Virus Attenuation in Managed Aquifer Recharge – Position Paper

Position Statement

In many states, conservative regulatory requirements impede the potential use of managed aquifer recharge (MAR)[1] for communities pursuing supplemental groundwater for municipal supply. The existing regulatory approaches do not take into sufficient account the current science of in situ processes that affect viruses in the subsurface. Adsorption and virus inactivation by natural processes in the vadose zone and saturated aquifer sediments provide significant pathogen reduction during recharge, enhancing the safety of MAR for municipal water supply. Complexities and costs in these regulatory approaches are limiting the implementation of MAR for communities in need of supplemental water supply. NGWA supports incorporating the most recent findings on attenuation of viruses during subsurface transport into more workable MAR regulatory frameworks.

Issue Overview

Options for communities pursuing supplemental water supplies are increasingly restricted. As a result, interest in MAR has become widespread in order to manage water supply during droughts and provide increased water supply reliability. Viruses in source water are among the primary contaminants of concern in MAR operations.

United States regulations that apply to viruses and other pathogen risk protection in MAR systems were developed over a decade ago based on the best scientific understanding available at the time (Rauch-Williams et al. 2023). Some regulatory controls on MAR have evolved in coordination with the increase in our understanding of related processes. Even so, natural virus removal and inactivation resulting from subsurface attenuation is site-specific and can be difficult to quantify. This makes the process challenging to incorporate into standardized regulatory approaches.

A Water Research Foundation report on MAR (Rauch-Williams et al. 2023) recently observed: "Long-term experiences operating full-scale MAR processes confirm significant pathogen reduction. MAR processes can be very cost effective relative to other pathogen barriers, while not sacrificing water recovery. Thus, in terms of energy, sustainability, and longevity, it may be one of the most robust treatment processes for our use." . . . "[D]espite decades-long experience of high-quality treatment performance demonstrated at various MAR systems for pathogen removal, regulators, designers, and system operators continue to be challenged with assigning and demonstrating appropriate treatment credits for pathogen reduction."

[1] Managed aquifer recharge (MAR) is the purposeful recharge of water to aquifers for subsequent recovery or for environmental benefit.

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Viruses in Source Water

The type of source water used for MAR is a primary determinant of pathogen concentrations. Source waters used for aquifer recharge include treated drinking water; surface water; groundwater; stormwater; and secondary, tertiary, and advanced treated wastewater. Of these, wastewater typically has the highest pre-treatment pathogen load. While treated drinking water is frequently utilized in aquifer storage recovery (ASR) wells, interest is increasing in storing advanced treated wastewater (Alley and Alley 2022).

The wide range of virus types and concentrations of viruses in source water make detection and quantification of viruses challenging. Viruses can be excreted in enormous numbers by infected people and relatively few may be needed to cause acute illness. A wide range of pathogen indicators and surrogates are used for assessing the potential presence of these viruses in water supplies (Rauch-Williams et al. 2023).

Some discussion has occurred on the use of plant viruses as indicators of pathogenic viruses. Plant viruses pose no risk to human health and are physiologically different from pathogenic animal viruses. Compared to pathogenic viruses such as enteric viruses and rotaviruses, plant viruses have high environmental stability and resist inactivation, resulting in a higher rate of transport in aquifers (Rauch-Williams et al. 2023). For example, Pepper Mild Mottle Virus (PMMoV) has been identified as a useful tracer of reclaimed water in MAR operations (Betancourt et al. 2014) but is poorly correlated to the presence of pathogenic viruses. The lack of correlation and significantly higher resilience of PMMoV compared to enteric viruses make it an inappropriate surrogate for risk assessments of virus contamination (Rauch-Williams et al. 2023).

Subsurface Virus Attenuation

Virus attenuation occurs through both engineered treatment and natural processes. Soil-aquifer treatment (SAT) is a biologically mediated natural process that results in pathogen reduction as recharged water is infiltrated through recharge ponds or recharged through wells and travels through the subsurface. In addition to biological degradation, natural processes of subsurface virus attenuation include those at the mineral-water interface, air-water interface processes, and physical-chemical inactivation (John and Rose 2005; Regnery et al. 2017; Sasidharan et al. 2017).

Enhanced sorption, irreversible attachment, and attachment-stress attenuation are some of the mechanisms that occur at the mineral-water interface. Physical-chemical attenuation processes are affected by temperature, dissolved solids content, pH, and redox reactions. Soil properties that may affect virus inactivation rates include soil type and texture, soil pH, soil ionic strength, presence and amount of organic matter, and the mineral content. Degradation via biological activities is perhaps the most significant process as evidenced by the consistent reduction in pathogens shown in long-term MAR studies of treated wastewater and operations.

The ability of a treatment process (engineered or soil-aquifer treatment) to remove viruses and other pathogens is commonly measured by taking the logarithm of the ratio of the pathogen concentration before and after the treatment process. A 1-log reduction is a 90% reduction in the number of the target pathogen(s). A 2-log reduction is a 99% reduction. A 3-log reduction is a 99.9% reduction, and so forth. Removal rates from each step in a treatment train can simply be added up using this system: a 1-log reduction by one process and a 3-log reduction by another yields a 4-log reduction.

Current MAR Regulatory Approaches

At the federal level, aquifer recharge by wells is regulated by the Underground Injection Control (UIC) program under the Safe Drinking Water Act (SDWA, Section 1421). MAR wells are regulated as Class V wells that prohibit "the movement of fluid containing any contaminant into [underground sources of drinking water], if the presence of that contaminant may cause a violation of the primary drinking water standards" (USEPA 2026a). Aquifer storage recovery (ASR) wells can be permitted by states with Primary Enforcement Authority ("Primacy") from the United States Environmental Protection Agency (EPA), or through Authorization by Rule by providing the required well data (USEPA 2025).

At the state level, pathogen regulations vary widely. California and Arizona illustrate the diversity of approaches.

California regulations for indirect potable reuse of treated wastewater require 12-log reductions of enteric viruses (99.9999999999% reduction). Water recharged through spreading basins must first undergo at least tertiary treatment with disinfection, which is credited with a 6-log reduction. A 1-log credit for virus reduction is received per month of aquifer retention time, requiring a minimum of six months of retention time. The retention time must be demonstrated using tracers or modeling. Full credit only applies if an added tracer is used to demonstrate the retention time; lesser credit is given for natural tracers or modeling studies (CSWRCB 2026).

Arizona regulates MAR of treated wastewater through the Aquifer Protection Permit (APP) program, which requires the use of Best Available Demonstrated Control Technology (BADCT) and meeting Aquifer Water Quality Standards (AWQS) at an established Point of Compliance (POC). BADCT requires: (1) use of Class A / A+ reclaimed water as the primary virus reduction step; and (2) a hydrogeologic study that demonstrates sufficient virus attenuation will occur through SAT processes (i.e., adsorption, inactivation) in the vadose zone and groundwater to prevent aquifer degradation and comply with AWQS at the POC. Both literature and modeling are typically used to demonstrate BADCT; virus log reduction rates are not specified. Monitoring and compliance at the POC are required (AZSOS 2025).

Evidence for Subsurface Virus Attenuation

Due to the site-specific conditions affecting viruses in the subsurface, guidelines for specifying virus removal/inactivation have historically taken rather precautionary and conservative approaches to protect groundwater quality and public health (Zhiteneva 2023). A review of eighteen studies of viruses in the shallow subsurface found that 2- to 4-log removal rates of enteric viruses could be achieved within 1.5 meters of infiltration (GeoSystems Analysis 2024). Maximum observed enteric virus transport was 45 meters horizontally and 11 meters vertically. The studies were of sediments of the southwest United States, the Great Plains, New England, and Florida, as well as of Australia. Additionally, temperature and solid surface attachment can affect virus attenuation (John and Rose 2005).

The Surface Water Treatment Rules (SWTR), promulgated by EPA, require public water systems using surface water or groundwater under direct influence (GWUDI) to filter and disinfect water (USEPA 2024). The primary drinking water standards are set at 4-log removal (99.99%) for viruses in both the Surface Water Treatment Rule and the EPA Ground Water Rule for wells directly drawing groundwater (USEPA 2026b). The virus standards address fecal contamination of groundwater to ensure that the water is safe for human consumption. A case can be made that similar regulatory requirements might apply to the introduction of surface water and other sources for managed aquifer recharge.

Riverbank filtration (RBF), a water treatment technology that has been in use for more than 150 years in Europe, provides further evidence of the effects of subsurface processes on virus removal. No documented disease outbreaks have been attributed to properly maintained RBF systems in alluvial aquifers (Ray et al. 2003; Schijven et al. 2003). Average well distance is 50 meters from the river in Europe (Grischek et al. 2003). Retention times vary from five to one hundred days with 2- to 6-log reductions of viruses (Schmidt et al. 2003). These results demonstrate the potential of continuous treatment in the biogeochemically active transition area between surface water and groundwater (the “hyporheic zone”). Similarly, attenuation processes occur in deep fresh and brackish aquifers.

Alternative Approaches

Various alternative approaches have been proposed or are in use in other countries.

The Water Research Foundation report proposed a 10-step workflow tailored to local conditions for moving towards determining removal credits for pathogens based on risk management principles (Rauch-Williams et al. 2023).

Recognition that virus attenuation processes in the vicinity of a recharge well can bring subsurface water into compliance with drinking water standards supports the concept of an aquifer "attenuation zone" as an alternative to regulating water quality at the wellhead (Dillon et al. 2009). The attenuation zone should be of limited spatial extent and would consist of the area surrounding the recharge well within which virus attenuation by natural processes can be demonstrated to be sufficient to protect public health beyond it. In addition to virus inactivation, the attenuation zone may also reduce and/or eliminate many other constituents of potential concern such as bacteria, protozoa, nitrogen, phosphorus, total organic carbon, disinfection byproducts, and color.

To gain regulatory approval, MAR practitioners would use desktop and laboratory studies, on-site data, groundwater fate and transport modeling, and monitoring wells to validate that the natural treatment capacity of an aquifer is sufficient to protect current or future users of an underground source of drinking water (USDW) beyond the attenuation zone. Sampling and/or operation triggers should be set for circumstances that warrant different or additional action(s) to protect public health.

To limit access to recharged water in the attenuation zone, "access controls" could include institutional controls, property interests, ordinances restricting use, rules that restrict well construction within the impacted area, implementation of water well setback rules, or similar measures. This approach has been proposed by the EPA to meet UIC requirements for arsenic and other constituents of concern in ASR wells in Florida (USEPA 2013).

Australian MAR regulations (NRMMC–EPHC–AHMC 2009) require a risk assessment of each project to account for different end uses and site-specific conditions, including appropriate retention time and identification of site-specific microbial and chemical contaminants. Subsurface retention time is required to meet 2×10^{-6} disability adjusted life years (DALYs) per person per year.[2] The Australian guidelines are less prescriptive than those in the United States and emphasize the site-specific risk assessment process for developing performance-based outcomes for public health protection. The risk assessment is used to determine the monitoring requirements to manage those risks.

The Netherlands applies strict water quality standards and prescribes a site-specific risk-based approach for managing pathogen risk in MAR systems (Smeets et al. 2009). Dutch drinking water suppliers must conduct a Quantitative Microbial Risk Assessment (QMRA) for possible infections, using enterovirus and other index pathogens. Risk assessment must be conducted at least once every four years to assess the microbial safety of finished drinking water. The health-based target for safe drinking water is set at less than one infection per 10,000 persons per year.

In the QMRA, source concentrations of pathogens are estimated, along with recovery efficiencies, treatment removals, final drinking water concentrations and consumption, exposure, dose-response, and infection risk. Groundwater recharge systems must also have a retention time of at least 60 days to assure proper inactivation. Well monitoring requirements target fecal indicator organisms (somatic coliphages), which occur at greater concentrations than enteroviruses.

Conclusions and Recommendations

Managed aquifer recharge is a mature technology that has been well documented to provide pathogen reduction through soil-aquifer treatment processes that act to trap and inactivate pathogens during subsurface storage and transport. While those processes are difficult to quantify, our understanding of them continues to evolve.

Existing regulations that fail to adequately account for subsurface attenuation of viruses are limiting implementation of MAR as a tool for augmenting municipal water supplies and achieving other water management objectives. To achieve regulatory requirements that meet water demands, while providing adequate protection of human health, NGWA supports high priority be given to incorporating the most recent findings on virus attenuation during subsurface transport into more workable and cost-effective MAR regulatory frameworks.

[2] One DALY equals loss of one year of full, healthy life. Thus, 2×10^{-6} DALY per person per year is equivalent to two additional cases of death or debilitating disease per million people per year.

There are several lines of evidence that subsurface processes in virus attenuation effectively protect groundwater from unacceptable contamination by levels of virus typical of a surface water source: (1) scientific studies of virus log removal rates; (2) the success of the EPA Surface Water Treatment Rule (SWTR) (4-log removal/inactivation of enteric viruses); and (3) the long-term record of riverbank filtration systems.

Alternative regulatory approaches for aquifer recharge include those tailored to local subsurface conditions that have been demonstrated for decades in Europe and Australia. Recognition that virus attenuation processes in the vicinity of a recharge well can bring subsurface water into compliance with drinking water standards also supports the concept of an aquifer “attenuation zone” with confirmatory monitoring as an alternative to regulating water quality at the aquifer storage recovery wellhead.

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