GROUNDWATER AND PUBLIC HEALTH

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Contents

Summary

Groundwater needs to be protected against contamination with pathogenic microorganisms from fecal origin. Surface water may be contaminated by the same fecal sources, but by passing surface water through soil for drinking water production, pathogens may be removed effectively.

Particularly in small communities and developing countries, contaminated groundwater can contribute to high morbidity and mortality rates from diarrheal diseases and lead to epidemics. In Europe, information on illness associated with fecal contamination of groundwater is scarce. In The Netherlands, a policy for safe drinking water production has been incorporated into legislation which is based on a maximum infection risk of one per 10,000 persons per year. The World Health Organization (WHO) has decided to base the Guidelines for Drinking Water Quality on a similar approach.

Because of their small size and persistence in the environment, viruses are transported over greater distances through soil than bacteria and protozoa. In addition, given their high infectivity, viruses may be regarded as the most critical microorganisms.

During soil passage, viruses are removed from the aqueous phase by attachment to solid particles and by inactivation. Major factors affecting virus attachment to soil are virus type, the presence of heterogeneously distributed sites for attachment, pH, ionic strength and organic matter. Major factors affecting virus inactivation are temperature, virus type and microbial activity. Under unsaturated conditions virus attachment and inactivation may be enhanced.

Enteric bacteria and pathogenic protozoa such as *Cryptosporidium* and *Giardia* are also subject to attachment and inactivation during soil passage. Especially oocysts of *Cryptosporidium* and bacterial spores may be very persistent. Because they are larger in size than viruses, straining of these microorganisms also comes into play. Straining is a physical removal process whereby microbial particles are too large to pass part of the pore space of the soil.

1. Introduction

1.1. Drinking Water Production

Both groundwater and surface water are extensively used as sources of potable water. Groundwater may become contaminated with viral, bacterial and protozoan pathogens from domestic wastewater via improperly designed or malfunctioning septic systems, leaking sewer lines, land application of wastewater or its mixing with infiltrated surface water. Surface water may be contaminated with pathogenic microorganisms from discharges of treated and untreated wastewater and by manure run-off from agricultural land.

During the passage of pathogens through soil, their numbers are reduced by a combination of processes, such as attachment to soil grains and inactivation. Therefore, to protect groundwater from fecal contamination, certain setback distances from sources of wastewater and subsurface residence times can be applied to achieve a sufficient reduction in pathogen concentrations.

To produce safe drinking water from surface water or domestic wastewater, pathogens need to be removed. This can be done by soil passage of the (pre-treated) water, also called soil aquifer treatment, as is the case in riverbank filtration, artificial recharge and deep well injection. Figure 1 shows a schematic representation of riverbank filtration, or dune recharge. Treated water from the bank of a river or canal enters the aquifer and is pumped up after a residence time ranging from several months to years for riverbank filtration, or several months following artificial recharge. In the case of deep well injection, pretreated surface water or wastewater is injected into a well at a depth of hundreds to thousands of meters; after a prescribed residence time in the subsurface, the water can then be recovered by pumping it to the surface for use.

For decades, viruses and, more recently, protozoa have been recognized as pathogens of major health concern.

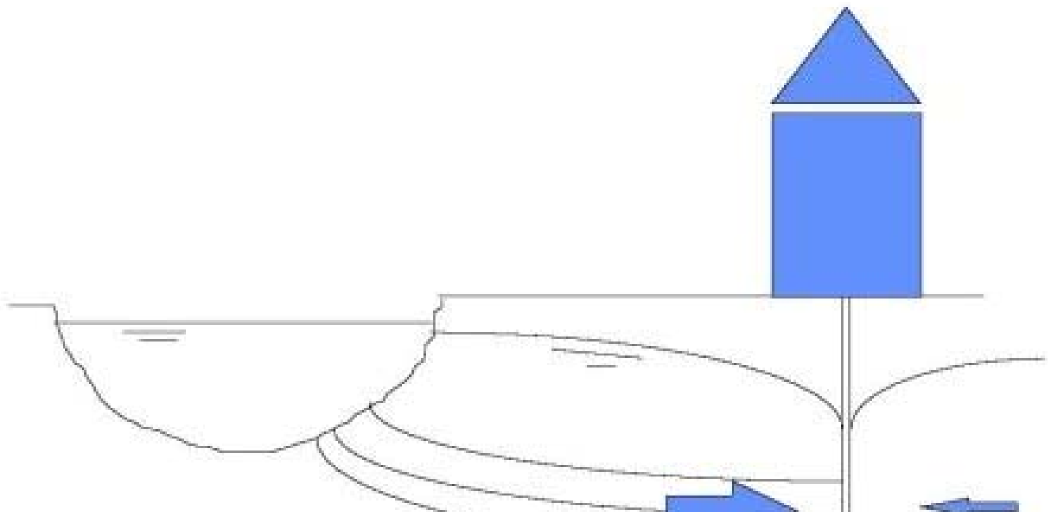

Figure 1. Riverbank filtration or artificial recharge from a canal with pretreated surface water

Due to their persistence in the environment and their infectivity, enteric viruses and pathogenic protozoa such as *Cryptosporidium* and *Giardia* may be considered as the most critical waterborne pathogens for drinking water production. Clearly, there is a need to study the behavior of these pathogens in order to be able to evaluate the vulnerability of groundwater systems to microbiological contamination.

1.2. Public Health Concerns Regarding Microbial Pathogens in Groundwater

Most of the waterborne viral, bacterial and protozoan pathogens are of fecal origin and are transmissible via a fecal-oral route of exposure. These pathogens can cause relatively mild gastrointestinal illness, but many of them can cause severe illness, such as infectious hepatitis, encephalitis, and myocarditis as well. The impact of contaminated water on public health may range from asymptomatic infections to a few days of mild diarrhea, to severe disease requiring a doctor's care or hospitalization, to death. The costs associated with even relatively mild gastroenteritis can be very high in terms of lost time at work, school, etc. Certain individuals may be at greater risk of serious illness than the general population. In general, depending on the pathogen, individuals who are at increased risk of developing more severe outcomes from infection by waterborne microorganisms are the very young, the elderly, pregnant women, the immuno-compromised (*e.g,*. individuals who have organ transplants, cancer, or AIDS), those predisposed with other illnesses (*e.g,*. diabetes), and those with a chemical dependency (*e.g.,* alcoholism).

Particularly in small communities and developing countries, the microbiological contamination of groundwater can have profound and severe implications for public health. Contaminated groundwater can contribute to high morbidity and mortality rates from diarrheal diseases and sometimes lead to epidemics. The proper disposal of excreta using land-based systems is a key issue in groundwater quality and public health protection. The use of inappropriate water supply and sanitation technologies in peri-urban areas can lead to severe and long-term public health risks. The use of poorly constructed sewage treatment works and land application of sewage in areas close to water supply sources can lead to groundwater contamination.

Although death from waterborne disease has largely been controlled in the USA, outbreaks continue to occur. To be considered a waterborne outbreak, acute illness must affect at least two persons and be epidemiologically associated with the ingestion of water. In the period from 1971 to 1996, 643 outbreaks and over 570000 cases of illnesses were reported for all public surface water and groundwater systems. Groundwater sources were associated with 58% of the total outbreaks and 16% of the associated illness. Contaminated source water was the cause of 86% of the outbreaks in groundwater systems. Of these outbreaks, 31% were associated with specific viral (enteric viruses), bacterial (*Shigella*, *Campylobacter*, *Salmonella*, *Yersinia*, *Escherichia coli*, *Plesiomonas shigelloides*), or protozoan pathogens (*Cryptosporidium* and *Giardia*), and 6% with chemicals. In 63% of cases, no causative disease agent was identified, but the majority of cases were probably viral. The numbers of outbreaks and infected individuals is generally believed to be an underestimation of the actual levels of microbial diseases associated with drinking water, because endemic levels have not been described and reporting of disease outbreaks is generally poor.

In Europe, consumption of drinking water has also led to gastrointestinal illness, but information on illness that can be associated with fecal contamination of groundwater is scarce. For example, in the United Kingdom, where groundwater is the source of 35% of potable water, 19 outbreaks that could be associated with the consumption of drinking water were reported in the period of 1992 to 1996. In seven of the 19 outbreaks (37%), drinking water from groundwater supplies was identified as the source. The causative agent was *Cryptosporidium* in two of these outbreaks, *Giardia* in one outbreak and *Campylobacter* in three outbreaks. In one outbreak no causative agent could be identified. With these seven outbreaks, 273 cases of illness were reported, of which 12 were hospitalized. In Finland, 24 waterborne outbreaks were reported in the period from 1980 – 1992. About 40% of these outbreaks – affecting 7700 people - were due to contaminated water from community drinking water supplies from undisinfected groundwater. Four outbreaks were found to be caused by viruses, three by *Campylobacter*, and two by *Salmonella typhimurium*. In the period from 1998 – 1999, 14 outbreaks and 7400 cases of illness were reported in Finland, of which 13 outbreaks were associated with groundwater. Seven of these outbreaks were caused by caliciviruses, three by *Campylobacter,* and in three outbreaks the cause was unknown. In Germany, only rare information concerning waterborne disease and outbreaks is available. However, by means of geostatistical analysis, disease incidence could be positively associated with the use of groundwater for drinking water production, *i.e.,* the districts with large surface water supplies were found to have a lower incidence of gastrointestinal infections. For many decades, no reported waterborne disease outbreaks have been associated with fecal contamination of groundwater in The Netherlands, probably primarily due to the application of multiple barriers in the treatment of surface water prior to recharge.. However, enteric viruses and the pathogenic protozoa *Cryptosporidium* and *Giardia* are ubiquitously present in Dutch surface waters. Clearly, a high potential for waterborne transmission of microbial pathogens exists in The Netherlands, where surface water is used as the source for drinking water production, and adequate treatment must be guaranteed under all circumstances.

1.3. Regulatory Approaches

In The Netherlands, a new policy for production of safe drinking water was incorporated into legislation beginning in the year 2001. This approach is based on a maximum acceptable infection risk of one per 10,000 persons per year associated with drinking water consumption. Using dose-response relationships for pathogens (infectivity of pathogens) it can be deduced that pathogen numbers in drinking water may not be higher than about 10^{-6} per liter. Therefore, very high levels of reduction (e.g., 5 to 8 $\log_{10}$) may be required in order to produce drinking water in which the risk of infection of one per 10,000 persons per year is not exceeded. This raises the question as to the necessary travel times and travel distances to achieve such reductions in the case of treatment by soil passage.

The World Health Organization (WHO) has decided to base the coming edition of the Guidelines for Drinking Water Quality on a similar approach. The proposed Ground Water Rule (GWR) of the U.S. Environmental Protection Agency may require that groundwater systems found to be vulnerable to fecal contamination provide treatment to achieve a 4-$\log_{10}$ (10^4 times lower) removal of virus for public health protection.

Nevertheless, it may be clear from the foregoing that in order to assess compliance with the maximum risk of infection of one per 10,000 persons per year it is impractical from a technological and economic viewpoint to analyze very large volumes of drinking water, *i.e*,. on the order of $10^5 – 10^7$ liters. Therefore, another approach for determining compliance must be followed. Concentrations of pathogenic microorganisms in treated water can be calculated from the concentrations in source water and the effectiveness of the water treatment process, which can be determined by means of a computational model. In the case of soil passage as a water treatment methodology, a model is needed that describes the fate and transport of the pathogenic microorganisms during soil passage.

2. Subsurface Behavior of Viruses

2.1. Removal Processes

Because of their small size and their persistence in the environment, pathogenic viruses may be expected to be transported greater distances through the subsurface than bacteria and protozoa. In addition, given the high infectivity of viruses, they may be regarded as the most critical microorganisms in the production of drinking water from groundwater. This article is therefore focused on subsurface transport and removal of viruses. Many studies have been conducted on subsurface virus transport, but fewer on that of bacteria and protozoa. Nevertheless, at the end of this article, removal of these microorganisms will be discussed briefly.

During passage through soil, viruses are removed from the aqueous phase due to attachment to solid particles and by inactivation (rendering the virus particle incapable of infection). Moreover, advection (transport of the virus with the bulk flow of the water) and dispersion (spreading out of the virus-laden water as it moves around solid particles) affect spreading of viruses and thereby attenuation of virus concentrations. Theoretically, the effectiveness of soil passage for protection of groundwater wells or treatment of water can be evaluated by calculating the concentration of viruses at the production point from the concentrations in source water by means of a computational virus transport model that describes the removal processes. Processes that are generally included in modeling of virus transport in soil and groundwater are attachment, inactivation, advection and dispersion. The attachment and inactivation of viruses in the subsurface are dependent on the specific virus of interest and the environmental conditions. Attachment of viruses to soil may be irreversible or reversible.

Attachment is mainly kinetically limited relative to flow velocity, with constant attachment and detachment rate coefficients. Kinetically limited implies that no immediate equilibrium partitioning between attached and detached viruses during subsurface transport is achieved. The processes that determine virus removal by soil passage are schematically shown in Figure 2 with the following rate coefficients: k_{att} for attachment of viruses to soil grains, k_{det} for their detachment from the soil grains, μ_1 and μ_s for inactivation of free (detached) and attached viruses, respectively.

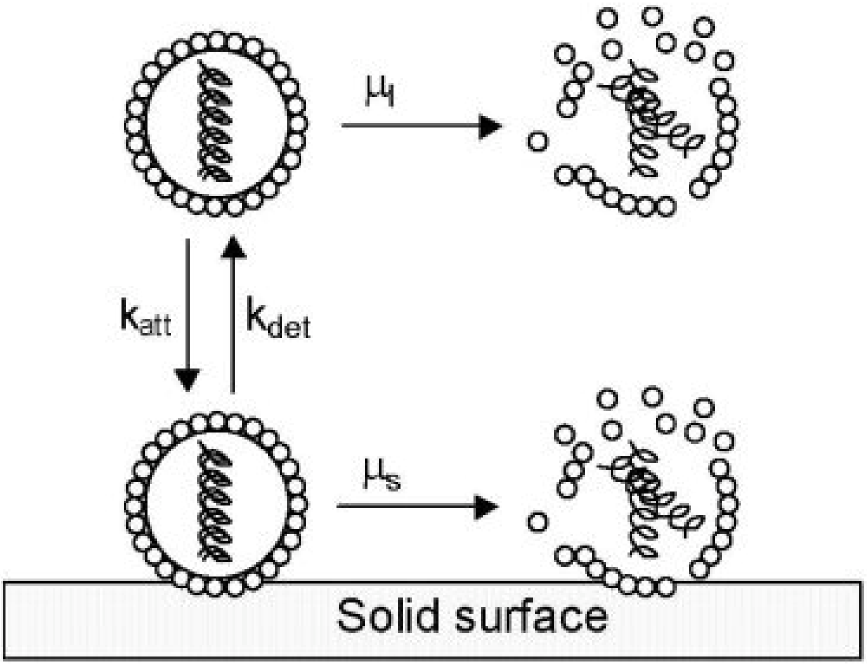

Figure 2. Attachment and inactivation of virus in bulk fluid and at the solid-liquid interface. Here, k_{att} is the attachment rate coefficient; k_{det} is the detachment rate coefficient; μ_1 is the inactivation rate coefficient of viruses in the aqueous phase and μ_{s} that of viruses attached to the solid surface.

Considering a one-dimensional steady state situation (continuous contamination with virus at a constant concentration), and neglecting dispersion, virus removal can be described by the following equation:

$$\log_{10}\left(\frac{C}{C_0}\right) = -\frac{1}{2.3}\left(\mu_1 + \frac{k_{\text{att}}}{1 + k_{\text{det}}/\mu_{\text{s}}}\right)t \qquad (1)$$

where C_0 is the initial concentration and $\log(C/C_0)$ is a measure of virus removal (logarithmic reduction of virus concentrations. From Equation 1, the relative contributions of attachment and inactivation to virus removal can be deduced. The first term between the brackets gives the removal rate by inactivation of free virus. The second term describes the removal rate of virus by interaction with kinetic sites, respectively. Interaction includes the combination of attachment, detachment and inactivation of virus at a particular type of site of the porous medium.

2.2. Colloid Filtration

According to colloid filtration theory, the attachment rate coefficient of a colloid (*e.g.* a virus) can be expressed in terms of a single collector efficiency η and a collision efficiency α as follows:

$$k_{\text{att}} = \frac{3}{2}\frac{(1-n)}{d_{\text{c}}}\alpha\eta v \qquad (2)$$

Here, d_{c} is the average diameter of the single collector (soil grain). The fraction of particles that collide with the collector (soil grains), due to interception, sedimentation or diffusion, is given by η, the single collector efficiency. The single collector efficiency is determined by physical properties, like the size of the transported particles and the soil grains, porosity, pore water velocity and temperature. Bacteriophages are small in size, about 20 - 60 nm, and their transport in the immediate vicinity of the collector surface is dominated by Brownian diffusion.

The collision efficiency, α, represents the fraction of the particles colliding with the collector that remain attached to the collector. The collision efficiency reflects the net effect of repulsive and attractive forces between surfaces of the particles and the collector. It depends on the surface characteristics of the virus and soil particles. Therefore, it depends on pH, organic carbon content, and ionic strength. It is believed that α is independent of hydrodynamic effects (velocity and dispersion). So, if α is known for a given set of conditions, like type of virus, type of soil, pH, organic carbon content and ionic strength, then it is possible to calculate the value of k_{att} for a different set of hydrodynamic conditions. Commonly, α is derived from experimental values of k_{att} and calculated values of the single collector efficiency η. For calculating the value of η a correlation equation has been developed. It should be noted that colloid filtration theory is based on indirect observations using almost perfectly spherical glass beads and smooth surfaces. Colloid filtration theory fails in accounting for straining or colloid trapping in pores, clustering of colloids near the grain surface, stagnant zone colloid accumulation, and detachment or re-entrainment of colloids.

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Biographical Sketches

J.F. Schijven: Scientist in the field of modeling the microbiological quality of water. This includes modeling and observational and experimental studies on the emission and distribution of pathogenic microorganisms to surface waters from human and farm animal sources. PhD-research on modeling the removal of micro-organisms, especially viruses, by passage through soil, as in river bank filtration, dune infiltration and deep well injection. Current activities also include analyses of the risk of infection with waterborne pathogens due to drinking water consumption and due to exposure to surface waters during bathing, diving, surfing, kayaking.

M.V. Yates: Professor of Environmental Microbiology. Conducts research on fate and transport of pathogenic microorganisms in environmental media including soil, ground water, and air; development of methods to improve detection of infective enteric microorganisms in environmental samples; use of indicators of fecal contamination of the environment, especially ground water; use of models to predict the fate and transport of microorganisms in the environment.