VIRUS SURVIVAL AND TRANSPORT IN GROUND WATER

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ABSTRACT

Viruses are a significant cause of waterborne disease in the United States; it has been estimated that they may be responsible for as much as 50% of the reported outbreaks. This fact has led the U.S. Environmental Protection Agency to propose a maximum contaminant level goal (MCLG) for viruses in drinking water. Septic tanks, which contribute over one trillion gallons of waste to the subsurface every year, are a major source of viruses in soils and ground water. The purpose of this research was to develop a model which could be used to estimate safe distances between septic tanks, or other sources of contamination, and drinking-water wells. The model was based on ground-water flow characteristics and the length of time that viruses remain infective in the subsurface environment. Water samples were collected from 71 continuously pumping municipal drinking-water wells. Viruses were inoculated into the water samples, and the rate at which the viruses were inactivated was calculated for each sample. The inactivation rates were determined to be spatially correlated by calculating a semivariogram. Kriging, a geostatistical technique, was used to estimate virus inactivation rates at unsampled locations using the measured values at nearby locations. The measured and kriged virus inactivation rates were used in conjunction with the regional ground-water flow characteristics to calculate septic tank setback distances over a city-wide area. The setback distance was defined as the distance required for a 7-log reduction in virus number in the time that the water traveled from the source of contamination to a drinking-water well. The model has been extended to account for alterations in the flow field caused by the presence of pumping wells. Setback distances of less than 15 m to greater than 300 m have been calculated using these models. The results of this research may be useful for community planning purposes, because areas with higher potentials for viral contamination of ground water may be identified based on the maps generated by the model. In addition, the models may be useful in granting variances from the mandatory ground-water disinfection requirement under consideration by the Environmental Protection Agency.

KEYWORDS

Ground-Water Flow, Septic Tank Setback Distances, Geostatistics, Kriging

INTRODUCTION

Ground water represents a major source of drinking water for a significant number of people in the United States. It has been estimated that over 100 million Americans rely on ground water for drinking purposes, and in rural areas up to 95% of the water used is ground water (Bitton and Gerba, 1984). It has been assumed traditionally that ground water is safe for consumption without treatment because the soil acts as a filter to remove harmful compounds as the water percolates through the soil matrix. As a result, private wells generally do not receive treatment (DiNovo and Jaffe, 1984), nor do a large number of public water supply
systems (U.S. Public Health Service, 1965). However, the use of contaminated, untreated or inadequately treated ground water has been the major cause of waterborne disease outbreaks in the U.S. since 1920 (Craun, 1986a, b).

Septic tanks contribute 820 to 1460 billion gallons of waste to the subsurface every year (OTA, 1984), and are the most frequently reported sources of ground-water contamination. The overflow or seepage of sewage, especially from septic tanks or cesspools, was responsible for 43% of the reported outbreaks and 63% of the reported cases of illness caused by the use of contaminated, untreated ground water from 1971-1979 (Craun, 1984).

Domestic sewage may contain many types of pathogenic microorganisms including enteric viruses. Over 100 different types of enteric viruses capable of infecting humans may be present in domestic sewage (Gerba et al., 1975). The concentration of viruses may be as high as $10^6$ to $10^{10}$ virus particles per gram of fecal material (Tyrrell and Kapikian, 1982). Several studies have shown that viruses are not necessarily inactivated in the septic tank (Hain and O'Brien, 1979; Stramer, 1984), and that they are capable of moving through the soil absorption field into the underlying ground water (Hain and O'Brien, 1979; Sinton, 1986; Stramer, 1984; Vaughn and Landry, 1977; Vaughn et al., 1978, 1983). Once in the ground water, viruses can remain infective for prolonged periods of time. (Stramer, 1984; Yates et al., 1985).

There have been a number of outbreaks of waterborne disease caused by the contamination of ground water with viruses present in septic tank effluent; these have been reviewed recently (Yates, 1985). In some instances, the septic tank was located very close to the drinking water wells (less than 3 m away) (Vogt, 1961), while in others, the viruses traveled more than 30 m to contaminate the drinking water. (Wellings et al., 1977).

From 1946 to 1980, viruses were identified as the causative agent in 12% of the waterborne disease outbreaks in the United States (Lippy and Waltrip, 1984). However, in over one-half of all outbreaks, no causative agent of disease was identified. The results of recent retrospective serological studies suggest that many of these outbreaks were caused by Norwalk and Norwalk-like viruses, as well as rotaviruses (Kaplan et al., 1982). In fact, it has been estimated that the Norwalk and Norwalk-like viruses may be responsible for as much as 23% of the reported waterborne disease outbreaks in this country (Keswick et al., 1985).

The facts that the number of septic tanks in the United States is increasing by approximately 500,000 per year (Scalf et al., 1977), that septic tanks are one of the major sources of viruses in ground water (OTA, 1984) and that viruses are being implicated as the etiologic agent in an increasing number of waterborne disease outbreaks, illustrate the importance of proper septic tank placement to try to prevent ground-water contamination. One way to minimize the probability that viruses in septic tank effluent will pose a health hazard would be to place the septic tank far enough from a drinking water well that any viruses in the effluent would be inactivated by the time the effluent reached the well.

A previous study (Yates et al., 1986) described the use of a geostatistical technique, kriging, to predict virus inactivation rates in ground water over a city-wide area. That investigation found that virus inactivation rates in ground water are spatially dependent, that is, the rates were more similar in wells close together than in wells separated by a large distance. In the previous study, it was assumed that the viruses were transported only by the natural conditions of regional ground-water flow. However, another mechanism affecting virus movement in the subsurface is the movement of water caused by pumping wells. Adding the effects of pumping will result in an increased rate of water flow, and thus affect the septic tank setback distances calculated to minimize the possibility of virus contamination. This study considers two cases: two pumping wells in a static field, and one pumping well in a regional flow field. The separation distances calculated in these cases are compared with the results obtained for the same wells when pumping was not included in the calculations.

**MATERIALS AND METHODS**

**Determination of Virus Inactivation Rates**

Water samples were collected from 71 continuously pumping city drinking-water supply wells in the Tucson basin. The data from all 71 wells were used in the calculations; however only 62 wells were located in the region of interest and are shown in Figure 1. The samples were collected after flushing the line for two to three minutes to remove stagnant water. The temperatures of the water samples were measured at the time of collection.
Virus survival and transport

In the laboratory, a 50-ml aliquot of each water sample was placed in sterile, polypropylene containers, and approximately $10^5$ plaque-forming units (pfu) of virus per ml were added. The bacteriophage MS-2 was used as a model for the human enteric viruses. Each container was incubated at the measured in situ temperature ±1°C. On days 0, 1, 2, 3, 5, 7, 10, 15, and 20, 1-ml subsamples were withdrawn and assayed to determine the number of infective virus particles remaining using the agar-overlay plaque technique described by Adams (1959).

The number of infective virus particles remaining in the water was plotted as a function of time; the slope of this line is the inactivation rate of the virus. All inactivation rates are expressed as positive numbers; therefore, a large inactivation rate means that the viruses were inactivated more rapidly in that water sample than in a sample for which a smaller inactivation rate was calculated.

Calculation of Separation Distances

Separation distances between wells and potential sources of contamination were calculated as the distance required to effect a 7-log decrease in virus number as the water moves from the point of introduction of the viruses to the point of water use. The assumptions used in this model are discussed in Yates et al. (1986). Distances were calculated using Darcy's Law (Freeze and Cherry, 1979):

$$D = \frac{tk_i}{n_e}$$

where $D$ is the separation distance (m), $t$ is the travel time (days), $K$ is the hydraulic conductivity (m day$^{-1}$), $i$ is the hydraulic gradient (m m$^{-1}$), and $n_e$ is the effective porosity of the aquifer. Distances were calculated on a grid system using values for the virus inactivation rate, hydraulic conductivity and gradient at each location.

Travel times were calculated using the known and estimated virus inactivation rates as the number of days required for 7 logs of virus inactivation. Transmissivity values were obtained from the State of Arizona Department of Water Resources; these were used to calculate hydraulic conductivities. Hydraulic gradients were estimated from a water table elevation map obtained from the City of Tucson. The effective porosity was considered to be a constant throughout the basin at 0.1. This assumption was made because porosity data for the entire basin were not available.

Calculation of Setback Distances in Pumping Well Field

One method for determining the travel time between a source of virus contamination and the drinking-water well uses potential flow theory (Churchill, 1960; Bird et al., 1962). Using this theory, the complex potential for a system of wells in a static or uniform flow field
can be determined. The potential (i.e., hydraulic head) and stream functions can be found by separating the complex potential into real and imaginary parts, respectively. Analytical solutions for the travel times from any point in the flow field to the pumping well can be found by integrating an expression of the radial velocity, found from the hydraulic head or stream function, with respect to time. The techniques are described in more detail by Kirkham and Affleck (1977) and Brauns and Hötzl (1982).

Two wells were chosen to illustrate the effects of pumping on the calculated septic tank setback distances. The wells were located 284 m apart and both pumped at a rate of 9.46 x 10^{-3} m^3 sec^{-1}. The regional ground-water flow rate was assumed to be a constant at 0.137 m^3 day^{-1}. Three setback distances were calculated for each well based on the number of days required for 4, 7, and 10 logs of virus inactivation.

Geostatistical Analyses

Unlike classical statistics, which generally assume independence between samples, geostatistical analyses account for the common observation that samples that are located near to one another have values which are relatively similar compared to samples that are located farther apart. The measure of this correlation is found by calculating the semivariogram or covariance function for the property of interest. Once the semivariogram has been determined, it can be used in an estimation technique called kriging (Journel and Huijbregts, 1978) to obtain a best linear unbiased estimate of a property at any unsampled location using several nearby samples.

Semivariograms. Experimental semivariograms were calculated using the program GAM3 (Journel and Huijbregts, 1978). Model semivariograms and cross-semivariograms were calculated and validated using the jackknifing technique (Vauclin et al., 1983; Russo, 1984) where a reduced mean, R_m, and variance, R_2, are calculated and should be approximately 0 and 1, respectively. One difficulty in using R_m and R_2 to verify the correctness of the model semivariogram is that there is no independent means for determining how close to 0 and 1, respectively, R_m and R_2 should be.

Kriging. Kriging, which produces a best linear unbiased estimator, is a moving average technique where the value of a spatially variable property at an unsampled location is estimated from a weighted sum of nearby samples. Each sample value used in the estimation process is multiplied by a weight factor which is determined from the spatial orientation of the samples and the functional relationship of the semivariogram. A more detailed description of the kriging method can be found in Journel and Huijbregts (1978). Its use for the data set of interest is described in Yates et al. (1986).

RESULTS AND DISCUSSION

Setback Distances under Regional Ground-Water Flow Conditions

Virus inactivation rates were found to be spatially correlated, as shown by the semivariogram in Yates et al. (1986). This spatial correlation is most likely due to the high correlation between virus inactivation rates and temperature, which is also a spatially correlated variable. The experimental semivariogram was modeled using a spherical model (Journel and Huijbregts, 1978), with a sill of 0.044, a nugget of 0.018, and a range of influence of 6 km. A contour map of the virus inactivation rates estimated by kriging using the 10 nearest neighbors can be found in Yates et al. (1986). The reduced mean and variance, R_m and R_2, for this variogram were 0.028 and 0.99, respectively.

The ground-water flow characteristics in the basin and the kriged estimates of virus inactivation rates were used in Eq. 1 to calculate setback distances. The distances that would be required to achieve a 7-log decrease in virus number as the ground water flowed from the point of introduction of viruses to the point of abstraction are shown in Figure 2. A wide variation in setback distances was calculated for the city, ranging from 15 m to greater than 150 m. The greatest setback distances were calculated in areas with very high ground-water flow velocities and low rates of virus inactivation.

Setback Distances in a Pumping Well Field

Case 1: One well. In the first example, setback distances were calculated around one well pumping at 9.46 x 10^{-3} m^3 sec^{-1}. The regional ground-water flow was also considered in the
calculations. As shown in Figure 3, setback distances of 93 m, 156 m, and 222 m were calculated for 4, 7, and 10 logs of virus inactivation, respectively. The distance calculated for this well in the absence of pumping, considering only regional ground-water flow, was 60 m (See Figure 2). Adding the effects of pumping results in a 2 1/2-fold increase in the setback distance.

Case 2: Two wells. In this example, septic tank setback distances were calculated for 2 wells located 284 m from one another, both pumping at rates of $9.46 \times 10^{-3} \text{ m}^3\text{sec}^{-1}$. In this case, the regional ground-water flow rate was not considered in the calculations. The results are shown in Figure 4. For 7 days of virus inactivation, 51 and 45 m would be required by wells 1 and 2. If the regional ground-water flow had been included, the distances would have been larger.

Figure 2. Septic tank setback distances (m) estimated by kriging.

Figure 3. Setback distances (m) estimated for a pumping well in a regional flow field.

Figure 4. Setback distances (m) estimated for two pumping wells in a static field.
CONCLUSIONS

The results of this study have shown that the currently mandated setback distance of 100 ft (30 m) may not be adequate to protect the drinking water from contamination by viruses in all areas of the city. The largest setback distances were calculated along a dry river bed, where the soil is relatively highly transmissive. Because of the high transmissivity, this is also where many of the city’s wells are located, and are pumped at higher rates. Unfortunately, the high pumping rates combined with the low virus inactivation rates make the wells in these areas prone to contamination by viruses.

REFERENCES


