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REVIEW ARTICLE

A review of the occurrence, fate, and transport of SARS-CoV-2 in the aqueous environment, with specific reference to groundwater

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Abstract

The SARS-CoV-2 virus has led to the COVID-19 pandemic, creating significant global health challenges. Primarily, the virus spreads through respiratory droplets, however there is also a notable risk of waterborne transmission due to its presence in the feces and swabs of infected individuals. Groundwater, as part of the aqueous environment, is potentially vulnerable to contamination by SARS-CoV-2. Therefore, understanding the occurrence, fate, and transport of the virus in groundwater is essential for managing risks to human health associated with groundwater contamination by SARS-CoV-2. This paper reviews the sources, fate, and transport mechanisms of SARS-CoV-2 in groundwater and the subsurface environment. It identifies existing knowledge gaps and offers recommendations for protection groundwater resources. SARS-CoV-2 has been detected in stormwater, sanitary sewer overflows, leaking wastewater pipes, landfill leachates, and non-human animal waste. These possible contamination pathways suggest that stormwater and wastewater may act as environmental reservoirs and transmission routes for SARS-CoV-2. The virus can travel from untreated wastewater, potentially contaminating shallow groundwater systems and subsequently affecting deeper aquifers. The transport of viruses in groundwater is influenced by various physical factors (such as sorption, inactivation, moisture, pH, and temperature), geochemical factors (including suspended solids, organic material, cation and ionic strength), and hydrogeological factors (advection, dispersion, diffusion, porosity, aquifer flow regime, and recharge). This paper proposes the feasibility of using SARS-CoV-2 as a tracer, given appropriate health considerations.

Keywords SARS-CoV-2 · Groundwater · COVID-19 · Karst

Introduction

Groundwater is a crucial component of the hydrological cycle. Viruses that are present in soil and surface waters can infiltrate the unsaturated zone and aquifers through various pathways such as soil infiltration, stormwater runoff, sewer overflows, and leakage through karst systems. Consequently, it is unsurprising that many viruses, including coronaviruses, have been detected in groundwater (Krauss and Griebler 2011). Infections caused by SARS-CoV-2 were first identified in December 2019 in Wuhan, China (WHO 2020), and the World Health Organization (WHO) declared the COVID-19 outbreak a pandemic on March 11, 2020. This has presented a significant health risk, with approximately 586 million reported cases worldwide and over 6 million deaths as of August 2022 (WHO 2022). Various transmission mechanisms of COVID-19 have been identified, including aerosols, fomites (Guan et al. 2020), respiratory droplets, and close personal contact (Cui et al. 2019; Kang et al. 2020). Coronaviruses belong to a family of enveloped, single-stranded, positive-strand RNA viruses classified within the Nidovirales order, which includes pathogens affecting both animals and humans, such as SARS-CoV (Krauss and Griebler 2011). These viruses are also potential

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pathogens of viral gastroenteritis (Weiss and Navas-Martin 2005). The infection process for these viruses depends on an intact lipid layer envelope, which makes them more vulnerable to environmental changes in physical and chemical conditions. Enveloped viruses, however, tend to be more stable in reduced environmental conditions compared to non-enveloped viruses. Coronavirus, for instance, has shown significant resistance in cold water, remaining infectious for over 100 days in pasteurized settled sewage (Casanova et al. 2009). SARS-CoV-2 is generally more sensitive to water and wastewater treatment than other enteric viruses and can potentially be eliminated through conventional treatment and disinfection methods. However, its resistance to specific water treatment processes and disinfectants remains unclear (Vammen and Guillen 2020).

Groundwater is particularly vulnerable to contamination by viruses from various natural and anthropogenic sources. Studies in the U.S. have shown the presence of viruses in groundwater, including in deep aquifers (Borchardt et al. 2007; Bradbury et al. 2013). Enteric viruses, for instance, have been linked to six of the ten major waterborne disease outbreaks in karst regions of the United States between 1976 and 2005 (USEPA 2006). Karst aquifers, characterized by sinkholes, caves, and fractures, allow rapid water flow, facilitating the transport of viruses into the subsurface (White 1988). These aquifers often provide high-yield water supplies, sometimes even untreated. The USEPA estimates that approximately ten million people in the U.S. rely on untreated groundwater from karst aquifers (Johnson et al. 2011).

The potential impact of SARS-CoV-2 on groundwater resources has been largely overlooked, despite its widespread presence in the environment. Understanding its occurrence, fate, and transport in groundwater is critical for managing water safety and developing relevant treatment strategies. This review aims to address the knowledge gaps concerning the virus's behavior in the aqueous environment, particularly groundwater, and offers insight into how these findings could inform water management practices.

Methodology

A systematic review of peer-reviewed literature, including research articles, reviews, short communications, reports, and books, was carried out to examine the occurrence and fate of SARS-CoV-2 in the aqueous environment. The literature search was conducted using multiple databases, including the Web of Science Core Collection, Google Scholar, Scopus, ScienceDirect, and others. The search strategy employed specific keywords such as SARS-CoV-2, COVID-19, groundwater, and aqueous environment to identify studies focusing on the behavior and environmental impact of viruses, with an emphasis on SARS-CoV-2. In total, 254 relevant articles were retrieved. Following a screening process, 138 articles were excluded, leaving 116 articles for full-text review. Data extracted from these studies were systematically analyzed and incorporated into the present review. The conceptual framework of this study is organized into five interconnected stages (Fig. 1), which are influenced by various factors, including hydrochemistry, aquifer properties, geochemical processes, the geomicrobiology of SARS-CoV-2, and climatic conditions.

Fate of SARS-CoV-2 in the water environment

Recent studies have confirmed the presence of SARS-CoV-2 in wastewater, surface water and groundwater across multiple countries Table 1 and Fig. 2, including Australia, France, India, Israel, Italy, Japan, the Netherlands, Spain, Turkey, the USA, Mexico, Iran, Portugal, Germany, Czech Republic and the UAE (Ahmed et al. 2020; Haramoto et al. 2020; Kumar et al. 2020a; Medema et al. 2020; Nemudryi et al. 2020; Mahlknecht et al. 2021; Hosseinian et al. 2024; Salvador et al. 2022; Westhaus et al. 2021; Mlejnkova et al. 2020; La Rosa et al. 2020). SARS-CoV-2 primarily originates from the excreta of infected individuals and is subsequently transported to wastewater treatment plants (WWTPs). Wastewater from households, hospitals, and quarantine centers plays a significant role in potential viral spread. The concentration of SARS-CoV-2 in the feces of infected individuals ranges from 10^4 to 10^8 copies/L. Once mixed with wastewater, viral loads reduce to 10^2–$10^6$0.5 copies/L.

In countries with inadequate sewage treatment systems, contaminated effluents are often discharged directly into water bodies, posing a significant risk of contamination for both surface water and groundwater. Groundwater

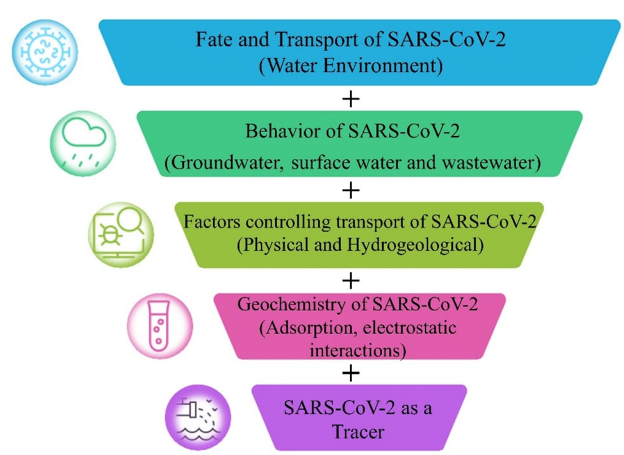

Fig. 1 Flowchart of the research methodology

Table 1 Certain studies deals with SARS-COV-2 in water environment

Country	Water environment	Time of study	Method	Reference
South Africa	Groundwater	2020	Potential SARS-CoV-2 contamination of groundwater as a result of mass burial	van Wyk et al. 2022
Quintana Roo, Mexico	Groundwater	2021	Environmental surveillance of SARS-CoV-2 RNA in wastewater and groundwater	Rosiles-González et al. 2021
India	Groundwater, Surface water	2020	Propensity and repercussion of SARS-CoV-2 migration to aquatic environment	Kumar et al. 2020a, b
Monterrey, Mexico	Groundwater, Surface water	2021	Presence of SARS-CoV-2 RNA in different freshwater environments	Mahlknecht et al. 2021
Tehran, Iran	Groundwater	2023	SARS-CoV-2 genome in the groundwater	Hosseinian et al. 2024
Barcelona, Spain	Groundwater, surface water	2020	Exploring viral contamination in urban groundwater and runoff	Itarte, Marta, et al. 2024
Lisbon, Portugal	Groundwater, surface water	2022	Surveillance of SARS-CoV-2 virus in natural and drinking water	Salvador et al. 2022
Monza, Italy	Wastewater, surface water	2020	Presence and infectivity of SARS-CoV-2 virus in wastewater and rivers	Rimoldi et al. 2020
Ahmedabad, India	Wastewater, surface water	2022	Spectre of SARS-CoV-2 RNA in the ambient urban waters	Kumar et al. 2022
Rotterdam, Netherlands	Wastewater	2021	Normalisation of SARS-CoV-2 concentrations in wastewater	Langeveld et al. 2023
Australia	Wastewater	2020	First confirmed detection of SARS-CoV-2 in untreated wastewater in Australia	Ahmed et al. 2020
Jaipur, India	Wastewater	2020	Sewage surveillance for the SARS-CoV-2 genome as a useful wastewater-based epidemiology tracking tool	Arora et al. 2020
Ohio, USA	Stormwater	2022	Detection of SARS-CoV-2 in urban stormwater	Bernard et al. 2022
Barcelona, Spain	Wastewater	2021	Time evolution of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) in wastewater	Chavarria-Miró et al. 2021
Yamanashi, Japan	Wastewater, surface water	2020	Presence of SARS-CoV-2 RNA in wastewater and river water in Japan	Haramoto et al. 2020
Netherlands	Wastewater	2020	Presence of SARS-Coronavirus-2 RNA in sewage	Medema et al. 2020
Montana, USA	Wastewater	2020	Temporal detection and phylogenetic assessment of SARS-CoV-2 in municipal wastewater	Nemudryi et al. 2020
Paris, France	Wastewater	2020	Time course quantitative detection of SARS-CoV-2 in wastewaters	Wurtzer et al. 2020
Milan, Italy	Wastewater	2020	First detection of SARS-CoV-2 in untreated wastewaters in Italy	La Rosa et al. 2020
Massachusetts, USA	Wastewater	2020	SARS-CoV-2 titers in wastewater are higher than expected from clinically confirmed cases	Wu et al. 2020
Istanbul, Turkey	Wastewater	2020	First dataset on SARS-CoV-2 detection for Istanbul wastewaters in Turkey	Kocamemi et al. 2020
NRW, Germany	Wastewater	2020	Detection of SARS-CoV-2 in raw and treated wastewater in Germany	Westhaus et al. 2021
Czech Republic	Wastewater	2020	Preliminary study of Sars-Cov-2 occurrence in wastewater in the Czech Republic	Mlejnkova et al. 2020

contamination can occur from wastewater treatment systems or untreated effluent, with combined sewer overflows and the discharge of partially treated wastewater acting as contributors (Saawarn and Hait 2021). Fecal shedding of viral genomes by infected individuals near water sources further exacerbates the risk. Decentralized wastewater

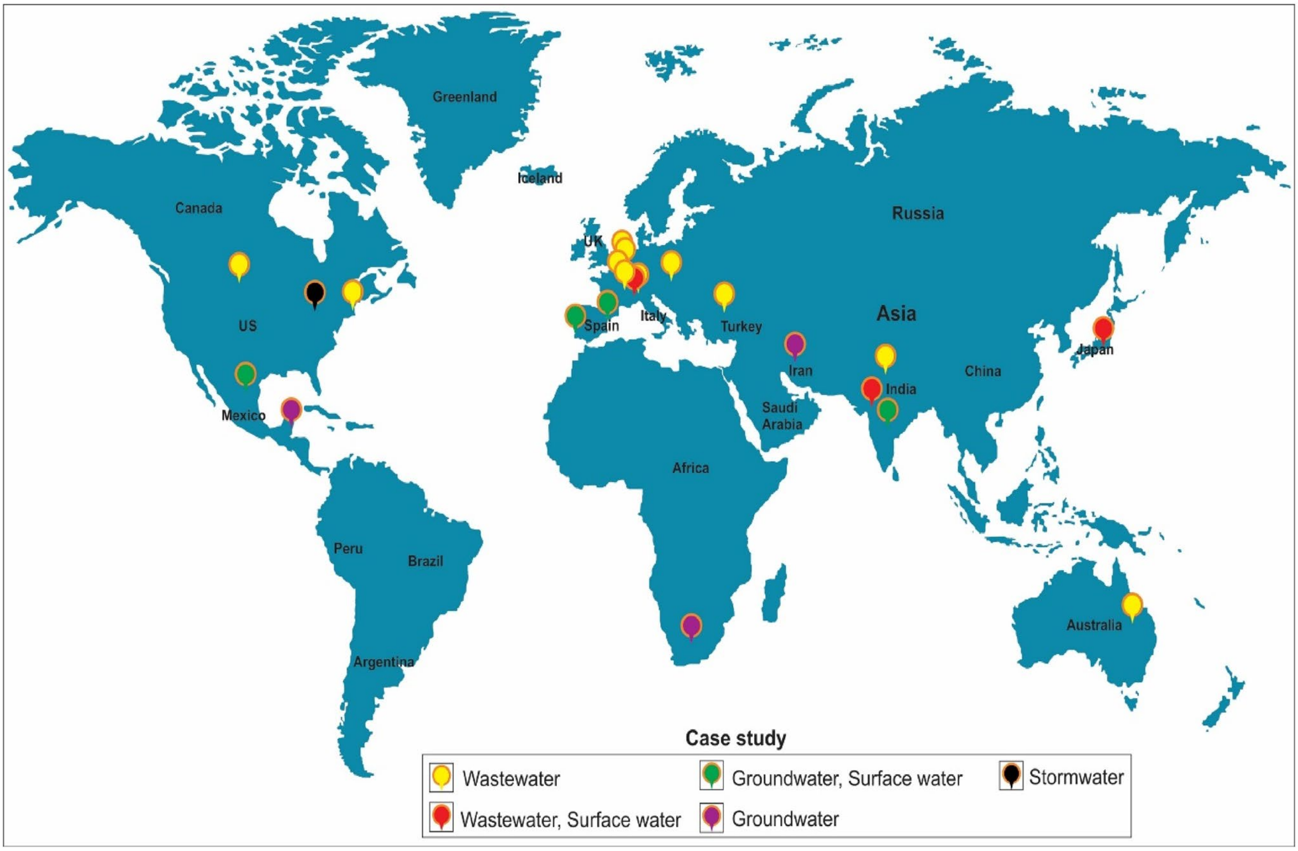

Fig. 2 Location of conducted studies of SARS-CoV-2 in water environment

treatment systems and non-point pollution sources, along with effluents from improperly disinfected systems, may lead to viral contamination of shallow groundwater, particularly in areas prone to flooding or near open wells used for drinking water (Banks et al. 2002). Wastewater effluent recharge, septic tanks, cemeteries, and diffuse sources such as leaking sewers are all significant point sources of viral pollution (Fig. 3). Additional potential sources contributing to viral contamination of groundwater include stormwater runoff, sewage sludge, farm slurry, sewage overflows, surface water flooding, and combined sewer overflows. These sources introduce viruses into groundwater through mechanisms like riverbank infiltration or via karst features, collectively representing induced groundwater recharge sources.

Karst and fissured geological structures, mines, abandoned wells, and other man-made infrastructure enhance the transport of viruses in aquifers (Aldous et al. 2021) by providing preferential pathways that shorten travel time, thus increasing aquifer vulnerability. Conversely, a deeper unsaturated zone offers some level of protection against viral intrusion, as viral migration can be slowed due to sorption at the air–water interface. However, during high-recharge events, such as heavy rainfall, the risk of viral transport in groundwater rises significantly. Bypass flow and mobilization of sorbed viruses reduce the protective effect of the unsaturated zone, further increasing aquifer vulnerability during these conditions.

Viruses in groundwater

Approximately 140 enteric viruses are known to infect humans (Table 2). These viruses are excreted in the feces of infected individuals and can directly or indirectly contaminate water sources intended for drinking. Groundwater may be contaminated by fecal matter from various sources, such as sewage treatment plant effluents, septic waste discharge systems, urban and agricultural runoff, and leachates from landfills (Bernard et al. 2022; Mouhamad et al. 2017). Due to their small size and extended survival, viral contamination in groundwater tends to be more widespread than bacterial or protozoan contamination (Schijven and Hassanizadeh 2000).

This increased contamination is attributed to the large numbers of viruses released into the environment, their longer survival times in water, and their resistance to common disinfection techniques (Fong and Lipp 2005). Pathogenic viruses are the primary concern when assessing fecal

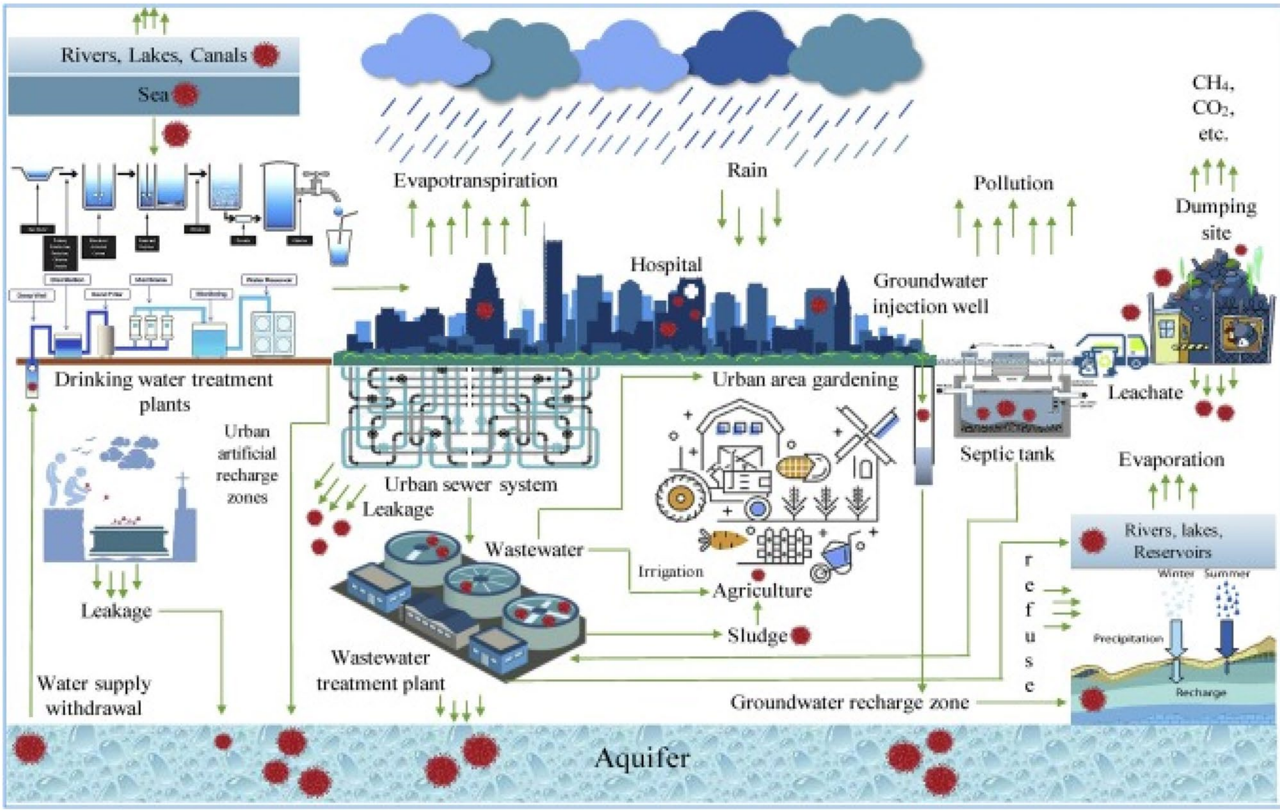

Fig. 3 Fate of SARS-CoV-2 in aqueous environment (Kumar et al. 2020b)

Table 2 Viruses in groundwater (after Krauss and Griebler 2011)

Virus	Health effect
Poliovirus	Poliomyelitis
Coxsackievirus	Fever, pharyngitis, rash, respiratory disease, diarrhea, haemorrhagic conjunctivitis, myocarditis, pericarditis, aseptic meningitis, encephalitis, reactive insulin-dependent diabetes
Echovirus	Respiratory disease, aseptic meningitis, rash, fever
Enteroviruses 68–71	Polio-like illness, aseptic meningitis, hand, foot and mouth (E71), epidemic conjunctivitis (E70)
Hepatitis A	Fever, nausea, jaundice, liver failure
Hepatitis E	Fever, nausea, jaundice
Norovirus (Norwalk virus)	Gastroenteritis
Calicivirus	Gastroenteritis
Astrovirus	Gastroenteritis
Sapovirus	Gastroenteritis
Orthoreovirus	Gastrointestinal and upper respiratory disease
Rotavirus A and C	Gastroenteritis
Coronavirus (including SARS-CoV-2)	Respiratory disease, gastroenteritis
Adenovirus	Respiratory disease, gastroenteritis

contamination in groundwater. Key factors influencing the transport and attenuation of viruses in aquifers include virus size, shape, motility, surface charge, and inactivation rate, as well as physical processes such as adsorption and filtration (Krauss and Griebler 2011).

The attenuation of viral particles in the saturated zone is influenced by virus-specific properties, such as the hydrophobic content of their capsids and their isoelectric points (Powelson and Gerba 1994). The effectiveness of viral filtration in porous media depends on the electrostatic interactions between viral particles and the aquifer matrix (Redman et al. 1997). Adsorption can effectively slow down a significant number of virus particles over short distances in both unsaturated soils and aquifer sediments. However, some virus populations may still migrate through groundwater without substantial decreases in concentration (Blanford et al. 2005).

Behavior of SARS-CoV-2 in the aqueous environment

SARS-CoV-2 in surface water and wastewater

SARS-CoV-2 has been detected in stormwater samples, likely due to fecal contamination from sources such as sanitary sewer overflows, leaking wastewater pipes, and animal waste. These contamination pathways suggest that stormwater could act as an environmental reservoir and transmission route for the virus (Bernard et al. 2022). This concern has gained more attention following the detection of SARS-CoV-2 in wastewater, leading to critical evaluations of the potential risks posed by inadequately treated wastewater (Ahmed et al. 2020).

A notable case highlighting the waterborne transmission risk of coronaviruses occurred during the 2003 SARS outbreak in Hong Kong, where a faulty sewage system was linked to a major outbreak (Peiris et al. 2003). Similarly, in India, Arora et al. (2020) identified SARS-CoV-2 in wastewater samples at ambient temperatures of 45 °C, with studies by Goswami et al. (2020) suggesting a positive correlation between COVID-19 cases and environmental factors like temperature and humidity.

The virus has been detected in both treated and untreated wastewater across many countries, including the USA, India, France, Italy, the Netherlands, Turkey, Israel, the UAE, Japan, and Australia, often in regions with high COVID-19 prevalence. Although transmission primarily occurs through respiratory droplets and contact, viral RNA has been found in wastewater through fecal and urine discharges, increasing the potential for environmental spread (Saawarn and Hait 2021; Wang et al. 2020). Additionally, the virus has been detected in river water and sludge (Godini et al. 2021; Mohapatra et al. 2021), and leaking sewer systems are recognized as significant pathways for subsurface virus transport (Mohapatra et al. 2021). Monitoring sewer systems has even been used to locate COVID-19 hotspots and support rapid response measures by health authorities, as seen in Barcelona, Spain (Chavarria-Miró et al. 2021).

SARS-CoV-2 in groundwater

Groundwater contamination by SARS-CoV-2, used as a drinking water source, can occur through seepage from sanitation systems, landfills, and leachates from septic tank systems (Girón-Navarro et al. 2021). The first detection of SARS-CoV-2 in groundwater was reported in the Monterrey Metropolitan Area, Mexico, where Mahlknecht et al. (2021) found viral loads ranging from 2.6 to 38.3 copies/ml in 44% of the tested groundwater samples. This contamination was linked to surface infiltration of untreated sewage or leakage from sewer systems.

Surface water bodies such as streams and lakes, when contaminated with wastewater discharges, can also serve as a transmission pathway for SARS-CoV-2 into groundwater (Adelodun et al. 2020; Sunkari et al. 2021). In Africa, hospital sewage, as well as waste from isolation and quarantine centers, were identified as potential sources of groundwater contamination by the virus (Sunkari et al. 2021). Additionally, the improper disposal of surgical masks, tissues, and personal protective equipment (PPE) without proper treatment has been highlighted as a potential transmission route. Poor solid waste management practices in the region were recognized as key contributors to SARS-CoV-2 contamination of water systems, which eventually reach groundwater.

Kumar et al. (2020b) emphasized the risk posed by SARS-CoV-2 to surface and groundwater, mainly through leaching and infiltration from healthcare facility effluent, sewage, and drainage water. They further noted that fecally transmitted viruses show significant persistence in aquatic environments, suggesting that SARS-CoV-2's persistence in water plays a crucial role in understanding its fate in groundwater and its potential impact on human health.

Factors controlling the transport of SARS-CoV-2 in groundwater

Physical controls

The transport of viruses in groundwater is influenced by various factors (Table 3) including sorption, inactivation, pH, and temperature. Laboratory experiments indicate that suspended solids, organic matter, pH, and temperature adversely affect virus survival in groundwater (Keswick & Gerba 1980; Saawarn and& Hait 2021). For instance, Riddell et al. (2020) studied the survival rates of SARS-CoV-2 at different temperatures, finding half-lives of 1.7–2.7 days at 20° C, which decreased significantly with temperatures up to 40° C. Xie et al. (2022) further found that the optimal pH for SARS-CoV-2 survival is between 7.5 and 9.

Table 3 Factors affecting the survival and transport of viruses in groundwater (modified from Krauss and Griebler 2011; Yates et al. 1987)

Factor	Impact
Temperature	Long survival at low temperatures, rapid inactivation rate at high temperatures
Moisture content	Desiccation is detrimental for viruses. Viruses are more active in saturated soil
Sunlight	More rapid die-off at the soil surface due to UV irradiation
pH	Bacteria die-off more rapidly in acid soils (pH 3–5) than in alkaline soils. The pH influences the adsorption of microorganisms and viruses to the soil matrix and indirectly influences survival
Microflora	Soil bacteria and fungi may produce exo-enzymes that damage the structure of fecal microorganisms, while amoebae and other protozoa may feed on them. Microbial activities contribute to viral inactivation due to extracellular enzymatic activity
Organic carbon content	The presence of organic carbon increases the survival of viruses and interacts with pathogens and facilitates their migration
Ionic strength	Ionic strength is affecting pathogenic attachment efficiency and migration ability through the change of pathogenic surface charge and membrane composition by ionic strength
Adsorption	Affects the virus survival and its transport
Aggregation	Make pathogens more resistant to external stressors and retards movement
Dissolved solids	Affects the activity and mobility of viruses
Hydraulic gradient	Migration of viruses increases with increasing hydraulic loads and flow rates

SARS-CoV-2 is sensitive to other environmental parameters such as oxidants, detergents, salinity, and micropollutants (Foladori et al. 2020). For example, free chlorine is more effective in inactivating the virus than chlorine dioxide (Wang et al. 2005). The survivability of SARS-CoV-2 in the aqueous environment has been evaluated in different contexts. Hart and Halden (2020) noted that the virus persists longer in winter than in summer, with its half-life at 20 °C estimated between 4.8 and 7.2 h, but survival times increased in groundwater (Keswick & Gerba 1980; Mohapatra et al. 2021). Viral loads rapidly decline at higher temperatures, such as 23–25 °C, compared to lower temperatures like 4° C (Saawarn and Hait 2021). Chin et al. (2020) presented that virus stability declines from 14 days at 4° C to just 5 min at 70 °C, as increased temperature reduces water viscosity, enhances virus attachment, and limits migration. The attachment rates of bacteriophages PRD1 and UX174 increased by 109% when temperature rose from 4° C to 20 °C (Sasidharan et al. 2017b).

Groundwater temperature, which generally ranges between 10 and 22° C in the thermostatic zone, rises by 1 °C for every 33 m of depth (Zhan et al. 2022). When pathogens enter groundwater through the vadose zone, their movement is influenced by moisture content (Flury and Aramrak 2017). Decreased moisture increases virus attachment to solid particles, delaying their vertical migration. Attachment at the solid-water interface becomes dominant over the air–water interface, depending on factors like hydrochemistry, surface charge, and hydrophobicity (Wan and Tokunaga 2002).

Pathogen migration is relatively slow in deep groundwater, but faster in shallow groundwater, posing significant risks to drinking water safety (Zhan et al. 2022). Low relative humidity makes SARS-CoV-2 more resistant to thermal inactivation, as water interacts with the virus's lipid envelope (Guillier et al. 2020). Chan et al. (2011) found that SARS-CoV remained viable between 22 and 25 °C and 40–50% humidity for five days but was eliminated at higher temperatures (38° C) and relative humidity (> 95%).

The stability of SARS-CoV-2 across a wide pH range (3–10) at room temperature was confirmed by Chin et al. (2020). Increased salinity, often resulting from evaporation, can lead to virus inactivation, but the hydrophobic nature of the virus's envelope reduces this likelihood (Chattopadhyay and Taft 2018). Groundwater monitoring is recommended after heavy rainfall to assess whether adsorbed viruses are eluted from soil into aquifers (Keswick & Gerba 1980).

Soil texture significantly impacts virus migration in groundwater, with grain size, surface roughness, and heterogeneity affecting transport (Sasidharan et al. 2017a). Coarser-grained media, such as sands, promote physical filtration, which helps retain pathogens (Bradford et al. 2006). Rougher surfaces with higher specific areas provide more attachment sites, limiting virus migration (Torkzaban and Bradford 2016). Heterogeneous porous media also influences pathogen transport, with viruses adhering at secondary minima or detaching from primary minima at nanoscale asperities (Shen et al. 2020). Increased virus migration correlates with the standard deviations of hydraulic conductivity in heterogeneous aquifers (Torkzaban et al. 2019).

Hydrogeological controls

Fractures in aquifers commonly serve as transport pathways for pathogenic viruses in groundwater. Boreholes, along with deformities in well casings—whether active or abandoned—facilitate viral movement into aquifers. Additionally, recharge zones play a critical role in introducing viruses from surface waters into groundwater systems.

The migration of pathogens in groundwater is heavily influenced by hydrogeological conditions, particularly flow rate (Yan et al. 2020). Lower flow rates, coupled with a higher hydraulic residence time, slow down pathogen movement and provide more time for their attenuation (Sasidharan et al. 2017a). Conversely, higher flow rates promote faster pathogen migration and facilitate rapid distribution within an aquifer (Prédélus et al. 2017). The relationship between flow rate and pathogen migration can be attributed to the increased residence time of pathogens in porous media, which impacts deposition kinetics. At lower flow rates, weaker hydrodynamic forces act on pathogens in the aquifer, making their transport more difficult (Bradford et al. 2011). Due to their smaller size and higher resilience to extreme conditions, viruses tend to be transported farther in groundwater compared to bacteria and protozoa (Kumar et al. 2020b).

Flow velocities in fissured aquifers can vary widely, from less than 1 m per day to over 100 m per day, with karst aquifers exhibiting even higher velocities, often exceeding 1000 m per day (Matthess et al. 1988). These high velocities and long travel distances increase the vulnerability of karst aquifers to contamination due to their low filtration capacity (Kačaroğlu 1999). Consequently, waterborne diseases are frequently linked to fractured rock and karst aquifers (Fong et al. 2007). The migration of viruses in subsurface environments can also be explained by the structural heterogeneity of aquifers (Sinton et al. 2000). In addition to flow mechanisms, porosity plays a key role in determining viral attenuation and transport in aquifers (Pang 2009).

The type of aquifer—whether porous, fissured, or karst—also significantly impacts the travel distance of viruses (Fig. 4), as it is closely related to groundwater flow velocities (Krauss and Griebler 2011). Viruses reaching the saturated zone are influenced by processes such as advection, dispersion, and diffusion (Sen 2011).

The entry of viruses into groundwater is dependent on the vulnerability of the aquifer, which is controlled by several factors: the thickness, structure, and activity of the soil and vadose sediment layers covering the aquifer, the flow regime, the contamination source, and the presence of abandoned or poorly constructed boreholes (Cronin et al. 2003; Harter and Walker 2001).

Geochemistry of SARS-CoV-2 in groundwater

Laboratory studies have demonstrated that viruses show distinct adsorption properties, which significantly influence their movement from contamination sources, such as septic systems, into groundwater (Armanious et al. 2016; Keswick

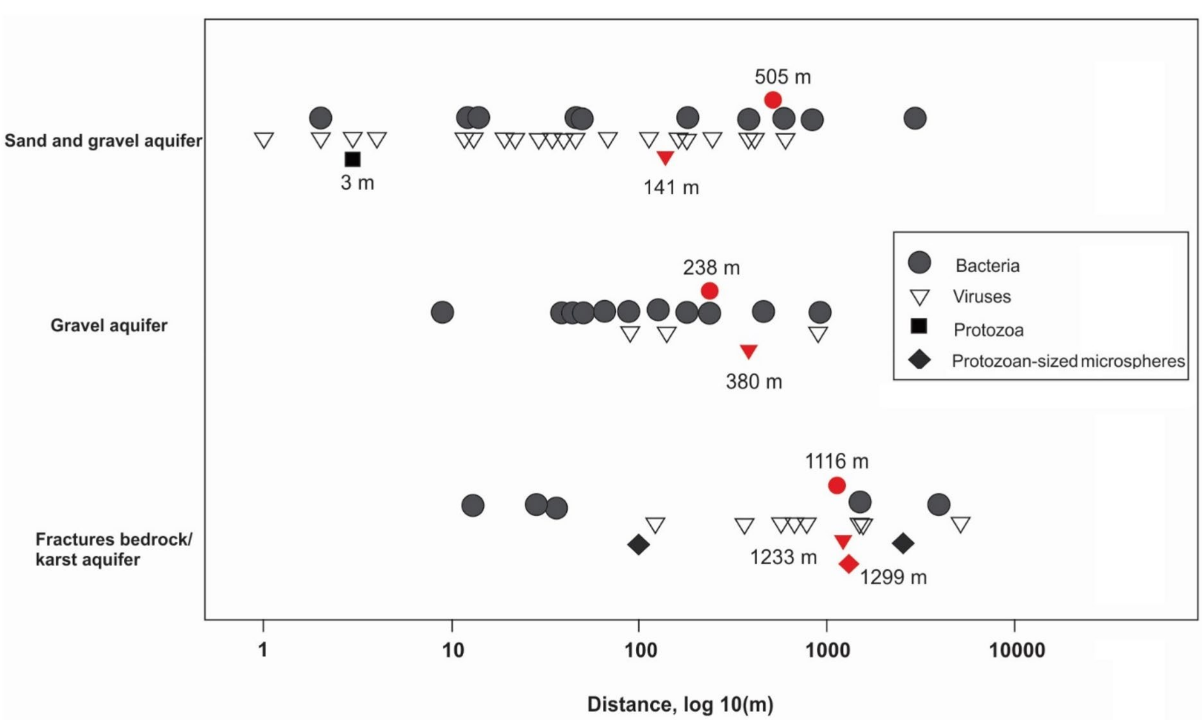

Fig. 4 Transport distances of pathogens in different aquifers. Red color is average transport distance (after Krauss and Griebler 2011)

& Gerba 1980). This information is crucial for assessing the migration potential of viruses, as understanding their behavior in subsurface environments aids in evaluating groundwater contamination risks. Therefore, to effectively assess groundwater systems, testing for the presence of various viruses is essential to ensure comprehensive representation (Keswick & Gerba 1980). Research has shown that increased ionic concentrations in groundwater enhance viral adsorption within subsurface environments (Moore et al. 1981).

Virus attachment to aquifer materials is primarily governed by electrostatic interactions (Gerba 1984) and is further enhanced in groundwater with lower pH and higher ionic strength (Penrod et al. 1996). Since most viruses are negatively charged at typical groundwater pH levels (6–8.5), their attachment is facilitated by positively charged groups on minerals like iron oxyhydroxides and clay (Ryan et al. 1999). While virus attachment plays a key role in inactivation—preventing the contamination of water bodies, the specific impact of attachment on surface inactivation remains uncertain. In the presence of disinfectants, attachment inhibits virus inactivation, whereas in their absence, attachment to mineral surfaces generally promotes inactivation (Murray and Parks 1980). The degree of virus inactivation through attachment is influenced by the strength of the attachment and the virus type (Schijven and Hassanizadeh 2000).

Several factors, including aquifer organic matter content, groundwater ionic strength, and pressure, significantly affect virus transport and attenuation (Krauss and Griebler 2011; McCarthy and McKay 2004). High concentrations of humic substances and organic matter compete with viruses for hydrophobic sites on soil and aquifer surfaces, thereby increasing the risk of viral entry and transport within aquifers (Lance and Gerba 1984). Fractured aquifers, which have reduced surface area for adsorption, typically exhibit lower levels of viral retardation (Cronin et al. 2003).

Groundwater chemistry plays a critical role in determining pathogen migration through hydrophobic and hydrophilic interactions (surface hydrophobicity). Groundwater contains a variety of inorganic and organic materials, such as colloids, iron and manganese oxides, mineral fragments, and natural organic matter, all of which influence pathogen migration (Foppen et al. 2008). Phosphate in groundwater can increase the electrostatic repulsion between pathogens and aquifer material, hindering migration (Wang et al. 2011). Conversely, silicate minerals have been shown to enhance pathogen surface charge, reducing electrostatic repulsion and thus decreasing pathogen migration (Dong et al. 2014). Colloid transport can further impact pathogen migration, with organic and inorganic colloids displaying distinct mechanisms of transport (Jin et al. 2000). Organic colloids tend to form stable aggregates with pathogens, accelerating migration, whereas inorganic colloids often agglomerate, leading to porosity blockage and inhibiting migration (Qin et al. 2020).

Natural dissolved organic matter can adsorb hydrophobic organic compounds, increasing their solubility and, consequently, facilitating the migration of pathogens adsorbed to these complexes (Foppen et al. 2008). Pan et al. (2017) demonstrated a positive correlation between virus abundance and dissolved organic carbon (DOC), indicating that viruses are influenced by the geochemical conditions of groundwater. Additionally, their study showed a strong correlation between uranium concentrations and virus abundance in groundwater. Virus transport and abundance are thus closely linked to aquifer geochemical conditions, which also regulate microbial host cell populations, further controlling viral abundance. The relationship between organic matter from lysed cells and viral interactions with microbiota is crucial for understanding subsurface biogeochemical cycling and contaminant mobility (Pan et al. 2017).

Viral transport of SARS-CoV-2 in groundwater

In certain conditions, viruses have been observed to travel distances exceeding 100 m through the subsurface. Due to their smaller size (ranging from 23 to 80 nm), viruses are transported farther in groundwater than bacteria (0.5–3 µm) or protozoan parasites (4–15 µm). As a result, the presence of viruses in groundwater without the detection of coliform bacteria is not unusual (Abbaszadegan et al. 2003). Several fundamental processes control the transport of virions in aquifers, including adsorption of soil particles, aggregation with other pathogens, temperature, microbial activity, moisture content, pH, and dissolved salts, all of which affect viral activity and mobility. Additionally, factors such as organic content and viral structure, such as diameter, genome composition, and whether the virus is enveloped or non-enveloped play significant roles in determining virus behavior (Yates et al. 1987).

The movement of viruses in groundwater is a highly complicated process influenced by both the physical flow of water and various chemical reactions. Understanding how viruses travel through groundwater is essential for assessing the health risks linked to consuming groundwater, especially from private or residential wells. To ensure public health safety, it is crucial to establish adequate separation distances between sources of contamination, such as septic systems, and wells. These distances must allow enough time for viral concentrations in the groundwater to decrease to safe levels before reaching the wells. Risk assessments across a variety of input parameters are compared to the international health risk benchmark, which limits infections to a maximum of 10^{-4} infections/person/year. Additionally, a 30 m setback distance is used to highlight key subsurface conditions that should receive regulatory attention to protect public health (Rafini et al. 2023), as explained in Fig. 5.

Enveloped viruses, such as SARS-CoV-2, possess an additional lipid membrane surrounding their capsid protein, which differentiates them from non-enveloped viruses. This structural difference influences viral partitioning, fate, and transport in the soil. For non-enveloped viruses, electrostatic interactions and hydrophobic effects between viral capsid proteins and sorbent surfaces govern the rate of adsorption. Studies have suggested that SARS-CoV-2, due to its amphoteric nature, may associate with negatively charged solid fractions under equilibrium conditions. Consequently, the migration of SARS-CoV-2 is expected to be slower than that of non-enveloped viruses. Viral transport tends to occur more rapidly under saturated conditions compared to unsaturated conditions, as saturated flow reduces contact between the virus and soil particles (Betancourt et al. 2019). Furthermore, increased rainfall and a decrease in pore water ionic strength can result in virus desorption, facilitating its migration in the subsurface (Yates et al. 1987).

Geomicrobiology of SARS-CoV-2 in groundwater

Viral transmission often follows an episodic pattern but is traditionally considered to operate within a closed, systemic biological cycle. However, this assumption may be flawed. The increasing episodic nature of viral transmission suggests the need for a more nuanced examination of potential physiographic and climatic factors. These factors may be linked to geogenic properties, particularly hydrodynamic characteristics, in relation to terrestrial biology and ecology. The environmental factors associated with the spread of SARS-CoV-2 remain unstable. In response to this uncertainty, studies incorporating topography-controlled genomics in soil geomicrobiology, as well as invertebrate medical geology for species-to-species transmission, are recommended. The possibility of virus transmission via air, water, and earth has largely been overlooked by geologists. However, the emerging field of medical geology can help clarify the relationship between the Earth's systems and human health, shedding light on how these factors influence viral transmission. For instance, the potential of closed spaces to either facilitate or hinder virus transmission should be subject to certification. Geomicrobiological studies, as a developing discipline, are proving to be valuable in understanding these dynamics. It is essential to investigate

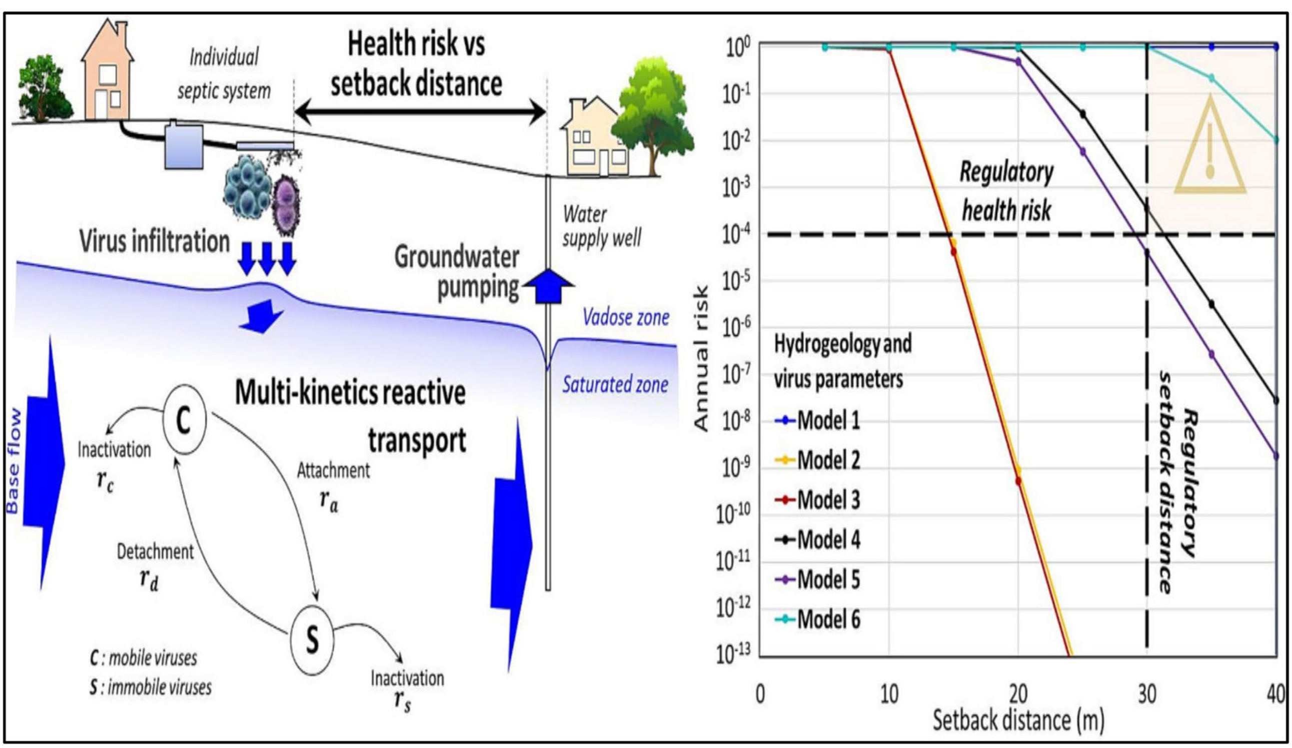

Fig. 5 Model of producing mass transfers reactions of viruses (Rafini et al. 2023)

geological terrain factors in enclosed spaces and assess whether they are conducive to viral transmission (Cruz-Rodrıguez et al. 2020). Viral transmission often follows an episodic pattern but is traditionally considered to operate within a closed, systemic biological cycle. However, this assumption may be flawed. The increasing episodic nature of viral transmission suggests the need for a more nuanced examination of potential physiographic and climatic factors. These factors may be linked to geogenic properties, particularly hydrodynamic characteristics, in relation to terrestrial biology and ecology. The environmental factors associated with the spread of SARS-CoV-2 remain unstable. In response to this uncertainty, studies incorporating topography-controlled genomics in soil geomicrobiology, as well as invertebrate medical geology for species-to-species transmission, are recommended. The possibility of virus transmission via air, water, and earth has largely been overlooked by geologists. However, the emerging field of medical geology can help clarify the relationship between the Earth's systems and human health, shedding light on how these factors influence viral transmission. For instance, the potential of closed spaces to either facilitate or hinder virus transmission should be subject to certification. Geomicrobiological studies, as a developing discipline, are proving to be valuable in understanding these dynamics. It is essential to investigate geological terrain factors in enclosed spaces and assess whether they are conducive to viral transmission (Cruz-Rodriguez et al. 2020).

Barton (2020) explored the potential for various surfaces within show caves to serve as sources of SARS-CoV-2 infection. Based on the isoelectric potential of SARS and SARS-like coronaviruses, it is likely that these viruses are adsorbed onto limestone surfaces through electrochemical interactions. High humidity and the presence of bicarbonate ions in these environments can contribute to the inactivation of SARS-CoV-2. However, show caves also contain infrastructure made of non-porous surfaces, which are more conducive to maintaining coronavirus viability (Barton 2020).

SARS-CoV-2 as a tracer

Chakraborty et al. (2021) monitored the presence of SARS-CoV-2, combining it with organic tracers in a wastewater treatment plant in India during both the partial and post-lockdown phases of the coronavirus pandemic. Long-term periodic sampling was conducted by Bradbury et al. (2013), using viruses as tracers to infer the time of travel between the suspected virus source in leaking sanitary sewers and groundwater wells. Hunt et al. (2014) used viruses as tracers to study the contamination of municipal well water from a sanitary sewer source. Similarly, Taylor et al. (2004) used viral tracers to study groundwater microbial contamination and wellhead protection zones, relying on the natural attenuation of microorganisms and average groundwater flow velocities.

Viruses are known to travel in groundwater at different rates. Therefore, studying the potential migration of viruses in groundwater requires the development of tracers that reflect their behavior in the subsurface. One alternative approach is to develop bacteriophage tracers that exhibit movement and survival patterns similar to animal viruses (Keswick & Gerba 1980). In karst and sand aquifers, where larger pore sizes reduce the impact of size exclusion, microbial tracers have been observed to move at velocities similar to those of conservative tracers (Aldous et al. 2021). Viruses, including SARS-CoV-2, are useful tracers for short travel times in aquifers (less than three years) due to their unique genetic signatures, which can be detected in trace quantities, and their mobility in groundwater. Virus outbreaks result from infections and viral shedding over time (Hunt et al. 2010). Viruses shed in the feces of infected individuals at specific times can be used as tracers for tracking both viral and groundwater movement (Bradbury et al. 2013).

A significant occurrence of sulfonamide resistance genes has been documented across various aquatic environments, including surface water, groundwater, and drinking water, on a global scale (Calero-Cáceres et al. 2017; Stange et al. 2019; Stoll et al. 2012; Storteboom et al. 2010). The macrolide resistance gene ermB, which was analyzed, exhibited the highest prevalence among the genes studied, being detected in 42.1% of the samples (Stange and Tiehm 2020) (Fig. 6). Previous research indicates its presence in two aquifer recharge systems in Germany (Böckelmann et al. 2009), and the existence of both ermA and ermB genes has also been identified in surface water (Stoll et al. 2012).

The virus tracing approach provides valuable understandings into travel times in high-velocity groundwater settings, offering a unique perspective compared to standard hydrogeological methods. However, characterizing a preferential flow path does not usually account for solute transport characteristics in groundwater, such as the center of the plume mass or the tail of the breakthrough curve. In contrast, virus tracers can track very short-duration transport events, filling an important knowledge gap in hydrogeology (Hunt et al. 2010).

Conclusions

The occurrence of SARS-CoV-2 in human excreta and wastewater highlights the importance of understanding the environmental conditions that influence the virus's persistence. The detection of SARS-CoV-2 in wastewater

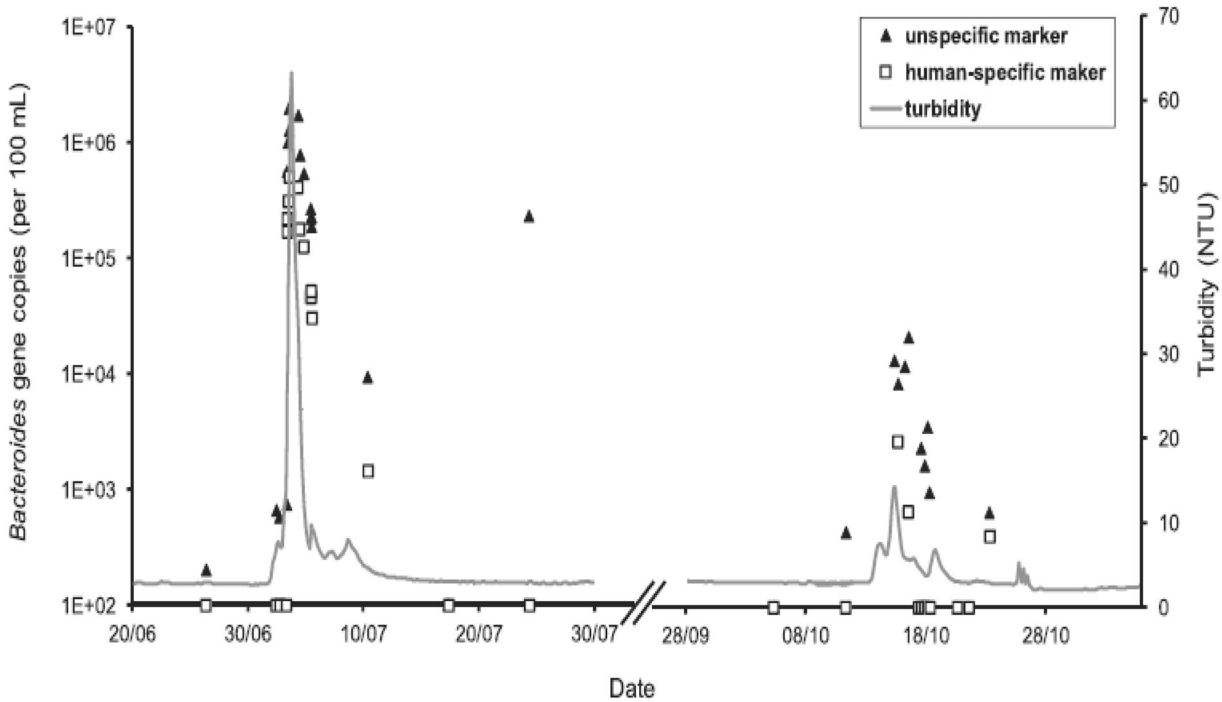

Fig. 6 Turbidity, fecal indicator bacteria during the different investigation periods in July and October 2012 in Germany (Stange and Tiehm 2020)

further underscores the urgent need for effective environmental monitoring systems. Managing the fate of SARS-CoV-2 within the urban water cycle and ensuring its inactivation during wastewater treatment are critical steps for controlling and preventing future outbreaks.

Environmental factors such as rainfall, temperature, pH, organic matter, turbidity, and salt concentrations in water and wastewater can affect the persistence of SARS-CoV-2 in groundwater. Additionally, hydrogeological settings, including fractures, flow modes, aquifer materials, depth, and hydraulic gradients, play a role in virus transport. Physical processes like sorption, adsorption, and aggregation, along with physicochemical factors such as ionic strength, further influence the virus's mobility and survival.

Viruses, including SARS-CoV-2, may assist as tracers in groundwater studies in the future. Unlike non-viral tracers, viruses are less likely to be affected by mixing waters of different ages, as waters older than three years typically contribute minimal viral load. Due to their small size, viruses can easily travel through aquifer matrices, and their negative charge facilitates repulsion from grain surfaces, promoting transport along preferential flow paths.

Despite these challenges, understanding viral behavior in groundwater may offer a significant insight into contamination routes and potential environmental hazards.

Limitation of the study

This study is subject to certain limitations, primarily due to the lack of representative and reliable data, particularly regarding the occurrence and behavior of SARS-CoV-2 in groundwater systems. In addition, the detection of SARS-CoV-2 in aqueous environments is influenced by several sensitive factors, including sampling techniques, preservation methods, and varying physical and chemical conditions. To address these limitations, further comprehensive studies are necessary to establish robust correlations between water environments and the behavior of SARS-CoV-2. Moreover, the application of viruses as environmental tracers presents its own challenges. The long-term stability of viral signals in subsurface environments is often inconsistent, the controlling factors of viral transport remain poorly understood, and viral concentrations in groundwater exhibit significant temporal variability.

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Declarations

Conflict of interest The authors declare no competing interests.

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