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Setback distances between small biological wastewater treatment systems and drinking water wells against virus contamination in alluvial aquifers

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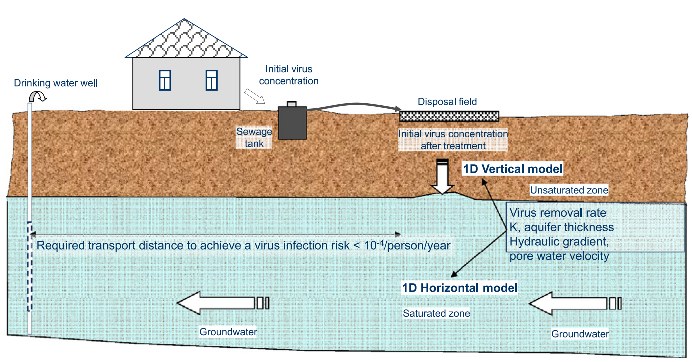
HIGHLIGHTS

- To ensure $<10^{-4}$ enteric virus infection/year/person, it needs a 12-log reduction.
- This would need a horizontal setback distance of 39–144 m in sand aquifers.
- It increases to 66–289 m in gravel aquifers and 1–2.5 km in coarse gravel aquifers.
- For unsuitably large setback distance, extra treatment is needed before disposal.
- Using on-site information, results help to guide decision making in rural planning.

GRAPHICAL ABSTRACT



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ABSTRACT

Contamination of groundwater by pathogenic viruses from small biological wastewater treatment system discharges in remote areas is a major concern. To protect drinking water wells against virus contamination, safe setback distances are required between wastewater disposal fields and water supply wells. In this study, setback distances are calculated for alluvial sand and gravel aquifers for different vadose zone and aquifer thicknesses and horizontal groundwater gradients. This study applies to individual households and small settlements (1–20 persons) in decentralized locations without access to receiving surface waters but with the legal obligation of biological wastewater treatment. The calculations are based on Monte Carlo simulations using an analytical model that couples vertical unsaturated and horizontal saturated flow with virus transport.

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Hydraulic conductivities and water retention curves were selected from reported distribution functions depending on the type of subsurface media. The enteric virus concentration in effluent discharge was calculated based on reported ranges of enteric virus concentration in faeces, virus infectivity, suspension factor, and virus reduction by mechanical-biological wastewater treatment. To meet the risk target of $<10^{-4}$ infections/person/year, a 12 $\log_{10}$ reduction was required, using a linear dose-response relationship for the total amount of enteric viruses, at very low exposure concentrations. The results of this study suggest that the horizontal setback distances vary widely ranging 39 to 144 m in sand aquifers, 66–289 m in gravel aquifers and 1–2.5 km in coarse gravel aquifers. It also varies for the same aquifers, depending on the thickness of the vadose zones and the groundwater gradient. For vulnerable fast-flow alluvial aquifers like coarse gravels, the calculated setback distances were too large to achieve practically. Therefore, for this category of aquifer, a high level of treatment is recommended before the effluent is discharged to the ground surface.

1. Introduction

Many waterborne disease outbreaks are caused by the consumption of groundwater that is contaminated by microbial pathogens (Beer et al., 2015; Beller et al., 1997; Borchardt et al., 2011; Craun et al., 2002; Fong et al., 2007; Jalava et al., 2014; Miettinen et al., 2001; Parshionikar et al., 2003). Faecal bacterial indicators are commonly used to indicate water contamination by pathogens even though pathogenic viruses and protozoa can have higher persistence than bacteria (Rose and Gerba, 1991). Protozoa have generally lower input concentrations and are one and two orders of magnitude larger in sizes than bacteria and viruses, respectively, so they are more likely to be filtered out (Farnleitner et al., 2010). Viral contamination tend to be overlooked due to the large volumes of water required for obtaining representative samples as well as the high costs associated with their analyses. However, recent studies have demonstrated that not only faecal bacteria- but also pathogenic viruses are widespread in groundwater, e.g., in the United States (Abbaszadegan et al., 2003; Borchardt et al., 2003; Borchardt et al., 2007; Borchardt et al., 2004; Fout et al., 2003). Virus-positive samples have even been found in the absence of bacteria (Borchardt et al., 2003; Frost et al., 2002; LeChevallier, 1996). In a survey of 448 groundwater sites in 35 US states, 31.5% sites were positive for at least one pathogenic virus type (Borchardt et al., 2003). Enteric viruses have also been detected in groundwater in many other developed countries (Gallay et al., 2006; Jung et al., 2011; Karamoko et al., 2006; Masciopinto et al., 2007; Powell et al., 2003) and developing countries (Guerrero-Latorre et al., 2011).

Leaching of pathogens from human and animal effluent and wastes through subsurface media is a major contributor to groundwater contamination. This has increased the need to establish safe setback distances between on-site disposal fields and drinking water supply sources (e.g., wells, springs, reservoirs), food-growing waters (e.g., shellfish and salmon farms), and recreational water bodies (e.g., lakes, bathing beaches). Setback distances, when properly determined, ensure the sustainable removal of pathogens by natural attenuation processes in subsurface media so that the quality of the receiving water is acceptable for specific purposes.

Subsurface media act as natural filters and buffers that can mitigate faecal contamination, but they vary widely in their ability to remove microbial contaminants. This is shown in the observed maximum horizontal travel distances of microbes. For example, injected bacteria traveled 14 km in a karst aquifer with a velocity of 250 m/h (Batsch et al., 1970), bacteria traveled 15 km at 167–190 m/d in chalk aquifer (Hutchinson, 1972), bacteriophages (phages) traveled 920 m in a contaminated coarse gravel aquifer (Noonan and McNabb, 1979), bacteria traveled 600 m in a contaminated sandy fine gravel aquifer (Harvey, 1991; Harvey and Garabedian, 1991), phages traveled 30 m in a contaminated coastal sand aquifer (Schijven et al., 1999), and phages traveled <6 m in a clean pumice sand aquifer (Wall et al., 2008).

In this paper, the term 'setback distance' is defined as the distance between a wastewater disposal field and a drinking water well in the direction of flow. Several examples in the United States (Azadpour-Keeley et al., 2003; Deborde et al., 1999), Australia (Geary and Pang, 2005), Canada (Dunn et al., 2014), and Italy (Masciopinto et al., 2007) show diverging management strategies for the choice of setback distances to protect down-gradient receiving waters. The scientific background for the design of setback distances is often unclear. Some states in the USA have adopted a setback distance of 30.5 m as a standard distance between wells and septic systems (Deborde et al., 1999). Likewise, many states in the U.S. recommend a vertical separation distance of 30–45 cm between the drain-field trench bottom and a limiting soil interface or groundwater (Karathanasis et al., 2006).

In 7 out of 10 Canadian provinces, a minimum of 4 $\log_{10}$ reduction of enteric viruses are required by law from the pollution source towards the point of water use, regardless of the concentration in the source water (Dunn et al., 2014). In many countries (e.g., Austria, Denmark, Germany Ghana, Indonesia, the Netherlands, UK), groundwater used for drinking is protected from other uses in the vicinity of the wells using a travel time of 50–60 days. Some faecal pathogens and in particular enteric viruses, however, were found to survive several months in groundwater. For example, Rotavirus can persist in groundwater up to seven months (Espinosa et al., 2008), and Adenovirus can remain infectious for at least one year in groundwater (Charles et al., 2009). Thus, resource management authorities and the public increasingly request more specific criteria for designing setback distances as they relate to different subsurface media.

Setback distances were previously estimated from different authors for some aquifer media (Table 2). Earlier estimates of setback distances were often based on reductions in microbial numbers from inactivation only (Yates and Yates, 1989), while later development considered total removal (attachment, straining, and inactivation) in the calculations (Charles and Ashbolt, 2004; Masciopinto et al., 2007; Masciopinto et al., 2008; Moore et al., 2010; Pang et al., 2005b; Pang et al., 2004; Schijven and Hassanizadeh, 2002; Schijven et al., 2006; van der Wielen et al., 2006; van der Wielen et al., 2008). Both unsaturated and saturated flow conditions were considered for estimating setback distances from septic tank systems, e.g., as part of the pre-development phase of the Groundwater Rule by the United States Environmental Protection Agency (Berger, 1994), (USEPA, 2006b), and other studies from different parts of the world (Gunnarsdottir et al., 2013; Kroiss et al., 2006; Moore et al., 2010). Usually, there are soils and vadose zones above the water table and depending on their thicknesses, the horizontal setback distances required can be significantly reduced (Charles and Ashbolt, 2004). Despite these past efforts, there is still a need for a more systematic evaluation of small wastewater treatment systems in remote areas for alluvial aquifers that depend on the vadose zone thickness and groundwater flow conditions (Charles and Ashbolt, 2004; Gunnarsdottir et al., 2013). In recent years, an extensive database of