PROCEEDINGS

of the 13th Annual

WATER RESOURCES SYMPOSIUM

Water Quality and Its Effect on Human and Biological Health

June 3-5, 1992
Turkey Run State Park
Marshall, Indiana

Edited By

Glenn Hodgkins

DEVELOPING AN EFFECTIVE GROUNDWATER MONITORING SYSTEM FOR DETECTING RELEASES FROM WASTE DISPOSAL FACILITIES

by

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ABSTRACT

An important part of the siting and design of solid or hazardous waste storage facilities is the development of an appropriate groundwater monitoring system to detect possible contaminant releases if they should occur. The selection of the number of wells and their placement to accomplish detection has, in general, been based on a considerable amount of professional judgment on the part of the hydrogeologist or engineer given adequate knowledge of the site geology, groundwater flow directions, and waste disposal area configuration. Regulatory guidelines have also depended on somewhat arbitrary rules of thumb for evaluating well spacing and placement. This paper attempts to outline a simple methodology that allows for a more quantitative assessment of the adequacy of a proposed system. Site specific factors considered include: groundwater flow directions, hydraulic gradients, soil and rock stratigraphy, geometric orientation of the waste disposal area, and distances between the assumed release location and the point of monitoring compliance. In addition, a two-dimensional analytical contaminant transport modeling solution is used to incorporate these site specific factors into conservative release scenarios that ultimately control the effective monitoring well spacing (EMWS) required for detection. Recommendations are given to suggest a regulatory framework for evaluating proposed monitoring systems based on the direction of groundwater flow in relationship to the waste boundary, the areal size and concentration of the assumed potential release source, well offset distance from the waste boundary, and the time period of post-closure monitoring.

INTRODUCTION

Current regulations for both existing and proposed solid and hazardous waste storage facilities specify the general requirements for groundwater monitoring systems (40 CFR 264.97, 40 CFR 265.91, 329 IAC 2-16-1). The general regulatory purpose is to allow for the detection of contamination when hazardous waste or hazardous constituents have migrated from the waste disposal (management) area to the uppermost aquifer. Whether a particular monitoring system has been designed to effectively accomplish this purpose has, for the most part, been left to the judgment of state and federal regulators during their technical review of such facilities.

Unfortunately, because the regulations have not been specific enough in their description of what level of releases should be detected and what is a suitable time frame for detection, monitoring well system evaluations have often relied on rules of thumb and experience with existing facility well networks to evaluate the appropriate number and placement of wells.

To develop a methodology for aiding in a more quantitative assessment of the adequacy of a well system, several specific questions can be asked:

(1) How should monitoring well spacing be measured with respect to the contaminant transport direction?

(2) What is the assumed mechanism for contaminant release?

(3) What is the size, concentration and location of contaminant release that the monitoring well system will be designed to detect?

(4) What level of contamination is allowed to move beyond the point of compliance monitoring before the monitoring well network detects a release?

(5) What size and concentration of a contaminant release will be detected with a specific well spacing?

(6) Will a contaminant release of a specific size, concentration, and location be detected within the post-closure monitoring period?

If all the answers to the above questions can be answered for a specific waste disposal facility, then the answer to the ultimate question "Is the monitoring well system suitable for the detection of releases?" can be provided with a higher degree of confidence then is currently the case. The following sections address several of these questions and provide a framework with which to better evaluate existing or proposed systems.

GROUNDWATER FLOW DIRECTION AND WASTE BOUNDARY ORIENTATION

In order to detect possible contaminant releases from a waste facility, the direction of groundwater flow beneath the site needs to be assessed. Initially, a set of piezometers are installed and screened in the uppermost aquifer and the potentiometric surface determined by taking groundwater level measurements in the wells. Figure 1 illustrates four basic conditions that may be encountered once the potentiometric surface is determined. In Figure 1a, the most simple case, the potentiometric lines are parallel to each other and to two sides of the waste boundary. This represents a site with a uniform flow direction. Only one side (right) of the waste boundary is considered downgradient and would require monitoring. Figure 1b represents a case of uniform groundwater flow direction with the potentiometric lines again parallel to each other. However, they are now oriented at an angle to the waste boundaries. Two sides are considered downgradient (right and bottom) and must be monitored to detect potential contaminant releases.

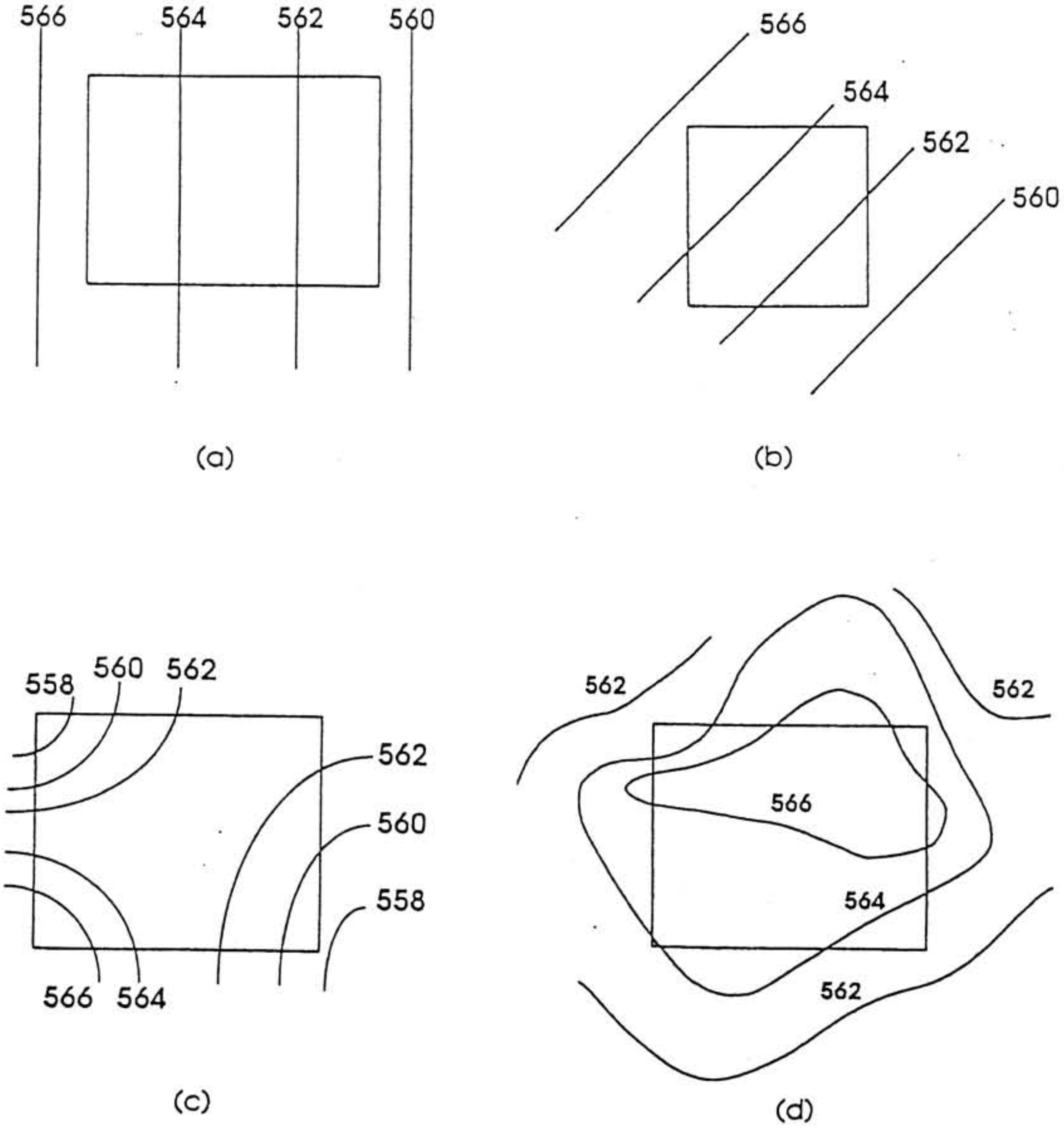

Figure 1. Groundwater Flow Direction and Waste Boundary Orientation

More complex groundwater conditions are shown in Figures 1c and 1d. In Figure 1c, groundwater flow moves from the upgradient corner (bottom left) outward and downgradient through some portion of all four waste boundaries. A monitoring well network would need to be placed along a large portion of the entire site for adequate coverage. A site with no apparent upgradient monitoring position is shown in Figure 1d. The potentiometric high occurs within the waste disposal area, and the full extent of the waste boundary is downgradient and must be included in the monitoring plan.

From these simple illustrations, it is apparent that the relationship of groundwater flow direction to waste boundary orientation determines the general well locations and degree of monitoring that may be necessary to assure adequate detection.

EFFECTIVE MONITORING WELL SPACING (EMWS)

Critical areas for modeling analyses are those downgradient regions where groundwater flow is at a significant angle to the waste boundary. These areas represent locations in which the "effective monitoring well spacing" (EMWS) is the greatest. The EMWS is defined herein as the straight line distance between groundwater flowlines that pass through adjacent monitoring wells (see definition in Figure 2). For example, if the groundwater flow direction is perpendicular to a line segment connecting two adjacent monitoring wells (e.g. the right waste boundary in Figure 1a), the EMWS is the straight line segment distance, L, between the wells. If, however, groundwater flows at some angle, β, to the straight line segment between the wells (e.g. the bottom and right waste boundaries in Figure 1b), the EMWS is equal to L sin β, which is less than the straight line segment distance L. In cases where the groundwater flows parallel to the straight-line connecting the monitoring wells, the EMWS is zero. Under these conditions, a contaminant release detected by the upgradient-most well would also be detected by the other well. For this reason, there are many instances in which wells along a waste boundary having the greatest straight line distance between them actually have the smallest EMWSs.

In assessing an existing monitoring well network at a waste disposal facility, the EMWSs would need to be evaluated along all downgradient waste boundaries. Areas that had the largest EMWSs would be the least likely to detect a potential contaminant release, and would therefore be the most critical to evaluate.

CONTAMINANT RELEASE SCENARIOS

For a monitoring well network to be designed to detect releases, the possible size, location, and severity of the release must be postulated. Two possible release scenarios are considered that would result in very conservative results: release of unattenuated contaminants through an unknown and unsealed abandoned borehole from the base of the waste area through the existing intact natural barrier confining soils to the uppermost aquifer; release of unattenuated contaminants through a small (e.g. 50 ft wide) source area resulting from the failure of the waste disposal cell base due to excavation heave. Both of these release scenarios are assumed to occur very near the actual deposited waste area inside of the designated or regulatory defined waste disposal boundary. Release from this location results in a more rapid and direct pathway away

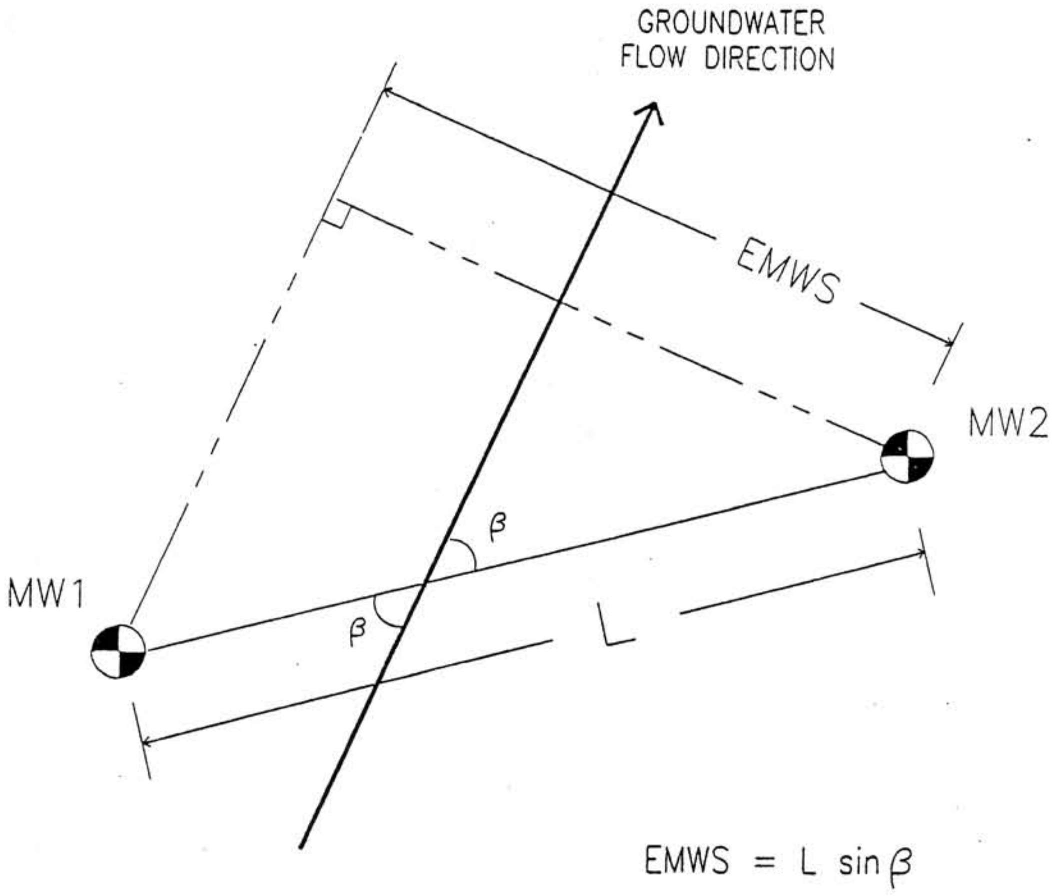

Figure 2. Definition of the Effective Monitoring Well Spacing (EMWS)

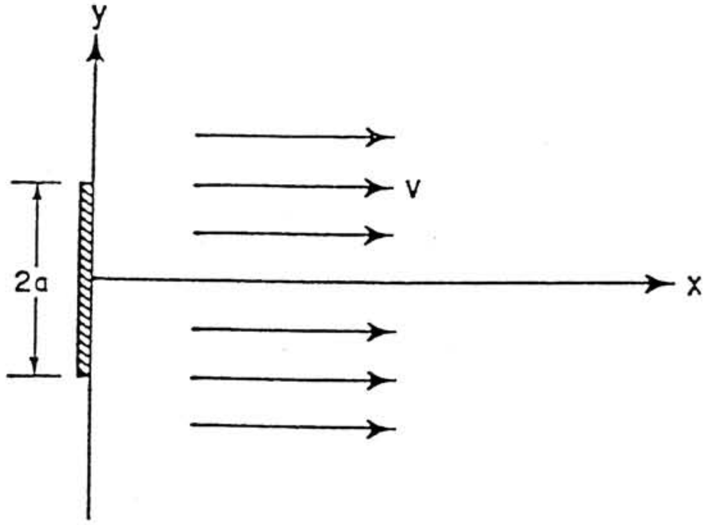

Figure 3. Two-Dimensional Plane Dispersion of a Strip Source with Unidirectional Steady State Flow (After Javandel et. al. 1984)

from the disposal area without the benefit of excessive hydrodynamic dispersion that would aid plume detection through the enlargement of the contaminated area.

CONTAMINANT TRANSPORT MODELING

As a conservative evaluation of the two worst case scenarios (unsealed borehole point source and small source area) determined, a two-dimensional plane dispersion analytical analysis of contaminant transport was performed using the solution published by Cleary and Ungs (1978) for two-dimensional advection-dispersion. The solution assumes a homogeneous, isotropic porous medium having a unidirectional steady state flow with constant seepage velocity. Further, it assumes that initially the porous medium is free of a particular solute species and at a certain time, a strip source orthogonal to the groundwater flow direction is introduced (see Figure 3).

A more comprehensive approach using a numerical model (e.g. Konikow and Bredehoeft, 1978) to model additional complexity and allow for the assumption of a specific injection rate of contamination into the uppermost aquifer based on the vertical hydraulic gradient and the hydraulic conductivity of the failure pathway between the waste cell base and the uppermost aquifer could have been used as well. However, the analytical solution selected herein does not allow for the specification of the injection rate of the contaminant but rather assumes the contaminant is a constant source existing within the uppermost aquifer. This simpler approach removes the influences of the injection rate on the plume dispersion behavior and eliminates radial flow away from the source caused by localized increases in the groundwater potentiometric surface. Therefore, this approach should be more conservative than the more complex simulation approach.

If a Cartesian coordinate system is introduced with the x axis oriented along the direction of flow (see Figure 3), υ representing the seepage velocity, the coefficients, D_L and D_T, defined as the longitudinal and transverse dispersion coefficients, respectively, and C defined as the concentration of the solute, then the two-dimensional advection-dispersion equation can be written as:

$$D_L \frac{\partial^2 C}{\partial x^2} + D_T \frac{\partial^2 C}{\partial y^2} - \upsilon \frac{\partial C}{\partial x} - \lambda R C = R \frac{\partial C}{\partial t} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

For the general case in which the source of contamination is a strip of length *2a* that may diminish with time, the initial and boundary conditions of this mathematical model may be written as:

$$\begin{array}{ll} C(0,\ y,\ t) = C_o e^{-\alpha t} & -a \le y \le a \\ C(0,\ y,\ t) = 0 & \textit{other values of } y \end{array} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

$$\lim_{y\to\pm\infty} \frac{\partial C}{\partial y} = 0 \quad \ldots \quad (3)$$

$$\lim_{x\to\infty} \frac{\partial C}{\partial x} = 0 \quad \ldots \quad (4)$$

An analytical solution (Cleary and Ungs, 1978) to equations (1) to (4) is:

$$(C(x,\ y,\ t) = \frac{C_o x}{4(\pi D_L)^{1/2}} \exp\left(\frac{vx}{2D_L} - \alpha t\right)$$

$$\cdot \int_0^{t/R} \exp\left[-\left(\lambda R - \alpha R + \frac{v^2}{4D_L}\right)\tau - \frac{x^2}{4D_L \tau}\right] \tau^{-3/2}$$

$$\cdot\left[erf\left(\frac{a - y}{2(D_T \tau)^{1/2}}\right) + erf\left(\frac{a + y}{2(D_T \tau)^{1/2}}\right)\right] d\tau \quad \ldots \quad (5)$$

The computer program TDAST (Two-Dimensional Analytical Solute Transport) (Version 1.1, 11/88) described by Javandel et al (1984) and included in the American Geophysical Union AGU-10 Groundwater Package distributed by the International Groundwater Modeling Center (IGWMC) in Golden, Colorado, was used to generate the solutions. The program calculates the non-dimensional ratio of the contaminant concentration to the constant source concentration, C/C_o, for any selected downgradient point at any given time.

Input parameters to TDAST for these simulations (required in metric units) include:

Longitudinal dispersion coefficient (D_L): 0.40 m^2/d
Transverse dispersion coefficient (D_T): 0.040 m^2/d
Pore Water Velocity (υ): 1.30×10^{-2} m/d
Half length of source (a): 0.15, 7.6 m
Radioactive decay factor (λ): 0 d^{-1}
Retardation factor (R): 1
Decay factor of the source (α): 0 d^{-1}

For the simulations included in this study, it has been assumed that the input source concentration of the release remains constant ($\alpha = 0$) throughout the simulation period and the contaminants are transported conservatively (i.e unretarded) and do not undergo any significant decay ($\lambda = 0$). The contaminant source release is assumed to occur 100 ft (30.5 m) inside the waste storage area boundary. This is a reasonable worst case assumption since the actual extent of waste deposition occurs within the formally defined waste boundary. In addition, the monitoring boundary (i.e. point of compliance) of the waste facility is assumed to be at 50 ft (15.2 m) from the waste boundary, making the total distance between the source release and the monitoring point 150 ft (45.7 m). It is further assumed that the source release occurs at the closure of the facility, and the post-closure monitoring period is 30 years.

Simulations were performed to determine the source release concentrations detected by monitoring wells spaced at varying EMWSs at selected time intervals. For both the point and small area source release scenarios, the assumed detection limit was 5 parts per billion (ppb) since many volatile organic constituents are a concern at this level. Plume centerline concentrations were also determined at the monitoring boundary at the time when contamination is first detected at the monitoring well locations. Finally, the source concentrations required for the arrival of a 5 ppb concentration level at the monitoring boundary at various times was determined. These results are summarized in the following sections.

Point Source Release

Results of the simulations for the hypothetical abandoned, unplugged borehole release scenario are shown in Figures 4, 5, and 8. From Figure 4, it is evident that for the conditions of the simulation, effective monitoring well spacings (EMWSs) of less than 250 ft should be able to detect a moderate source concentration release of up to 10,000 ppb within a 30 year post-closure monitoring period. Areas with EMWSs of between 250 and 500 ft should be able to detect significant source releases of up to 100,000 ppb within the 30 year period.

It should be noted from Figure 4 that smaller EMWSs are required if releases of the same magnitudes are desired to be detected at times earlier than the 30 year post-closure period. This is also evident in Figure 5, which shows that plume centerline concentrations beyond the compliance boundary will exceed 100 ppb for EMWSs of less than 250 ft, and increase up to 10,000 ppb for EMWSs of 250 to 500 ft prior to detection after a 30 year release period. EMWSs will need to be less to detect releases within shorter time periods for plume centerline concentrations at the compliance boundary of an equivalent level.

From Figure 8 for the assumed site conditions and point source release conditions, source concentrations must exceed 500 ppb in order to have a greater than 5 ppb contaminant concentration beyond the compliance boundary within a 30 year post-closure monitoring period. This represents a concentration of the contaminant of only about 1 percent of the original source concentration at the compliance boundary after 30 years. In general, the simulations support the conclusion that point source releases from random locations far inside of the waste storage area would not easily be detected within a 30 year time frame.

Small Source Area Release

Results of simulations for contaminant release near the waste boundary from a small source area (50 ft width) are presented in Figures 6, 7, and 8.

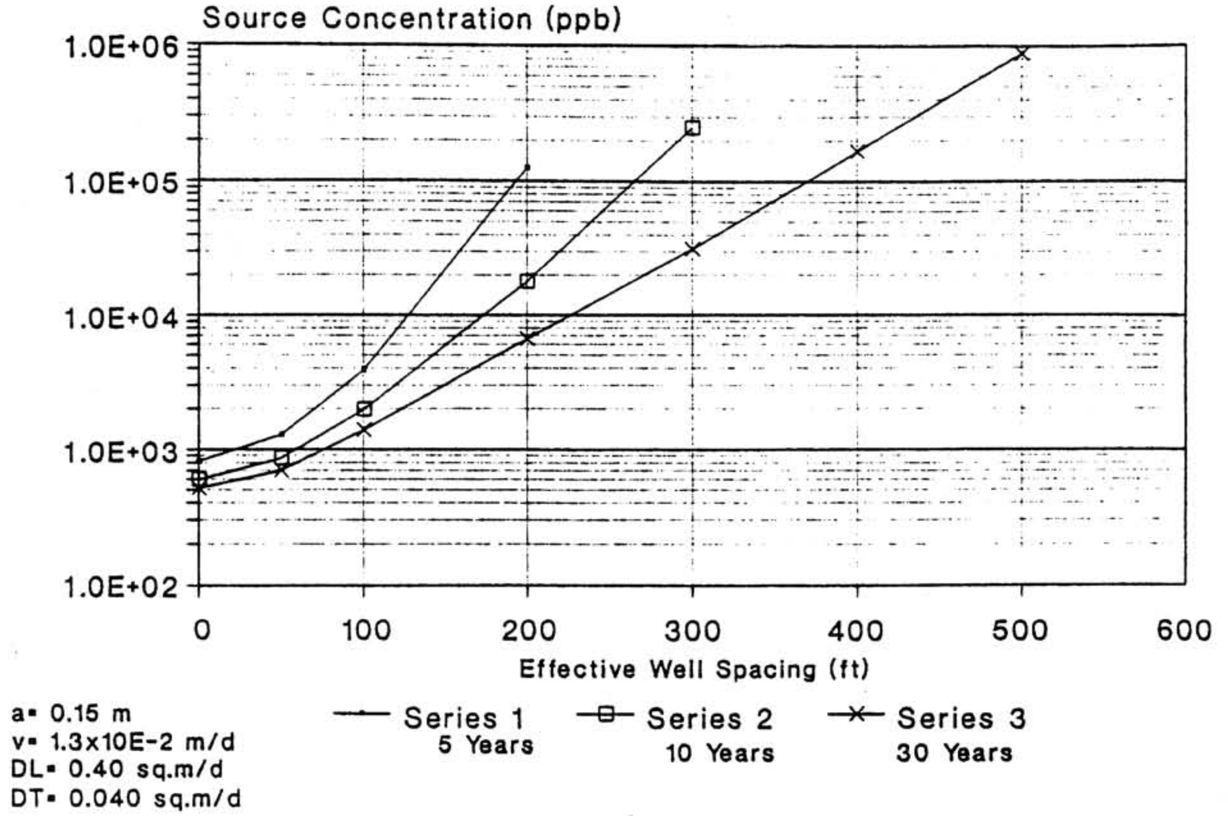

Figure 4. Point Source Area - Effective Monitoring Well Spacing Required for Source Concentration Detection

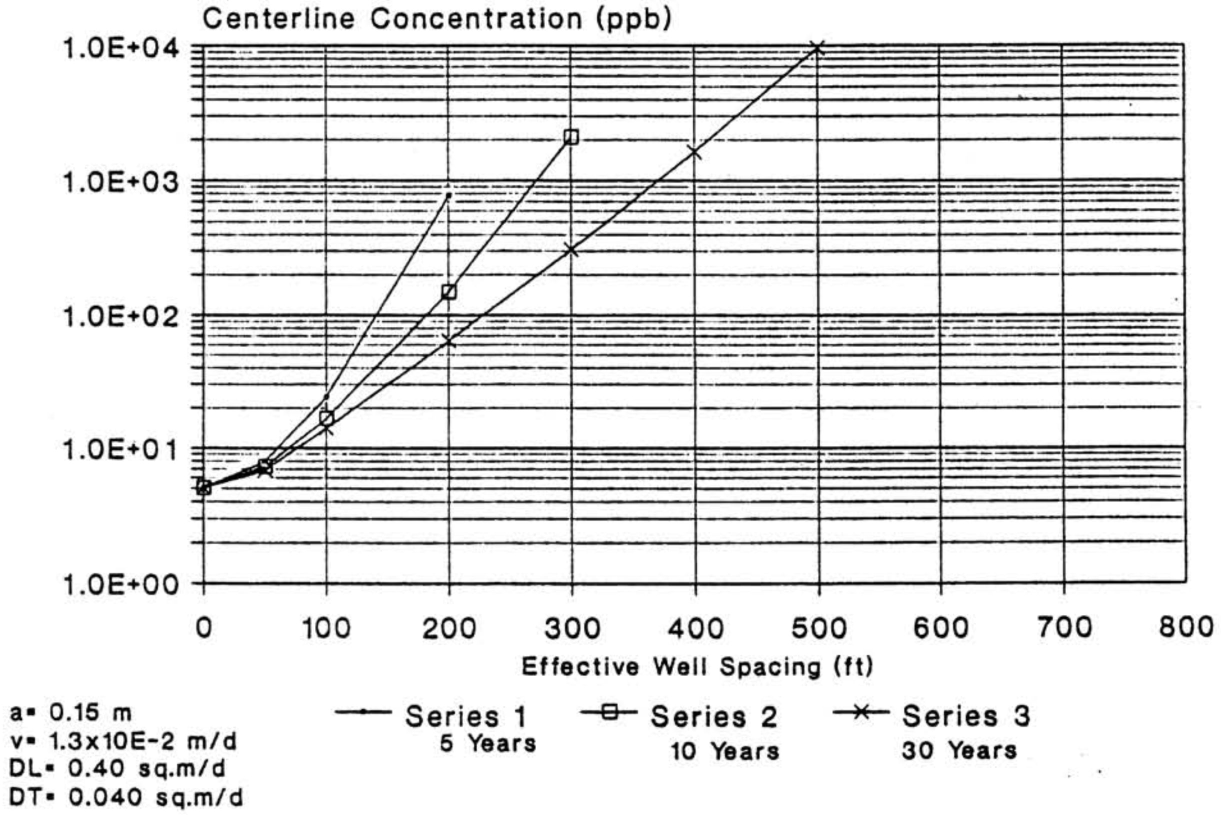

Figure 5. Point Source Area - Plume Centerline Concentration at the Compliance Boundary When Contaminant Detected

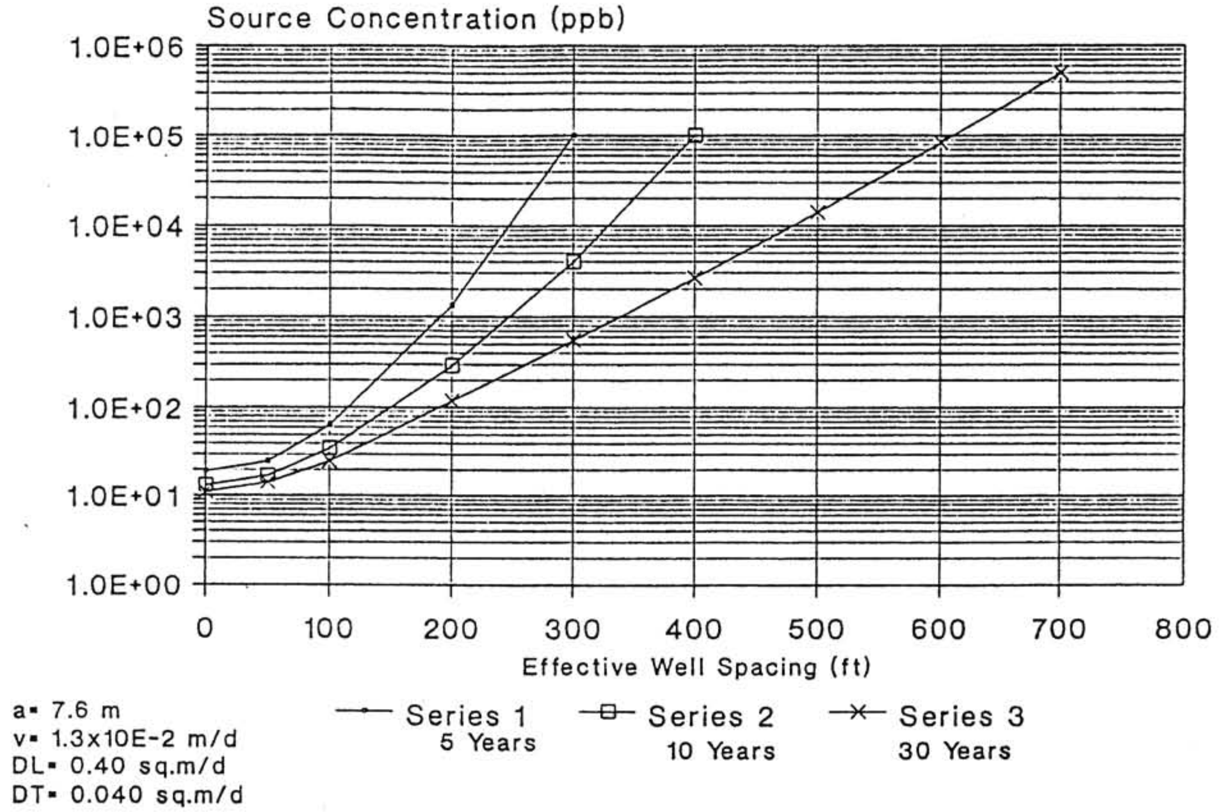

Figure 6. Small Source Area - Effective Monitoring Well Spacing Required for Source Concentration Detection

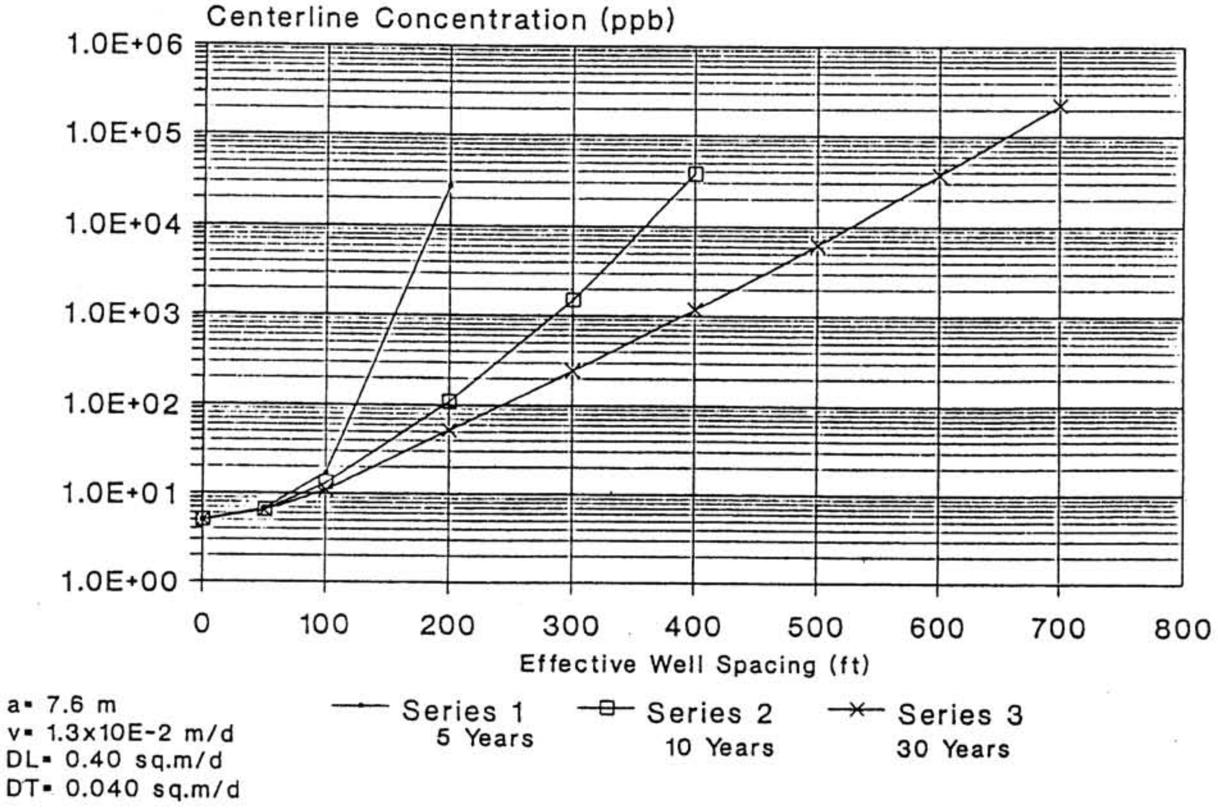

Figure 7. Small Source Area - Plume Centerline Concentration at the Compliance Boundary When Contaminant Detected

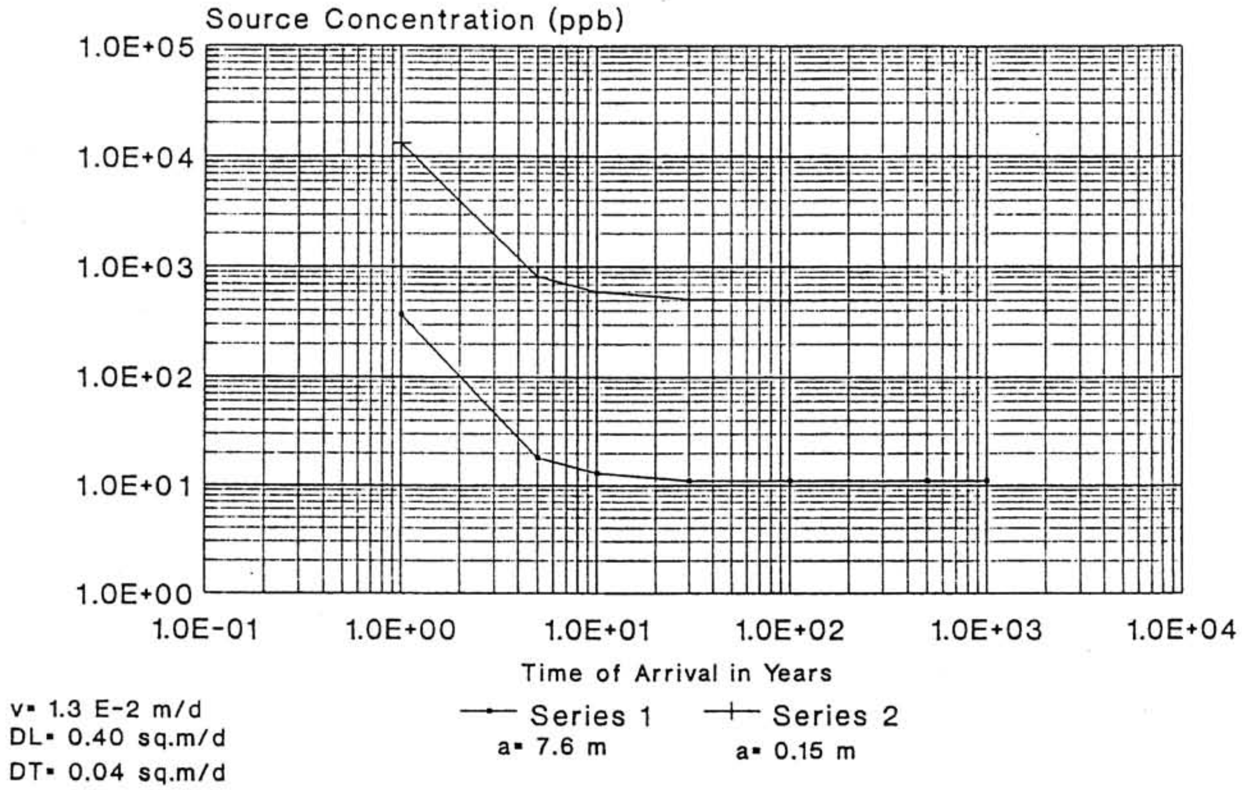

Figure 8. Source Concentration Versus Time of Arrival of 5 ppb at Compliance Boundary

As seen in Figure 6, the detection of low contaminant source release concentrations (between 100 to 1,000 ppb) within a 30 year monitoring period is accomplished with an effective monitoring well spacing of about 200 to 350 ft. Moderate (1,000 to 10,000 ppb) and high (10,000 to 100,000) source concentration releases can be detected within 30 years with EMWSs ranges of about 350 to 500 ft and 500 ft to 600 ft, respectively.

Figure 7 shows that detection of contaminants at wells with EMWS values less than 300 ft will occur when plume centerline compliance boundary concentrations reach about 250 ppb. For wells with EMWSs of 300 to 500 ft, compliance boundary plume centerline levels of about 250 to 6,000 ppb will occur when detection occurs in the wells.

Again, as suggested in the point source simulation results, smaller EMWSs will be required to detect equivalent source release concentrations in a time less than the 30 year post-closure period. Furthermore, higher plume concentrations must have moved beyond the monitoring boundary if detection at earlier times is desired for the same EMWS.

In general, source concentrations must exceed about 11 ppb to result in contaminant levels above 5 ppb at the plume centerline compliance boundary within a 30 year period for the assumed site conditions (Figure 8).

CONCLUSIONS

A general methodology has been presented for aiding the evaluation of the adequacy of groundwater monitoring systems for detecting releases from waste disposal sites. The methodology uses the concept of the effective monitoring well spacing (EMWS) with conservative contaminant release scenarios and analytical transport modeling to determine if a specific EMWS will detect a release of a given size and concentration located near the waste disposal boundary. As expected, the results of this conservative approach indicated that a closer effective well spacing would be required to detect releases from the constant point source (unplugged borehole) than for the constant small source area (50 ft width base heaving failure). However, the concentration levels observed at the compliance boundary for equivalent source concentrations were much less for the point source than for the small source area.

If a constant point source release (via an unplugged borehole scenario) or a constant small area release (via a heaving failure of a waste cell base) occurs near the waste boundary under a set of assumed site conditions, the speed at which it is detected, and whether it is detected at all within a 30 year post-closure time period, will depend on the level of the release source concentration and the effective monitoring well spacing (EMWS) in the vicinity of the release.

The results of this study suggest that the regulatory concept of "immediate detection" may be incompatible with the purpose of "detection" for specific monitoring well spacings. Wells placed close to the waste disposal boundary for "immediate detection" purposes may be able to immediately detect gross, large scale contamination while missing significant contamination from smaller release areas. Well placement at greater distances from the waste boundary allows for greater well spacing for achieving detection, albeit at the cost of immediacy. A better regulatory approach may be to require a hybrid well system in which some wells will be used as "immediate detection" wells for gross contamination and others placed at greater distances from the waste boundary to act as "detection" wells for smaller release areas.

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