CALCULATED FIXED RADIUS ISSUES
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Henk Haitjema

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For almost one and a half century we relied on groundwater as a bacteriologically safe source for drinking water, as opposed to surface water. In fact, Darcy's experiments in 1856 were aimed at "filtering" surface water through columns of soil in order to achieve purification (disinfection). Even when during the last decades chemical contamination became a problem, at least in urban areas, we still assumed groundwater to be bacteriologically safe. Although this empirical rule probably remains valid in general, it now appears that under certain circumstances groundwater may require (additional) disinfection before being used as drinking water. This is particularly true if known sources of microbiological contamination occur close to the pumping well.

It is proposed to use a "source-free area" concept as one of the criteria to allow groundwater use for drinking water purposes without mandatory disinfection. A minimal residence time criteria of one (1) year has been proposed to ensure sterile water, although a two (2) year residence time may be needed under some circumstances. Regardless of the residence time limit to be used, a "time of travel capture zone" must be determined for the well or group of wells in order to delineate the source-free area. Under current Wellhead Protection Plans time of travel capture zones (isochrones of groundwater residence time) are determined by some form of computer modeling, although for smaller systems a *calculated fixed radius* concept may be used. It are these smaller systems which are the focus of the disinfection rule, as most larger systems already routinely use chlorination to avoid infection in the drinking water distribution system.

The radius for a circular isochrone, concentric around the well, may be calculated in different ways, but in all cases two important assumptions are made:

1. The Dupuit–Forchheimer assumption applies (2D flow equations).

2. Ambient groundwater flow is ignored.

Depending on circumstances, one or both of these assumptions may be violated.

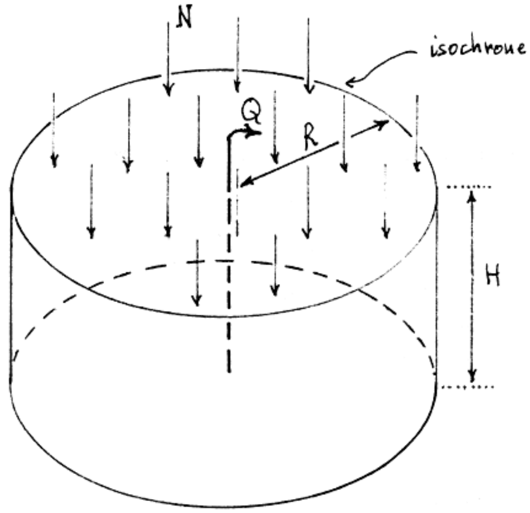

Figure 1: Water balance for radial flow toward a well in a domain bounded by an isochrone of residence time t.

If so, the resulting time of travel capture zones (isochrones) are *unsafe* (too small)!

What follows is a brief outline of the fixed radius calculation, a discussion of its limitations, and a discussion on research needs.

Radius of Isochrone

Assume radial flow toward a well in an aquifer with a constant saturated thickness H [ft]. The cylindrical boundary of radius R [ft] in the figure is an isochrone of residence time t [days], which means that any water particle that enters the cylinder or is present in the cylinder will travel no longer than t days to be pumped up by the well. The pumping rate of the well is Q [ft^3/day], the areal recharge rate due to precipitation is N [ft/day], and the aquifer porosity is n [-]. Water balance for the period t yields:

$$N\pi R^2 t + n\pi R^2 H = Q\,t \tag{1}$$

The first term represents the inflow due to aquifer recharge, the second term represents the amount of water contained inside the cylindrical aquifer, and the term on the right-hand side is the total amount of water removed by the well. The radius R follows from (1) as:

$$R = \sqrt{\frac{Q\,t}{N\pi t + n\pi H}} \tag{2}$$

When t becomes infinitely large the radius R represents the entire capture zone:

$$R = \lim_{t\to\infty} \sqrt{\frac{Q\,t}{N\pi t + n\pi H}} = \sqrt{\frac{Q}{\pi N}} \tag{3}$$

If, on the other hand, t is relatively small the recharge term in (1) and (2) may be ignored:

$$R \approx \sqrt{\frac{Q\,t}{n\pi H}} \tag{4}$$

Equation (4) represents an overestimation of the radius R for the isochrone, which is conservative for the purpose of wellhead protection. The advantage of this simplification is that no determination of (local) recharge is required; a parameter that is often difficult to obtain.

Limitations

As mentioned, these equations only apply if the Dupuit–Forchheimer assumption applies. If the isochrone radius is smaller than say twice the saturated aquifer thickness, and the well is partially penetrating, the Dupuit–Forchheimer approximation does lead to an underestimation of the isochrone. This unsafe result may be avoided by replacing the saturated thickness H in (4) by the *length of the well screen*.

The radially symmetric isochrone will only occur in the absence of ambient flow. If the well dominates the flow in its proximity the circular isochrone, which for t is 1 or 2 years is relatively close to the well, may be an acceptable approximation of the actual isochrone. However, a low capacity well in a strong ambient flow field will exhibit elongated isochrones which extend in one direction well beyond the circular representation of that isochrone. Under these circumstances the direction and magnitude of the ambient flow must be determined and isochrones should be constructed using the solution for a well in a uniform flow field, for instance by use of WHPA.

The isochrone calculations, whether with or without ambient flow, are based on average aquifer properties. In reality, an aquifer is often stratified exhibiting different layers with different hydraulic conductivities and porosities. Depending on the layer in which microbiological contaminants are being transported, they may travel faster or slower than average aquifer properties dictate. This may lead to substantial reductions in the time of travel, perhaps of several factors. In unconfined aquifers the saturated thickness H is not constant, but declines near the well due to the cone of depression surrounding the well. This too leads to a (moderate) decrease in travel time. On the other hand, the isochrones also don't include the delay of transport in the unsaturated zone (vadose zone), nor does it include any retardation effects. The latter two would cause an increase of the total time of travel. During the deliberations in Irvine, these complications have been consciously left out in order to arrive at a simple and straight forward calculation of a contributing area that requires extra protection (preferably no microbiological sources).

Research Needs

It was apparent from the discussions at the workshop that little is known about the transport of microbiological contaminants (viruses). Their adsorption characteristics to aquifer material may differ from the frequently used equilibrium sorption for chemical contaminants. The deactivation rate for viruses in the saturated zone is also crucial for developing meaningful rules, yet is insufficiently known. The above presented simple time of travel capture zone analysis, therefore, is merely a crude attempt at providing a scientific background for drinking water disinfection rules. The crude approach is somewhat consistent with our current knowledge, but acceptable only as a temporary measure; providing protection until more is known. Research is needed in the field, in the lab, and on the computer (*models*) in order to acquire this knowledge.