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Potential SARS-CoV-2 Contamination of Groundwater as a Result of Mass Burial: A Mini-Review

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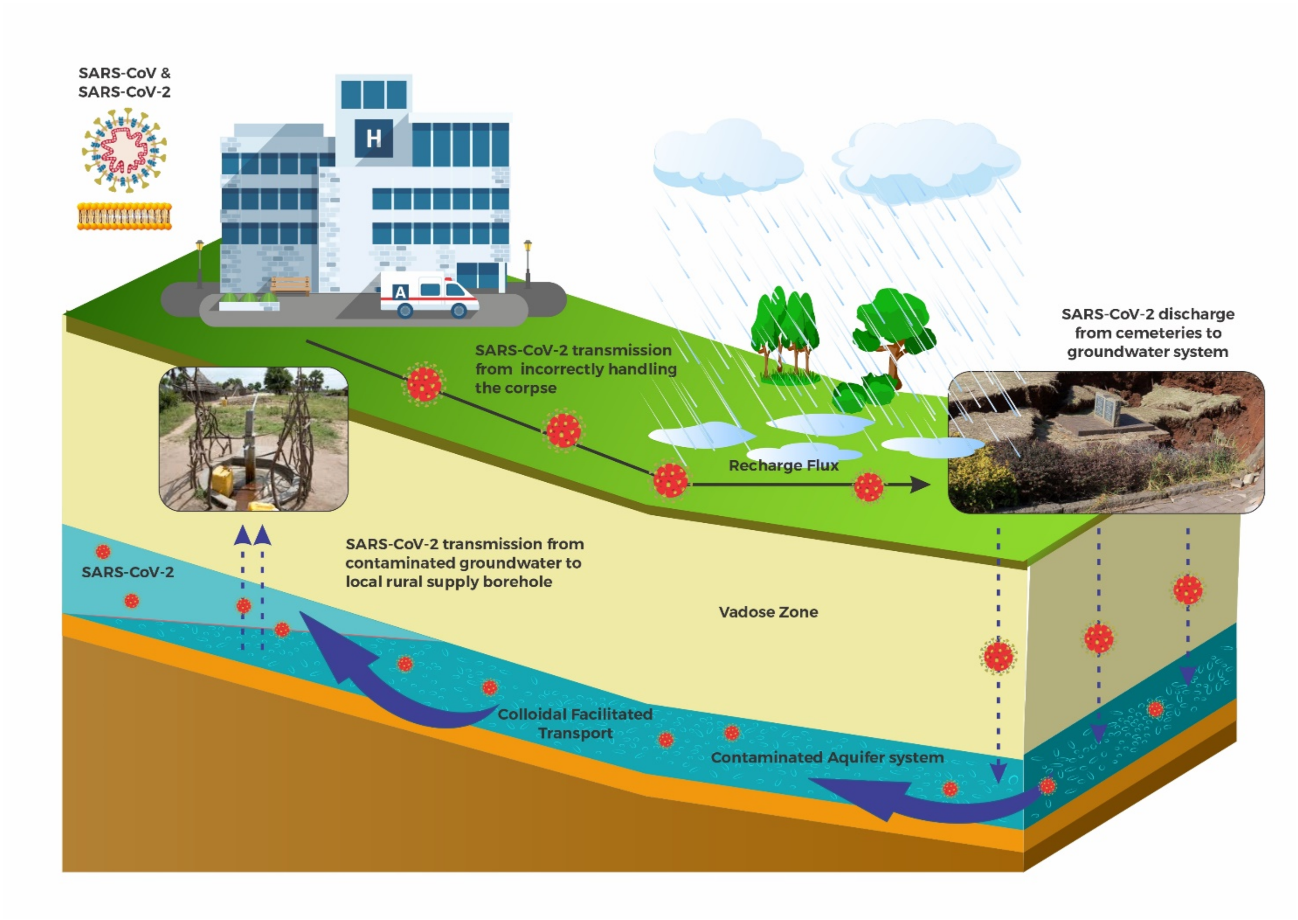
Graphical Abstract



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Highlights

- Viral contamination dynamics in groundwater due to burial is not well understood
- Shallow vadose zones with heterogenous structures causes groundwater contamination
- Biological contamination is unlikely to occur unless preferential flow exists
- Viruses can survive in both shallow and deeper vadose zones

Abstract

The recent COVID-19 disease has highlighted the need for further research around the risk to human health and the environment because of mass burial of COVID-19 victims. Despite SARS-CoV-2 being an enveloped virus, which is highly susceptible to environmental conditions (temperature, solar/UV exposure). This review provides insight into the potential of SARS-CoV-2 to contaminate groundwater through burial sites, the impact of various types of burial practices on SARS-CoV-2 survival, and current knowledge gaps that need to be addressed to ensure that humans and ecosystems are adequately protected from SARS-CoV-2. Data available shows temperature is still likely to be the driving factor when it comes to survival and infectivity of SARS-CoV-2. Research conducted at cemetery sites globally using various bacteriophages (MS2, PRD1, faecal coliforms) and viruses (TGEV, MHV) as surrogates for pathogenic enteric viruses to study the fate and transport of these viruses showed considerable contamination of groundwater, particularly where there is a shallow vadose zone and heterogeneous structures are known to exist with very low residence times. In addition, changes in solution chemistry (e.g., decrease in ionic strength or increase in pH) during rainfall events produces large pulses of released colloids that can result in attached viruses becoming remobilised, with implications for groundwater contamination. Viruses cannot spread unaided through the unsaturated zone. Since groundwater is too deep to be in contact with the interred body and migration rates are very slow, except where preferential flow paths are known to exist, the groundwater table will not be significantly impacted by contamination from SARS-CoV-2. When burial takes place using scientifically defensible methods the possibility of infection will be highly improbable. Furthermore, the SARS-CoV-2 pandemic has helped us to prepare for other eventualities such as natural disasters where mass fatalities and subsequently burials may take place in a relatively short space of time.

Keywords: cemetery; groundwater; vadose zone; pathogens; viruses; SARS-CoV-2; COVID-19

1.1 SARS-CoV-2: An Introduction

The Severe Acute Respiratory Syndrome-Coronavirus (SARS-CoV-2) that causes the disease COVID-19, which originated in late December 2019 in Wuhan of the People’s Republic of China, has swept through more than 220 countries worldwide at an unprecedented rate, affecting the young, elderly and those with underling health conditions who are dependent on chronic medication (e.g., HIV, TB, cancer, lung disease and hypertension) (Huang et al., 2020). With an exponential rise in the number of deaths, the World Health Organization (WHO) under the International Health Regulations (IHR) has for the sixth time declared a Public Health Emergency of International Concern (PHEIC), the last one dating back to the 2019 Kivu Ebola epidemic (Eurosurveillance Editorial, 2020).

Globally, the total confirmed cases of COVID-19 have exceeded 460 million with more than 6 million deaths reported. There is a huge debate on whether mass burial of the bodies of COVID-19 victims may facilitate the spread of the virus through the unsaturated (vadose) zone to the groundwater table (phreatic surface). This is a valid concern, and the need to conduct more research particularly at field scale to validate this claim is an essential prerequisite to mitigate its potential impact on the environment. Many other countries around the world including South Africa, USA, and India are facing an unprecedented situation, whereby a large number of people are being buried in a relatively short space of time in cemeteries. There is also a pressing need to site new cemetery grounds for mass burial; although finding enough physical space for mass burial is a priority, the depths, locations of graves, and the way in which bodies are interred are all critical elements to ensure that water sources do not become contaminated. This will require trade-offs between the low economic benefit of using good land for burial, against developing the land for greater economic benefit through residential development.

This mini-review gives a brief introduction to the potential of SARS-CoV-2 as an enveloped virus to contaminate groundwater from cemeteries and the role played by different types of burial practices in either facilitating or restricting microbial transport. Additionally, research to address the importance of correctly siting cemeteries and managing mass fatalities in response to COVID-19 are also addressed.

1.2 Literature search methodology

Publications in peer-reviewed journals were accessed to identify the potential impacts of viral contamination of groundwater due to mass burial. The electronic literature search was conducted from December 2021 to February 2022 using the electronic databases Web Science Core Collection, Google Scholar, and Semantic Scholar with no restriction for publication date or language. Search terms and keywords related to viral contamination, SARS-CoV-2, groundwater impact and cemeteries were used to allow for the identification of studies examining a variety of viruses and a range of outcomes, varying from enveloped and non-enveloped viral behaviour to geotechnical considerations of the vadose zone when siting cemeteries.

A total of 514 articles were retrieved and duplicates (de-duping) from two databases (n = 90) were removed using the Endnote Reference Manager software online. The remaining 424 articles were screened and a further 305 records eliminated as these were deemed not relevant to the study. Full text screening was undertaken on the retained 119 articles and data from 93 studies abstracted and used in this review paper. Figure 1 presents the flowchart describing the literature search methodology applied in this review.

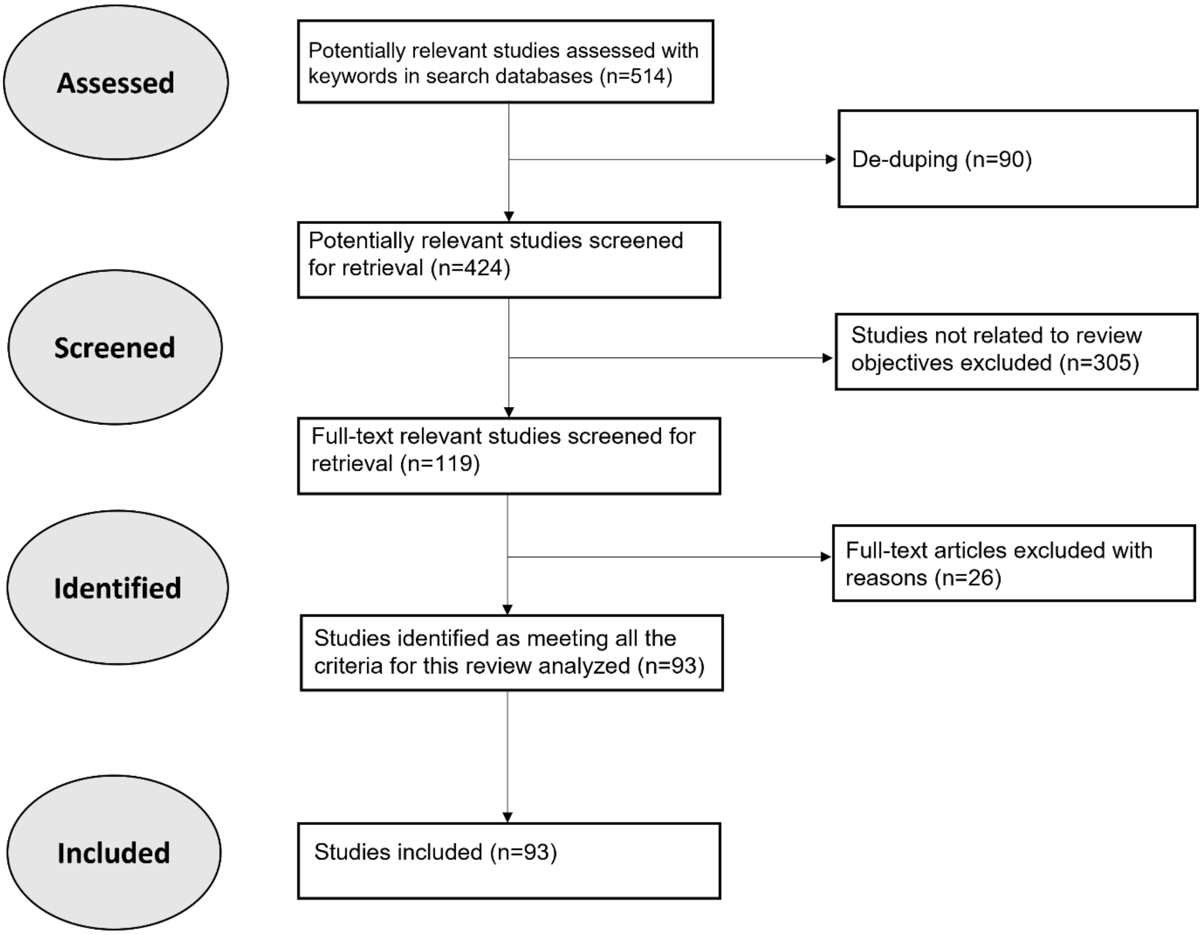

Fig.1. Stages of the selection of studies for analysis

1.3 SARS-COV-2: Current research trends

The family Coronaviridae has been around since the mid-1960s and known to cause common colds and flu, but only until fairly recently in 2003 and 2012 with the emergence of the highly pathogenic strains including the severe acute respiratory syndrome (SARS-CoV) and Middle East Respiratory Syndrome (MERS-CoV) has it become clear that coronavirus infection could result in serious and fatal diseases within humans (Casanova et al., 2009; Wigginton et al., 2015).

Coronaviruses are enveloped, positive-sense single-stranded RNA viruses that range from 60 to 220 nm in size that can infect birds and mammals (including humans) through aerosols or the faecal-oral route (Gundy et al., 2009; Hanley et al., 2020; Shakil et al., 2020). The SARS-CoV-2 virus has been detected in respiratory, faecal and blood specimens (Wang et al., 2020; WHO, 2020). The main route of transmission is considered to take place through the large respiratory droplets by inhalation or deposition on mucosal surfaces, but other modes of transmission (i.e., airborne, and faecal-oral route) have also been proposed. The most important factors that have been scientifically proven to influence the coronavirus survival in water are temperature, solar or UV inactivation, organic matter facilitated transport, and the presence of antagonistic microorganisms (Casanova et al., 2009; Abia et al., 2019; Naddeo & Liu, 2020).

Research on enveloped viruses present in natural waters has focused primarily on avian influenza viruses as natural waters serve as environmental reservoirs for these (Wigginton et al., 2015). Enveloped viruses are generally more susceptible to disinfectants than non-enveloped viruses, with the recent coronavirus outbreak highlighting the importance of disinfection. Furthermore, enveloped viruses (e.g., influenza viruses, coronaviruses, Ebola virus) consist of an outer envelope made up of lipids and proteins, and they can relatively easily be inactivated by exposure to high temperatures (Gundy et al., 2009). This is one of the main reasons that enveloped viruses such as SARS-CoV-2 lose their infectivity in aqueous solutions and are less stable in the environment than non-enveloped viruses. In other enveloped viruses such as HIV, it has been shown that infectivity decreases rapidly in aqueous environments (Tegally et al., 2020). In comparison, laboratory-based studies for an enteric non-enveloped poliovirus showed a 90% reduction (T90) value of 56 days in water at room temperature. Inactivation rates were clearly shown to be highly dependent on the water temperature and matrix conditions (Wigginton et al., 2015). However, a 2009 study demonstrated that the persistence of coronaviruses (in this case SARS-CoV) using transmissible gastroenteritis virus (TGEV) and mouse hepatitis virus (MHV) as surrogates, can remain infectious for long periods of time (weeks) in reagent grade waters, natural environmental waters, and water contaminated with human faecal waste at both low (4 °C) and ambient (25 °C) temperatures. In reagent-grade water at 25 °C, TGEV and MHV were reduced by 99.9% after 33 days and 26 days, respectively (decline of ~0.6 $\log_{10}$/week for TGEV and ~0.8 $\log_{10}$/ week for MHV). In reagent-grade water at 4 °C, neither TGEV nor MHV were significantly reduced after 49 days (Casanova et al., 2009).

The SARS-CoV-2 virus itself and its occurrence, and persistence in the environment have been studied by La Rosa et al. (2020). Data from the study suggest that CoV seems to have a low stability in the environment and is very sensitive to oxidants, like chlorine; it also appears to be inactivated significantly faster in water than non-enveloped human enteric viruses with known waterborne transmission. Temperature again seems to be an important factor influencing viral survival (the titre of infectious virus declines more rapidly at 23 °C – 25 °C than at 4 ℃). Also, there appears to be no current evidence that human coronaviruses are present in surface water or groundwater or are transmitted through contaminated drinking water (La Rosa et al., 2020). Shakil et al. (2020) conducted a critical analysis of 57 studies on the nexus between COVID-19 and the environment. The cluster under COVID-19 and temperature indicated that the virus is highly stable at 4 °C, but sensitive to heat. At 4 °C, there was only around a 0.7 log-unit reduction of infectious titre after 2 weeks. The temperature of groundwater during the year in a temperate climate is about 8 ℃, and therefore the virus can be stable at this temperature as well. With the incubation temperature increased to 70 °C, the time for virus inactivation was reduced to 5 min. It was also found that a 1 °C increase in temperature was linked to a 4.9% decline in daily COVID-19 transmissions when the temperature was lower than 25.8 °C. However, the same study found no evidence for the reduction in COVID-19 transmissions for temperatures above 25.8 °C. Nevertheless, as with other coronaviruses, it is an enveloped virus that is not likely to persist and remain infective in the environment given their unstable nature and susceptibility to unfavourable conditions (high temperature, light exposure, and antagonistic microorganisms like *Escherichia coli*, *Enterococcus* spp., *Bacillus* spp., *Clostridium* spp.).

In contrast, other microorganisms, although not relevant to this study, are long-lived and can survive in appropriate environmental conditions in soil profiles or groundwater systems for quite some time (e.g., *B. anthracis, variola virus, and Clostridium* spp.). The survival and transport rate of pathogens in soils and aquifers are controlled by climate, soil or aquifer type, pore fluid properties, and the pathogen itself (Bitton & Harvey, 1992). Batch and column experiments have shown that viruses do not readily sorb to or are released from soil particle surfaces when suspended in low ionic strength solutions (Sasidharan et al., 2017). Rainwater having low ionic strength can be instrumental in the redistribution and transport of viruses within the vadose zone (Bitton & Harvey, 1992). Changes in solution chemistry (e.g. decrease in ionic strength or increase in pH) produce large pulses of released colloids (Walshe et al., 2010). As a result, there is growing concern that attached viruses can become remobilised with a decrease in ionic strength or divalent cation concentrations during rainfall events (Sasidharan et al., 2017). This can have implications for groundwater contamination, particularly where the vadose zone is relatively thin and heterogeneous structures are known to exist with very low residence times.

Most studies on SARS-CoV-2, Coronaviruses, influenza viruses, transmissible gastroenteritis virus (TGEV) and mouse hepatitis virus (MHV) have been conducted on a laboratory scale as shown in the previous section; however, the extent to which these results are reproducible in field-scale situations is an area that needs more attention to further enhance the understanding of pathogen interactions in the environment.

Gundy et al. (2009) investigated the survival of a human coronavirus (HCoV-229E) and of an animal coronavirus (FIPV, feline infectious peritonitis virus) in tap water (filtered and non-filtered) and wastewater (primary and activated sludge effluents), comparing results with those of Poliovirus-1 (PV-1, Sabin attenuated strain LSc-2ab). In wastewater, the tested HCoV died off quite rapidly, with a T99.9 of 2.77-3.54 days at 23 °C. Significantly, the PV-1 lasted 2 to 3 times longer than CoV did, requiring 10.9 days for a comparable reduction in primary wastewater and 5.7 days in secondary effluents. In tap water at 23 °C, a 99.9% reduction in HCoV and FIPV was reached after 12.1 and 12.5 days, respectively. In tap water at 4 °C, a 99.9% reduction in HCoV and FIPV was predicted after >100 days. These yields highlight once again that virus survival decreases with increasing temperature. Similar to the results obtained on wastewater, PV-1 survived six times longer than CoV in both filtered and unfiltered tap water, confirming the observation that non-enveloped viruses display higher resistance in water environments compared to enveloped viruses. The study conducted by Gundy et al. (2009) further showed that CoV inactivation was faster in filtered tap water than in unfiltered tap water, suggesting that suspended solids in water can provide protection for viruses adsorbed to these particles.

Wang and co-workers studied the persistence of SARS-CoV in various water types (hospital wastewater, domestic wastewater, and dechlorinated tap water) and in faeces and urine (Wang et al., 2005). In the study, the performance of sodium hypochlorite and chlorine dioxide in inactivating SARS-CoV, *Escherichia coli,* and the Enterobacteria phage f2 spiked in wastewater was evaluated. The SARS-CoV virus was detected in hospital wastewater, domestic wastewater, and tap water for 2 days at 20 °C and for up to 14 days at 4 °C, thus demonstrating once again that temperature strongly influences viral persistence. Indeed, it has been universally demonstrated that higher temperatures are associated with rapid inactivation of enteric viruses, and temperature is recognised as the main factor affecting virus survival in the environment, through protein denaturation, damage to nucleic acid, or capsid dissociation (Pinon & Vialette, 2018).

As indicated, it is well documented that SARS-CoV-2 is susceptible to various environmental factors; however, some uncertainty still remains as to whether or not and through which mechanisms the SARS-CoV-2 virus could potentially contaminate groundwater systems. Research carried out by Zhang et al. (2022) on the evaluation of pathogen migration capacity using an assessment algorithm on five key physiological indices gave a migration ability for SARS-CoV-2 (size 60-140 nm) of 0.70. This shows that SARS-CoV-2 has a strong migration potential in the vadose zone. Given that groundwater is not exposed to sunlight as most surface water streams are, and the fact that the spatial distribution of groundwater temperature is mainly affected by geographical latitude, air temperature and local topographic elevations, the groundwater temperature usually stays within a narrow range year-round (Smith, 1982). As a result, the likelihood of SARS-CoV-2 surviving in groundwater remains a possibility. Preliminary results using a simulation-based approach to better understand the transport mechanisms of coronavirus through soil media, show that viruses can move through porous soil media and eventually contaminate groundwater systems (Petrosino et al., 2021). In a limited area of the selected soil section, the contamination was seen to be limited to a maximum of 0.1 PFU/mL after just 20 days of contaminated water drainage.

1.4 The impact of cemeteries and different burial practices on groundwater systems

The World Health Organization (WHO) has released an interim guidance document aimed at faith-based communities and religious leaders to consider the practical considerations and recommendations in the context of COVID-19 (WHO, 2020a). The guidance document states that it is important to safely plan and perform funeral rituals and services by having appropriate funeral and burial practices in place. The establishment of burial grounds according to the best environmental options should take into account the sensitivity to social, religious and cultural practices, as burial sites are not only places for the disposal of dead bodies, but also places where people visit and mourn.

The burial of a large number of bodies in a particular area within 24 hours, as opposed to a body that has to lie in a morgue for two weeks before burial, can potentially aid in the survival of pathogens and as a result pose a risk to the receiving environment. This need for rapid disposal has contributed to the current crisis and will have implications on how to safely handle various burial practices as the pandemic worsens.

In the process of decomposition, a human body can produce in the range of 0.4-0.6 L of cemetery leachate per 1 kg of body weight that can contain pathogenic bacteria and viruses that may possibly contaminate surface water and groundwater systems (Żychowski & Bryndal, 2015; Leong et al., 2021). Organic nitrogen compounds typically found in cemetery leachate are biogenic amines such as cadaverine (1,5-pentanediamine) and putrescine (1,4-diaminobutane) that are produced by decarboxylation of amino acids through enzymatic processes. These amines are highly toxic due to their high solubility in water and generate, when degraded, ammonium ions (NH_4^+) in the environment (Gonçalves et al., 2022). Depending on certain environmental conditions, it can take approximately 10-12 years for a corpse to decompose excluding the bone, with a decline in the number of substances leaching into the soil and groundwater each year (Vaezihir & Mohammadi, 2016). After 10 years, less than 0.1% of the original loading will remain. Decomposition of the human corpse results in a necroleachate containing salts, water, and some organic substances, followed by the final remains composed essentially of hydroxyapatite, which accounts for approximately 5% of the original body that is considered inert. Previous studies (Jonker & Olivier, 2012; Neckel et al., 2021) have shown significant exceedances of the content of ions from decomposition and these can be considered a threat to human health and life. The rate of degradation is promoted by high nutrients in the subsurface, neutral soil pH, warm temperatures, well-drained soils, and burial practices promoting accessibility of the corpse to decay by invertebrates and vertebrates (Trick et al., 1999; Dent et al., 2004; da Costa Silva & Malagutti Filho, 2012; Fiedler et al., 2012; Żychowski & Bryndal, 2015).

For a long time, groundwater has been thought of as being entirely free of microbial contaminants and viruses, assuming that vertical transport is slow enough and microbial survival too short to reach the underlying aquifer system. However, the risks of water contamination are emphasised considering the many small and huge endemic outbreaks from pathogenic microbes and viruses during the past 200 years, all linked to contaminated groundwater (Dent, 1998; Ucisik et al., 1998; Liang et al., 2006; Theng-Theng et al., 2007; Yoder et al., 2008).

1.4.1 Test results in cemeteries

There can be no doubt that groundwater has been and continues to be contaminated by microbial pathogens. However, internationally, very few studies have investigated the impact of cemeteries on the microbial contamination of groundwater (Oliveira et al., 2013; Żychowski & Bryndal, 2015; Abia et al., 2019). It has been shown that cemeteries may have large adverse impacts on groundwater when the water table is high (e.g., during periods of extensive precipitation) and can be a source of infectious diseases.

The main factors contributing to groundwater contamination from cemeteries are the number of interments; the physical, chemical, and biological properties of natural habitats; fluctuation in groundwater tables; circulation of water in the substrate and processes of binding between the decomposition products and the substrate; and soil and organic matter (Żychowski & Bryndal, 2015). Groundwater can be seen as a critical component of the hydrological cycle, constituting 95% of the Earth's usable freshwater reserve and supplying drinking water for over 2 billion people (Bradford & Harvey, 2017; Murphy et al., 2017) Pathogenic contamination of groundwater may increase in the future and most of the known pathogenic microorganisms and viruses have already been detected in groundwater. Clearly, surrounding land use activities that are not directly related to the cemeteries (such as landfills, septic tanks, sewage system leakages, etc.) cannot be discounted as potential sources of groundwater contamination.

Based on only a handful of research studies conducted in Europe (Rodrigues & Pacheco, 2010), Brazil (Pacheco et al., 1991; Costa et al., 2002), and Australia (Dent, 1998; Dent & Knight, 1998; Knight & Dent, 1998) a definitive impact of cemeteries on both surface water and groundwater quality has been shown. Research has been conducted in South Africa by Engelbrecht (1993) and Abia et al. (2018), with Abia et al. (2019) also showing significant microbial contamination of groundwater and surface water by *E. coli*, *Streptococcus faecalis* and *Staphylococcus aureus*. In addition, multi-drug resistant pathogenic *E. coli* bacteria were found in both surface water and groundwater from cemeteries in the Western Cape Province, and it was shown that pathogens and saprophytes can survive for up to two years and more during which time they can easily migrate to the groundwater table (Creely, 2004). Studies on the migration of pathogens, particularly bacteria and viruses, in the subsurface was carried out in Brazil by (Pacheco et al., 1991; Pacheco, 2017). Samples collected in cemetery environments showed that viruses have a greater capacity for mobility in the soil when compared to bacteria. The key physiological properties that need to be taken into account in terms of pathogen migration ability are pathogen size, surface charge, surface hydrophobicity, and membrane structure (Zhang et al., 2022). Studies on microbial purification generally track the behaviour of faecal coliform bacteria as indicators of human pathogens. This highlights the potential value of using bacteriophages infecting enteric bacteria as indicators and surrogates for assessing the occurrence and behaviour of human pathogenic viruses in aquatic environments and during water treatment (Stetler, 1984; Havelaar et al., 1993). Phages meet many of these requirements, but are not universal indicators, models, or surrogates for enteric viruses in water environments as enteric viruses have, for instance, been detected in treated drinking water supplies in which phages were not detected (Ashbolt, 2004).

Using molecular analysis (high throughput sequencing of the 16S rRNA gene), Abia et al. (2019) demonstrated the potential health threats to surrounding populations through groundwater contamination. The study showed lower alpha diversity at the surface while harbouring more human disease functional classes at a depth of 2 m. This change in microbial diversity as a function of sampling depth, with the surface samples being dominated by *Prauserella* and *Staphylococcus* genera and the 2 m samples being more abundant in *Pseudomonas* and *Rhodococcus*, suggests that areas with shallow aquifers such as Cape Town are possibly affected by microbial groundwater contamination from cemeteries. However, it is important to note that the presence of these organisms in the soil cannot necessarily be attributed solely to dead bodies.

Groundwater near urban cemeteries has shown high concentrations of intestinal flora, ions, and amino acids. However, upon death, the environment in which pathogens live can no longer sustain them, but it has been shown that sufficient time remains for transmission to occur (Całkosiński et al., 2015).

In Nigeria, Turajo et al. (2019) investigated whether mostly Islamic burial practices affect the groundwater within the vicinity of an active municipal cemetery in the Gwange area of the Maiduguri metropolis. The site is underlain by sedimentary rocks of the Chad Formation and is characterised by coarse-grained soils of high permeability ($1.04 \times 10^{-4} – 2.38 \times 10^{-4}$ cm/s). The research team analysed groundwater samples from three boreholes, namely BH1, BH2 and BH3, and found high nitrate concentrations at BH1 (at a distance of 1.4 m from the cemetery) with a value of 67.4 mg/L. The nitrite concentrations in the groundwater samples from BH1, BH2 and BH3 were 0.92, 0.51 and 0.49 mg/L, respectively, and thus the nitrite concentrations at BH1 and BH2 were above the WHO (2017) tolerance level of 0.5 mg/L. It is thus clear that with increasing burial over time, the cemetery has the potential to pose a significant threat to the aquifer. In terms of future planning, there is a need for best management practices for the proper siting of cemeteries in order to prevent contamination, and to conserve and protect the underlying groundwater resource from potential pollution.

Vaezihir and Mohammadi (2016) investigated the impact of the main cemetery of Tabriz, Iran on the underlying aquifer in terms of both microbial and hydrochemical contaminants; this cemetery is located on porous and highly permeable volcanic tuffs. The site has over 268 800 corpses with a burial rate of between 43-50 burials per day (over 9 000 per annum) with double stacking in some graves. Sampling and analysis of groundwater showed considerable microbial contamination (total coliform, > 3 to 110 000 MPN/100 mL, and for faecal coliform, > 3 to 2 300 MPN/100 mL) and chemical pollution, thus confirming the vulnerability model results. The NO_3^- and Na concentrations and Cl:Na ratios as well as the good correlation between NO_3^- and F^- concentrations confirmed the source of contamination as being the cemetery.

In the Geheina cemetery in Sohag, Egypt it was found that there is appreciable leaching from the dead bodies in graves that might contaminate the underlying aquifer (Mohammed & Abudeif, 2020). This cemetery was selected as two burial methods are practised here, namely Christian burials in coffins (Site 1) and Muslim burials without coffins (Site 2); a control area without cemeteries was added (Site 3). The results revealed the presence of three resistivity zones, namely a high resistivity zone (1 000–3 000 Ω m), moderate resistivity zone (50–1 000

Ω m) and low resistivity zone (<50 Ω m). The main constituents of these three zones are clastic sedimentary rocks with different grain sizes. The rapid decrease in the resistivity values at Site 2 compared to Site 1 is because of the rapid decomposition of the dead bodies due to the direct burial of the body in the ground without coffins, leading to higher pollution rates of the soil and the groundwater than burying in coffins. An increase in the burial depth causes an increase in the contamination rate of the shallow groundwater aquifer. Positive and negative values of potentials were recorded in 3D iso-potential contour maps reflecting the flow direction from low to high potentials. The negative values were attributed to the leakage of larger amounts of putrefaction fluids resulting from the decomposition of dead bodies. Positive potential values were due to the semi-fluid masses consisting of water and putrefied tissues which are mainly generated by the corpses buried in coffins with lower amounts of fluids and the evaporation of putrefaction fluids, and low humidity (Mohammed & Abudeif, 2020).

Microbial and chemical contamination can also occur in cemeteries because of unmanaged, untreated, and incorrectly sited sanitation services, solid waste, and wastewater, which allows for the flow of microorganisms and contaminants into cemeteries (Abia et al., 2019). When these cemeteries become a reservoir for contaminants, especially microbial contaminants, there is a possibility that the underlying groundwater, surface water and soil can also become contaminated as movement of these contaminants is mainly by underground water or by surface water (Hunt & Johnson, 2017). Generic guidelines exist for cemeteries, mainly addressing sanitary and geotechnical risks. These have been compiled cognisant of typical contaminants emanating from cemeteries, including a variety of metals, nutrients, organics, and pathogens (Kaczmarek, 2019; Neckel et al., 2021). From the studies above, it can be seen that cemeteries can pose a groundwater contamination risk under certain conditions; however, the human risk cannot be discounted if the groundwater is consumed.

1.4.2 Test results in laboratories

Various bacteriophages (MS2, PRD1, and ϕX174) were used as surrogates for pathogenic viruses to better understand the fate and transport of viral pathogens in UK aquifers (Collins et al., 2006). It was shown that MS2 bacteriophage and poliovirus displayed rapid initial die-off rates followed by a reduced die-off rate to approximately 50% of the initial concentration over a 77-day period. Similarly, poliovirus also exhibited similar initial die-off rates over the 77-day period when subjected to four different solution types. These findings indicate long survival times for poliovirus and MS2 in four water types emphasising the threat they pose to groundwater quality. Long survival rates for both groundwater and UV-sterilised groundwater indicate that microbial activity, at 12 °C, has little effect on the viruses (Gordon & Toze, 2003). Hence, at typical UK groundwater temperatures, viruses can survive for several months. This is further shown by the slow inactivation coefficient rates (μ) for both poliovirus and MS2. Even-though the study was done at laboratory scale, there is enough evidence to suggest that the groundwater can become contaminated and can be considered as a potential threat to the public if it is consumed.

1.5 Geotechnical and hydrological considerations for cemetery development

The WHO guidelines clearly stipulate that to date, there has been no evidence to suggest that individuals become infected through exposure to bodies of persons deceased due to COVID-19 (WHO, 2020). If conducted according to normal best practice, choosing to bury or cremate a person who has passed away from COVID-19 should pose no additional risk to persons alive or the environment, as was affirmed by Ubomba-Jaswa et al. (2020). However, in many other places worldwide, including South Africa, due to very diverse religious and cultural practices around death often requiring burial, as well as the lack of sufficient crematoria, COVID-19 victims are highly likely to be buried in cemeteries. These countries also often have serious issues with access to land in metropolitan areas given the economic benefit of alternative developments, and in rural areas where agriculture, conservation, and residential developments take precedence.

Poorly located and incorrectly managed burial grounds pose a severe pollution potential. The geotechnical design adopted for mass burial should guarantee minimum rainwater infiltration into the burial site to reduce the amount of necroleachate. In addition, it should also provide an opportunity to maximise virus retention by adsorption process (Leong et al., 2021). Leachate produced from burial grounds (cemeteries, churchyards, park cemeteries, and green cemeteries) is of a highly pathogenic nature and can pollute the soil zone and groundwater representing a public health hazard (Oliveira et al., 2013). Pollution problems generally occur in areas with vulnerable aquifers and climate conditions, which favour rapid seepage of decay products. It becomes vital that when establishing meaningful cemetery site selection criteria, adequate measures should be taken to ensure environmental protection and to promote rapid aerobic decomposition. Therefore, a sustainable development approach and the best environmental options should be adopted.

Corpses that are treated and buried in a correctly sited and constructed cemetery generally do not pose a threat to public health and are not a source of pollution. Currently, best practice is very generic and based on aspects related to the depth of excavation and the distance from surface water, drinking water, and the groundwater table (Hall & Hanbury, 1990; Dent &

Knight, 1998; Ucisik et al., 1998; Young et al., 1999; Croucamp & Richards, 2002). Additional generic specifications include:

- Deep water table
- Absence of perched water tables
- Soil conductivity $1\text{x}10^{-7}$-$5\text{x}10^{-5}$ cm/s
- Thick/deep excavatable soils
- No proximate water supply or drainage features
- Stability of sidewalls
- Surface gradient 2-6° (9° in exceptional cases)
- Space for adequate future expansion.

As noted, when cemeteries are sited properly and according to sound scientific judgement, surface water and groundwater should be protected from contamination regardless of the cause of death. The siting of cemeteries, described in detail by Dippenaar et al. (2018), provides for subsurface properties and allows adequate conditions for the natural attenuation of contaminants, of course on condition that the capacity of the cemetery not be breached. In general, cemeteries pose a low probability of adverse effects given the likelihood of on-site natural attenuation of contaminations; however, they pose a very high risk in the event of contamination ensuing. Poorly sited cemeteries are intrinsically at higher risk, and here groundwater or surface water will be the most direct receptors of pollution, and the most at risk will be on-site users of water such as workers. Another worst-case scenario is perhaps when a cemetery is placed on top of a karst aquifer; however, to the best of the authors' knowledge, this has not been documented.

The WHO (World Health Organization) (2020), Department of Health/National Institute of Communicable Diseases (2020) and the South African Cemeteries Association (SACA) compiled guidelines for the preparation of COVID-19-related mass burials and cremation (SACA, 2020). The guideline document gives clear specifications for the identification of new burial land within cemeteries to be prepared for emergency burials for bodies identified as infected. If this is unavailable, then consideration should be given to adjacent vacant land to existing cemeteries that may be expropriated if private or incorporated into the existing boundary of the cemetery if the land is municipal owned.

Cemetery development entails anthropogenic changes to the receiving environment and the environment inevitably affects the suitability of a site as a cemetery. Poorly compacted backfill of graves can result in a preferential infiltration zone, rapidly flooding the coffin. Mounded backfill, on the other hand, can divert water to preferentially infiltrate areas adjacent to graves, resulting in surface runoff and erosion. When coffins eventually collapse, the backfill may also create a depression, allowing water to collect in the grave itself. Excessive irrigation for landscaping purposes adds an unnecessary amount of water to the cemetery, all potentially at risk of pollution from the corrosion of the coffin and mobilisation of pathogens and embalming fluids (Dippenaar & van Rooy, 2019).

Cemeteries are generally considered low risk developments, and, although requiring a mandatory environmental impact assessment and recommended water use licence in South Africa, they do not always receive the risk assessment required to ensure environmental sustainability and socially acceptable development.

In the natural environment, infiltrating water moves through the soil profile, either vertically or laterally, until it encounters the interface with bedrock. Here, perching tends to occur as moisture builds up upwards, failing to breach into bedrock, resulting in the formation of a dispersion plume of moisture overlying the bedrock interface (Brouwers & Dippenaar, 2019). This, coupled with the already-complex flow in the unsaturated state (i.e., where moisture content is below saturation, and where pore water pressure is negative), results in several flow scenarios in the vadose (or unsaturated) zone above the groundwater table (Dippenaar & van Rooy, 2019):

Burial involves excavations typically exceeding 1.80 m in depth (Leong et al., 2021). These excavations are through the upper soil horizons, possibly extending into rock, and represent a highly variable vertical distribution of materials in terms of mechanical and hydraulic properties. As graves are supposedly above the permanent phreatic surface (water table), changes in the water cycle and changes in the mechanical properties are inevitable, mainly due to the removal and replacement of material through burial and backfill. The obvious influence of excavations on the stability of the sidewalls is exacerbated by altering moisture conditions, with significant changes in moisture content also directly affecting stability.

Excavating through these shallow soil horizons affected by small-scale variations in mechanical and hydraulic properties has an obvious consequence: interruption of these specific flow scenarios affects the greater subsurface water cycle. Waterlogged soils may now be removed, resulting in increased vertical drainage of surface water. Well-drained soils may be forced to waterlog upwards through perching or ponding. Ultimately, anticipating these changes dictates whether contamination may spread from the burial sites, whether excavations will be stable and accessible, and whether the burial site will be aesthetically and environmentally friendly on the surface. Situations where such perched or interflow systems were encountered are further detailed by Dippenaar (2014) for a burial site near an anthropogenic wetland in the north of Pretoria (Gauteng, South Africa), as well as by Mahlangu et al. (2020) for a burial site upstream of an ephemeral stream in Middelburg (Mpumalanga, South Africa). These flow scenarios affect the physical water cycle through flow alterations.

Placement of the coffin in the excavated grave in terms of the interface between the soil profile and the underlying bedrock dictates whether a preferential flow path is generated in the vertical or lateral directions. This can result in increased vertical percolation of infiltrated water or result in upward waterlogging and development of perched flow systems in the vadose (unsaturated) zone. Further to this, the influence of existing interflow or perched groundwater systems is exacerbated, and previously-moist soil can now become flooded excavations. The excavation of graves itself generates a bucket system where infiltrated water will most likely move towards less-compacted backfill or coffin voids. This changes the redox conditions, while also increasing moisture content to levels which can induce further vertical percolation or lateral flow of water. This is enhanced through compacting backfill or allowing depressions in backfilled soil, while the converse is true for mounded backfill whereby surface runoff and resulting erosion is more pronounced (Dent et al., 2004). However, to reduce the possibility of rainwater infiltrating the burial site, geosynthetic clay liners (GCLs) with low hydraulic conductivities can be installed. In addition to clay liners, Neckel et al. (2017) also proposed vertical cemetery deployment to reduce the impacts of necroleachate-linked pollution.

When investigating the various sources of microbial pathogens, whether it be from wastewater effluents or cemeteries, it is critical to conduct geological, geotechnical, and hydrogeological studies to build an accurate conceptual model of the system under investigation as outlined above (Żychowski & Bryndal, 2015; Dippenaar et al., 2018). Furthermore, a full vadose zone characterisation using both microbes and hydrological tracers will be required to gain an understanding of the influence on pathogenic bacteria/viruses and tracer mobilisation in the subsurface. This will allow for realistic setback distances to be calculated using numerical codes (Blaschke et al., 2016). Travel times dictate whether viruses will remain viable and/or how viruses will be removed. Rates of removal depend on the texture of the soil or backfilled material, its composition, and various reactions occurring in the soil, with different aquifer types also posing very different susceptibilities to virus transport. The substrates that influence microbial transport are coarse-textured soils; there is a high degree of virus retention by the clay fraction of the soil and where organic matter is present in sufficient quantities, it can increase the survival and possible reactivation and aid in the filtration process (Yates et al., 1988; Matos & Pacheco, 2002).

Pathogen transport is also affected by subsurface and surface hydrological processes. This includes geochemical variables (e.g., grain size, porosity, heterogeneity, moisture content, pH, ionic strength, temperature) and hydrodynamics like flow rate and direction (Zhang et al., 2022). In addition, the migration of pathogens in the subsurface is well correlated with the physiological characteristics of the pathogens like morphology, size, and hydrophobicity, whereby pathogens with smaller size, higher hydrophilic and spherical shapes are more favoured for migration (Pang et al., 2021). Complexity increases through variable soil hydraulic properties, surface topography, temporal variability in temperature, water inputs, and pathogen sources. Intense rainfall events can generate runoff and preferential flow that can rapidly transport pathogens over large distances. Mobilisation of pathogens surviving for very long periods is more likely through such rapid-transport events. Many studies have addressed quantification of the influence of different factors on microorganism transport, although specifically for homogeneous porous media. These include physical factors such as microbe size and concentration, properties of the porous medium, water content and velocity, and surface roughness, as well as chemical factors such as surface chemistry of both the microbe and the soil, pH, ionic strength, and chemical composition (Pedley et al., 2006; Wang et al., 2014; Żychowski & Bryndal, 2015).

However, most subsurface systems in South Africa are characterised by fractures, where flow and transport are concentrated along preferential flow paths, implying that transport is not associated with homogeneous porous media. As indicated above, preferential pathways (macropores, roots, and cracks associated with soil structure) make a substantial contribution to the transport of microorganisms, given their strong retention in the soil matrix. These structural heterogeneities can serve as important pathways for the transport of bacteria and viruses to depth in the vadose zone and can be independent of both soil moisture and total soil porosity (Unc & Goss, 2003). The separation distance between the bottom of a dry well and the bottom of the flow domain to achieve a 6 $\log_{10}$ removal of viruses was shown to be much larger than the currently recommended guideline of 1.5 to 13 m (Sasidharan et al., 2017). This was based on numerical modelling results showing that subsurface heterogeneity of vertically extended fractures and preferential flow pathways facilitated the virus transport and resulted in rapid arrival of viruses at the groundwater table.

Although little quantitative research has addressed this issue, optimum conditions for pathogen transport in preferential flow systems will therefore likely depend on the size of the pathogen, matrix pores, and macropores. Having said that, groundwater pollution potential can be greatly enhanced by the large numbers of burials over short periods, as well as the cumulative effects of many burials over longer time periods. This has already happened in New York, USA, where the number of mass burial plots dug daily increased from 1 to 25 to account for the surge in COVID-19 victims (Entress et al., 2020). It is therefore essential that, in addition to the geotechnical and hydrological considerations discussed above, government also invest early in the development of mass fatality management plans. With the sole purpose to better manage mass fatalities during the COVID-19 pandemic, cemetery operators should follow appropriate interventions such as those stated by the World Health Organization (WHO, 2020). Locally, the South African Cemeteries Association (SACA, 2020; WHO, 2020) or the updated environmental risk assessment guidelines for cemeteries can be used as an example to avoid any form of groundwater contamination.

The methodology outlined in these guidelines should be strictly adhered to in terms of environmental protection zoning, correctly sited and constructed cemeteries, so that the groundwater system can be protected from future microbial contamination (Dippenaar & van Rooy, 2019; Leong et al., 2021). Proper burial practice and risk assessment should reduce the likelihood of viruses surviving and remaining infectious in the environment. Increased risk is, however, posed by receptors encroaching cemetery sites due to the availability of amenities such as running water or electricity, access being quicker through cemeteries, and cultural aspects related to burial practices and the handling of the corpse.

1.6 Conclusions

The COVID-19 pandemic, as it is unfolding today, can have serious repercussions on the viral contamination of groundwater due to mass burial. It is thus important to understand the likely impact that cemeteries and mass burials may have on the viral spread through the unsaturated (vadose) zone to the groundwater table. The major factors that determine the survival and ultimate fate of SARS-CoV-2 in the environment are temperature sensitivity, it being an enveloped virus with a high susceptibility to chlorination and water treatment processes. The review clearly illustrates the significance of temperature controls on SARS-CoV-2 infectivity. The various types of burials are an important aspect that cannot be overlooked, as the need for the rapid disposal of bodies increases, so too will policy and legislative requirements change to address the safe handling of bodies as per the religious practices. Cemeteries and different burial types have been shown to be active sources of microbial contamination to groundwater systems, and can potentially constitute a human health risk if the borehole water in the vicinity is consumed. Research conducted at cemetery sites internationally using various bacteriophages (MS2, PRD1), faecal coliforms and viruses (TGEV, MHV) as surrogates for pathogenic enteric viruses to study the fate and transport of these viruses showed considerable contamination of groundwater. This can have implications for groundwater contamination, particularly where there is a shallow vadose zone and heterogeneous structures are known to exist with very low residence times.

Concerns regarding the potential of SARS-CoV-2 in groundwater highlight the importance of protecting boreholes against pathogens through proper siting, design, operation, and maintenance of cemetery sites using the recommended guidelines. It is common knowledge that viruses cannot replicate without a host and as a result cannot spread through the unsaturated zone unaided. In this instance, the groundwater table will not have any significant impact on infection levels from SARS-CoV-2 since groundwater is too deep to be in contact with the body and migration rates are very slow, except where preferential flow paths are known to exist. When burial takes place using scientifically defensible methods as outlined, the possibility of infection will be highly improbable.

Future research efforts might investigate other mass fatalities taking place in a relatively short space of time from either flood events, earthquakes, and other climatic factors; the body of knowledge developed around SARS-CoV-2 in dealing with this pandemic from a groundwater perspective, will provide a guiding framework on how to better prepare for mass burials in a short space of time. Other future areas of research could include examining the role of hydrogeological settings in microbial contaminant loading from cemeteries, tracing groundwater flow paths from cemeteries through the vadose zone using artificial and environmental isotopes, and investigating the interaction of groundwater with surface water and the potential of cemetery leachate to contaminate surface water resources. Finally, further research is required on the presence of pathogenic microorganisms and/or antibiotic resistance genes in cemetery leachate, especially on their source, transport, and fate within the vadose zone.

The SARS-CoV-2 pandemic has challenged the scientific community to think and prepare for other eventualities and at the same time created a broader understanding of burial practices and how to best manage and protect freshwater resources.

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