the limited water resources of the region. Figure 4 shows the disparity in the percentage of piped water supply systems serving the general population (household) against those living in towns and cities (urban) in Asia and the Pacific. This figure is based on data provided in appendices 2 and 4 of AWDO (ADB, 2016) and shows that for several countries, such as Afghanistan, Bangladesh, Cambodia, India, Indonesia, Laos, Nepal and Vietnam, less than 30% of the population, in 2016, received piped water.

Currently, about 1.7 billion people in Asia lack access to basic sanitation. Figure 5, based on data in appendix 4 of AWDO (ADB, 2016), shows the ten countries in Asia and the Pacific where less than 50% of their urban population have access to a sewerage collection network (Figure 5(a)) and the top ten countries in the same region where more than 70% of the urban population have access to a central sewerage system (Figure 5(b)).

The urgency to address health-related infrastructure issues between water and sanitation, and public health and environmental pollution, calls for research in some of the following areas:

- application of cost-effective methods for detection of infectious viruses in water and waste water systems (Gall *et al.*, 2015; Pejcic *et al.*, 2006; Wigginton *et al.*, 2015) and the use of novel remediation technologies (e.g. Koshy and Singh, 2016) in the case of contamination (Mohamed *et al.*, 2020; Paleologos *et al.*, 2014)
- evaluation of the survival rate of infectious viruses in water bodies and waste water systems under different conditions of temperature, humidity, pH and so on (Wigginton *et al.*, 2015; Ye *et al.*, 2016)
- development of techniques for inactivation of infectious viruses within water and waste water bodies and prevention of cross-contamination in distribution networks (Ye *et al.*, 2016)

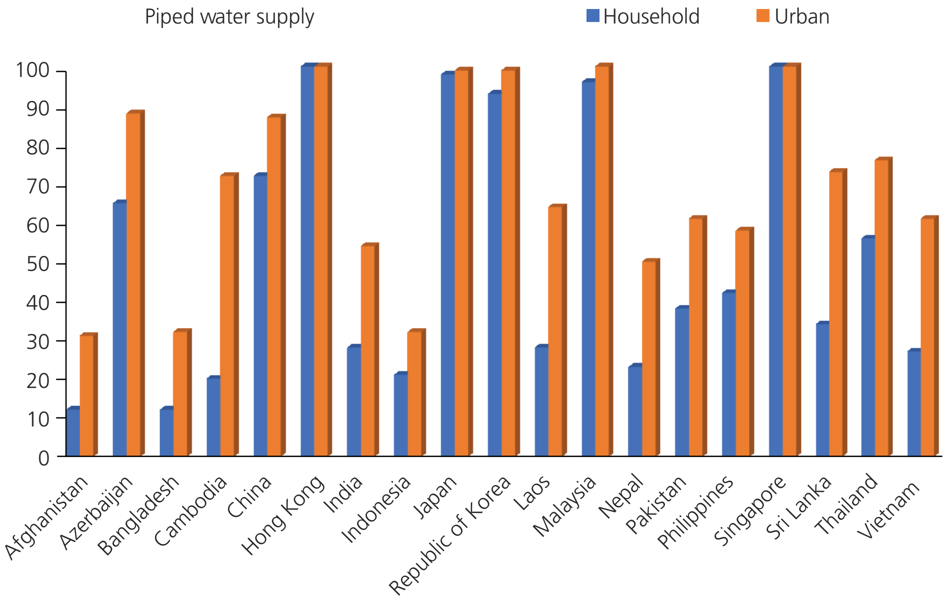

Figure 4. Percentage of piped water supply in households and urban centres in Asia and the Pacific

- risk assessment of the threat on the quality of surface water, groundwater and coastal water that may have received waste waters containing high loads of viruses, disinfectants and disinfectant by-products and pharmaceuticals during the pandemic (Li and Mitch, 2018; Wen *et al.*, 2017).

Simultaneously, humanitarian response infrastructure, such as building/improving water services and providing additional water supply points, must be quickly upscaled during the Covid-19 pandemic. In the least developed countries, for example, 22% of healthcare facilities have no water service, 21% have no sanitation service and 22% have no waste-management service (WHO, 2019).

There exists the possibility that a potential spread of the Sars-CoV-2 virus through waste water may not be as significant in rural areas in Asia compared with urban centres, due to their lack of centralised waste water systems. To treat the smaller volumes of waste water that are generated in remote areas, constructed wetlands may be considered (Wu *et al.*, 2011), taking precautions that no secondary contamination of local soil and groundwater sources takes place. To avoid the latter, geosynthetic liners (Patil *et al.*, 2017), pure zeolites (natural and synthetic types) and fly ash zeolites (processed from class F fly ash) may be used (Jha and Singh, 2011, 2016; Koshy and Singh, 2016).

Reuse of waste water, to recover water, nutrients and/or energy, is becoming an important strategy, particularly in water-stressed areas. Biosolids, treated by-products of the waste-water-treatment process, contain high levels of nutrients and are used as organic fertilisers in agriculture and forestry, although co-disposal in sanitary landfills remains a common practice in various parts of the world (O'Kelly, 2005; O'Kelly *et al.*, 2020). The presence of the Sars-CoV-2 and other pathogens in these residue streams requires careful consideration. Similar concerns exist for the residue materials from the various processes at WTPs, which include temporary storage/stockpiling and stabilisation, and the properties/behaviour of these materials during in situ biodegradation (Babatunde and Zhao, 2007; Fei *et al.*, 2017; O'Kelly, 2008).

Challenges and risks of Sars-CoV-2 in waste water systems

The presence of coronaviruses in human excrement and environmental media

Sars-CoV-2 has been found to be followed by diarrhoea in 2–50% of cases (D'Amico *et al.*, 2020), viral ribonucleic acid to have remained detectable in children's stools for longer than 4 weeks (Xing *et al.*, 2020) and children to test positive on rectal swabs after they had tested negative for Covid-19 in nasopharyngeal testing (Xu *et al.*, 2020a), all of which led Zhang *et al.* (2020) to warn that Sars-CoV-2 may be shed through multiple routes. Similarly, both Sars-CoV-1 (the coronavirus that caused Sars in 2003) and Mers-CoV (the coronavirus that caused Mers in 2012) were found in blood, urine and faeces (Corman *et al.*, 2016; Wang *et al.*, 2005b, 2005c).

van Doremalen *et al.* (2020) compared the viability of Sars-CoV-2 and Sars-CoV-1 in aerosols and on plastic, stainless steel, copper and cardboard. They found that the stability of the two viruses was similar in the examined media and concluded that the transmission of Sars-CoV-2 is 'plausible' by way of aerosols and fomites 'since the virus can remain viable and infectious in aerosols for hours and on surfaces up to days'. Wang *et al.* (2005a: p. 171) found that '…

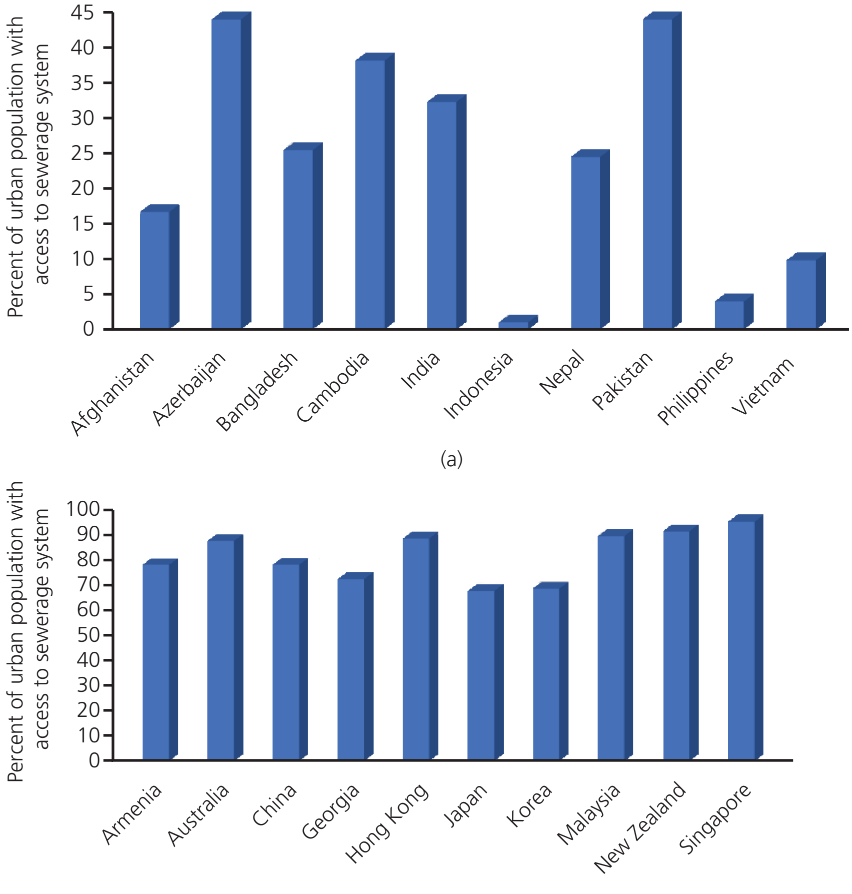

Figure 5. Countries in Asia and the Pacific where (a) less than 50% and (b) more than 70% of the urban population have access to a sewage collection system

in vitro experiments demonstrated that the … [Sars-CoV] … virus could only persist for 2 days in hospital wastewater, domestic sewage and dechlorinated tap water … at 20 degrees C. However, at 4 degrees C, the SARS-CoV could persist for 14 days in wastewater …'. In accordance with Liu (2003) that Sars-CoV 'could be inactivated within a few minutes by 500–1000 mg/L of chlorine' or 'be killed with ultraviolet radiation or heating for 30 min', Wang *et al*. (2005a: p. 176), based also on past studies (Cyranoski and Abbott, 2003), concluded that 'SARS-CoV … is highly sensitive to conventional disinfectant,' and hence 'there is little possibility for another outbreak caused by SARS-CoV from environmental sources'. In terms of Sars-CoV-2, its presence has been documented in hospital sewage lines (Wang *et al*., 2020) and community waste water collection sites, setting the stage for the virus to enter community waterways (Lodder and de Roda Husman 2020; Núñez-Delgado, 2020).

Water droplet transmission from faulty plumbing was implicated in an outbreak of Sars-CoV-1 in an apartment building in Hong Kong (McKinney *et al*., 2006; WHO, 2003). The cause was identified as defects in the sewage system, which facilitated the transport of 'virus-laden droplets' through empty U-bends in bathrooms, from where their ventilation system drew them into other rooms (Gormley *et al*., 2020). The last authors asserted that 'the potential for a substantial viral load within the wastewater plumbing system (and therefore the main sewer system), in combination with the potential for airborne transmission due to aerosolisation of the virus, calls for wastewater plumbing systems to be considered as a potential transmission pathway for COVID-19. The interconnectedness of the wastewater plumbing network can facilitate exposure to SARS-CoV-2 within, or even between, buildings' (Gormley *et al*., 2020: p. 1). Such aerosolisation and droplets produced during toilette flushing has been seen as a mechanism for the spreading of several types of enteric viruses (Naddeo and Liu, 2020; Verani *et al*., 2014).

Investigations of related animal coronaviruses indicated that these can persist in lake water and pasteurised sewage water, remaining infectious for a period of days to weeks (Casanova *et al*., 2009). Taken together, the available evidence suggests that the Sars-CoV-2 virus may also appear in environmental water systems, which may serve as reservoirs for human diseases.

The USEPA (2020b) has stated that standard treatment and disinfection processes at WWTPs are expected to be effective in eliminating the virus from waste water. Utilities in several Europe countries, such as the Czech Republic or Poland (IGWP, 2020), have issued similar communiqués. In contrast, China has asked WWTPs to increase the use of chlorine for disinfection in order to ensure that Sars-CoV-2 will not be spread by way of waste water (Taleb *et al*., 2020; Zambrano-Monserrate *et al*., 2020).

The 23 April 2020 interim guidance by WHO and the UN Children's Fund (WHO and Unicef, 2020: p. 2) on water and waste water has reassured that 'significant (99.9% removal) of coronaviruses was observed in 2 days in primary sewage effluent at 23°C, 2 weeks in pasteurised settled sewage at 25°C and 4 weeks in reagent grade water at 25°C. High temperature, high or low pH, and sunlight all facilitate virus reduction'. The same communiqué has opined that in 'well-designed and well-managed centralised wastewater treatment works, each stage of treatment (as well as retention time and dilution) results in a further reduction of the potential risk' from the virus (WHO and Unicef, 2020: p. 2). WWTPs that are not optimised to remove viruses are recommended to include a final disinfection.

The biosolid by-products of WWTP processes contain various pathogenic microorganisms, bacteriophages and human viruses (Pepper *et al*., 2006; Sharma *et al*., 2016). Some typical pathogens that have been seen to transfer from biosolids to the geoenvironment are bacteria, enteric viruses and helminths. Biosolids have been classified into class A and class B depending on the desired type of application and the corresponding level of treatment, with the content of pathogens varying in these two classes (USEPA, 2003b).

The transfer of pathogens from biosolids into soil and water systems has been a cause of concern. It is estimated that the amount of pathogens in the biosolids from anaerobic digestion is generally on the order of 10^3–10^4 plaque-forming units/g (Bitton *et al*., 1984; Wong *et al*., 2010). The survival of these pathogens in the environment depends on the physiological state of cells (Pepper *et al*., 2006) and geoenvironmental factors, such as clay and organic matter content, soil mineralogy, nature of pore fluid, degree of saturation and temperature (Xagoraraki *et al*., 2014). Adsorption of viruses onto soils depends on the pH of the geoenvironment. Viruses in biosolids have been found to leach significantly even after sequential extraction under laboratory conditions, indicating their slow desorption from soil surfaces. However, once leached into the geoenvironment, they tend to migrate with minimal retention into the porous matrix, particularly in the case of coarse-grained soils (Chetochine *et al*., 2006). The relatively low degree of adsorption of viruses onto sands results in their transport in the subsurface environment through groundwater flow. Not only can this contaminate groundwater resources but it also has the potential to pollute surface water bodies that are in hydraulic communication with affected aquifers. Land application of biosolids is also a potential aerosol-generating operation (Brooks *et al*., 2005) that may favour the propensity of viruses to transmit through aerosols (Wigginton *et al*., 2015). Given the nature of transmission of Sars-CoV-2 through droplets and its stability in aerosols (van Doremalen *et al*., 2020), it is necessary to re-examine the use of biosolids for land applications under the current conditions.

Containment of the migration of Sars-CoV-2 from septic tanks, waste water effluent disposal sites and landfills to the geoenvironment is critical (Qin *et al*., 2020; Seetha *et al*., 2015). It should be noted that the mobility of viruses varies under saturated or unsaturated subsurface conditions and that their survival depends on temperature, moisture content, viral adsorption onto soils, the presence of antagonistic microorganisms, organic matter content and so on (Gundy *et al*., 2008; Hurst *et al*., 1980; Qin *et al*., 2020; Seetha *et al*., 2015). In this regard, the influences on the migration of Sars-CoV-2 in soils and water should be studied more extensively.

The xenobiotic paradigm in waste waters and the environment

An analogy could be drawn between the spread of xenobiotics in the geoenvironment and that of the Sars-CoV-2. Xenobiotics, substances foreign to biotic systems, such as pharmaceuticals, food additives, hydrocarbons and other man-made products, are seen to be present in waste water effluents in ever-increasing quantities. Current waste water discharge practices appear to have contributed to the spread of these pollutants, and treatment options are being developed to address them. With respect to the likelihood of Sars-CoV-2 entering aquatic and geologic environments, it would be helpful to review briefly the xenobiotic history of how these contaminants, which remained undetected for some time, were able to spread in the geoenvironment.

Municipal waste water contains a complex mixture of xenobiotic organic compounds that are discharged into waste water from households, hospitals, industries and so on (Lindblom *et al*., 2009). Such emerging environmental pollutants include pharmaceutical compounds (PhCs), which are extensively and increasingly being used in human and veterinary medicine (Fent *et al*., 2006). Around 80–100 pharmaceuticals and their metabolites have been measured in both effluent and surface waters in numerous countries (Fent *et al*., 2006; Kot-Wasik *et al*., 2007). Pharmaceuticals have similar physiochemical characteristics as harmful xenobiotics – for example, they can pass through membranes, are relatively persistent and may also be mobile in the environment (Kot-Wasik *et al*., 2007; Quinn *et al*., 2008). When released in the environment, they may impose toxicity on all levels of the biological hierarchy – that is, cells, organs, organisms, population, ecosystems or the ecosphere. In addition to toxic effects, certain classes of PhCs, such as antibiotics, may cause long-term and irreversible changes to microorganism genomes, even at low concentrations, making them resistant to antibiotic treatment (Klavarioti *et al*., 2009).

Most municipal WWTPs include preliminary, primary and secondary treatment processes with the final effluent being discharged into surface water bodies and often indirectly reused for irrigation (Michael *et al*., 2013). Verlicchi *et al*. (2012) showed that many PhCs are present in raw sewage influents at concentrations between 10^{-3} and 10^{2} µg/l and that common WWTPs are not able to remove them efficiently. The effect of biological treatments, membrane filtration, activated carbon adsorption, AOPs and disinfection on different classes of antibiotics has been investigated over recent years (e.g. Michael *et al*., 2013).

In retrospect, it has been realised that the spread of PhCs has been aided by the release of treated waste water in the aquatic environment and by the use of 'grey water' for irrigation. In addition, the land applications of sludge that is produced by WWTPs have also contaminated soils with PhCs. When considering the present pandemic situation, careful thought must be given to the vectors by which the Sars-CoV-2 could spread through liquid and solid waste disposal practices, and scientists and engineers should re-examine the relevant civil infrastructure in light of the 'new normal' posed by the Covid-19 pandemic. As final thoughts, sewage surveillance pilot programmes could be implemented to monitor Sars-CoV-2 circulation at different treatment stages in WWTPs with changing levels of organic matter and suspended solids (at ambient temperatures), along with sampling of the treated waste water that is released into water bodies in order to quantify the potential presence of the virus.

Conclusions and future research directions

The present paper highlights a multidisciplinary perspective on the potential of water and waste water to operate as transmission routes for the Sars-CoV-2 virus, which may further become the origin of geoenvironmental degradation. Migration of viruses, pathogens and contaminants in water, waste water and soil under various environmental conditions (viz. temperature, humidity and pH) is crucial to understand their fate and threat posed to surface and coastal waters and groundwater, as well as the geoenvironment in totality. Other realities of the Covid-19 pandemic are increased demand on water supply and waste-water-management systems across the world owing to more frequent personal hygiene measures. In this context, the following research directions should be explored in order to enhance the management of water and waste water systems under conditions of public health crises.

- Development of low-cost virus detection systems is essential, along with urgently needed water- and waste-water-based epidemiology systems for controlling the spread of waterborne pandemics.
- Studies are needed on the influence of pollutant load and viruses on the self-cleaning mechanisms and eutrophication of surface water bodies.
- Environmental scientists/engineers should work together with scientists in other disciplines to understand the spread of infectious viruses and pharmaceuticals through biosolids (in many occasions used as soil fertilisers) and by the use of grey water and untreated water for irrigation.
- The effectiveness of willow evapotranspiration and constructed wetland methods for in situ treatment of domestic waste water contaminated with disinfectants and pathogens should be studied for their feasibility in rural localities.
- Utilisation of fly-ash-based zeolites in the treatment of water and waste water for removal of contaminants (viz. heavy metals, pharmaceuticals and pathogens) should be explored.
- The fate and spread of xenobiotic substances present in waste-water-treatment systems should be modelled to estimate their toxicity to the organisms, cells and plants species present in waste-water-treatment systems.
- The migration and leachability of pathogens and viruses into the geoenvironment from biosolids stored at temporary storage facilities require special attention.
- Metagenomic sequencing operations should be considered for water and waste water transmission and treatment systems in order to avoid degradation of the geoenvironment.
- Studies are needed to assess the potential for THM formation in landfill leachate and the retention and diffusion properties of THMs through landfill clay liners.
- Finally, given the injection of disinfectants into the storm drainage systems of cities practicing public space disinfection during the Covid-19 pandemic, the effect on the ecosystems of rivers, streams and coastal waters where these systems discharge must be studied.

In conclusion, the time has come, after 150 years of successful measures for the treatment of water and waste water, which have vastly improved the health of the population, to re-evaluate the operation of the WTP and WWTP systems in view of the recent pandemic. Research efforts on the aforementioned areas can potentially help in augmenting the role of WTPs and WWTPs during the Covid-19 pandemic and to address future health and environmental challenges.

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