Wellhead protection area delineation for viral contaminants – Case study of Urmia City drinking water wells

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ABSTRACT

The majority of cities in Iran depend on the groundwater resources for public drinking water supply. The environmental health authorities and groundwater and drinking water managers in the country has the responsibility to control the ground water resources from the risk of virus contamination. Part of this control includes delineation of wellhead protection areas (WHPAs) using a viral transport model. A series of WHPA and virus concentration analyses were performed for drinking water pumping well No. 20 of Urmia City, Iran, using the Bacteriophage – Φ x – 174 as a sample virus, and a leaky sewer pipe or a sewage septic tank as virus sources in the calculations. The effect of an adjacent pumping well and a recharge well on WHPA and virus concentrations was evaluated. The results showed that WHPAs of two adjacent pumping wells affect each other and the location of WHPA displaces compared to WHPA analysis for one well. When an adjacent recharge well presents, the groundwater pathlines inside WHPA shift towards the recharge well and WHPA expands. Moreover, the recharge well causes more virus transport from the source towards the pumping well; it causes early appearance of virus and increases the maximum virus concentration at the pumping well. The results showed that among other virus transport parameters, the viral decay rate constant, or die-off rate, plays a significant role on the amount of virus concentrations at the pumping well. The lower the die-off rate of virus, the more viruses are transported and their concentration rise up at the target pumping well. The results showed that in the aquifer with higher hydraulic gradient the shape of WHPA is more elliptical while when the hydraulic gradient is lower (lower groundwater velocity) the shape is more circular and the ratio of length to width of WHPA approaches to unity.

RÉSUMÉ

La majorité des villes en Iran dépendra des ressources en eaux souterraines pour l'approvisionnement en eau potable publique. Les autorités sanitaires de l'environnement et des eaux souterraines et les gestionnaires de l'eau potable dans le pays a la responsabilité de contrôler les ressources en eaux souterraines contre les risques de contamination par virus. Une partie de ce contrôle comprend la délimitation de zones de protection des têtes de puits (ZPTPs) en utilisant un modèle de transport viral. Une série d'ZPTP et analyses de la concentration du virus ont été réalisées pour l'extraction de puits d'eau potable n ° 20 de Urmia City, l'Iran, en utilisant le bactériophage - Φ x - 174, selon un échantillon de virus, et un tuyau d'évacuation d'eau qui fuient la collecte ou un réservoir d'eaux usées septiques sources du virus dans les calculs. L'effet d'une extraction puits adjacent et un puits d'injection sur l'ZPTP et les concentrations de virus a été évaluée. Les résultats montrent que ZPTPs de deux puits d'extraction à proximité s'influencent mutuellement et l'emplacement de l'ZPTP déplace par rapport à l'analyse de l'ZPTP pour un bien. Lorsque l'injection adjacente présente bien, le changement de l'intérieur des eaux souterraines lignes de trajectoires ZPTP vers le puits d'injection et ZPTP se dilate. En outre, l'injection provoque ainsi le transport plus de virus de la source vers le puits d'extraction, il provoque l'apparition précoce du virus et augmente la concentration du virus au maximum le puits d'extraction. Les résultats ont montré que, parmi d'autres paramètres de transport du virus, le taux de décroissance virale constante, ou taux final-libre (die-off), joue un rôle important sur le montant des concentrations de virus dans le puits d'extraction. Plus le taux de mortalité massive de virus, des virus plus sont transportés et leur concentration se lever à l'extraction de cibles bien. Les résultats ont montré que, dans l'aquifère avec un gradient hydraulique plus la forme de l' ZPTP est plus elliptique tandis que lorsque le gradient hydraulique est faible (vitesse inférieure eaux souterraines) est la forme plus circulaire et le ratio longueur / largeur des approches ZPTP à l'unité.

1 INTRODUCTION

The groundwater resources in the cities used for public drinking water supply should be protected from contamination due to viruses (U.S. EPA, 1994, 1998, 2000, Davis and Witt, 2000, Doherty, 2002, and Schijven et al., 2006). Viruses are usually negatively charged colloidal particles (Bitton, 1980). Colloids are problematic contaminants in ground water because they do not behave strictly as a solid or as a solute (Bitton, 1975). Unlike a solid, colloids do not settle out and are carried with the mobile phase (Keswick et al., 1982, and Keswick and Gerba, 1980, and Gerba, and Bitton, 1984). The colloid is a hydrated solid held in suspension. Usually the particles are small enough so as to be subject to Brownian motion and cannot b separated from solution by conventional means such as gravity settling, normal filtration or normal centrifugation. Surface charge density plays a large role in colloidal behaviour (Gerba, 1983). Human enteric viruses cause diseases such as meningitis, respiratory infection, infectious hepatitis, among many others (Kreissel, 1983). They may resist conventional water and waste water treatment procedures, including chlorination, and may be found far from the original source of contamination.

In majority of cities in Iran, some or all part of the drinking water is being supplied by groundwater system using some wells (Badv and Deriszadeh, 2004, 2005). The environmental health authorities and groundwater and drinking water managers in the country should have guidance whether a ground water system is at risk from virus contamination (U.S. EPA, 1994, 2000). Part of this guidance includes use of a viral transport model to predict virus concentrations at the wellhead and delineate Well-Head Protection Area (WHPA) as a function of aquifer characteristics, pumping rates, and assumed virus concentrations at potential contaminant sources such as septic tanks, sewer lines, and solid waste landfills (U.S. EPA, 1998, and Hurst, 1991). Wellhead protection area delineation should be performed both for chemical, microbial, and viral contaminants. Relatively good public domain theoretical models have been developed by U.S. Environmental Protection Agency (EPA) for wellhead protection area delineation. Among those are the WhAEM (Haitjema, 2002) and VIRALT (Park et al., 1994) models. The WhAEM model is developed for wellhead protection area delineation against chemical contaminants and has been discussed in separate published articles by the author (Badv and Deriszadeh, 2004, 2005). The VIRALT model is developed for viral contaminants and will be discussed in this paper.

2 CHARACTERISTICS OF THE VIRAL CONTAMINANTS

Viruses, which are obligate intracellular parasites, are composed of a protein coat (capsid) containing a nucleic acid core (Bitton, 1980). Viruses reproduce only inside an appropriate host-cell. According to the type of host-cell, they are classified as animal viruses, bacterial phages, blue-green algae viruses and fungal viruses. Human enteric viruses that replicate in the intestinal tract fall into the first category. Raw sewage can contain 100,000 infectious virus particles per litre.

Various types of viruses can be found in ground water. Polioviruses, group A and B coxsackieviruses, and echoviruses are different species of enterovirus. Viruses travel with groundwater and could migrate more straight distances and could reach the wells even faster than the chemical contaminants. Travel distances as far as 67 meters in vertical and 408 meters in horizontal distances in subsurface has been reported by some researchers (Keswick and Gerba, 1980).

Viruses are removed from the pore water by particle fixation on soil grains. In practice, the particle capture mechanism takes place with more than one particular mechanism dominating the process. Removal mechanisms include filtration process such as straining, sedimentation, diffusion, and interception; and adsorption processes such as physical, chemical and exchange adsorption (Caropcioglu and Haridas, 1985). The small size of the virus and its surface properties indicate that removal is primarily through adsorption to the particles rather than straining and other effects, as is the case with bacteria. Since viruses are electrically charged colloidal particles, their adsorption to soil surfaces is governed by surface forces.

Thousands of varieties of phage exist, each of which may infect only one type or a few types of bacteria. Phages are classified in a number of virus families, including Inoviridae and Microviridae. Like all viruses, phages are simple organisms that consist of a core of genetic material. Bacteriophage, also called phage, or bacterial virus, is applied for any of a group of viruses that infect bacteria. The term bacteriophage, means "bacteria eater," and describes the agent's bacteriocidal ability. The Φ x - 174 (or phi X) bacteriophage was the first DNA-based genome to be sequenced. This work was completed by Fred Sanger and his team in 1977 (Sanger et al., 1977). In 1962, Walter Fiers had already demonstrated the physical, covalently closed circularity of Φ x - 174 DNA (Fiers and Sinsheimer, 1962). Bacteriophage – Φ x – 174 virus was chosen as a sample virus in WHPA calculations in this article.

3 THEORY, AND VIRUS TRANSPORT MODEL

The mechanism of virus transport in soil is similar to the transport of colloidal particles of similar size. In general, the one dimensional virus transport equation could be written as follows (Corapcioglu and Haridas, 1984, 1985, and Corapcioglu et al., 1987),

$$\frac{\partial c}{\partial t} = \frac{D}{R}\frac{\partial^2 c}{\partial x^2} - \frac{V}{R}\frac{\partial c}{\partial x} - \lambda C \qquad [1]$$

in which, c is virus concentration, D is the longitudinal hydrodynamic dispersion coefficient, R is the retardation coefficient, V is the groundwater velocity, λ is the viral decay rate (inactivation rate), x is the virus travel distance from the source, and t is the virus travel time. The hydrodynamic dispersion coefficient, D, is sum of the effective diffusion coefficient, D_e, and the mechanical dispersion, D_{md}, ($D = D_e + D_{md}$). The mechanical dispersion is calculated by multiplying the longitudinal dispersivity, α_L, to the groundwater velocity, V ($D_{md} = \alpha_L . V$). The adsorption mechanism of the virus to the soil particles is of the linear adsorption isotherm and is written by the following equation,

$$R = 1 + \frac{K_d \rho_B}{\theta} \qquad [2]$$

in which K_d is the linear adsorption isotherm constant, ρ_B is the bulk density of dry soil, and θ is the volumetric water content of soil. For a saturated medium, the volumetric water content is equal to porosity (θ =n).

Successful application of viral transport models depends on the reliable determination of model parameters. In particular, constants controlling capture and decay mechanisms of viruses are quite important for a meaningful interpretation of simulation results. For most cases, parameters determined for a specific medium and type of virus are not applicable to other cases due to changes in conditions under which the measurements are obtained.

The viral transport model used is this study is the VIRALT code (Park et al., 1994). The primary objective of the VIRALT code is to provide technical staff of water resources management offices a tool for estimating concentrations of viruses in ground water withdrawn from pumping wells that are located in the vicinity of viral contaminant sources. VIRALT is a modular, semi-analytical and numerical code that simulates the subsurface transport and fate of viruses in both the unsaturated and saturated zones. The code also delineates ground-water pathlines and wellhead protection areas (well capture zones), and computes viral concentrations in extracted ground-water.

VIRALT provides both steady-state and transient transport analyses taking into account the major physical processes of advection and dispersion of viral particles along ground water pathlines, adsorption, and inactivation or die-off. The code can handle contaminant sources of various shapes; both areal and line sources can be accommodated. Typically, areal sources may be used to represent leaky septic tanks, cesspools or surface and subsurface disposal of waste water. Line sources may be used to represent leaky sewer lines or pipes.

A number of other researchers have developed viral transport models with various degree of complexity (e.g., Corapcioglu and Haridas, 1984, 1985; Vilker, 1981, and Bales et al., 1989). The model used in this study was reviewed in the document "Viral Transport Modeling in Porous Media" prepared by M. Yavuz Corapcioglu for EPA (Corapcioglu, 1990). The model represented by Equation 1 is favoured over others due to advantages in application to practical problems. The model parameters R, λ, and D can be obtained from the literature or determined by experimental procedures.

4 TRANSPORT PARAMETERS FOR BACTERIOPHAGE – Φ X – 174 VIRUS

Table 1 shows the reported transport parameters in three types of soils for Bacteriophage – Φ x – 174 virus (Burge and Enkiri, 1978a, 1978b). The parameters include the linear adsorption constant, the Freundlich constant, and the viral decay rate constant.

Table 1. Transport parameters for bacteriophage – Φx – 174 virus

Transport parameters	Clayey soil	Silt	Sand & gravel
Linear adsorption constant, K_d (mL/g)	$2\text{x}10^4$	300	0
Freundlich constant (L/m)	0.916	0.916	0.916
Viral decay rate constant, λ(day^{-1})	0.05	0.05	0.10

The selected transport parameters for bacteriophage – Φx – 174 virus in the WHPA calculations in this study are as follows. The longitudinal dispersivity, α_L is 16.7 m, the decay rate constant, λ is 0.08 (day^{-1}), the linear adsorption constant, K_d is 0.0, and the retardation coefficient, R is 1.0. As listed in Table 1, the decay rate constant for aquifers with silty or loamy materials is 0.05 (day^{-1}) and with sand and gravel mixtures is 0.1 (day^{-1}). The aquifer in which the well No. 20 of Urmia city is located, include the sand and gravel with some silty and loamy material. Hence, the decay rate constant of λ= 0.08 (day^{-1}) was selected in the calculations.

The concentration of the bacteriophage virus at the source was assumed to be 100000 (PFU/Liter) in the WHPA calculations. Two types of sources of virus were assumed; an open type leaky sewer pipe, or a closed type sewage septic tank near well No. 20. A closed solid waste landfill could also be assumed as a source of virus instead of a leaky septic tank. The length of the leaky part of the sewer pipe is assumed to be 200 meters located in up-gradient of the well perpendicular to the groundwater flow direction (the up-gradient refers to the area at the upstream side of well and down-gradient refers to the area at the downstream side of well, at the groundwater flow direction).

5 WELLHEAD PROTECTION AREA (WHPA) DELINEATION FOR BACTERIOPHAGE – Φ X – 174 VIRUS

5.1 WHPA Calculations with 1, 2, 3, 4, and 5 Years Virus Travel Time Limits

Table 2 shows the input data for WHPA calculations in the VIRALT code. The data refers to 5 years virus travel time limit. The input data may vary according to the type of calculations. Figure 1 shows the calculated plan areas of WHPAs (also called capture zones) for 1 to 5 years time limits for well No. 20. Time limit is in fact the travel time of virus from the source towards the pumping well No. 20. The following conclusions could be made: (1) The WHPAs are elongated towards the direction of flow, (2) when the travel time of virus increases, the area of WHPA increases as well, (3) with the considered 0.0049 aquifer hydraulic gradient in the calculations, WHPAs are mainly located in the up-gradient of the well, (4) when the travel time of virus increases, the ratio of length to width of WHPAs increases (for example, according to Figure 1, for virus travel time of 5 years, the length of WHPA is 1420 m, its width is 470 m, and its area is 667400 m^2), and (5) as shown in Figure 1, except in WHPA for 1 year virus travel time, the leaked virus from the sewer pipe could reach and contaminate well No. 20. As shown in Figure 1, in 2 to 5 years WHPAs the pipe is located inside the WHPAs. The 667400 m^2 WHPA for 5 years virus travel time is significant and might raise management issues in the populated area of the city when the authorities try to protect the well by safeguarding the delineated area around the well.

Table 2. Input data for 5 years bacteriophage – Φx –174 virus travel time limit in WHPA calculations for well No. 20.

Parameter	Data	Parameter	Data
Number of pumping wells	1	Longitudinal dispersivity (m)	17.0
Number of recharge wells	0	Molecular diffusion coefficient (m^2/day)	0.0
Transmissivity (m^2/day)	1141	Ambient groundwater temperature	Non temperature dependent
Hydraulic gradient	0.0049	First order decay rate (day^{-1})	0.08
Angle of ambient flow (degrees)	52	Bulk density of aquifer material (gr/cm^3)	1.99
Aquifer porosity	0.25	Distribution coefficient (mL/g)	0.0
Aquifer thickness (m)	38	Retardation factor (R)	1.0
Boundary type & location	No boundary	Boundary condition type	Prescribed concentration (transient)
Time limit for pathline computation (days)	1825	Well X-Coordinate (m)	1500
Time limit for virus transport simulation (days)	1825	Well Y-Coordinate (m)	1500
Virus source configuration	Open source	Well discharge rate (m^3/day)	3137
Initial virus concentration in the aquifer (PFU/Liter)	0.0	Delineate capture zone	Yes
Type of viral transport analysis	Transient	Number of pathlines	20

Figure 2 shows the concentration of the bacteriophage virus against time for 5 years (1825 days) of virus travel time limit. After about 175 days the virus appears at the well, its concentration increases, after about 280 days the concentration reaches to the maximum value of 0.29E-5 (PFU/Liter), and after that the virus concentration becomes constant.

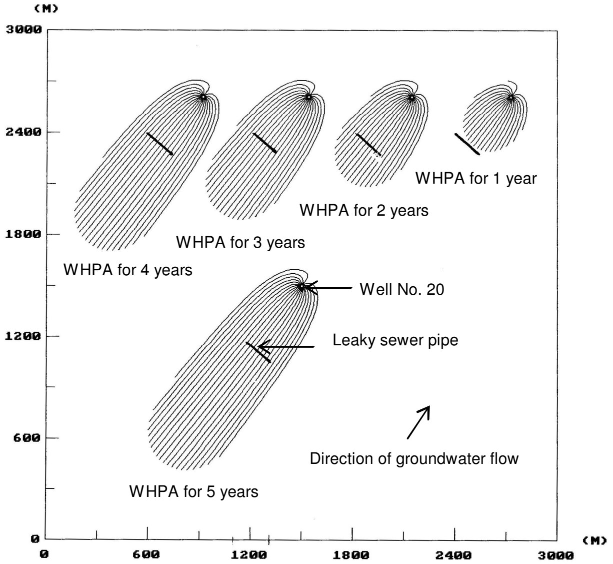

Figure 1. WHPAs for well No. 20 for 1 to 5 years virus travel time limits

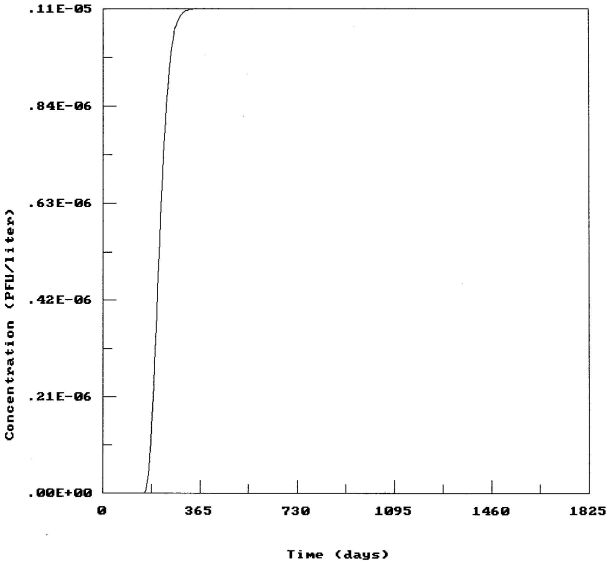

Figure 2. Virus concentrations at well No. 20 against time for 5 years virus travel time limit (l=0.08 day^{-1})

5.2 The Effect of Viral Decay Rate Constant (l) on the Virus Concentrations at the Well

The viral decay rate constant (l, also called first order decay rate or die-off) specifies the rate of die-off of virus when it travels through the porous media. In Figures 1 and 2 the value of l was selected to be 0.08 (day^{-1}) based on the porous media material. To verify the effect of l on the concentration results, the analysis was repeated with l=0.0 (day^{-1}). The value of zero for this parameter means that the virus does not die-off during its migration through the soil. Figure 3 shows the virus concentrations at well No. 20 against the virus travel time. The following conclusions are made: (1) the peak or maximum virus concentration at the well increases significantly, (2) more virus is transported into the well, and (3) a delay occurs in the virus concentrations with respect to elapsed travel time, when the rate of die-off of virus is zero, compared to Figure 2 when the virus dies-off with the rate of 0.08 (day^{-1}). This verifies the important role of viral decay rate constant on the rate of concentration of virus in the well. The lower the die-off rate of virus, the more viruses are transported and their concentration rise up at the target pumping well.

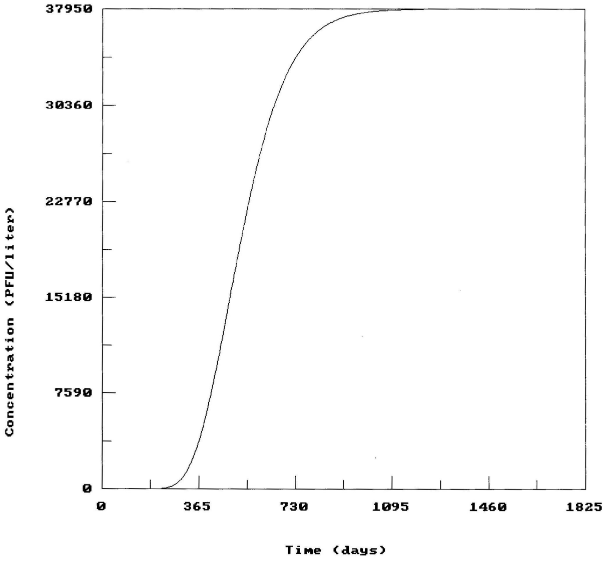

Figure 3. Virus concentrations at well No. 20 against time for 5 years virus travel time limit (l=0.0 day^{-1})

5.3 The Effect of the Hydraulic Gradient of the Aquifer on the Shape of WHPAs

To investigate the effect of the aquifer hydraulic gradient on the shape of WHPAs of well No. 20, the analyses were performed with two other aquifer hydraulic gradient values of 0.00245 and 0.001225. The remaining parameters are as listed in Table 2 including the initial hydraulic gradient of 0.0049 and the virus travel time of 5 years. Figure 4 shows the plan views of 5 years virus travel time WHPAs for well No. 20. By comparing the shape of WHPAs it is concluded that when the aquifer hydraulic gradient decreases (i.e., the groundwater flow velocity decreases) the shape of the wellhead protection area changes so that its length along the direction of groundwater flow decreases and its width perpendicular to the groundwater flow increases. This causes that the wellhead protection area changes its shape from a more elliptical shape to a more circular shape. Moreover, as shown in Figure 4, when the aquifer hydraulic gradient decreases, the distance from well to the up-gradient limit of WHPA decreases and from well to the down-gradient limit increases. Hence, in the aquifers with lower hydraulic gradient or lower groundwater velocity, the shape of WHPAs will be more circular and the length to width ratio of WHPA will approach to unity.

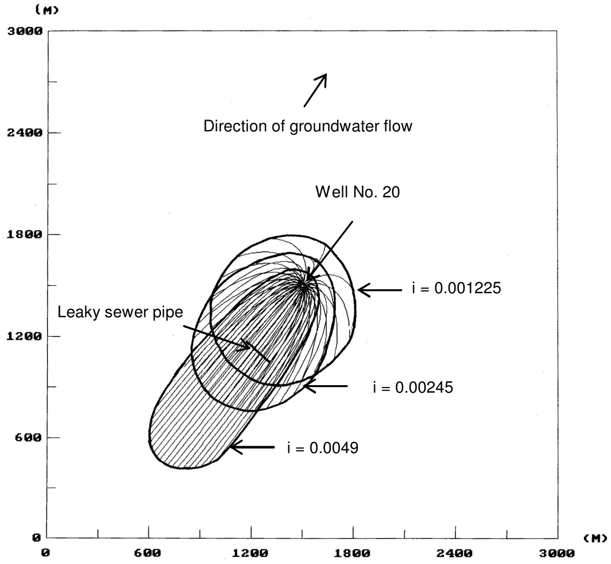

Figure 4. WHPAs for well No. 20 with three different aquifer hydraulic gradients for 5 years virus travel time

5.4 WHPA for 5 Years Virus Travel Time and a Leaky Septic Tank

The WHPA analysis was performed when virus leaks from a septic tank located in up-gradient of well No. 20. All other data are as listed in Table 2. Figure 5 shows the plan view of WHPA for 5 years virus travel time. As shown, WHPA surrounds the septic tank; hence, the leaked virus from the septic tank will reach and contaminate the well within the specified travel time.

6 WELLHEAD PROTECTION AREA DELINEATION FOR TWO ADJACENT WELLS

To investigate the effect of an assumed nearby well close to well No. 20 (called well No. 21), on the shape of WHPAs, the analysis was performed with two pumping wells. The pumping rate of well No. 21 is equal to well

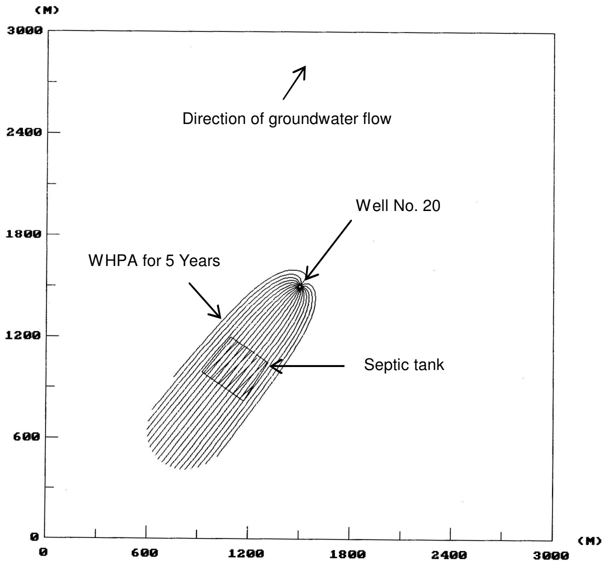

Figure 5. WHPA for well No. 20 with 5 years virus travel time limit and a leaky septic tank

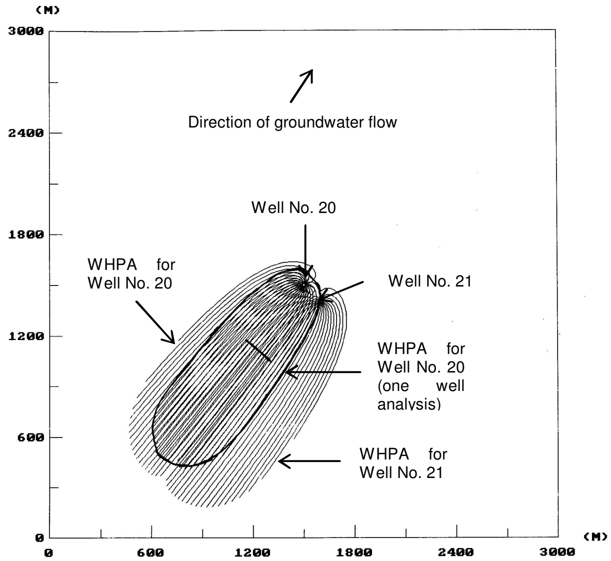

Figure 6. WHPAs for wells No. 20 and No. 21 with 5 years virus travel time limit and a leaky sewer pipe (WHPA of well No. 20 in one well analysis is superimposed)

No. 20. All other data are as listed in Table 2 except for the coordinates of well No. 21.

Figure 6 shows the plan view of WHPAs for two wells. For comparison, the WHPA of well No. 20 alone is superimposed on the WHPAs of wells No. 20 and No. 21 in Figure 6. The following conclusions could be made: (1) when an adjacent well is located close to well No. 20, the WHPAs of two wells affect each other; (2) the location of WHPA of well No. 20 is displaced compared to one well analysis (see Figure 1 and justification made below), (3) WHPAs of two adjacent wells overlap and they share a part of their WHPAs (meaning that they share in water resources of some part of the aquifer). As shown in Figure 6, the area of WHPA of well No. 20 has expanded somewhat and covered some more areas on the left and up-stream side of well, compared with the case with well No. 20 alone. When well No. 21 presents adjacent to well No. 21 and both share one aquifer, well No. 20 has to extract water from wider areas of aquifer compared to one well situation. This could justify displacement of WHPA of well No. 20 as described above.

7 THE EFFECT OF A RECHARGE WELL ON WHPA OF THE PUMPING WELL NO. 20

To investigate the effect of a recharge well on WHPA of pumping well No. 20, a recharge well was assumed adjacent to well No. 20 with the coordinates of X = 1200 m and Y = 600 m. The recharge capacity of the well is assumed to be 2000 m^3/day. All other data is as listed in Table 2. Figure 7 shows the wellhead protection area of well No. 20 with the assumed recharge well nearby. For comparison, the wellhead protection area of well No. 20 without considering a recharge well is superimposed on the figure. As shown in Figure 7, the recharge well has affected WHPA of well No. 20 and the groundwater pathlines inside WHPA have somewhat shifted towards the recharge well and WHPA has somewhat expanded. This is due to the contribution of the recharged water (into the recharge well) in the prevailing groundwater flow. This means that well No. 20 supplies some of its water from the water recharged into the recharge well nearby and that is why the pathlines have shifted towards the recharge well.

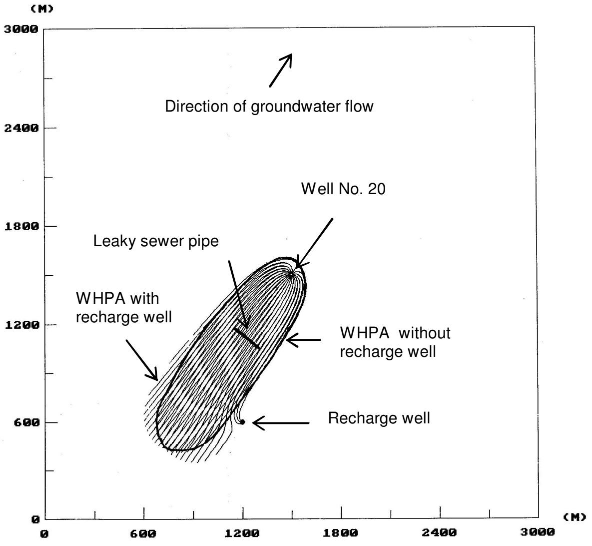

Figure 7. WHPA for well No. 20 with 5 years virus travel time limit, an adjacent recharge well, and a leaky sewer pipe (WHPA of well No. 20 without a recharge well is superimposed)

Figure 8 shows the change in virus concentrations with time in well No. 20 with and without the recharge well. According to this figure, when the recharge well does not exist, the virus concentration at well No. 20 reaches its maximum value of 0.29E-05 (PFU/Liter) after about 280 days (see also Figure 2), while when recharge well exists, the virus concentration at the well appears somewhat earlier (after about 130 days), its concentration increases with time, and after about 320 days its concentration reaches to a maximum value of 0.75E-05 (PFU/Liter) and becomes constant afterwards. It appears that the recharge well has the following effects: (1) it caused more virus transport from the source towards the pumping well No. 20, (2) it caused early appearance of virus at the well, and (3) it increased the maximum virus concentration at the well.

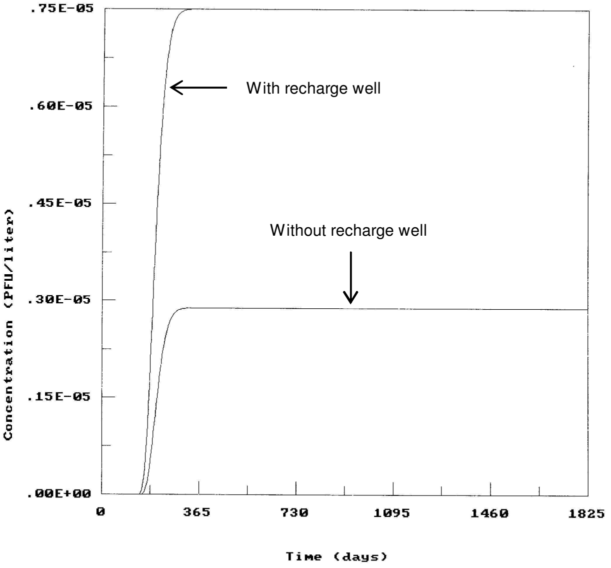

Figure 8. Virus concentrations at well No. 20 against time for 5 years virus travel time limit, with and without the recharge well

8 SUMMARY AND CONCLUSIONS

A series of wellhead protection area delineation analyses were performed for drinking water pumping well No. 20 of Urmia City, Iran, using the bacteriophage – Φx – 174 as a sample virus. A leaky sewer pipe or a septic tank was considered as sources of virus contamination in the direction of groundwater flow towards the well.

Using the aquifer hydrogeologic parameters and sample virus transport parameters the wellhead protection areas were delineated for 1 to 5 years virus travel time limits for well No. 20. When the virus travel time increased, WHPAs expanded. The effect of viral decay rate constant or die-off rate was evaluated and the results showed that when this parameter is ignored (no die-off of virus), the peak or maximum virus concentration at the well increases significantly and a delay occurs in the virus concentrations with respect to elapsed travel time. The lower the die-off rate of virus, the more viruses are transported and their concentration rise up at the pumping well. The WHPAs were calculated for three different hydraulic gradients of the aquifer. The results showed that when the aquifer hydraulic gradient is higher, the shape of WHPA is more elliptical, compared to lower hydraulic gradient which the shape becomes more circular and the ratio of length to width of WHPA approaches to unity. The effect of an adjacent pumping well and a recharge well on WHPA and virus concentrations was evaluated. The results showed that WHPAs of two adjacent pumping wells affect each other and the location of WHPA displaces compared to WHPA analysis for one well. When two wells present, they extract water from wider areas of aquifer and hence, their WHPAs displace and expand somewhat, compared to one well situation. When an adjacent recharge well presents, the groundwater pathlines inside WHPA shift towards the recharge well and WHPA expands. Moreover, the recharge well causes more virus transport from the source towards the pumping well; it causes early appearance of virus and increases the maximum virus concentration at the pumping well.

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