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Post COVID-19 Water and Wastewater Management to Protect Public Health and Geoenvironment

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Abstract

The COVID-19 pandemic is posing severe threats to humans and the geoenvironment. The findings of SARS-CoV-2 traces in wastewater network and treatment systems, and the daily practice in several cities in the world of disinfecting outdoor spaces, which can result into the entry of disinfectants into the storm drainage systems and the subsequent discharge into rivers and coastal waters, raises the issue of environmental, ecological, and public health impacts. The aims of the current article are to investigate the potential of water and wastewater to operate as transmission routes for the SARS-CoV-2, and the risks and threats by a potential entry of the virus into water and wastewater treatment systems to both public health and the geoenvironment. Especially for developing countries where measures for the protection of water resources, and controls on the treatment of drinking water and wastewater may be sub-standard or not in place, it is critical to identify potential transmission routes and threats. The article also calls for multidisciplinary research investigations, including, among others, migration mechanisms and impact of viruses and disinfectants in the geoenvironment, in a belief that such efforts would result in the development of robust solutions in water/wastewater system upgrades to combat future pandemics.

Keywords: COVID-19; drinking water; wastewater management; transmission routes; geoenvironmental degradation; public health

1. Introduction

Humanity is facing the most demanding challenge of the 21st century to date, a global pandemic caused by a new kind of coronavirus, the SARS-CoV-2. However, the COVID-19 pandemic is just one among many possible deadly diseases that humans can face, caused by different types of microorganisms, such as viruses, bacteria, and protozoa. Historically, humanity has faced several infectious diseases that on some occasions have left it significantly reduced in numbers (History Channel, 2020). In almost all cases, infectious diseases have a zoonotic origin, that is, the infectious agent is transmitted from an animal to a human. This zoonotic origin is just the initial transmission step, the spread of a pandemic requiring the confluence of several factors, such as international travel and trade, globalization of food supplies, changes in food processing, use of antibiotics, environmental changes, adaptation of microorganisms, etc. (Manivannan, 2008).

Transmission routes of infectious diseases are varied and include direct contact with respiratory droplets from infected persons, mosquito bites, and/or consumption or contact with polluted food or water. Water can be polluted via many pathways and especially by wastewater, either through the discharge of inadequately treated wastewater into water bodies, or leakage from defective and/or deteriorated sewerage systems that can contaminate the groundwater.

The presence of the SARS-CoV-2 virus has recently been detected in untreated wastewater (sewage) in Schiphol Airport, Amsterdam, and Tilburg, the Netherlands (Lodder and de Roda Husman, 2020; Medema *et al.*, 2020), in Queensland, Australia (Ahmed *et al.*, 2020), in Thessaloniki, Greece (Papaioannou, 2020), and in Massachusetts, USA (Wu *et al.*, 2020). Recently, Xiao *et al.* (2020) found evidence of SARS-CoV-2 RNA in a stool specimen, Zhang *et al.* (2020) found the virus present in anal swabs and blood, while Guo *et al.* (2020) reported the virus in the saliva of infected dental patients, raising the question of viral gastrointestinal infection, and of oral and fecal transmission routes for the virus.

Generally, water is the main vehicle of transmission of pathogenic germs such as bacteria

(*Campylobacter jejuni, Campylobacter coli; Escherichia coli*, *Legionella spp.*, *Pseudomonas aeruginosa*, *Vibrio cholerae*, *Salmonella typhi*, etc.); viruses (*Adenovirus*, *Enterovirus*, *VHA*, *Rotavirus*, etc.); protozoa (*Cryptosporidium parvum*, *Entamoeba histolytica*, *Giardia intestinalis*, *Naegleria fowleri*, etc.), and helminths (*Dracunculus medinensis*, *Schistosoma spp.*) (Mosteo *et al.*, 2013). Usually, most of these microorganisms have a fecal origin, because they inhabit the gastrointestinal tract of humans and warm-blooded animals. These microorganisms are discharged via human and animal feces, and they can reach surface and/or ground waters through discharged wastewater or in diffuse ways, including via contaminated runoff waters from agricultural areas and septic tanks (Mosteo *et al.*, 2013). The main pathways to a person is through the direct intake of contaminated water, or the consumption of raw vegetable or fruit that has come into contact with such water (Marín-Galvín, 2003). Additional routes can be the inhalation of polluted water droplets (this is the case of *Legionella spp.* and the primary amoebic meningoencephalitis caused by the amoeba *Naegleria fowleri*), or even dermal contact with polluted water (some of the causative species are *Pseudomonas aeruginosa*, *Klebsiella* and *Aeromonas*).

The pathogens that can grow and proliferate in water, or those with high resistance to decay outside of the human or animal bodies are the ones that can cause infectious diseases. This is the case of bacteria such as *Legionella spp.*, *Vibrio cholerae*, *Nagleria fowleri* and *Acanthamoeba*, whose growth is favored by high contents of biodegradable organic matter and high temperature. Some pathogens, such as viruses and parasites (cysts, oocysts and eggs) do not have the ability to grow or proliferate in water. After leaving the body of an infected human or animal they lose their viability and ability to live and infect, making them undetectable after a certain period. Importantly, it should be noted that although a pathogen’s lifetime in water may be short, this does not prevent a possible transmission through water.

Gundy *et al.* (2008) conducted a study on the survival of coronaviruses and polioviruses in tap water and wastewater. They observed that the coronavirus survived for up to 100 days in tap water at 4ºC, whereas it got inactivated within 10 days in room-temperature water. Temperature appeared to be the main factor for survival of the virus, 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 favored by unfiltered tap water and wastewater having high suspended solids. Casanova *et al.* (2009) have shown that coronaviruses can be infectious for long periods of time while in water and wastewater (17 to 22 days at room temperature and more than 4 weeks at 4ºC). In addition, Slater *et al.* (2011) found out that antivirals and antibiotics, which were given for treatment during the 2009-2010 influenza pandemic, entered wastewater treatment plants (WWTPs), thereby affecting the efficacy of their bacterial communities.

In order to minimize disease transmission during epidemics from hospital wastewaters that may have a high load of pathogens, Sozzi *et al.* (2015) suggested that they are first treated in-situ, before being discharged into the municipal sewerage network. Two protocols were tested, coagulation and disinfection at high pH levels, and disinfection followed by coagulation at low pH levels by varying the disinfecting agents, with both protocols proving to be successful in disinfecting hospital wastewaters and sludge.

Wigginton *et al.* (2015) reviewed the effects on drinking water and wastewater treatment systems of viruses, such as Influenza-H1N1, SARS, MERS, and Avian flu, which can be expelled via body fluids like vomit, urine and feces. They mentioned that “many enveloped viruses are capable of retaining infectivity for days to months in aqueous environments.” Hence, during the outbreak of an epidemic/pandemic it is important to frequently test and disinfect drinking water and wastewater in order to control the spread of the epidemic. Bibby *et al.* (2015) investigated the survival of Ebola virus in wastewater. Although viral count rapidly subsided over a period of 8 days in a laboratory setting, the same could not be confirmed in an active sewage system. These authors suggested retaining the viral-contaminated wastewater for at least one week before allowing it to enter the sewerage network and on to a wastewater treatment plant (WWTP), as well as implementing higher-level protective measures for WWTP staff. This is consistent with the earlier mentioned recommendation by Sozzi *et al.* (2015) for in-situ treatment of hospital wastewaters suspected of high pathogen loads during epidemics.

Because of this risk of transmission via water, disinfection of drinking water is vital in order to prevent waterborne diseases. Although there are references about water disinfection dating back thousands of years, it was not until John Snow related the cholera epidemic occurring in London in 1854 with the public fountains in the city that the public health aspects of water were understood in modern times (Smith, 1999). Since then, removal of pathogens from potable water has been the primary focus of water utilities. Unfortunately, access to safe water is not yet possible in many areas of the world.

Numerous techniques have been developed for the removal of pathogenic microorganisms from drinking water and wastewater. Pathogens can be removed by physical adsorption on biological or inert solids, filtration, or biological treatments (e.g. activated sludge) (López *et al.*, 2019). However, the most widely used method to eliminate pathogenic microorganisms from water is disinfection (Gerardi and Zimmerman, 2005).

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. In addition to these methods, more recent developments include the application of advanced oxidation processes (AOPs) that combine high oxidation chemical compounds with elements capable of activating them (UV, ultrasound, heat, catalysts) 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 the disinfection techniques described can inactivate pathogenic microorganisms, not all of them have the same efficacy in the elimination of viruses. Comparison of the most widely used chemical disinfectants reveals that for most viruses the efficacy decreases as follow: *Ozone*> *Chlorine dioxide*> *Chlorine* (Watts *et al.*, 1995; USEPA, 1999a). However, it is essential to note that this is not always the case, as the result may vary depending on the species studied and the characteristics of the water. The importance of securing wastewater systems has been pointed out by Nghiem (2020), who referred to a potential SARS-CoV-2 viral transmission from aerosols from wastewater systems. Scientists at some US universities have also called for the assessment of drinking water and wastewater systems especially those in developing countries (ScienceDaily, 2020).

During the COVID-19 pandemic, the World Health Organization (WHO) has advised hand wash with sanitizer/soap for mitigating the transmission of SARS-CoV-2 from any suspicious/infected persons and/or surfaces. However, more than 3 billion people worldwide lack sanitizers/soap and water to maintain proper hygiene. In addition, in rural areas, especially in developing countries, people are often driven to use untreated water obtained from rivers, ponds, spring, wells and hand-dug wells that are often located at considerable distances from their residence, and the quality of which may be questionable. Hence, transmission of SARS-CoV-2 in those areas is possible with the congregation of people at water sources and their exposure to infected persons. A side effect of the frequent use of sanitizers/soap would be the future eutrophication of local water bodies due to excessive input of phosphate and nitrogen. In addition, the presence of SARS-CoV2 traces in the wastewater management systems of several developed countries, which operate under strict environmental regulations, is worrisome, but possibly of greater concern are the sanitary systems of densely populated developing countries, where the majority of the population (over 65%) resides in rural areas.

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 wastewater may be sub-standard by World Health Organization (WHO) guidelines (WHO, 2017) or not in place, the current article has the following three major overarching aims. Firstly, to investigate the potential of water and wastewater to operate as transmission routes for the SARS-Co V-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 wastewater treatment systems, both for developed and developing countries.

Thirdly, to raise the issue of disinfectants' application on outdoor public spaces in many cities in the world, which upon entering storm drainage systems find their way to surface and coastal waters.

2. Geoenvironmental Engineering's Role in Pandemics and Public Health Issues

Pandemics such as COVID-19 and their health, financial, and social impacts are not new. The plague of ancient Athens in 430BC is perhaps the first famous case of an epidemic, recorded in Thucydides' *History of the Peloponnesian War* (http://classics.mit.edu//Thucydides/pelopwar.html) with even the victims' symptoms detailed. It appears to have originated from Ethiopia and transferred to Egypt and Greece with the agent debated as being the Salmonella or typhoid bacteria or even the Ebola virus (Papagrikorakis *et al.*, 2008; Smith, 1996). The Plague of Justinian (541-542 AD, but with recurrences until 750AD) was the first known major pandemic caused by the gram-negative bacterium *Yersinia pestis*. It probably originated from Central Asia and afflicted the Byzantine Empire, the Sasanian Empire (the last kingdom in Iran before the spread of Islam), and cities in the Mediterranean area. It was imported in Constantinople, the capital of Byzantium by infected rats on ships carrying grain from Egypt (Procopius, *History of the Wars Book II* http://www.gutenberg.org/files/16764/16764-h/16764-h.htm). 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 the Plague of Justinian. It originated from Central Asia and through trade passed from Crimea to Italy. Estimates of its deaths are in the several tens of millions and its aftermath was the complete transformation of European medieval society and rebellions (Cartwright, 2020). This was the first time that official patient isolation was enforced in Venice, with returning sailors put under a 40 day "*quarantino*". The plague did not subside in London, where it lasted from 1348 until 1665, resurfacing during this period roughly every twenty years, and in its last appearance claiming 100,000 lives in seven months (History Channel, 2020).

Smallpox caused by the *variola virus* was imported by the Europeans in the New World (North and South Americas) and decimated the indigenous people of Mexico in the 15th century (History Channel, 2020), and later on in the 1600s about seventy percent of the native American population in the Northeast of the United States (Healthline, 2020).

The association between liquid and solid waste contamination of the water resources and public health became obvious during the cholera (a bacterial infection) outbreaks of the 19th century. Descriptions of the poor water quality at several European cities can be found in the memoirs of Benjamin Franklin, James Madison, and of other prominent Americans visiting Europe in the 18th century. In Imperial Paris at mid-nineteen century there were no public water-supply or sewerage systems. "*The citizens of Paris took their water supplies from roof-fed cisterns, or from occasional wells, or from the River Seine and its various minor tributaries*" (Freeze, 1994). At the same time, "*the Seine was both the source and the sink for the Parisian water system … In 1848 … 20,000 Parisians died in a cholera epidemic"* (Freeze, 1994). As a result of this, Paris developed a citywide drinking water and sewerage system by the mid-1860s. Henry Darcy, who was Chief Engineer of the Côte d' Or (one of the 83 administrative departments in France), conducted his famous experiments during the planning and construction of the water distribution system at Dijon, France, which he initiated in 1830 and concluded in 1840, twenty-five years earlier than Paris (see Freeze (1994) for a description of the life and career of Darcy).

The city of London faced four major cholera outbreaks, in 1831, 1848–49, 1853–54 and again in 1866. John Snow, a British doctor mapped the radius of cholera deaths in 1854 London and traced them to a popular drinking water well in SoHo that had been contaminated, thus establishing one of the first epidemiological studies in modern times (Smith, 1999; Ball, 2009). The cholera problem in London was eventually solved after Joseph Bazalgette, Chief Engineer of London's Metropolitan Board of Works, supervised the creation of a series of sewers (finalized in 1875), which moved the wastewater away from River Thames (Mohamed and

Paleologos, 2017).

Finally, after a series of cholera outbreaks the city of New York (NYC) started constructing its sewerage system in 1849, connecting almost all of the city by 1902, and finalizing it in the 1930s in order to address the pollution problems from raw sewage entering the NYC harbor. The NYC water supply system had relied on wells until the mid-nineteen century, with reservoirs and aqueducts being constructed from 1842 onward. John B. Jervis was Chief Engineer of the Croton Aqueduct, which after five years of construction brought fresh water to NYC in 1842 (Pierce, 2018). 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.

Numerous field studies have confirmed the entry of human and animal viruses in water bodies. For example, Corsi *et al.* (2014) reported that human and bovine viruses were present in 63% and 46%, respectively, of runoff samples in the Milwaukee River in Wisconsin, USA. Human viruses in the samples included "*adenovirus (40% of samples), GI norovirus (10%), enterovirus (8%), rotavirus (6%), GII norovirus (1.6%) and hepatitis A virus (1.6%)*," while the bovine viruses were "*bovine polyomavirus (32%), bovine rotavirus (19%), and bovine viral diarrhea virus type 1 (5%)*" (*Corsi et al*., 2014). Benschop *et al.* (2017) analyzed sewage samples from refugee centers in the Netherlands and "*detected PVs* [polioviruses], *nonpolio EVs* [enteroviruses], *and measles virus in sewage*." Ivanova *et al.* (2019) summarized the sampling campaigns from 2004-2017 at four wastewater treatment plants in Moscow, Russia and found that 20% from a total of 5,450 samples tested positive for various viruses. These viruses included types 1-3 polioviruses (43%) and 29 different types of non-polio enteroviruses (51%).

Some of the most fatal pandemics have been viral pandemics, such as the flu, HIV/AIDS, and now COVID-19 (MPH, 2020). Another example is the Spanish flu pandemic of 1918, which was caused by an H1N1 virus of avian origin, that with its post-pandemic recurrences lasted for five years (Morens and Fauci, 2007), and resurfacing again in 1957 and 1968 (MPH, 2020). Public health and medical experts had raised the possibility of a flu pandemic if the avian influenza A (H5N5) virus "or another zoonotic influenza virus, gain the ability of sustained human-to-human transmission" (Greene, 2006; Longini *et al.*, 2007; Taubenberg *et al.*, 2007; Yang *et al.*, 2007).

In recognition of the threat to public water supplies, chlorination that was discovered in Sweden in 1774 and initially used to remove water odors, was applied as a disinfection technology in Great Britain in the late 1800s, and later, in 1908 in the United States, and in Canada in 1917 (SDWF, 2020). By the mid-20th century, chlorination was commonly performed in most developed countries' water systems, both for the treatment of drinking water to the populace and for the sanitization of wastewater prior to its discharge from WWTP. These measures have largely eliminated disease outbreaks arising from drinking water (USEPA, 2000). Levels of pathogens and of other contents in drinking water have been recommended by WHO (WHO, 2018), the European Union (EU) (European Directive 98/83/EC, 1998), among others, and regional, national, and local governments (e.g., Ontario, 2002, Health Canada, 2019). Water bodies have to be regularly monitored, sampled, and verified to assure that the quality of their water meets regulatory requirements with appropriate remedial actions needed to be taken in the opposite case (for example, see EU Water Framework Directive (2000)). 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 large mortality rates and major tolls on the population's general physical and mental wellbeing, other serious aspects to ponder for the major epidemics and pandemics described here are the huge financial instability they created followed by an equally troubling decline in the social order, the morality and ethics of the societies afflicted. The lessons from the aforementioned case examples are relevant for current epidemics and pandemics. This is because the successful reaction, from, among others, the civil, environmental, geotechnical, and municipal engineering communities, depends strongly on both the maintenance of social consensus regarding necessary public health measures (some of which, such as the lockdown measures may cease to be appealing after some time for certain parts of the population), and on the safeguarding of 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 article and in the companion paper by Tang, Paleologos, Vitone *et al*. (2020), recently published in this journal.

3. Challenges and Risks of the SARS-CoV-2 in Waters

3.1 SARS-CoV-2 in fresh and bathing waters

There have not been any studies, to date, that report infection from the SARS-CoV-2 arising from water bodies. The US Centers for Disease Control and Prevention (CDC) has stated that standard disinfection methods used in municipal water treatment plants should be sufficient to inactivate the virus (CDC, April 23, 2020). CDC has also mentioned that recreational waters in swimming pools, hot tubs, and spas, which are treated with chlorine and bromine, should pose no risk to public health if proper operation and maintenance are maintained (CDC, April 23, 2020). International standards for water chlorination recommend both a specific concentration and a Contact time (Ct), the time needed for the chlorine to act so that pathogens are killed. For drinking water this is at least 15 mg.min/l (i.e., exposure of 1 liter of water to 1 mg of free chlorine for at least 15 minutes). For swimming pools ‘current recommendations/best practice’ stipulate a free chlorine residual of at least 1.0 mg/l (depending on pool type and disinfectant used) (HPSC, 5 March 2020). Higher doses are mandated in the UK for spa pools with free chlorine at 5mg/l before emptying them, and 50mg/l for at least one hour upon refilling them (PWTAG, 20 March 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 analyze the risks posed by the new virus (HPSC, 5 March 2020; PWTAG, 20 March 2020; Water Environment Federation, 11 February 2020; WHO/UNICEF, 23 April 2020). Coxsackievirus, 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 (i.e., it is surrounded by an outer lipid membrane) and according to the Health Protection Surveillance Centre of Ireland (HPSC) it "will be inactivated at lower Ct values" (HPSC, 5 March 2020, p. 2).

However, it should be noted that the Ct of water sub-volumes 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 residence time [that is] less than τ", where τ is the average global residence time of water based on plug flow (Irish EPA, 2011). In order to account for non-ideal flow conditions, a time t_x is considered for disinfection purposes, defined as the time needed for the fastest flowing x% of water to exit from the outlet of the tank (based on tracer tests). US EPA guidelines for disinfection (USEPA, 1999b, 2003a) 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 fully disinfected, and hence potentially to pose a drinking health risk in terms of SARS-CoV-2.

In addition, despite reassurances about the effect of disinfection in swimming pools, the need for social distancing and the novelty of the risk have led many countries to issue orders for the closure of swimming pools and other recreational water bodies (the UK, for example (PWTAG, 20 March 2020)). Although rare, incidents, such as that reported by UK's Pool Water Treatment Advisory Group (PWTAG, 12 February 2020) of four children contracting the gram-negative rod bacterium

Pseudomonas aeruginosa in a holiday park in the UK, do occur. In the United States, CDC has left open the matter of the operation of recreational water venues, delegating the decision to local and state authorities (CDC, April 23, 2020).

3.2 Potential contamination of groundwater, and surface and coastal waters by disinfectants and disinfection byproducts

The current CoVID-19 pandemic has changed drastically the types of disinfectant that are used for regular cleaning. The use of disinfectant products has expanded well beyond normal practices at medical settings and much higher hygienic standards are required to combat the spread of the SARS-CoV-2 virus. Some countries, such as Italy, South Korea, Greece, the United Arab Emirates, and China are even imposing night curfews in order to clean the streets in major cities with a weak disinfectant solution. The US Environmental Protection Agency has listed 392 disinfectant products (List N) which are effective against the SARS-CoV-2 virus (USEPA, 2020). These disinfectants can be broadly divided into alcohol, bleach, hydrogen peroxide, and quaternary ammonium compounds. Among these, 51.5%, 14.8%, and 13.5% list quaternary ammonium, sodium hypochlorite and hydrogen peroxide, respectively, as the active ingredients. 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 centers are sodium hypochlorite-based (Rutala and Weber, 1997). Sodium hypochlorite has numerous advantages and can be tailored for either cleaning or disinfecting purpose (Fukuzaki, 2006). According to the Environmental Services and Regulation, Department of Environment and Science, The Queensland Government, Australia (ESR/2015/1571, Version 4.01) chemical disinfection processes should be used to treat clinical waste (excluding animal carcasses). This involves shredding and soaking clinical waste in sodium hypochlorite-based disinfectant fluids for at least 15 minutes, dewatering, and transporting the waste for disposal in a municipal waste landfill. During the COVID-19 pandemic, heavy usage of sodium hypochlorite-based disinfectant products has been done for cleaning purposes in households. In most cases, disposable paper products (kitchen towels and paper wipes) have been used for this purpose. It is therefore expected that the percentage of landfill waste that would contain traces of sodium hypochlorite would significantly increase during the pandemic, and it would be reasonable to expect that some of these chemicals may find their way into the soil and groundwater. In addition, the practice to spray outdoor public spaces, including roads, schools, and buildings having hosted infected persons, etc., has directly inserted disinfectant products into the storm drainage systems of many cities, thus discharging them into rivers, streams, and coastal waters.

Rook (1974) found out 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 (DBPs), including the four primary trihalomethanes (THM), which are chloroform, bromodichloromethane, dibromochloromethane and bromoform, referred to as total trihalomethanes (TTHM). Medeiros *et al.* (2019) reviewed the toxicological aspects of THM and concluded that they pose potential genotoxic and carcinogenic health risks, particularly in the liver and kidney.

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

Landfill leachate is a complex liquid that contains organics and inorganics matter. The chemical composition of leachate is controlled by waste type and nature, among other factors (Iskander *et al*., 2018; Renou *et al*., 2008; Viraraghavan and Singh, 1997). During the pandemic, the impact of excess sodium hypochlorite in the landfill waste on the leachate chemistry should be monitored. Although the composition of leachate is site-specific, leachate organic content is generally a few tens to thousands times higher than sewage (Li and Deng, 2012). The presence of organic matter and hypochlorite in a landfill’s leachate could trigger the formation of THM. This could be troubling, especially, for landfills that have not been designed with leachate collection systems (Li and Deng, 2012), such as several smaller regional landfills in Australia, which, fall within this category (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. They detected THM concentrations up to 4.551 mg/L at several monitoring wells of the study sites.

Therefore, 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 direct 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.

3.3 Clean water under the COVID-19 pandemic in poor rural areas

3.3.1 Pathways of the virus to enter water bodies

With the outbreak of the COVID-19 pandemic, water resources protection and infection prevention in poor rural areas face huge challenges. There are many poor and underdeveloped areas in Africa, Asia and South America, where there are no modern water supply industry and water purification facilities, and there are also a lack of professional infectious disease medical personnel and hospitals. The reception and dissemination of pandemic prevention and control related information are also relatively lagging and slow. Although the population density or the intensity of social activities in these poor rural areas is much lower than those in cities, once an infection occurs or is imported from outside, the virus may enter surface waters or the groundwater through various channels, and quickly spread and infect people. For example, in remote mountainous areas many villages or small towns rely on natural rivers, reservoirs, or wells to obtain drinking water. At the same time, these sources are also important for household use with people using their water to take a bath, or wash food, clothes, and many other things. The virus carried by an infected person may easily enter local water resources through these activities, or by the disposal and discharge of solid wastes and sewage, thereby infecting nearby residents.

Casanova and Weaver (2015) suggested that envelope viruses could survive in sewage for 6 to 7 days, while van Doremalen *et al.*, (2020) reported that SARS-CoV-2 may live from 4 to 72 hours 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).

Pathogens such as the SARS-CoV-2 can also go through natural transport cycles into the air, soil, and surface/groundwater, which can result in their reemerging at a later date. Hence, their fate, transport and interaction with surface/groundwater and soil need to be considered. Soil is a complex ecosystem composed of various physical, chemical, and biological components and microorganisms, including aerobic and anaerobic microbial life and pathogens. Interactions between surface water and groundwater, agricultural water use, and groundwater extraction can transport pathogens from soil to above the ground surface and *vice versa*, creating a cycle causing the reemergence of pathogens, potentially resulting in new pandemics.

SARS-CoV-2 can enter the soil and groundwater by a range of pathways including the disposal and discharge of solid and fluid medical wastes, the discharge of patient and suspects feces, and the sputum from suspects and infected people who have not been detected.

Hence, the transport and spread of the virus via soil and surface/groundwater are possible and the virus may spread to dozens or even hundreds of kilometers through surface water bodies, greatly increasing the risk of infection for downstream residents. The discharges of patient feces were also reported to contain the SARS-CoV-2 virus (Xu *et al.*, 2020). In some regions, feces constitute traditionally a very important organic fertilizer source that is poured onto farmland to promote crop growth. In rainy days, virus-contaminated runoff may enter surface waters, or the groundwater by infiltration, causing their contamination. The Asian Water Development Outlook 2013 (Asian Development Bank, 2013, Table 7) reported that about 45% of the rivers in Asia were polluted and they were classified as having a bad or poor River Health Index.

Burial grounds for newly deceased victims of the virus present also the potential for the virus to enter the soil and groundwater. This indicates that, in poor rural areas, it is very important to take effective measures to block the virus from entering the water resources, which has positive significance for infection prevention and control of the COVID-19 pandemic.

Various guidelines for the disposal of pathogen-contaminated substances have been developed in some states and countries (e.g., California Department of Health, 2020; WHO 2005). For instance, if leakage of pathogen-laden wastewater occurs, contaminated groundwater can be pumped out for treatment. This emphasizes the need for research into the fate and transport of the SARS-CoV-2 virus and other pathogens in soil and surface/ground water (Bender *et al.*, 2017). This is critical for rural areas where groundwater is commonly used for agricultural purposes and as the source of drinking water, and where there may exist less uniform control on water treatment or quality. This can be achieved by a systematic disposal approach for contaminated substances that aims to isolate them from the hydrologic cycle, such as disposing downstream of water resources, locating favorable disposal formations that can eliminate or reduce further transport of contaminants, preventing infected leachate from leaking from disposal sites by the use of liners, and so on.

Although disinfection ensures rapid inactivation of the virus, there remains a threat by COVID-19 against well water and water supplies within rural and undeveloped or uncontrolled water supplies. The appearance of SARS-CoV-2 in wells, streams, rivers, and lakes will likely be more prevalent in developing countries and poorer, rural areas of Asia, Africa, and South America where open defecation is practiced by 20-50% of the population (WHO/UNICEF, 2019), and sewage sanitation systems are either rudimentary, aging, or non-existent. Particularly in poor, arid, or semi-arid environments, the risk of COVID-19 spread associated with water supplies could arise from several sources. Scarce water availability from open sources, wells, and boreholes can lead to the congregation of people at sites where the risk of direct respiratory droplet- or fomite-spread of disease increases. Finally, fecal contamination of these water sources has the added potential to serve as a source of infection, thus putting these populations at risk of acquiring COVID-19.

3.3.2 Threats and risks to rural areas and developing countries

The COVID-19 pandemic presents an unprecedented challenge for countries all around the world, and especially to developing countries it poses an acute threat, particularly for those that are densely populated and struggling with the impact of conflict, natural disasters, climate change and/or malnutrition that cause humanitarian crises and mass population displacement. For such an easily transmitted and potent virus like SARS-CoV-2, mass congregations in areas, poorly served by basic civil infrastructure can quickly become breeding grounds for the rampant transmission of the disease. As the COVID-19 pandemic continues to spread, the international community needs to urgently rally behind governments to contain the virus and support those who are most vulnerable, with close collaboration between government health sectors and NGOs actively working on the ground in this global humanitarian challenge. The reality is that the pandemic does not recognize national boundaries, and before the widespread availability of a vaccine, a cornerstone for the suppression and management of the virus in the community is safe and readily available drinking WAter, Sanitation and Hygiene (collectively known as WASH). Because of climate change, management of all water resources also needs to be improved to ensure provision and quality of clean water. Urban solid waste disposal is another sanitation-related challenge, where failure to adequately collect and safely dispose of solid waste can increase the proliferation of disease-carrying vectors. Here *Environmental Geotechnics* plays central roles in the supply of safely managed potable water from catchment to consumer, and the delivery of wastewater and solid waste collection, treatment and disposal services, while effectively identifying and managing risks to protect both human health and the environment (Johnston and O’Kelly, 2016).

The developed world has generally responded to the pandemic by assuming that everyone is at risk, and everyone is also a risk to others, especially to older people and those with underlying health conditions. But as COVID-19 continues, some of the world's poorest countries are potentially facing catastrophe. Figure 3 clearly shows for Asia and the Pacific the relation between per capita gross domestic product (GDP) and household water security (HWS); countries with low GDP have also low HWS (Asian Development Bank, 2013).

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 extremely 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 for self-isolation when required. Hygiene facilities, for example handwashing stations may be shared with multiple households, making infection control and social distancing measures practically impossible. In addressing these realities, the first consideration is not to make the situation worse by bringing the virus into such areas, and then to implement public information campaigns on hand sanitation measures in order to stop the spread of the COVID-19 virus and of other diseases. This may be facilitated by the provision of handwashing stations and distributing soap, detergent and hygiene kits to vulnerable households, since for many, access to clean water and soap is far from easy. For instance, in 2017, only 60% of the global population, or about 4.5 billion people, had a basic handwashing facility with soap and water available at home (Concern Worldwide, 20 March 2020). Another 22% (1.6 billion) had handwashing facilities that lacked water or soap, and 18% (1.4 billion) had no handwashing facilities at all. Where water is not readily available, people may decide handwashing is not a priority, thereby adding to the likelihood of COVID-19 and other disease infections. In countries such as Sierra Leone and the Democratic Republic of Congo, for instance, the same channels of community mobilization and hygiene sensitization that were used to fight the Ebola virus are now being used to channel messaging on COVID-19 (Concern Worldwide, 15 April 2020).

The major issue in rural areas is the lack of sufficient public water supply systems, the shortage of such facilities despite the low per capita water demand and the population density. Hence, quite a large portion of the rural population finds difficulties in accessing properly disinfected water even for livelihood (viz., drinking and cooking purposes). With the spread of the pandemic, the situation becomes more critical to such rural communities to maintain a hygienic environment (Gall *et al.*, 2015). The spread of the virus can also occur at public places (for example, religious or commercial centers, bus and train stations, airports, restaurants, hotels, industrial complexes, etc.) where water facilities are shared. Figure 4 shows that the availability of tap water facilities in several countries, which host a large portion of the world's population is below 50%. Hence rural populations there depend mainly on untreated surface water or groundwater, which given the lack of sewage networks and wastewater treatment facilities in most of these rural towns, makes the quality of water consumed questionable.

According to the Asian Water Development Outlook (Asian Development Bank, 2016) Asia accounts for half of the world's poorest people and where poor irrigation and agricultural practices consume 80% of the limited water resources of the region. Currently, 1.7 billion people in Asia lack access to basic sanitation. This is expected to create severe pressures by 2050 where estimates indicate that up to 3.4 billion people could be under water-stress conditions.

Further, because of increased hand sanitization with soaps to guard against COVID-19 transmission, the per-capita water consumption would visibly increase, thereby creating a water stress situation globally. Hence, the availability of sufficient water to combat infectious viruses such as coronaviruses would be a major challenge. Additionally, the design of a complex water supply and distribution network to serve small communities in all the rural areas is impractical, due to the huge investment, operation and maintenance cost and the lack of skilled personnel to operate. In this context, the design of low-cost water supply systems, probably with indigenous technology, is worth being explored.

Figure 5 demonstrates the vulnerability of the vast majority of the countries in Asia and the Pacific where a large number of countries is characterized by both a low water-related disaster resilience indicator and a relatively high number of water-related fatalities.

Another important aspect that should be investigated is the possible level of contamination of water due to infectious viruses (Gall *et al.*, 2015). Studies have confirmed the secondary transmission of the SAR-CoV-2 virus through genetic material in the feces of infected individuals (Wigginton and Boehm, 2020). Hence improper sanitation in the rural areas may lead to potential contagion of the water bodies and cross-contamination of distribution networks due to cavitation and accidental depressurization. This has motivated researchers to investigate the following aspects of rural water supply systems:

- Development of cost-effective technologies for timely detection of infectious viruses present in the water and wastewater systems (Gall *et al.*, 2015; Wigginton *et al.*, 2015).
- Establishment of the existence and survival of infectious viruses in water bodies and wastewater systems under different environmental conditions, such as temperature, pressure, pH and humidity (Wigginton *et al.*, 2015; Ye *et al.*, 2016).
- Development of efficient methods/techniques for inactivation of infectious viruses within the water and wastewater bodies, and prevention of cross-contamination in distribution networks (Ye *et al.*, 2016).
- Surface water bodies that receive partially treated or untreated wastewater from cleaning of health care facilities during the pandemic can be a possible source of viruses, including the SAR-CoV-2, disinfectants, and pharmaceuticals that can cause contamination of drinking and/or irrigation water. Such activities may cause significant changes in the pollutant load of surface water bodies and affect the self-cleaning mechanisms, and hence, the quality of drinking and irrigation water in rural areas (Wen *et al.*, 2017).
- In rural areas the treatment or removal of disinfection by-products (viz., trihalomethanes, chloroform and dibromo chloromethane) in drinking and irrigation water is crucial (Li and Mitch, 2018).
- Utilization of water contaminated with sodium ions from disinfectants may lead to an increase in the sodium adsorption ratio of water bodies and make them unfit for irrigation purpose.

Apart from the above examples, the mentioned contaminants may migrate into the aquifers, affecting the quality of groundwater (Mohamed *et al*., 2020; Paleologos *et al*., 2014). Care should be taken to (i) prevent the release of wastewater obtained from hospitals and isolation facilities into surface water bodies that are sources of water, or are connected with subsurface water, and (ii) monitor contaminants with, among others, real-time monitoring sensor-based techniques that are based on micro-electro-mechanical systems and in case of contamination use permeable reactive barriers (PRB), zeolite-based sorbents, etc. (Pejcic *et al*., 2006; Koshy and Singh, 2016).

Simultaneously, ambitious humanitarian response infrastructure (building/improving sustainable water services, and provision of additional water supply points, thereby allowing people to access vital supplies while providing basic social protection) must be quickly up-scaled, concurrently increasing COVID-19 preparedness as best as possible, along with maintaining current lifesaving programs. In least developed countries, for example, 22% of health care facilities have no water service, 21% no sanitation service, and 22% no waste management service (WHO, 14 June 2019). Tackling such problems is challenging, especially so during pandemics where rapid access to services becomes vital.

In tandem with the aforementioned measures directed at stopping the spread of viruses, installation and operation of sewerage infrastructure in urban settings are required to protect from bacterial and other waterborne diseases. Here *Environmental Geotechnics* plays central roles, for instance, in studying the fate and transport of water-borne pollutants in the natural and built environments, as well as the development of passive treatment processes. This can include extensive tracer-study field investigations that are then used in developing mathematical models to gain further insight into the biological processes occurring in soils. Examples are the effective distribution of on-site wastewater effluent into percolation areas and investigations of the wastewater treatment efficiency of various subsoils and stratified sand filters. Compared to attenuation of pollutants in sandy subsoils, depending on the setting, sustainable wastewater treatment systems for rural communities could include constructed wetlands and willow evapotranspiration systems. These can be used for on-site wastewater treatment in order to mitigate surface water pollution from domestic wastewater. Integrated constructed wetlands are planned to integrate into the surrounding environment and are built using natural materials like native wetland plants including reeds, rushes and sedges.

Reuse of wastewater, to recover water, nutrients, and/or energy, is also becoming an important strategy particularly in water-stressed areas. Biosolids, the treated by-product of the wastewater treatment process, contain high levels of nutrients and preferably are sustainably used as an organic fertilizer in agriculture and forestry, although co-disposal in sanitary landfills or monofill disposal at dedicated landfills (O'Kelly, 2004, 2005, 2020) remains common practice in various parts of the world. The presence of the SAR-CoV-2 (and pathogens) in these residues streams also requires careful consideration. Similar concerns exist for the residue materials from the various processes at water treatment plants, which includes the temporary storage/stockpiling, stabilization, and improvement of the properties/behavior of these materials (Babatunde and Zhao, 2007; Fei *et al.*, 2017; O'Kelly and Quille, 2009, 2010). Other considerations are the effectiveness and required dosages of various chemicals added during the treatment process, the environmental consequences from the properties of the derived sludge and residue materials, as well as the changes in them arising from the ongoing in-situ biodegradation (O'Kelly, 2008a, b).

3.3.3 Threats and risks to developed countries

Although great strides have been made, in the developed world economies, ailing water and sewerage networks, mainly arising from prolonged under-investment in their maintenance, upgrade, and modernization are also a reality. In everyday life, there are occasionally severe knock-on effects for both consumers and the geoenvironment when these systems do not meet regulatory requirements in terms of operation (supply), or should they unexpectedly fail. For instance, 'Boil Water' notices are put in place arising from cryptosporidium virus outbreaks in drinking water supply networks due to inadequate treatment at the waterworks, with these notices sometimes extending for many months, until the ageing infrastructure has been repaired/upgraded and the water network cleared of contaminants. In some urban centers, there is a legacy of leaky cast iron supply pipes. Historically, lead piping may have been used for connecting the mains water supply to individual households. Rupture of sewerage network lines causes collateral damage to the geoenvironment and public health risks arising from contamination of surface water and groundwater sources, including human and animal exposure to viruses, as well as possible structural damage where foundations experience differential settlement due to localized ‘soft spots’ produced in the underlying ground. On the waste management and disposal side, there remains a legacy of non-engineered landfills that have their own particular problems, including slope instability issues (Zekkos et al., 2014) and/or groundwater contamination (Papapetridis and Paleologos, 2011, 2012). Here, again, *Environmental Geotechnics* plays central important roles in addressing these challenges.

4. Challenges and Risks of the SARS-CoV-2 in Wastewater Systems

4.1 The presence of coronaviruses in human excrement and environmental media

Both the SARS-CoV-1 (the coronavirus that caused the severe acute respiratory syndrome (SARS) in 2003) and MERS-CoV (the coronavirus that caused the Middle East respiratory syndrome (MERS) in 2012) have been found in blood, urine, and feces (Wang *et al*., 2005a, b; Corman *et al*., 2016). In terms of the SARS-CoV-2 it has been found to be followed by diarrhea in 2% to 50% of the cases (D’Amico *et al*., 2020), viral RNA to have remained detectable in children’s stools for longer than 4 weeks (Xing *et al*., 2020), children to test positive on rectal swabs, after they had tested negative to COVID-19 in nasopharyngeal testing (Xu *et al*., 2020), all of which led Zhang *et al.* (2020) to warn that SARS-CoV-2 may be shed via multiple routes.

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 the stability of the two viruses was similar in the examined media with “the longest viability of both viruses…on stainless steel and plastic; the estimated median half-life of SARS-CoV-2 was approximately 5.6 hours on stainless steel and 6.8 hours on plastic." These authors concluded that the transmission of SARS-CoV-2 is "plausible" via aerosols and fomites "since the virus can remain viable and infectious in aerosols for hours and on surfaces up to days."

Some important findings regarding the resilience of coronaviruses in environmental media and surfaces include the following. Otter *et al.* (2016) evaluated the survival of enveloped viruses (in which SARS-CoV-2 also belongs) on dry surfaces and aerosols and found that these "can survive on surfaces for extended periods, sometimes up to months." Wang *et al.* (2005c) found that "… 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 … Free chlorine was found to inactivate SARS-CoV better than chlorine dioxide." Despite the claim by Liu (2003) that the 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.* (2005c), based also on past studies (Cyranoski and Abbott, 2003), concluded that "there is a great concern on the disinfection of SARS-CoV in patient excrements and wastewater." In terms of SARS-CoV-2, its presence has been documented in hospital sewage lines (Wang *et al.*, 2020) and community wastewater collection sites, setting the stage for the virus to enter community waterways (Lodder *et al.*, 2020; Nuñez-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. This path of airborne transmission was aided by bathroom ventilation that drew in contaminated air into 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." Such aerosolization 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).

Other investigations of related animal coronaviruses indicated that these can persist in lake water and pasteurized 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 will also appear broadly in environmental water systems, which will serve as a reservoir for potential human disease.

The US EPA has stated that standard treatment and disinfection processes at WWTPs are expected to be effective (https://www.epa.gov/coronavirus/do-wastewater-treatment-plants-treat-covid-19). Similarly, in Europe, such as in the Czech Republic or in Poland, most utilities have issued communiques that current methods of treatment are effective in eliminating the virus from water and wastewater (https://www.igwp.org.pl/index.php/informacje/koronawirus-info/1562-covid-19-i-nasze-uslugi-stanowisko-eureau). In contrast, China has asked WWTPs to increase the use of chlorine for disinfection purposes in order to ensure that the SARS-CoV-2 will not be spread via wastewater (Koivusalo and Vartiainen, 1997; Taleb *et al.*, 2020; Zambrano-Monserrate *et al.*, 2020).

The April 23, 2020 interim guidance by WHO/UNICEF (2020) on water and wastewater has reassured that "significant (99.9% removal) of coronaviruses was observed in two days in primary sewage effluent at 23°C, two weeks in pasteurized settled sewage at 25 °C and four weeks in reagent grade water at 25°C. High temperature, high or low pH, and sunlight all facilitate virus reduction". The same communique has opinioned that in "well-designed and well-managed centralized 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. Finally, in WWTPs that are not optimized to remove viruses it is recommended to include a final disinfection.

The biosolid by-products of WTTP processes contain various pathogenic microorganisms, bacteriophages and human viruses (Pepper *et al*., 2006; Sharma *et al*., 2016). Biosolids have been classified into class A and class B depending on desired type of application and corresponding level of treatment, with the content of pathogens varying in these two classes (USEPA, 2003b). Some typical pathogens that have been seen to transfer from biosolids to the geoenvironment are: bacteria (such as, *Escherichia coli*, *Salmonella spp*,, *Shigella spp.*, *Campylobacter spp*., *Yersinia spp*., *Listeria spp*., *Staphylococcus spp*.), enteric viruses (such as, *Poliovirus*, *Rotavirus*), and helminths (such as, *Trichuris spp*. *Taenia spp*. *Ascaris spp.* Etc).

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 in the order of 10^3 to 10^4 PFU/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, degree of saturation, nature of pore fluid, degree of saturation, and temperature (Xagoraraki *et al*., 2014). In addition to these factors, adsorption of viruses depends on the pH of the geoenvironment and they tend to adsorb more onto soils under acidic conditions. 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, especially in the case of coarse-grained soils (Chetochine *et al*., 2006). The relative low degree of adsorption of viruses onto sands results in their transport in the subsurface environment via groundwater flow. This can, not only contaminate groundwater resources, but it also has the potential to pollute the surface water bodies that are in hydraulic communication with the affected aquifers.

The ongoing Covid-19 pandemic has reemphasized the need for research on the fate and transport of microorganisms and biological agents in the geoenvironment. At this juncture, it would be more prudent to device mechanisms for controlling the survival or transport of viruses. Knowledge of different materials, porous media, and geotechnical engineering would come in handy in addressing these novel geoenvironmental issues. Land application of biosolids is a potential aerosol generating operation (Brooks *et al*., 2005) that may favor 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 reexamine the use of biosolids for land applications.

Inactivation and containment of the migration of SARS-CoV2 from septic tanks, wastewater effluent disposal sites, and landfills to the geoenvironment is critical (Qin *et al*., 2020; Seetha *et al*., 2015). It should be noted that these could vary under saturated and unsaturated condition due to the interaction of viruses with different phases of the porous media. In this regard, the influence on the migration of SARS-CoV2 in soils and water, arising from surface characteristics (viz., zeta potential, contact angle) and hydrodynamic sizes of soils should be studied more extensively. It has further been reported that the survival of viruses on land depends on temperature, moisture content, viral adsorption onto soils, the presence of antagonistic micro-organisms and organic matter content (Gundy *et al*., 2008; Hurst *et al*., 1980; Qin *et al*., 2020; Seetha *et al*., 2015).

On the other hand, a potential spread of the SARS-CoV2 virus through wastewater may not be significant in rural areas compared to urban centers due to the lack of centralized wastewater collection and treatment facilities for the former. In this regard, to treat the fewer volumes of wastewater that are generated in remote areas, constructed wetlands may be considered as a solution for rural communities (Wu *et al.,* 2011). There exists though the possibility that the SARS-CoV2 viruses may be phytotoxic to the plant species used in the wetlands, or this practice may lead to secondary contamination of local soil and groundwater sources. To avoid the latter case geosynthetic liners (Patil *et al*., 2017), pure zeolites (natural and synthetic types), and fly ash zeolites (processed from Class-F fly ash) (Jha and Singh, 2011, 2013, 2016; Koshy and Singh,

2016) may be used. Hence, it is evident that in addition to the severe challenges related to the current health emergency, there exist several opportunities wherein the scientific community could focus not only to combat the current, but also future pandemics.

4.2 The xenobiotics paradigm in wastewaters and the environment

The recent threat by the COVID-19 pandemic to the environment has many similarities to xenobiotics and their spread in our environment. Xenobiotics, i.e., substances foreign (*xenos* in Greek) to biotic systems, such as pharmaceuticals, food additives, hydrocarbons, and other man-made products, are becoming present in wastewater effluents in ever-increasing quantities. These substances pose a dilemma with respect to their release into the environment, with a growing body of literature focusing on their fate, transport, and ecotoxicity. Until recently their presence in the environment had remained undetected due to the lack of analytical tools. There has been acknowledgement that our current wastewater discharge practices are contributing to the spread of these pollutants and treatment options are being developed that can address them within the scope of existing practices and technologies. With respect to the present pandemic situation, experience tells us that we could very well see the spread of the virus within the aquatic and geologic environment and it would help to review the xenobiotic history of how these 'hidden' contaminants were able to spread throughout the environment.

Municipal wastewater contains a complex mixture of xenobiotic organic compounds (XOCs) which are discharged into wastewater from households, hospitals, industry, etc. (Lindblom *et al.*, 2009). Such emerging environmental pollutants include pharmaceutical compounds (PhCs), that 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 physio-chemical characteristics as harmful xenobiotics, e.g., they can pass through membranes and 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, i.e., 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 micro-organisms' genome, even at low concentrations, making them resistant to antibiotic treatment (Klavarioti *et al.*, 2009).

Most of the municipal WWTPs include preliminary, primary, and secondary treatment processes (mainly activated sludge systems) with the final effluent being discharged into a surface water body and often indirectly reused for irrigation purposes (Michael *et al.*, 2013; Verlicchi *et al.*, 2012). 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 efficiently remove all of them. Observed removal efficiencies vary in a wide range for different PhCs as well as for the same substance due to compound physico/chemical differences and to operational conditions, mainly in the aerobic, anaerobic, anoxic reactors, the solids retention time (SRT), pH and water temperature (Verlicchi *et al.*, 2012). The effect of biological treatments, membrane filtration, activated carbon adsorption, advanced oxidation processes (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 realized that the spread of PhCs has been aided by releasing treated wastewater in the aquatic environment, and by the use of 'grey water' for irrigation purposes. In addition, the land application of sludge that is produced by WWTPs has 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 current liquid and solid waste disposal practices and scientists and engineers are called to reexamine the relevant civil infrastructure in light of the "new normal" posed by the COVID-19 pandemic. As final thoughts sewage surveillance pilot programs could be implemented to monitor SARS-CoV-2 circulation at different treatment stages in WWTP with changing levels of organic matter and suspended solids (at ambient temperatures), along with sampling of the treated wastewater that is released into water bodies in order to quantify the potential presence of the virus.

5. Conclusions and Future Research Directions

The present article highlights a multidisciplinary perspective on the potential of water and wastewater 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, wastewater and soil under various environmental conditions (viz., temperature, humidity, and pH) is crucial to understanding their fate and the threat posed to surface, coastal, and ground waters, as well as the geoenvironment in totality. Other realities of the COVID-19 pandemic are increased demand on water supply and wastewater management systems across the world owing to more frequent personal hygiene measures. In this context, the following should be attempted to strengthen the research in the field of water and wastewater management systems.

- Development of low-cost virus detection systems is essential, along with urgently needed water- and wastewater-based epidemiology systems for controlling the spread of waterborne pandemics.
- Studies are needed on the influence of pollutant load and of viruses on the self-cleaning mechanisms and eutrophication of surface water bodies, which are sources for potable and irrigation water.
- Environmental geotechnologists should work together with agriculturists and microbiologists to gain a full understanding of the fate and spread of infectious viruses and pharmaceuticals present in biosolids for their application as soil fertilizer. Further, the influence of greywater and undisinfected water on the agricultural yield should be investigated.
- Effectiveness of willow evapotranspiration and constructed wetland methods for in-situ treatment of domestic wastewater contaminated with disinfectants and pathogens should be studied for their feasibility in rural localities.
- Utilization of fly-ash-based zeolites in the treatment of water and wastewater for removal of contaminants (viz., heavy metals, pharmaceuticals and pathogens) should be explored.
- Fate and spread of xenobiotic substances present in the wastewater treatment systems should be

modelled to estimate their toxicity to the organisms, cells and plants species present in wastewater treatment systems.

- Migration and leachability of pathogens and viruses from biosolids stored at temporary storage facilities into the geoenvironment require special attention.
- Metagenomic sequencing operations should be considered to be performed on water and wastewater in 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 THM through landfill clay liner.
- Finally, given the direct injection of disinfectants into the storm drainage systems of cities that are practicing public space disinfection during the COVID-19 pandemic, the effect on the ecosystems of rivers, streams, and coastal waters where these systems are discharging must be studied.

In conclusion, the time has come, after one-hundred-and-fifty years of successful measures for the treatment of water and wastewater, which vastly improved the health of the population, to reevaluate the operation of the WTP and WWTP systems in view of the recent pandemic. Targeted research and developmental activities focused on the above-mentioned key areas would serve the purpose of augmenting the role of WTP and WWTP during the COVID-19 pandemic and future health and environmental challenges.

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Tables titles

Table 1. Active Ingredients and Their Working Concentrations Effective Against Coronaviruses (NEA (National Environmental Agency, Singapore), 2020).

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

Tables

Table 1. Active Ingredients and Their Working Concentrations Effective Against Coronaviruses (NEA (National Environmental Agency, Singapore), 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 – 0.5%)	5
Sodium chlorite (0.23%)	10

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

Trihalomethanes (THM)	Guideline values
Chloroform	0.3 mg/L
Bromoform	0.1 mg/L
Dibromochloromethane	0.1 mg/L
Bromodichloromethane	0.06 mg/L

Figure captions

Figure 1. Chlorine and UV doses required for the inactivation of various viruses in drinking water (Irish EPA, 2011; HPSC, 5 March 2020).

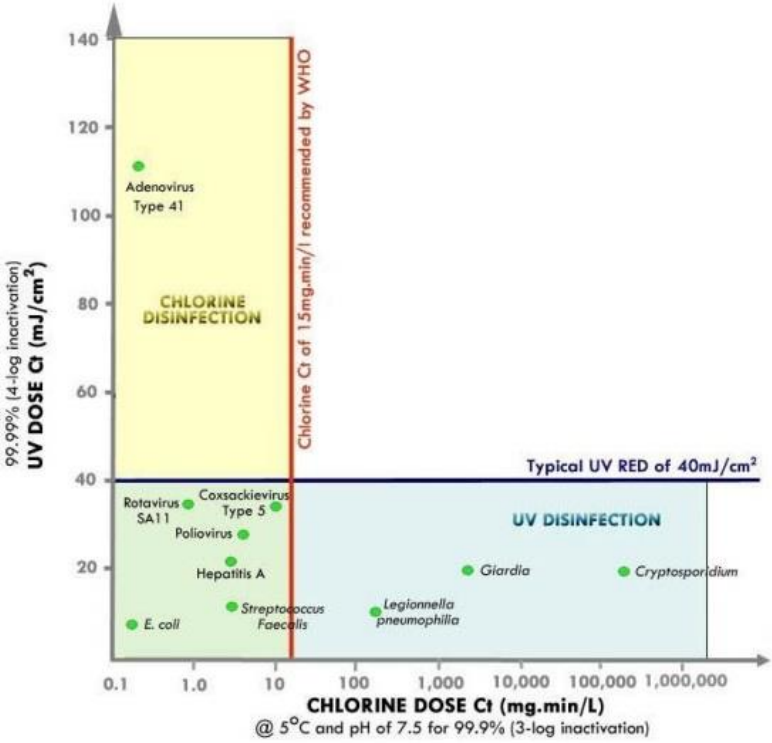
Figure 2. Poor baffling conditions in disinfection tank (USEPA, 2003a).

Figure 3. Relation between per capita GDP and household water security in Asia and the Pacific Region (Asian Development Bank, 2013, Figure 8).

Figure 4. Status of pipe water supply in Asia (RecapDATA, 2017).

Figure 5. Water security in Asia and the Pacific with respect to water-related disasters (Asian Development Bank, 2013, Figure 19).

Figures



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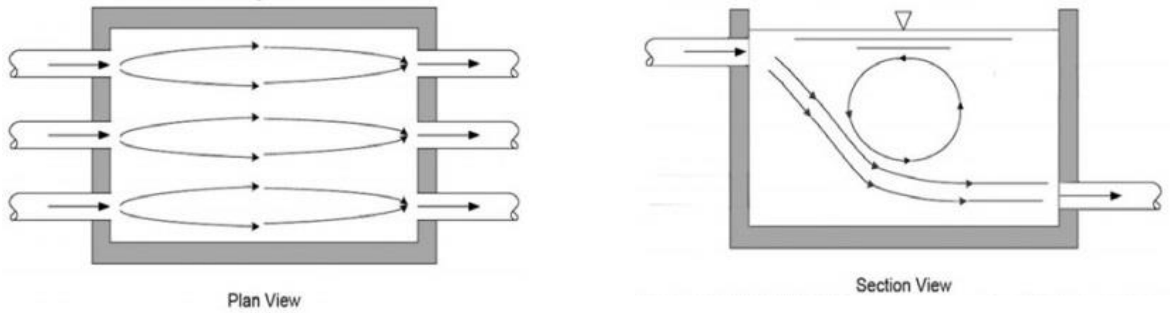

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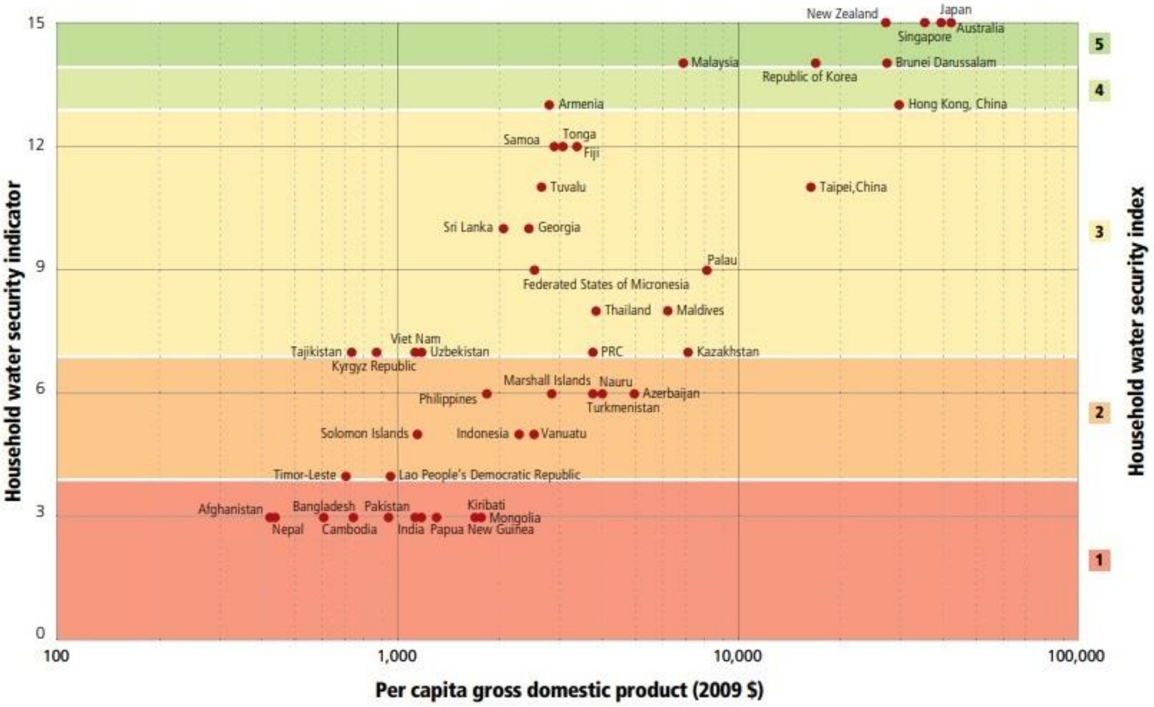

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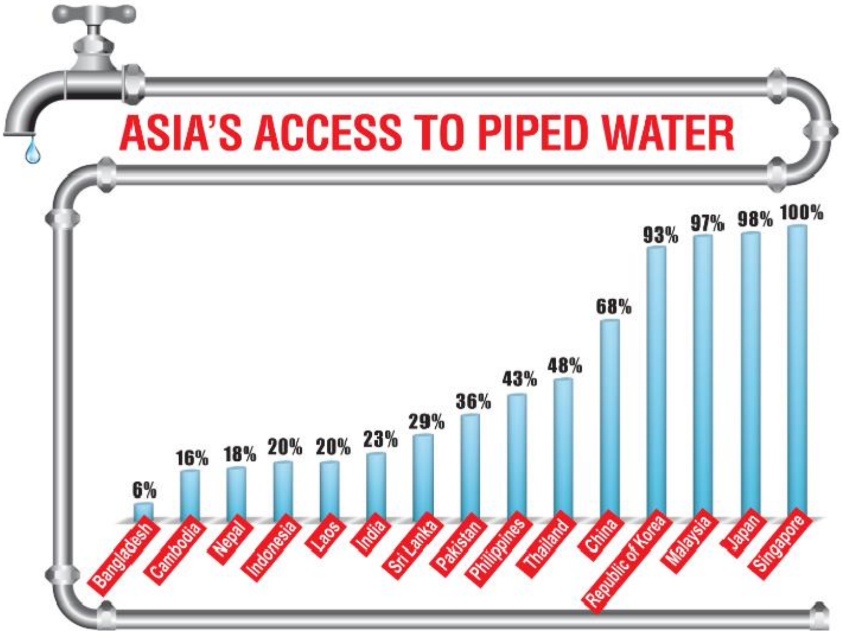

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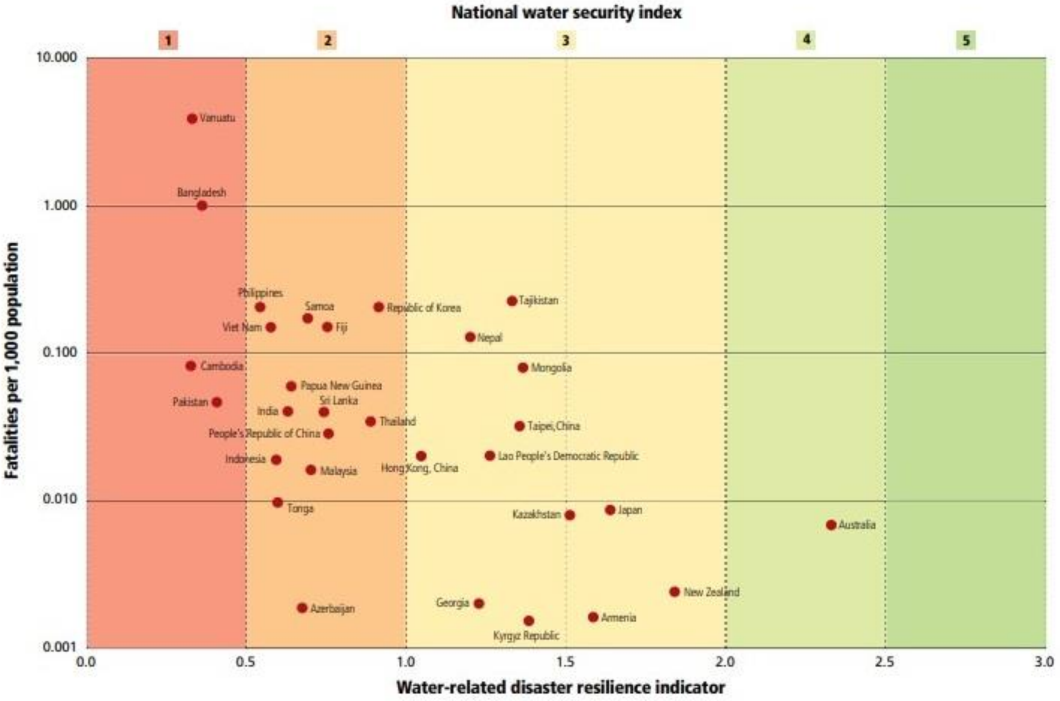

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