Modelling the length of microbiological protection zones around phreatic sandy aquifers in The Netherlands

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Abstract The aim of the current study was to calculate the size of protection zones around (sub)oxic and anoxic sandy aquifers without confining layers using a virus infection and transport model. The maximum allowable virus infection risk was $10^{-2}$ person/year at the 95% confidence level. Model results demonstrated that phreatic (sub)oxic sandy aquifers in The Netherlands required protection areas with a residence time of 43–117 d to ensure that the maximum virus infection risk would not be exceeded. This was 0.7–2 × the current guideline of 60 d. In contrast, phreatic anoxic sandy aquifers without confining layers needed protection zones of 585–898 d to stay below the maximum virus infection risk, 9.5–15 × the current guideline. A sensitivity analysis of the model demonstrated that the calculated protection zone was most sensitive for virus inactivation rate and collision efficiency. Values of both parameters were predicted from values obtained from previously published field and laboratory studies. At present, as it is unknown if these values can also be used at other locations, model results should be interpreted with care.

Keywords Attachment; groundwater well systems; inactivation; microbial protection zone; modelling; virus removal

Introduction Groundwater is an important source for drinking water in The Netherlands since two-thirds of the drinking water is produced from groundwater. In general, groundwater has a high hygienic quality which is caused by the effective removal of possible pathogenic microorganisms through soil passage. A minimum water travel time of 60 d is used in The Netherlands as a guideline to determine microbial protection zones around the well-field, based on the studies of Knorr (1937a, b) who studied the inactivation of bacteria in groundwater almost 70 years ago. However, progress in this field of research has shown that inactivation adsorption plays a pivotal role in the removal of microorganisms during soil passage (Schijven and Hassanizadeh, 2000). In addition, it has been observed that other microorganisms (e.g. viruses) are more persistent in groundwater and are removed in lower numbers during soil passage. Consequently, it is unknown whether the guideline of 60 d protects the well sufficiently against contamination with viruses.

Recently, a model has been developed to calculate the protection zones around groundwater aquifers without confining layers under a worst-case scenario of a leaking sewer and a 9 log reduction of viruses by soil passage (Schijven and Hassanizadeh, 2002a, b). It was concluded that, under the worst-case scenario, protection zones based upon water travel times of 400–800 d (considerably higher than the currently used 60 d guideline) were required to obtain 9 log removal of viruses. The new inspection guideline in The Netherlands states that the infection risk for viruses by drinking water should not exceed 1/10,000 persons/year (de Roda Husman et al., 2004). Ideally, the length of the protection zone around groundwater wells provides enough protection so that the infection risk of $10^{-4}$ persons/year at the 95% certainty level will not be exceeded.
The aim of the current study was to calculate protection zones around (sub)oxic and anoxic sandy groundwater aquifers without confining layers based on an infection risk of \(10^{-4}\) persons per year (de Roda Husman et al., 2004). In addition, a sensitivity analysis was performed to identify the most sensitive model parameters.

**Methods**

The protection zones around three anoxic and six (sub)oxic sandy groundwater aquifers in the Netherlands were calculated. Anoxic groundwater well systems had oxygen and nitrate concentrations below 0.5 mg/L, whereas nitrate or oxygen concentrations above 0.5 mg/L were considered to be (sub)oxic (Schijven and Hassanizadeh, 2002a). The overall equation to calculate the virus concentration at the abstraction well has been described previously (Schijven and Hassanizadeh, 2002a) and is given by:

\[
C_A = \frac{q}{Q} C_0 e^{-\left(\frac{q k_1 h^2 + k_2 R^2}{Q C_0 C_1}\right)}
\]  

where \(C_A\) is the virus concentration at the abstraction well, \(q\) is the leaking rate of a sewer, \(Q\) is the abstraction rate of the groundwater well system, \(k_1\) and \(k_2\) are constants that have been defined previously (Schijven and Hassanizadeh, 2002a), \(\alpha\) is the collision efficiency and \(\mu_{in}\) is the virus inactivation rate.

The infection risk \((p_{inf})\) was modelled with a dose-response model for the infection of rotavirus (Teunis et al., 1996):

\[
p_{inf} = 1 - \left(1 + \left(\frac{D}{0.422}\right)^{0.253}\right)
\]  

with \(D\) being the doses:

\[
D = \frac{C_A}{E} V
\]

where \(V\) is the volume of non-boiled drinking water intake/person/year and \(E\) is the recovery efficiency of the virus method. Combining equations (1) and (2) describes the infection risk as a function of the size of the protection zone in metres: \(P_{inf} = f(R)\).

The size of the protection zone based on residence time was calculated from the size in metres using the following equation:

\[
t = \frac{\pi n h R^2}{Q}
\]

where \(t\) is the residence time, \(n\) is the porosity, \(h\) is the aquifer thickness and \(R\) is the size of the protection zone (m).

All parameters used in modelling were either a constant value or described by a normal or a log-normal distribution (Table 1). A Monte Carlo analysis with 300,000 simulations from the distribution of the different model parameters was used to calculate the size of the protection zone. The maximum allowable virus infection risk used was \(10^{-4}\) persons/year at the 50 and 95% confidence level (de Roda Husman et al., 2004). In addition, a sensitivity analysis of the model was performed for the anoxic aquifer with the longest calculated protection zone (aquifer “Anoxic 1”). The sensitivity of the model was studied by changing each model parameter over a certain fixed range while the distribution of the other model parameters was kept the same. The fixed range was: (i) the mean of a parameter ± one tenth of the mean; (ii) the mean ± half the mean; (iii) one tenth of the mean; and (iv) ten times the mean.
Table 1 Values for used constants and means ($\mu$) and standard deviations ($\sigma$) of the normal and log-normal distribution of each model parameter and for each aquifer. For the parameters with a log-normal distribution, the values of $\mu$ and $\sigma$ were used to calculate the mean M and standard deviation S of the log-normal distribution.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Distribution</th>
<th>Oxic $\mu$ ($\pm \sigma$)</th>
<th>Anoxic $\mu$ ($\pm \sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1   2  3  4  5  6</td>
<td>1   2  3</td>
</tr>
<tr>
<td>Leaking rate (m$^3$/d)</td>
<td>Log-normal</td>
<td>1.00 (0.5)</td>
<td>1.00 (0.5)</td>
</tr>
<tr>
<td>Virus concentration (N/L)</td>
<td>Log-normal</td>
<td>164.0 (356.0)</td>
<td>164.0 (356.0)</td>
</tr>
<tr>
<td>Volume intake (L/person/d)</td>
<td>Log-normal</td>
<td>0.286 (0.205)</td>
<td>0.286 (0.205)</td>
</tr>
<tr>
<td>Porosity</td>
<td>Normal</td>
<td>0.37 (0.06)</td>
<td>0.37 (0.06)</td>
</tr>
<tr>
<td>Virus size (nm)</td>
<td>Normal</td>
<td>23.0 (3.1)</td>
<td>23.0 (3.1)</td>
</tr>
<tr>
<td>Inactivation rate (/d)</td>
<td>Log-normal</td>
<td>0.149 (0.0932)</td>
<td>0.149 (0.0932)</td>
</tr>
<tr>
<td>Grain size (mm)</td>
<td>Log-normal</td>
<td>0.5 (0.21)</td>
<td>0.5 (0.21)</td>
</tr>
<tr>
<td>Collision efficiency ($10^{-9}$)</td>
<td>Normal</td>
<td>3.9 (0.39)</td>
<td>3.9 (0.39)</td>
</tr>
<tr>
<td>Abstraction rate (m$^3$/d)</td>
<td>Constant</td>
<td>2.100</td>
<td>1.096</td>
</tr>
<tr>
<td>pH</td>
<td>Constant</td>
<td>7.20</td>
<td>7.10</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>Constant</td>
<td>10.0</td>
<td>10.5</td>
</tr>
<tr>
<td>Aquifer thickness (m)</td>
<td>Constant</td>
<td>30.0</td>
<td>27.0</td>
</tr>
</tbody>
</table>
Results and discussion

For most of the studied wells, the infection risk of $10^{-4}$ persons/year at 95% CL was realised when the distance of the protection zone was 54–84 m (Table 2). The exception was well “Anoxic 1” where model calculations resulted in a protection zone of 276 m. A pronounced difference between the (sub)oxic and anoxic aquifers was observed when the length of the protection zone was expressed in travel time (Table 2). The calculated protection zones around aquifers containing anoxic groundwater were 9.5–15× larger compared to the currently used Dutch guideline of 60 d. In contrast, protection zones around aquifers characterised by (sub)oxic groundwater were 0.7–2× the 60 d guideline. The relatively short distance but long travel time for the wells “Anoxic 2” and “Anoxic 3” was caused by a 12× lower abstraction rate at these two wells compared to the others (Table 1). As can be inferred from equation (4a), low abstraction rate ($Q$) resulted in a long travel time.

In an earlier study, setback distances around anoxic aquifers based on 9 log virus removal were calculated with the same virus transport model (Schijven and Hassanzadeh, 2002a, b). The water travel times obtained in that study were 400–800 d, similar to the ones we obtained at the 95% confidence level. However, the model approach differed considerably between both studies. In our study, normal or log-normal distributions for most parameters were used, whereas in the earlier study a constant value based on the mean was used for each parameter (Schijven and Hassanzadeh, 2002a). As a result, only mean water travel times obtained in our study could be compared with travel times obtained in the study of Schijven and Hassanzadeh (2002a, b). Interestingly, the mean water travel times we obtained were approximately twice as low. Schijven and Hassanzadeh (2002a, b) assumed in their study that the flow velocity towards the point of abstraction remained constant. However, as water moves in an aquifer towards the point of abstraction, the flow velocity will increase. We took into account this increase in velocity towards the point of abstraction with the calculation of the water travel time. This difference between both studies was the probable cause for the 2× longer water travel times in the study of Schijven and Hassanzadeh (2002a, b).

A sensitivity analysis was performed for each model parameter. Results demonstrated that the model was most sensitive for values of the inactivation rate, collision efficiency, grain size, abstraction rate, aquifer thickness and pH (Figure 1). The model was less sensitive for virus size, leaking rate, water intake, virus concentration, porosity, temperature and recovery efficiency of the virus method (data not shown). Values for abstraction rate and pH were measured at each abstraction well whereas aquifer thickness was determined from geohydrological profiles. Hence, accurate and reliable values for these three parameters were used in the model. The grain size was not measured for each aquifer. Instead, aquifers were divided into two: those with fine sand and those with more coarse sand. A log-normal distribution was used with an estimated mean of 0.25 mm for aquifers with fine sand and 0.5 mm for aquifers with coarse sand (Table 1).

Table 2 The predicted size of the protection zone (as distance and residence time) at a 50% (average) and 95%-confidence level that an infection risk of $10^{-4}$ persons/year will not be exceeded

<table>
<thead>
<tr>
<th>Aquifer</th>
<th>Average (95% percentile)</th>
<th>Oxic</th>
<th>Anoxic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Distance (m)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>53 (81)</td>
<td>42 (64)</td>
<td>48 (77)</td>
</tr>
<tr>
<td>Travel time (d)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>47 (109)</td>
<td>51 (117)</td>
<td>21 (55)</td>
</tr>
</tbody>
</table>
Publications about inactivation rates of viruses in groundwater at \( \sim 10^8 \) C are limited. Only for bacteriophage MS2 and Poliovirus 1 have sufficient inactivation rates under oxic conditions been published to calculate a log-normal distribution. The mean for the published MS2 inactivation rate (0.149 log/d) was lower than for Poliovirus 1 (0.175 log/d). In our study, we used the most conservative distribution (MS2) in the model (Table 1). Published inactivation rates of MS2 at \( 10^8 \) C range from 0.0085–0.3726 log/d (Yates et al., 1985; Yahya et al., 1993).

Specific ecophysiological conditions (such as organic content, nutrients, presence of eukaryotic predators and the composition of the autochthonous prokaryotic flora) influence the inactivation rate dramatically (Schijven and Hassanizadeh, 2000). As a result, inactivation rates of viruses would be different in each groundwater well system. Another ecophysiological condition that influences the inactivation rate of viruses is the redox state of groundwater with a lower inactivation rate at anoxic conditions (Gordon and Toze, 2003). Therefore, a lower inactivation rate for MS2, measured under anoxic conditions (Schijven et al., 2000), was used as the mean in the lognormal distribution for well systems with anoxic groundwater (Table 1).

The collision efficiency for viruses in well systems with (sub)oxic groundwater was obtained from a field study that investigated removal of bacteriophage MS2 in oxic groundwater at a dune area (Schijven et al., 1999). The collision efficiency for viruses in well systems with anoxic groundwater was obtained from a field study with bacteriophage MS2 conducted in an anoxic aquifer (Schijven et al., 2000). The collision efficiency was calculated using the colloid filtration theory and the obtained values were

\[ \text{Figure 1} \text{ Distance of the protection zone around aquifer “Anoxic 1” at different values of several model parameters} \]
10–100 × lower than the collision efficiency values calculated in the corresponding field study (Schijven et al., 1999, 2000). This difference was caused by the model assumption that favourable attachment sites were not present in the soil of groundwater abstraction wells. However, in field studies, favourable attachment sites have always been observed and as a result the low collision efficiencies used in our model have not been observed in field studies. A 10 × higher collision efficiency reduced the protection zone around aquifer “Anoxic 1” from 276 to 137 m. This finding emphasised that the choice for a conservative value results in a considerably longer protection zone.

Groundwater in many wells in The Netherlands has a redox state in between oxic and anoxic. Concomitant values for inactivation rate and collision efficiency for viruses probably also lie between oxic and anoxic values. Additional research is necessary to determine values for inactivation and attachment at suboxic conditions.

In summary, values for inactivation rate and collision efficiency were not known for each groundwater well system and were taken from field studies performed at other locations. The preceding discussion demonstrates that the model was most sensitive for these two parameters. However, the parameter values used for modelling the length of the protection zone were conservative and might not have reflected the actual values in each groundwater well. A slight change in values for inactivation rate and collision efficiency would have a profound effect on the calculated length of the protection zone. A consequence of the uncertainty of these two parameters was that the predictive value of the model outcome is currently unknown. As a result, the modelled length of the protection zone must be regarded indicative as opposed to definite.

Although model results should be interpreted with care, model results clearly demonstrated that the protection zone around unconfined anoxic aquifers should be considerably longer than the currently used 60 d guideline. In contrast, modelled length of the protection zone around groundwater well systems with (sub)oxic water were in the order of the 60 d guideline. In The Netherlands, just three groundwater abstraction wells are unconfined and anoxic. The protection zone around all three was calculated and model results demonstrated that only aquifer “Anoxic 1” needed a protection zone with a considerably greater distance. Therefore, the protection zone around groundwater well “Anoxic 1” should be reconsidered in The Netherlands. To identify the predictive value of the modelled length of the protection zone, results from a field study must be used to validate the model. At present, such information from field studies is lacking in The Netherlands. Therefore, a first field study, investigating removal of bacteriophages MS2 and ФX174 in an anoxic aquifer, is currently being conducted.

Conclusions

(1) Model results demonstrated that the predicted length of the protection zone around phreatic shallow (sub)oxic sandy aquifers was in the same order of the currently used guideline of 60 d.

(2) In contrast, the predicted length of the protection zone around phreatic shallow anoxic sandy aquifers was 9.5–15 × the guideline of 60 d.

(3) In The Netherlands, only three phreatic shallow aquifers are anoxic but only one of them also showed a protection zone with a long distance. The length of the protection zone around this aquifer should be reconsidered.

(4) Parameter values for virus inactivation and attachment were based on data from field studies at other locations. The reliability of these values is unknown and, thus, the predictive value of the model results is also unknown. Hence, model results should be considered indicative rather than definite.
References


