CONSIDERATIONS FOR PROTECTING PRIVATE WATER SUPPLY WELLS IN RURAL UNSEWERED SUBDIVISIONS

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Unsewered subdivision communities in areas with highly permeable soils are at risk from groundwater pollution by nitrate-N and other contaminants. Because of the high soil permeability, water for drinking is often obtained from shallow private wells that are screened near the water table. This situation is common at subdivisions in the Central Wisconsin sand plain, where well-water nitrate-N concentrations as high as 20 mg/L are common. Factors which increase potential groundwater contamination by nitrate-N include: closely spaced homes, each with a septic tank-drainfield; N sources (such as fertilized agricultural land) up-gradient of the subdivision; a well-aerated unsaturated zone ideal for nitrification; low soil cation exchange capacity with little fixation capacity for ammonium-N; and a low soil moisture holding capacity resulting in overfilling of the root zone and leaching of N due to moderate rainfall events or over-watering of lawns.

Potential contamination of a water supply well by effluent originating from a septic tank-drainfield can be minimized by excluding the drainfield from the area associated with the well capture zone. This paper will describe a computer model designed to estimate lateral and vertical separation distances necessary to prevent contamination of a well by a nearby septic tank-drainfield. Conditions necessary to apply the model to an actual situation are discussed. The factors discussed will also be of general interest for protecting water supply wells in unsewered subdivisions.

MODEL DESCRIPTION

Separation Distance Computer Model

Figure 1 illustrates the concept of the safe lateral (X-Y) separation distances, (SXSD and SYSD), and the safe well depth (SWD) as determined by the computer model. In the horizontal plane the area A-A'-B'-B (shaded) defines the well protection area (WPA). In theory the up-gradient end of the WPA (A-B) extends indefinitely in the negative x direction. In practice, A-B may be the up-gradient end of the lot or subdivision. Note also, that the width of the WPA is 2SYSD. This method provides detailed information on specific areas of a lot allowing one to judge where a septic tank-drainfield should be placed. Variations of this approach for protecting water-supply wells from contaminant sources (U.S. EPA 1987), and specifically from septic systems (Kerfoot 1987), have also been proposed.

The separation distances and well depth are determined by means of a flow-pathline analysis. The model is capable of handling three-dimensional, transient flow in an unconfined, homogeneous, anisotropic aquifer of infinite areal extent, under a regional horizontal hydraulic gradient. Vertical hydraulic gradients due to aquifer recharge resulting from rainfall and contaminant spreading due to hydrodynamic dispersion are ignored. Harmsen et al. (1991a) describe the model in detail. Results from simulations comparing the model with other numerical and analytical solutions show good agreement.

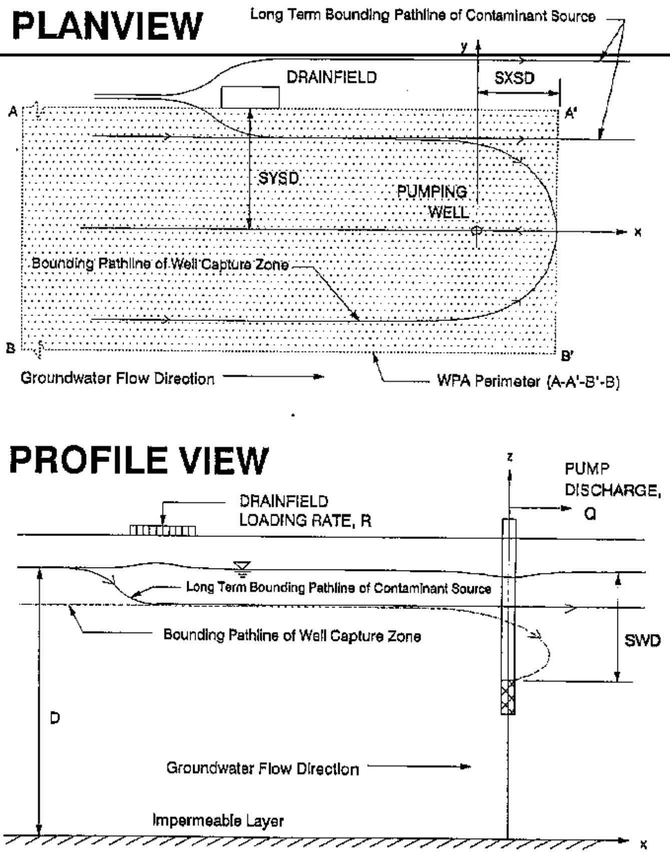

Fig. 1 The Safe X and Y Separation Distances (SXSD, SYSD), Well Protection Area (WPA) (planview, top) and Safe Well Depth (SWD) (profile view, bottom).

Using the model, a large number of Monte-Carlo simulations were performed to estimate mean and standard deviations of the lateral separation distances and safe well depth. The range of conditions simulated represented those found in the Central Wisconsin sand plain (Table 1). A sensitivity analysis revealed that the separation distances and minimum well depth are most sensitive to variations in the horizontal hydraulic conductivity, anisotropy ratio and horizontal regional hydraulic gradient.

As examples of results from the Monte-Carlo analysis, the simulated mean safe Y separation distance (SYSD) and safe well depth (SWD), are shown as functions of the pumping duration and daily pumping volume in Fig. 2. The upper range of values chosen for daily pumping volume are typical for homes in the Central Wisconsin sand plain with in-ground lawn sprinkler systems. As a worst case scenario, it was assumed that the wells used for the sprinkler systems were

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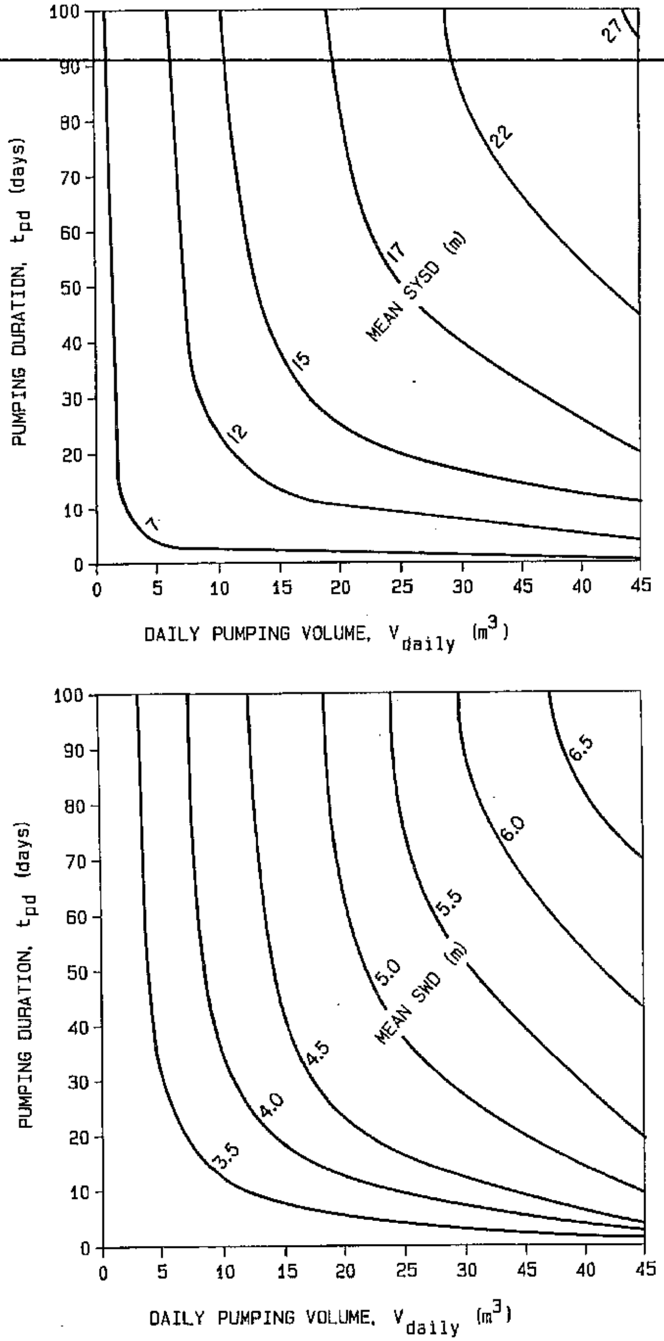

Fig. 2 The Mean SYSD and SWD with Pumping Duration and Daily Pumping Volume.

also used for drinking purposes. The maximum pumping duration is approximately the maximum length of time that lawn watering is practiced in Central Wisconsin (June-August). Details of the Monte-Carlo simulations, additional contour diagrams giving the associated standard deviations and a practical design example for a hypothetical subdivision in Central Wisconsin are given by Harmsen et al. (1991b).

Table 1. Range of Randomized Variables Used in Monte-Carlo Simulations.

RANDOMIZED VARIABLE	MINIMUM	MAXIMUM	MEAN	DISTRIBUTION
Horizontal Conductivity (m/d)	9.0	182.0	49.4	lognormal
Anisotropy	1.0	8.2	3.4	lognormal
Effective Porosity	0.38	0.15	0.24	lognormal
Regional Hydraulic Gradient	0.0009	0.006	0.0025	lognormal
Aquifer Thickness (m)	7.5	60.0	34.0	normal
Drainfield Recharge Rate (m^3/d)	0.5	1.3	0.9	normal
Drainfield Width (m)	1.4	7.4	4.4	normal
Drainfield Length (m)	7.6	17.4	13.0	normal

FACTORS AFFECTING WATER SUPPLY WELL PROTECTION

Direction of Groundwater Flow

Knowledge of the groundwater flow direction beneath the subdivision is essential for properly placing a septic tank-drainfield with respect to a well (or vice versa) to avoid well water contamination. In many cases, available water table elevation maps are inadequate at the subdivision scale. Therefore, a number of water table piezometers should be installed around the subdivision to determine the direction(s) of the local flow system. Harmsen (1989) found that four piezometers placed on corners of two subdivisions studied in Central Wisconsin were not adequate to determine the groundwater flow direction at some of the homes within the subdivisions. Therefore, the groundwater monitoring system should consist of piezometers placed within the subdivision as well as on the subdivision perimeter. The exact number of piezometers required will depend on the complexity of the groundwater flow field.

If the assumed flow direction is incorrect, then using the safe Y separation distance (SYSD) cannot be expected to provide supply-well protection. However, by also using the estimated safe well depth (SWD), the importance of groundwater flow direction is reduced, since the SWD analysis assumes the drainfield is located on the well centerline, directly up-gradient.

Vertical Hydraulic Gradients

An attempt should be made to determine the subdivision position within the regional groundwater flow system. Estimation of the design safe well depth by the model is based on the assumption of regional horizontal flow. If the subdivision is in a recharge area, vertical flow may render the design safe well depth inadequate. In some cases it is difficult to determine whether a particular area is a recharge, discharge or transitional area. At the two Wisconsin subdivisions Harmsen (1989) reported downward hydraulic gradients near the water table. These hydraulic gradients, however, disappeared within 2 m of the water table. In this situation it may be possible to use the estimated safe well depth, but to add to it the distance over which the downward gradients occur.

Stratigraphy

The stratigraphy at the subdivision should be determined. Geophysical techniques (e.g. ground penetrating radar) may be an economical way to determine the gross variations in aquifer stratigraphy. If significant variations are observed (e.g. layers of contrasting particle size), the estimated lateral separation distances and well depth should be used with caution. If, for example, a highly permeable gravel layer exists at some depth below the water table, the septic tank-drainfield plume may move preferentially downward and into the gravel layer. At the Jordan Acres subdivision in Central Wisconsin sand plain, Harmsen (1989) observed the vertical bifurcation of a nitrate-N plume, which may have been caused by a slight variation in the aquifer sand fraction.

Background Nitrate-N Concentration

The groundwater, background nitrate-N concentration at the up-gradient end of the subdivision should be determined. If the subdivision is located in the lower half of the groundwater basin and there is significant agricultural activity up-gradient, then the background nitrate-N concentrations may be elevated and concentrations may increase with depth below the subdivision. An example of this was observed at the Village Green subdivision in Central Wisconsin (Harmsen 1989). Figure 3 shows the average groundwater nitrate-N concentrations with depth and distance from the up-gradient end of the subdivision. If nitrate-N concentrations increase with depth the estimated safe well depth should not be used since the model is based on the assumption that water quality improves with depth. In this case, nitrate-N concentrations will probably be elevated near the water table as well, due to nitrate-N from septic tank-drainfields and lawn fertilizer, and a safe well depth may not exist. In this case an alternative source of water may be required.

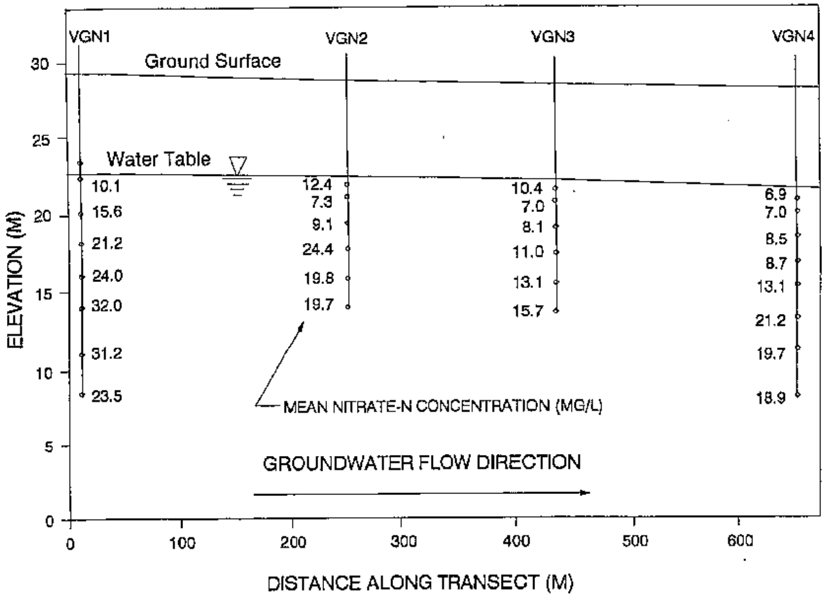

Fig. 3 Nitrate-N Concentrations from Village Green Subdivision Multilevel Sampling Wells. Concentrations are Averages of 7 or 8 Samplings During June 1987 to October, 1988.

During a homeowner survey at the Village Green subdivision it was learned that the home where multilevel groundwater sampling well VGN3 was located (Fig. 3), operated a child daycare center. Due to the commercial activity the State of Wisconsin required that their water-supply well be driven deeper than the wells at the surrounding homes. The nitrate-N concentration from the water-supply well obtained in June of 1987 was 17.5 mg/l. By treating the well-water with a home water treatment system the daycare operator was able to reduce the nitrate-N concentration to under 10 mg/l. This situation illustrates the need to consider the vertical distribution of the groundwater nitrate-N concentration when choosing the depth of a water-supply well.

Nitrate-N from Lawn Fertilizers

Leaching of nitrate-N to groundwater from fertilized turfgrass has been shown to be highly influenced by soil texture, nitrogen source, rate and timing, and irrigation/rainfall (Petrovic 1990). From a summary of eleven turfgrass studies Petrovic (1990) reported leaching percentages ranging from 0 to 54.6%. Owing to the large sand fraction in the soils and number of in-ground lawn sprinkler systems in the subdivisions in Central Wisconsin, conditions were favorable for nitrogen leaching.

The computer model does not account for leaching from fertilizer N. Harmsen et al. (1991a) recommended using the mean safe well depth plus two standard deviations as a factor of safety. Because this depth is conservative, leached fertilizer N will usually not be a problem.

Multiple Nitrate-N Sources.

Nitrate-N plumes originating from septic systems may remain relatively intact over distances of tens or even hundreds of meters. Figure 4 shows the spatial distribution of groundwater nitrate-N approximately 100 m down-gradient from the Village Green subdivision. Note that the cross-section is oriented normal to the direction of groundwater flow. In one case at this same subdivision, a 35 mg/L concentration change was observed between a sampling port at the water table and one 0.75 m below it. The sharp concentration contrasts observed in the vertical and horizontal direction suggest that mixing owing to hydrodynamic dispersion was limited. Others who have studied groundwater contamination from septic systems, under similar conditions, have reported

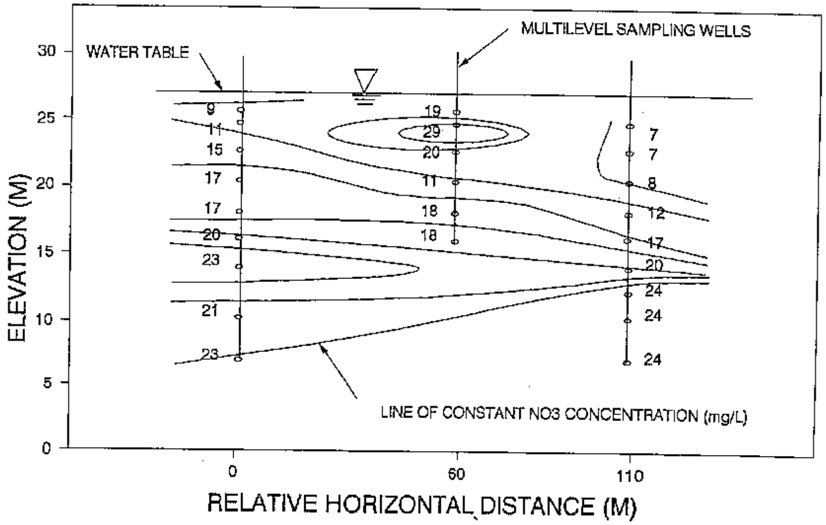

Fig. 4 Village Green Subdivision Down-Gradient Nitrate-N Distribution on August 8, 1989 (after Shaw, 1989). The Groundwater Flow is Normal to the Cross-Section.

similar results (Childs et al. 1974, Rea and Upchurch 1980, Robertson et al. 1989).

The implication of these findings is that wells located on down-gradient lots may become contaminated by septic systems which are located a significant distance up-gradient. Therefore, it may be possible and advisable to site the supply-well with these up-gradient drainfields in mind (or vice versa). In practice this involves extending the effective well protection area (WPA) (A-A'-B-B', Fig. 1) beyond the up-gradient edge of the lot, perhaps to the up-gradient end of the subdivision, and then maintaining it free of septic tank-drainfields.

Well Depth and Position within the Subdivision

Due to the effect of cumulative nitrate-N loading along the groundwater flow path the down-gradient end of the subdivision will usually be of poorer water quality than will be the up-gradient end. As an example, Table 2 presents the average, groundwater nitrate-N concentation with distance from the up-gradient end of the Jordan Acres subdivision. Note that this was not the case at the Village Green subdivision (Fig. 3) where the background concentrations at the up-gradient end of the subdivision were high. However, if background concentrations are low, such as at the Jordan Acres subdivision, concentrations at the down-gradient end of the subdivision will likely be elevated. In theory, the longer the subdivision (parallel with the groundwater flowpath) the higher will be the down-gradient concentration. Two practical implications arise: (1) that the estimated SWD may become invalid near the down-gradient end of the subdivision and (2) that for the subdivision, some "critical" length may exist, measured from the up-gradient end, beyond which the groundwater nitrate-N concentration will exceed some amount (e.g., 10 mg/L). The critical subdivision length (CSL) may be important in some cases and could influence the plans for development for future growth of the subdivision (e.g. expanding the subdivision in the direction normal to the flowpath instead of parallel with it).

Table 2. Depth and Time Averaged Nitrate-N Concentrations with Distance from Up-Gradient End of Jordan Acres Subdivision (Harmsen 1989).

Distance from Up-Gradient End of Subdivision (m)	Concentration (mg/L)
0	3.9
240	2.2
350	2.1
460	5.0
525	8.0

Concentration Fluctuations with Time

Because of varying conditions at the subdivision (e.g., N loading, groundwater recharge, and fluctuations in the water table) groundwater nitrate-N concentrations in the subdivision may vary greatly with time. At several of the wells at the Jordan Acres and Village Green subdivisions changes in concentration were significant, for example, varying between 1 and 22 mg/L during the one year sample period. These variations will tend to be greatest near the water table so well screens should be well below the water table provided the deeper groundwater quality is acceptable.

SUMMARY AND CONCLUSION

A model was described for estimating safe lateral and vertical separation distance for a water-supply well and a septic tank-drainfield. Water resource agencies and developers may find the model useful for planning and design.

Emphasis was placed on performing a field investigation to determine the direction of groundwater flow, the presence of vertical hydraulic gradients, aquifer heterogeneities, the background nitrate-N concentration and the general distribution of nitrate-N beneath the subdivision. Other relevant factors included the location of the well in the subdivision (i.e., distance from the up-gradient end), N from lawn fertilizer and the fluctuation of nitrate-N concentrations with time.

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