AN IMPROVED VIRAL DIE-OFF METHOD FOR ESTIMATING SETBACK DISTANCES

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Abstract

Setback distances are routinely applied as buffers between a wastewater disposal area and sensitive downgradient features. Setback distances vary between sites because of differences in pathogen levels in wastewater, groundwater temperature, aquifer characteristics and the sensitivity of the receiving environment.

It is still common in Australia for regulators to specify fixed setback distances, sometimes on a statewide basis, with little or no technical justification. This is despite the availability of the viral die-off method, presented by Beavers and Gardner (1993). Three limitations of this method have now been addressed. A family of curves is presented which generates viral die-off times for any groundwater temperature and wastewater quality. The setback distances derived from the die-off times can now be adjusted for delays due to vertical wastewater infiltration, as well for the effects of water table drawdown within the radius of influence of a bore. Examples are provided for each of the modifications. All three modifications appear in Trench®3.0, a computer application for assessing sites for on-site wastewater management.

Keywords

radius of influence, setbacks, temperature-adjustment, vertical infiltration, viral die-off, wastewater, water bores

1 Introduction

Setback distances are routinely applied as buffers between a wastewater disposal area and down-gradient features such as property boundaries, water bores and receiving waters. Their purpose is to minimise the potential human health and environmental impacts of domestic wastewater moving through the subsurface. Setbacks affect the size and overall density of residential lots, and the locations of house sites.

Setback distances depend on pathogen levels in wastewater, groundwater temperature, aquifer characteristics and the sensitivity of the receiving environment. Different sites or situations therefore require different setbacks. However, in Australia regulators commonly adopt fixed setback distances. This approach may be defensible if it is based on practical experience, but it becomes increasingly untenable if empirical setbacks are used across disparate climatic and soil conditions – a "one size fits all" approach.

We argue that where possible, setback distances should be derived from more rigorous physically based approaches. In this regard, the viral die-off method for estimating setback distances (Beavers and Gardner, 1993) has been available for several years. This simple, scientifically based technique has wide application for planning residential developments in unsewered areas.

This paper reviews the viral die-off method, but its primary purpose is to present modifications which allows more general applications.

The modifications also appear in Trench®3.0 (Cromer 1999a, 1999b), a computer application for on-site wastewater management marketed by the Australian Institute of Environmental Health.

These improvements are illustrated using practical examples.

2 The Basis of the Viral Die-off Method

The viral die-off method applies only to wastewater moving in saturated soils – for example, in shallow groundwater beneath an absorption trench or surface irrigation area. To determine a setback distance, two steps are required:

- Step 1 estimates the *time* required for viruses originating in the wastewater to be inactivated (i.e. reduced to acceptable numbers by natural mortality processes) as they move downgradient in the groundwater. The assumption is that during this *travel time*, bacteria will also have been reduced to acceptable numbers, since they generally survive for lesser times than viruses.
- Step 2 estimates the *distance* the groundwater has travelled during the travel time; this is the *setback distance*.

The setback distance refers to subsurface wastewater movement, and not, for example, to wastewater flowing over the ground surface from irrigated areas or failing absorption trenches.

Groundwater temperature is the single most important factor determining travel time. The equation linking temperature, travel time and viral concentration is:

$$M_t / M_o = e^{-kt} \qquad \text{Eqn 1}$$

where:

- M_t / M_o is the dimensionless ratio between the viral concentration in the groundwater at any time t (M_t), and the viral concentration in the wastewater at the time of its application to the subsurface (M_o),
- t is the travel time (days)of the viruses in the groundwater, and
- k is the first order rate coefficient for the die-off of the organism and is the temperature-dependent variable (^oC). Viruses do not replicate outside host organisms

The ratio M_t / M_o is an important concept and we repeat Beavers & Gardners' original example. If a septic tank effluent has an initial viral concentration of 10 viruses per mL (i.e. 10 000 000 viruses per cubic metre), and undergoes a *1-order* of magnitude reduction in viral numbers in the soil, viral numbers are reduced to a tenth of their original concentration, and the ratio M_t / M_o becomes 1 000 000/10 000 000, or 0.1. A *2-order* magnitude reduction would produce a M_t / M_o ratio of 100 000/10 000 000, or 0.01, and so on. To reach the World Health Organisation's (WHO) recommendation for human health (drinking water) protection of no detectable viruses (i.e. one or less) in a cubic metre of water, a reduction in viral numbers of 7 orders of magnitude would be required.

Different wastewater qualities require different orders of magnitude reduction in viral numbers to achieve the WHO recommendation. For example, reasonable assumptions might be 5 orders of magnitude reduction for greywater, 3 orders of magnitude reduction for wastewater treated in an aerated treatment plant, and 3 orders of magnitude reduction for wastewater treated in a sand filter.

The travel time for viral die-off in groundwater can be determined from Equation 1, provided the value of k is known, and a M_t / M_o ratio appropriate to a particular wastewater quality has been selected. But k depends on temperature. Accordingly, Beavers and Gardner (1993) produced a graph showing the travel times required to achieve a given order of magnitude reduction in viral numbers for four groundwater temperatures: 10°C, 15°C, 20°C and 25°C. Each temperature was associated with an experimentally-determined *k* value. The authors then used a modified form of Darcy's Law to convert travel time to a setback distance.

The main limitations of the 1993 approach were threefold:

1. users could only apply the die-off graph to four discrete groundwater temperatures,
2. the form of Darcy's Law used to convert the travel time to a setback distance did not include the time taken for the wastewater to first infiltrate vertically to the water table, and
3. in the vicinity of pumped water bores, setback distances may need to be adjusted to account for the radius of influence of the bore.

Each of these limitations is addressed below.

3 Modifications to the Viral Die-off Method

3.1 Generalising the Temperature Range

The temperature limitation of the 1993 approach has been removed by manipulating the original data.

This was achieved by plotting each *k* value against its corresponding temperature (T) to produce a straight-line relationship, the equation of which (to a sufficient accuracy) is $k = (T-8.5)/20$. This equation permits a *k* value to be determined for any groundwater temperature above 8.5°C (at T = 8.5, $k = 0$, and Equation 1 breaks down). This in turn allows a family of curves to be generated (Figure 1) showing the viral travel times required for eight different orders of magnitude reduction in viral numbers, for groundwater temperatures up to 36°C.

To use Figure 1 to estimate a travel time,

- select a groundwater temperature on the horizontal axis (a directly-measured temperature can be used, but it is probably acceptable to assume the mean annual air temperature as reasonably approximating shallow groundwater temperature),
- project the temperature value vertically to intersect the order-of-magnitude reduction curve appropriate to the wastewater quality, and
- move horizontally to the left to read off the travel time (in days) required to produce the selected level of viral reduction for the specified temperature.

This manual process is automated in Trench®3.0, which uses Figure 1 to calculate a travel time for any given set of inputs.

Example 1 (estimate a travel time)

Greywater infiltrates from a trench to groundwater at a temperature of 20°C. Estimate the travel time required to reduce viral numbers to non-detectable levels?

Assume viruses in greywater require a 5 order of magnitude reduction in numbers. Using Figure 1, project a vertical line up from 20°C on the horizontal axis to intersect the curve for 5 orders of magnitude reduction. Project horizontally to the left to read off a travel time of about 20 days. Note that the vertical axis is a logarithmic scale.

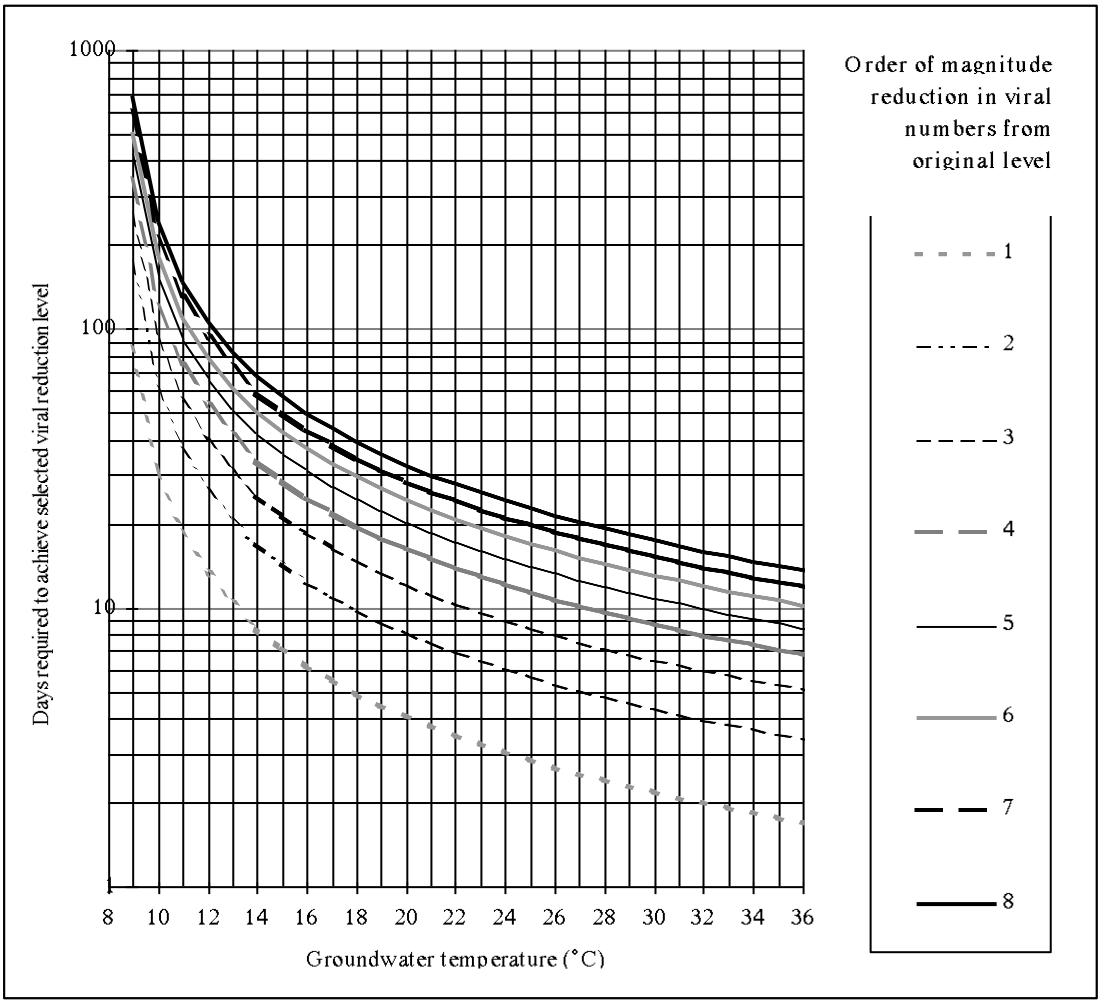

Figure 1. Relationship between Groundwater Temperature and Viral Die-Off Time for Various Order-of-Magnitude Reductions in Viral Numbers

3.2 Correcting Travel Time for Vertical Infiltration

The time required for groundwater to move a given distance in saturated material is described by a well-known form of Darcy's Law:

$$t = d.P / K.i \qquad \text{Eqn 2}$$

where

- t is the time (days) and d is the distance (m),
- P is the effective porosity of the soil (as a fraction; e.g. 0.2 instead of 20%),
- K is the saturated hydraulic conductivity (permeability) of the soil (m/day), and
- i is the groundwater gradient (as a fraction; e.g. 0.01 instead of 1 in 100).

Beneath an absorption trench or any similar land application area discharging wastewater to a uniform soil with a water table (Figure 2), the travel time for viral die-off is made up of two components:

- t_v, the time for wastewater to move vertically a distance d_v to a water table, and
- t_g, the time for wastewater to move a distance d_g with the groundwater.

The total distance is $d_v + d_g$ (of which only d_g is the setback distance). Similarly, the total travel time t is $t_v + t_g$, which can be expanded using Equation 2 to:

$$t = d_v.P/K + d_g.P/K.i \qquad \text{Eqn. 3}$$

The first term on the right hand side is the time for vertical infiltration, and the second term is the balance of the travel time. It is assumed that *saturated* vertical flow occurs in all situations, although this may not be the case for materials of relatively high permeability or if the effluent must first pass through a biofilm layer of low permeability. In saturated vertical flow, the gradient is usually equal to or near 1, so, for clarity, i has not been shown in the first term on the right hand side. Rearranging Equation 3 results in:

$$d_g = (t - d_v.P/K)/(P/K.i) \qquad \text{Eqn 4}$$

that calculates a setback distance corrected for the time taken for vertical saturated wastewater flow to the water table. Trench®3.0 uses Equation 4 to calculate a setback distance for any given set of inputs.

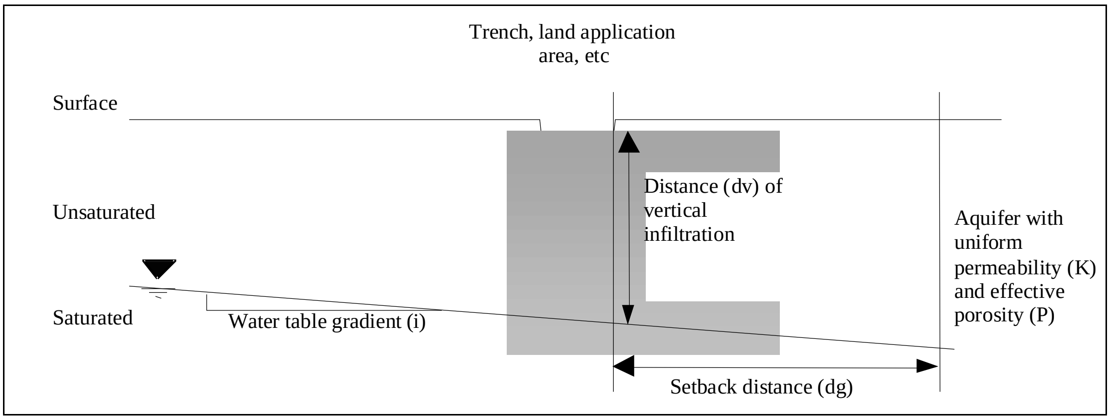

Figure 2. Cross-Section Showing Vertical Infiltration of Wastewater to a Water Table in a Uniform Soil

Example 2 (estimate a setback in a uniform soil with a water table)
Septic tank effluent is to be disposed of in absorption trenches on almost level ground in a silty sand soil with a shallow water table. What should the setback distance be if the soil permeability is 2.5 m/day, its effective porosity is 10% (i.e. 0.1 expressed as a ratio), the groundwater gradient is 0.02 (i.e. the water table has a slope of 1 in 50), and the mean groundwater temperature is 15°C? The distance between the base of the trenches and the water table is 3 m.

Step 1. Estimate the Travel Time
Assume that a 7 order of magnitude reduction in viral numbers is required for the wastewater. From Figure 1, the time required to achieve this reduction in viral numbers is 50 days. (Using Equation 2 and a water table gradient of 1 shows that only 0.1 days of the 50 days is required for the wastewater to infiltrate vertically to the water table.)

Step 2. Estimate the Setback Distance
Use Equation 4 and enter the given information

$$d_g = [50 - (3).(0.1)/2.5)]/[(0.1)/(2.5).(0.02)] \text{ m} \qquad \text{Example 1}$$

to verify that the setback distance is 49.9/2 m, or about 25 m. Beyond this distance, the original viral concentration in the wastewater would be expected to have been reduced by 7 orders of magnitude, to acceptable levels.

Example 3 (estimate a setback distance in a two-layered soil with no water table)
Wastewater from an aerated wastewater treatment plant is to be spray-irrigated on a hillside with sandy topsoil above a clay subsoil. There is no permanent water table in the topsoil, which is 0.5 m thick, has an effective porosity of 25% (i.e. 0.25) and a permeability of 3 m/day. The mean maximum daily air temperature for the coldest month is 16°C. What should the setback be if the hillside slope is 1 in 5?

Step 1. Estimate the Travel Time

The absence of permanent shallow groundwater is a very common situation. Assume that groundwater develops as a thin saturated zone of wastewater along the top of the clay subsoil, with a maximum gradient equal to that of the land surface (in this example, its gradient is 1 in 5, or 0.2). Also assume that a 3 orders of magnitude reduction in viral numbers is required for the treated wastewater. From Figure 1, the time required to achieve the required reduction in viral numbers is 18 days. [Equation 2 (using a gradient of 1) shows that 0.04 days (about 1 hour) of the 18 days is required for the effluent to infiltrate vertically to the water table.]

Step 2. Estimate the Setback Distance

Use Equation 4 and enter the given information

$$d_g = [18 – (0.5).(0.25)/3)]/[(0.25)/(3).(0.2)] \text{ m} \qquad \text{Example 2}$$

to calculate the required setback distance of 17.96/0.42 m, or about 45 m. Beyond this distance, the original viral concentration in the treated effluent would be expected to have been reduced by 3 orders of magnitude.

3.3 The Radius of Influence of a Water Bore

If an absorption trench or any similar land application area is located inside the radius of influence of a bore, groundwater contaminated with effluent may enter the bore. The radius of influence of a bore can be estimated from aquifer pump tests or calculated from the aquifer and bore hydraulic characteristics.

In Figure 3, when r is small or t is large (Jacob, 1963),

$$S = 2.25KHt / r^2 \qquad \text{Eqn 5}$$

Rearranging Equations 5 for the radius of influence, r, we get

$$r = 1.5 [(KHt / S)^{0.5}] \qquad \text{Eqn 6}$$

which is reasonably valid for

$$t = Kt / SH \geq 1 \qquad \text{Eqn 7}$$

Provided Equation 7 is satisfied, Equation 6 can be used to estimate a radius of influence for any bore by assuming values for aquifer permeability (K, m/day), the initial thickness of water (H, m) in the fully-penetrating bore, the time of pumping (t, days) and the specific yield of the aquifer (S fraction, dimensionless).

This process is automated in Trench®3.0, which uses Equation 6 but will not calculate a radius of influence unless the value of Equation 7 is between 1 and 2.

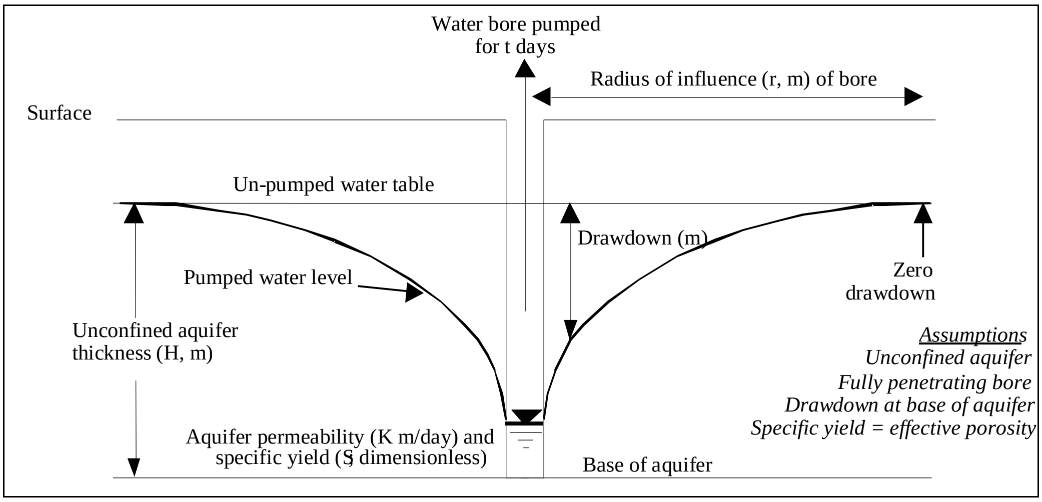

Figure 3. Cross-section of a Bore in an Unconfined Aquifer

The radius of influence of a bore pumped long enough to maintain maximum drawdown is a fixed, maximum distance determined by the characteristics of the bore and aquifer.

Example 4 (estimate the radius of influence of a bore in a uniform, unconfined aquifer)
The water table in a domestic water bore 20 m deep is 5 m below ground level. The bore extends to the base of the aquifer, which has a permeability of 1 m/day and a specific yield of 0.05 (i.e. 5%). The bore is pumped for one day. Estimate its radius of influence.

Step 1. Check that Equation 7 is satisfied
If K = 1 m/day, t = 1 day, S = 0.05 and H = 20 – 5 = 15 m, then Kt / SH = 1 / 0.75, or 1.3. Equation 7 is satisfied. If this had not been the case, any of the inputs, but usually t, is altered. It is advisable to keep the value of Equation 7 small (say, between 1 and 2).

Step 2. Estimate the Radius of Influence of the Bore
Use Equation 6 and enter the given information

r = 1.5 [(1.(20-5).1 / 0.05)^0.5] Example 3

to show that the radius of influence is 26 m.

3.4 Adjusting Setback Distances for Nearby Water Bores

As a conservative measure, an absorption trench or any similar wastewater application area should not be located within the maximum radius of influence of a water bore. Equations 6 and 7 can also be used to back-calculate how deep a future bore should be so that its radius of influence does not exceed a given value.

As a general comment (Figure 4),

- If an absorption trench or wastewater application area is to be located *downgradient or crossgradient* from a water bore, the appropriate separation distance is the radius of influence of the bore.
- If an absorption trench or wastewater application area is to be located *upgradient* from a water bore, the appropriate separation distance is the radius of influence of the bore **plus** the setback distance required for viral die-off.

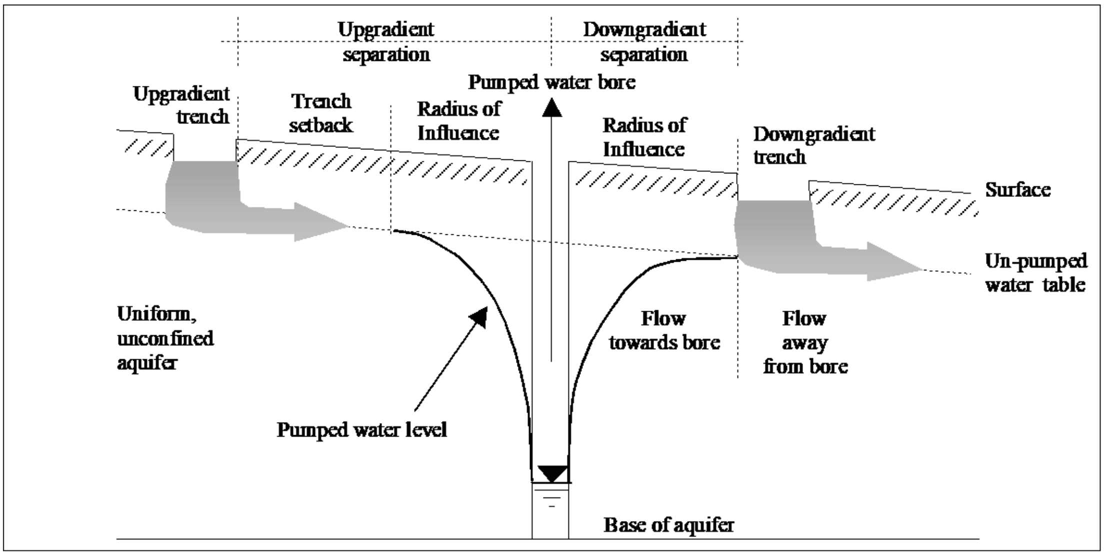

Figure 4. Downgradient (and Crossgradient) Absorption Trenches Can Be Located Closer To Water Bores Than Upgradient Trenches

The minimum separation distance in such instances should be the radius of influence of the bore.

4 Conclusions

We have extended the analysis of Beavers and Gardner (1993) to allow for a wide range of temperatures, vertical transport through the soil, and distance from a production bore in an unconfined aquifer. Calculating setback distances of absorption trenches or other similar wastewater disposal facilities using these relationships is neither difficult nor data-demanding. Calculation is made even easier using Trench®3.0.

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