POOR LEGIBILITY

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DUE TO THE QUALITY OF THE ORIGINAL
Mr. Walter Hoye  
Engineer of Design  
Los Angeles Dept. of Water and Power  
P.O. Box 111  
Los Angeles, California 90051  

Dear Mr. Hoye,

As promised at our meeting of June 28, 1987, enclosed are technical comments concerning the San Fernando Valley Operable Unit Feasibility Study (OUFS). I hope that the comments prove useful. Let me emphasize that the simulations should not be construed as a design for the extraction well field; my intent is to demonstrate the data requirements and well field geometry necessary to capture the maximum volume of contaminant at the minimum pumping rate.

If I can be of additional assistance, if you would like printouts of data files used in our simulations or if you would like to discuss findings from your aquifer evaluation program please call me at (415) 974-0826.

Sincerely,

Michael W. Dale  
Michael Dale, Hydrologist  
Policy, Standards and Technology Section  
Drinking Water Branch  
Water Management Division

Enclosure

cc: Art Van Orden  
Patti Cleary  
Wanda Smith
Figure 3  Outline Of TCE Plume Superimposed Upon The Eight Well Capture Zone.
Capture-Zone Type Curves: A Tool for Aquifer Cleanup

Iraj Javandel and Chin-Fu Tsang

Earth Sciences Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

ABSTRACT

Currently a common method of aquifer cleanup is to extract the polluted ground water and, after reducing the concentration of contaminants in the water below a certain level, the treated water is either injected back into the aquifer, or if it is environmentally and economically feasible, released to a surface water body. The proper design of such an operation is very important both economically and environmentally. In this paper a method is developed which can assist in the determination of the optimum number of pumping wells, their rates of discharge and locations, such that further degradation of the aquifer is avoided. The complex potential theory has been used to derive the equations for the streamlines separating the capture zone of one, two or more pumping wells from the rest of the aquifer. A series of capture-zone type curves are presented which can be used as tools for the design of aquifer cleanup projects. The use of these type curves is shown by an hypothetical field case example.
INTRODUCTION

A recent publication by the Environmental Protection Agency (EPA, 1984) refers to the location of 786 hazardous waste sites, out of which 538 had met the criteria for inclusion in the National Priorities List (NPL) and another 248 sites had been proposed for addition to the NPL. The NPL identifies the targets for long-term action under the "Superfund" law (CERCLA, 1980). This list has been continuously growing since October 1981 when EPA first published an interim priority list of 115 sites. In addition, as of October 1984, EPA has inventoried more than 19,000 uncontrolled hazardous waste sites. The ground water beneath many of these sites is contaminated with various chemicals. Based on the Sec. 104(a)(1) of CERCLA the EPA has the primary responsibility for managing remedial actions at these sites unless it is determined that such actions will be done properly by the owner or operator of the facility, or by any other responsible party.

Once a plume of contaminants has been identified in an aquifer and it has been established that remedial action should be undertaken, the major task for the person in charge is to determine which remedial alternative is cost-effective. This is required by Sec. 105(7) of CERCLA (1980) and Sec. 300.66(J) of the National Contingency Plan (1983). One alternative for remedial action is aquifer cleanup.

Currently a common method of aquifer cleanup is to extract the polluted ground water and, after reducing the concentration of contaminants in the water to a certain level, the treated water is either reinjected into the aquifer, or, if it is permitted and feasible, it is released to a surface water body.

Given a contaminant plume in the ground water and its extent and concentration distribution, and, further assuming the source of contamination has been eliminated, one has to choose the least expensive alternative for capturing the plume. Major questions to be answered for the design of such projects include the following:

1. What is the optimum number of pumping wells required?
2. Where to site the wells such that no contaminated water can escape between the pumping wells?

3. What is the optimum pumping rate for each well?

4. What is the optimum water treatment method?

5. Where should one reinject the treated water back into the aquifer?

The purpose of this paper is to introduce a simple method for answering four of the above questions which are of hydraulic nature.

First, we shall develop the theory and give a series of sample type curves which can be used as tools for aquifer restoration. Then, the procedure for application of the curves will be given in answering the above questions.

**THEORY**

Consider a homogeneous and isotropic aquifer with a uniform thickness $B$. A uniform and steady regional flow with a darcy velocity $U$ is parallel to and in the direction of the negative $x$-axis. Let us propose that a series of $n$ pumping wells penetrating the full thickness of the aquifer and located on the $y$-axis are used for extracting the contaminated water. For $n$ greater than one we want to find the maximum distance between any two wells such that no flow is permitted from the interval between the wells. Once such distances are determined we are interested in separating the capture zone of those wells from the rest of the aquifer. We shall start with $n=1$ and expand the theory for larger values of $n$. Following development is based on the application of the complex potential theory (Milne-Thomson, 1968).

Case 1, $n=1$. In this case for the sake of simplicity and without losing the generality, we shall assume that the pumping well is located at the origin of the coordinate system. The equation of the dividing streamlines which separate the capture zone of this well from the rest of the aquifer is

$$
y = \pm \frac{Q}{2BU} - \frac{Q}{2\pi BU} \tan^{-1} \frac{y}{z}
$$

(1)
noonoo?

where

\[ B = \text{aquifer thickness (m)} \]
\[ Q = \text{well discharge rate (m}^2/\text{sec}) \]
\[ U = \text{regional flow velocity (m/see)} \]

One may note that the only parameter in equation (1) is the ratio \( Q/BU \) which has the dimension of length (m). Figure 1 illustrates a set of type curves for five values of parameter \( Q/BU \). For each value of \( Q/BU \), all the water particles within the corresponding type curve will eventually go to the pumping well. Figure 2 illustrates the paths of some of the water particles within the capture zone with \( Q/BU = 2000 \), leading to the pumping well located at the origin. The intersection of each of the curves shown in Figure 1 and the x-axis is the position of the stagnation point whose distance from the well is equal to \( Q/2\pi BU \). In fact equation (1) may be written in nondimensional form as

\[ \gamma_D = \pm \frac{1}{2} - \frac{1}{2\pi} \tan^{-1} \frac{y_D}{x_D} \]

where

\[ y_D = BUy/Q, \text{ dimensionless} \]
\[ x_D = BUx/Q, \text{ dimensionless} \]

Figure 3 shows the nondimensional form of the capture-zone type curve for a single pumping well.

Case 2, \( n=2 \). Here, we shall consider two pumping wells located on the y-axis, each at a distance \( d \) from the origin. Each well is being pumped at a constant rate \( Q \). The complex potential representing the combination of flow toward these two wells and the uniform regional flow is given by

\[ W = Ux + \frac{Q}{2\pi B} \ln \left| \frac{x-id}{x+id} \right| + C \]

where \( r \) is a complex variable which is defined as \( x + iy \) and \( i = \sqrt{-1} \).
Fig. 1. A set of type curves showing the capture zones of a single pumping well located at the origin, for various values of \((Q/BU)\).
Fig. 2. The paths of some water particles, within the capture zone with \((Q/BU) = 2000\), leading to the pumping well located at the point \((0,0)\).
Fig. 3. Nondimensional form of the capture-zone type curve for a single pumping well.
The velocity potential $\phi$ and stream function $\psi$ for such flow system are the real and imaginary parts of $W$ in equation (3) which can be written as

$$\phi = Ux + \frac{Q}{4\pi B} \left( \ln |x^2 + (y-d)^2| + \ln |x^2 + (y+d)^2| \right) + C$$

$$\psi = Uy + \frac{Q}{2\pi B} \left( \tan^{-1} \frac{y-d}{x} + \tan^{-1} \frac{y+d}{x} \right)$$

In general, when the distance between two wells is too large for a given discharge rate $Q$, a stagnation point will be formed, behind each pumping well. In this case some fluid particles are able to escape from the interval between the two wells. When the distance between these two wells is reduced while keeping $Q$ constant, eventually a position will be reached where only one stagnation point will appear and that would be on the negative x-axis. In this case no fluid particles can escape from the space between the two wells. If we keep reducing the distance between the two wells, again two stagnation points will appear on the negative x-axis, one moving toward the origin and the other away from it and still no fluid particles could escape from the space between the wells. The following derivation gives the reason for such behavior.

To find the position of the stagnation points one must set the derivative of $W$ to zero:

$$\frac{dW}{dz} = U + \frac{Q}{2\pi B} \left( \frac{1}{x-id} + \frac{1}{x+id} \right) = 0$$

The roots of equation (6) are given by

$$z = \frac{1}{2} \left( \frac{-\frac{Q}{\pi BU} \pm \sqrt{\frac{Q^2}{(\pi BU)^2} - 4d^2}}{2} \right)$$

When $2d > \frac{Q}{\pi BU}$, that is the distance between the two wells is larger than $\frac{Q}{\pi BU}$, equation (7) would give two complex roots. Each of these roots corresponds to the position of a stagnation point behind each pumping well. The coordinates of these two stagnation points are

$$\left\{ -\frac{Q}{2\pi BU} \cdot \frac{1}{2} \sqrt{4d^2 - \frac{Q^2}{(\pi BU)^2}} \right\}$$
and

\[ \left\{ -\frac{Q}{2\pi BU}, -\frac{1}{2}\sqrt{4d^2 - \frac{Q^2}{(\pi BU)^2}} \right\} \]

Note that only when \( 2d > \frac{Q}{\pi BU} \) the coordinates of these two stagnation points become approximately \( (-\frac{Q}{2\pi BU}, d) \) and \( (-\frac{Q}{2\pi BU}, -d) \). When \( 2d > \frac{Q}{\pi BU} \), contaminated water can escape from the space between the two pumping wells; the larger the distance the more fluid will escape.

It is apparent from equation (7) that if the distance between the two wells \( 2d \) is equal to \( \frac{Q}{\pi BU} \), then both roots of equation (6) are equal and real such that

\[ \xi_1 = \xi_2 = \frac{Q}{2\pi BU} \]  

(8)

In this case we shall have one stagnation point on the negative x-axis whose distance from the origin is \( \frac{Q}{2\pi BU} \). Under this condition no flow can pass between the two pumping wells.

Finally, if \( 2d < \frac{Q}{\pi BU} \) equation (6) would yield two real roots. The coordinates of the two stagnation points corresponding to these two roots are

\[ \left\{ -\frac{Q}{2\pi BU} + \frac{1}{2}\sqrt{\frac{Q^2}{(\pi BU)^2} - 4d^2}, 0 \right\} \]

and

\[ \left\{ -\frac{Q}{2\pi BU} - \frac{1}{2}\sqrt{\frac{Q^2}{(\pi BU)^2} - 4d^2}, 0 \right\} \]

Obviously, when \( 2d \) becomes smaller and smaller one of these points tends to the origin and the other one tends to the point with coordinates \( (-\frac{Q}{\pi BU}, 0) \). When \( 2d < \frac{Q}{\pi BU} \), no flow can pass between the two pumping wells. Therefore, it is established that the condition for preventing the escape of contaminated fluid between two pumping wells separated by a distance \( 2d \) is

\[ 2d \leq \frac{Q}{\pi BU} \]  

(9)
The optimum condition is achieved at the limit when \( 2t = Q / \pi BU \) and the distance of the stagnation point from the origin is \((Q / 2\pi BU)\). The equation of the streamlines passing through this stagnation point is

\[
y + \frac{Q}{2\pi BU} \left( \tan^{-1} \frac{x-d}{z} + \tan^{-1} \frac{x+d}{z} \right) = \pm \frac{Q}{BU} \quad (10)
\]

One may note that again the only parameter in equation (10) is \((Q / BU)\). Figure 4 shows the plot of a pair of these streamlines for \((Q / BU) = 800\); some useful distances on this figure are also identified. Figure 5 gives a set of type curves illustrating the capture zones for two pumping wells and for several values of parameter \((Q / BU)\). One may note that equation (10) can also be written in nondimensional form as

\[
y_D + \frac{1}{2x} \left( \tan^{-1} \frac{y_D - (1/2x)}{x_D} + \tan^{-1} \frac{y_D + (1/2x)}{x_D} \right) = \pm 1 \quad (11)
\]

where

\[
y_D = BUy / Q, \text{ dimensionless}
\]

\[
x_D = BUx / Q, \text{ dimensionless}
\]

Case 3, \( n = 3 \). In this case we shall consider three pumping wells, one at the origin and two on the y-axis at (0,d) and (0,-d). The regional flow, as before, has a velocity of \( U \) and is parallel to and in the direction of the negative x-axis. The complex potential representing flow toward these three wells and the uniform regional flow is given by

\[
W = Us + \frac{Q}{2\pi B} \left( \ln x + \ln (x-id) + \ln (x+id) \right) + C \quad (12)
\]

The velocity potential \( \phi \) and the stream function \( \psi \) for this flow system are given by

\[
\phi = Ux + \frac{Q}{4\pi B} \left\{ \ln (z^2+y^2) + \ln [x^2+(y-d)^2] + \ln [x^2+(y+d)^2] \right\} + C \quad (13)
\]

\[
\psi = Uy + \frac{Q}{2\pi B} \left( \tan^{-1} \frac{y}{x} - \tan^{-1} \frac{x-d}{x} - \tan^{-1} \frac{x+d}{x} \right) \quad (14)
\]
Fig. 4. Capture zone of two pumping wells properly located to prevent any leakage from the space between the two wells.
Fig. 5. A set of type curves showing the capture zones of two pumping wells located on the y-axis for various values of $(Q/BU)$. 
Here also, when \( d \) is large, fluid will escape between the wells and three stagnation points will be formed, one behind each well. Keeping the rate of discharge of each well constant and reducing the distance between each pair of wells, eventually a position will appear where no flow will pass in between the wells.

Again, to find the position of the stagnation points one must set the derivative of \( W \) in equation (12) equal to zero:

\[
\frac{dW}{dz} = U + \frac{Q}{2\pi B} \left( \frac{1}{z} + \frac{1}{z-id} + \frac{1}{z+id} \right) = 0.
\]  

Equation (15) may be written as

\[
x^4 - \frac{3x^2}{A} + d^2x - \frac{d^2}{A} = 0
\]  

where \( A = -(2\pi BU)/Q \). The discriminant of equation (16) may be written as

\[
D = d^2 \left( \frac{d^4}{27} - \frac{d^2}{3A^2} + \frac{1}{A^4} \right)
\]  

It can be easily shown that \( D \) is positive, except for the limiting case when \( d = 0 \). In that case \( D \) vanishes, too. As a result, when \( d \neq 0 \) equation (16) has one real root and two other roots which are complex conjugates of each other.

When \( d \gg Q/2\pi BU \) we obtain three stagnation points located at

\[
z_1 : (-\frac{Q}{2\pi BU}, 0), z_2 : (-\frac{Q}{2\pi BU}, d), z_3 : (-\frac{Q}{2\pi BU}, -d)
\]

When \( d \) becomes smaller and smaller, that is, the distance between the wells decreases, the stagnation point on the \( x \)-axis moves away from the origin and the other two tend to come closer to the \( y \)-axis while approaching the \( x \)-axis. Such that for \( d = (2^{4}\sqrt{2}) Q/2\pi BU \) the position of stagnation points are

\[
z_1 : \left[ -1.54 \frac{Q}{2\pi BU}, 0 \right], z_2 : \left[ -0.73 \frac{Q}{2\pi BU}, 1.9 \frac{Q}{2\pi BU} \right], z_3 : \left[ -0.73 \frac{Q}{2\pi BU}, -1.9 \frac{Q}{2\pi BU} \right]
\]
The value of \( d = \left( 2^{\frac{n}{2}} \right) \frac{Q}{2xBU} \) is the maximum distance between two pumping wells where no fluid could escape between the wells. One may note that this distance is approximately 1.2 times the optimum distance between two wells for the case of \( n = 2 \).

Eventually, when \( d \) becomes zero, that is, when the outer two wells coincide with the middle one, three roots of equation (16) correspond to one stagnation point on the negative x-axis with a distance of \( 3Q / 2xBU \) from the origin and the other two collapse at the origin. At the optimum condition, the equation for the streamlines passing through the stagnation point on the negative x-axis becomes

\[
y + \frac{Q}{2xBU} \left( \tan^{-1} \frac{x}{z} + \tan^{-1} \frac{x - d}{z} + \tan^{-1} \frac{x + d}{z} \right) = \pm \frac{3Q}{2BU} \tag{18}
\]

where \( d = \frac{n^{\frac{n}{2}}}{2} \frac{Q}{(xBU)} \). Since \( d \) is only a function of \((Q/BU)\), it is apparent that once again equation (18) is dependent on one parameter \((Q/BU)\). Figure 6 shows a set of type curves illustrating the capture zones for three pumping wells located on the y-axis for several values of parameter \((Q/BU)\). Note that one of the pumping wells is located at the origin and the other two are on the positive and negative y-axis with a distance of \( \sqrt{2} \frac{Q}{xBU} \) from the origin.

Here, also one can write equation (18) in a nondimensional form as

\[
y_D + \frac{1}{2x} \left( \tan^{-1} \frac{y_D}{x_D} + \tan^{-1} \frac{y_D - \frac{\sqrt{2}}{x}}{x_D} + \tan^{-1} \frac{y_D + \frac{\sqrt{2}}{x}}{x_D} \right) = \pm \frac{3}{2} \tag{19}
\]

where \( x_D \) and \( y_D \) are dimensionless coordinates as defined before.

General Case. We shall now attempt to extend the solution for a larger number of pumping wells. Table 1 shows some characteristic distances for the cases that we have already discussed. There are two generalizations that one can infer from Table 1. (a) The distance between dividing streamlines far upstream from the wells is equal to \((nQ/BU)\) and it is twice the distance between these streamlines at the line of wells. (b) The equation of the dividing streamlines for the case of \( n \) pumping wells can be written down by comparing the corresponding equations for 1, 2, and 3
Fig. 6. A set of type curves showing the capture zones of three wells all located on the y-axis for various values of (Q/BU).
<table>
<thead>
<tr>
<th>Number of pumping wells</th>
<th>Optimum distance between each pair of pumping wells</th>
<th>Distance between dividing streamlines at the line of wells</th>
<th>Distance between streamlines far upstream from the wells</th>
</tr>
</thead>
<tbody>
<tr>
<td>one</td>
<td>-</td>
<td>$\frac{Q}{2BU}$</td>
<td>$\frac{Q}{BU}$</td>
</tr>
<tr>
<td>two</td>
<td>$\frac{Q}{\pi BU}$</td>
<td>$\frac{Q}{BU}$</td>
<td>$\frac{2Q}{BU}$</td>
</tr>
<tr>
<td>three</td>
<td>$\frac{\sqrt{2} Q}{\pi BU}$</td>
<td>$\frac{3Q}{2BU}$</td>
<td>$\frac{3Q}{BU}$</td>
</tr>
</tbody>
</table>
pumping wells:

\[ y + \frac{Q}{2\pi BU} \left\{ \tan^{-1} \frac{y-y_1}{x} + \tan^{-1} \frac{y-y_2}{x} + \ldots + \tan^{-1} \frac{y-y_n}{x} \right\} = \pm \frac{nQ}{2BU} \]  

(20)

where \( y_1, y_2, \ldots, y_n \) are y-coordinate of pumping wells 1, 2, \ldots, and n.

Finding the optimum distance between two adjacent pumping wells when \( n \) gets larger than four becomes quite cumbersome. Our investigation indicates that for the case of four pumping wells the optimum distance between two adjacent pumping wells is approximately \( \frac{Q}{2BU} \), which is about the same as for the case of three pumping wells. Figure 7 shows a set of type curves for the case of four pumping wells for several values of parameter \( \frac{Q}{BU} \). Note that two of the wells are on the positive and the other two are on the negative y-axis. The distance between each pair of wells depends on the type curve (i.e., \( \frac{Q}{BU} \) value) chosen. Once the type curve is selected the optimum distance between each pair is \( d = \frac{1.2 Q}{2BU} \).

APPLICATION

As was discussed earlier, presently a common method of aquifer cleanup is extracting the polluted ground water, removing from it the contaminants, and disposing or reinjecting the treated water. Naturally the cost of such operation is a function of the extent of cleanup. However the important point is that once the maximum allowable contaminant level of certain chemicals is given, the cleanup process should be designed such that

(a) The cost is minimum,

(b) The maximum concentration of a contaminant in the aquifer at the end of the operation does not exceed a given value, and

(c) The operation time is minimized.
To insure that the above conditions are satisfied one has to find the answer to those questions which were posed in the Introduction.

The exact solution to this problem could be quite complex and site specific. However, the following procedure, which is very simple to apply, could be quite a useful tool for many cases and could avoid the type of errors which are quite common in practice.

The criteria which we want to follow is that, to the extent which is possible, only those particles of contaminated water which are within the specified concentration contour line should fall in the captured zone of the pumping wells.

Suppose a plume of contaminants has been identified in an aquifer, the concentration distribution of certain chemicals has been determined, and the direction and magnitude of the regional flow field is known. Furthermore, assume that the sources of contamination have been removed. The last assumption is not a requirement for this technique, however, it is logical to remove the sources of contamination, if they are still active, before proceeding for cleanup. The following procedure leads to answers to the above questions.

1. Prepare a map using the same scale as the type curves given earlier in this paper. This map should indicate the direction of the regional flow at the site. Furthermore, the contour of the maximum allowable concentration in the aquifer of a given contaminant should also be indicated (from here on it will be called the contour line of the plume).

2. Superimpose this map on the set of type curves for one pumping well given in Figure 1. Make sure that the direction of the regional flow on the map matches the one in Figure 1. Move the contour line of the plume toward the tip of the capture curve and read the value of Q/BU from the particular curve which completely encompasses the contour line of the plume.

3. Calculate the value of Q by multiplying (Q/BU) obtained in step 2 by (BU) the product of the aquifer thickness, B, and the magnitude of regional velocity U.
4. If the well is able to produce the required discharge rate \( Q \), obtained in step 3 we have reached the answer. That is, one is the optimum number of pumping wells. Its optimum location is copied directly from the position of the well on the type curves to the contour map at the matching position.

5. If the well is not able to produce at such a rate then one has to follow the above procedure using the type curves for two pumping wells given in Figure 5. After identifying the appropriate type curve and calculating the rate of discharge for each well, one has to investigate the capability of the aquifer to deliver such discharges to both pumping wells. An important point to note is that because the zones of influence of two wells have some overlap, one may not be able to pump the same amount of flow rate from each individual well as one could from a single well, for the same allowable drawdown.

If the aquifer is capable of delivering such flow rates to both pumping wells, then the optimum number of pumping wells is two and their position can be traced directly from the type curves at the matching position. Note that the exact distance between each pair of wells depends on the choice of the type curve and should be calculated from the equations given before. However, if the aquifer is not able to deliver that rate of discharge required for each well, then one has to use the type curves for three-well case as given in Figure 6. This procedure could be carried out until the optimum number of wells are found.

If one decides to reinject the treated water back to the aquifer, then one strategy could be to do this at the upper end of the plume. This would substantially shorten the total cleanup time of the aquifer.

To find the appropriate location for the reinjection well(s) one can use the same technique which we introduced for siting the extraction wells, neglecting the interference between the recharge and extraction wells. Here, one should match the contour line of the plume with the type curves in a way that the direction of regional flow on the contour map becomes parallel and
opposite to the direction of regional flow on the type curves. By so doing, we ensure that all the particles of the injected water stay within the present position of the contour line of the plume and force the contaminated water toward the extraction wells. The only shortcoming of this technique is that a small volume of the contaminated water currently located at the tail of the plume will fall within a zone of relatively very small velocity and may stay there for a long time. This can also be overcome by moving the recharge well(s) upstream as much as half of the distance between the calculated location and the tail of the plume.

**EXAMPLE**

This example is designed to illustrate the use of this technique for aquifer cleanup. It is assumed that leakage from a faulty injection well has contaminated a confined aquifer with trichloroethylene (TCE). A thorough investigation of the site has identified the TCE concentration distribution as given in Figure 8. Hydrologic studies have revealed the following data:

- Aquifer thickness: 10 m
- Regional hydraulic gradient: 0.002
- Aquifer hydraulic conductivity: \(10^{-4}\) m/s
- Effective porosity: 0.2
- Storage coefficient: \(3 \times 10^{-5}\)
- Permissible drawdown at each well: 7 m

Suppose we are interested to clean the aquifer such that maximum remaining TCE concentration after the cleanup operation does not exceed 10 ppb. To optimize the aquifer cleanup operation cost we want to minimize the cost of pumping the contaminated water and treating it at the surface. Reinjection of the treated water is an option which should not be ignored.

The first step is to choose the optimum number of pumping wells, their location, and calculate their rate of discharge. To find the answer to these questions we followed the procedure given above. Figure 8 includes the contour line of 10 ppb. The area within this curve identifies
Fig. 8. Observed TCE concentration distribution.
the zone where the TCE concentration is above 10 ppb that should be captured and treated. Direction of the regional flow is also shown in this figure. The scale of this map is identical to that of Figure 1. Superposition of this map on Figure 1 and matching the direction of flow, indicates that the size of the area within the 10 ppb contour is larger than all of the type curves presented in Figure 1. Although one could easily prepare other type curves with larger values of (Q/BU), extrapolation suggests that a type curve with Q/BU = 2500 will encompass the 10 ppb contour line. Now we should first calculate the regional velocity U:

\[ U = K_i = (10^{-4} \text{ m/s})(0.002) = 2.0 \times 10^{-7} \text{ m/sec} \]  

Therefore, the corresponding discharge rate of the well is

\[ Q = (\frac{Q}{BU}) BU = (2500 \text{ m})(10 \text{ m})(2 \times 10^{-7} \text{ m/sec}) = 5 \times 10^{-4} \text{ m}^3/\text{sec} \]  

Since cleanup operation usually lasts for several years, corresponding drawdown at the well bore may be calculated using either equilibrium or nonequilibrium equation for large values of time such as a year or so:

\[ \Delta h = \frac{2.3Q}{4\pi KB} \log \frac{2.25Kt}{r_w^2S} \]  

where

- \( \Delta h \) = drawdown in the aquifer (m)
- \( Q \) = pumping rate (m\(^3\)/sec)
- \( K \) = hydraulic conductivity (m/sec)
- \( B \) = aquifer thickness (m)
- \( t \) = time elapsed since the start of pumping (sec)
- \( r_w \) = effective well radius (m)
- \( S \) = storage coefficient

Substituting for variables in equation (23), the value of drawdown after one year and for \( r_w = 0.2 \) m becomes 9.85 m. Note that this calculation gives drawdown only in the aquifer. To obtain
total drawdown in the well one has to add to it the well losses. These losses are a function of the well design and the best way to obtain the total drawdown in a well is to find the specific capacity of the well and its variation with the rate of discharge and time. In the above case, since the drawdown in the well is more than the permissible drawdown, we will have to use more than one pumping well. Thus, we superimpose the 10 ppb contour on the double-well capture zone type curves given in Figure 5. Matching the direction of the regional flow and moving the contour line to the left we see that the capture curve with $Q/BU = 1200$ completely encompasses the 10 ppb contour. The corresponding rate of discharge for each of the two wells now becomes $Q = 0.0024$ m$^3$/sec.

To check the drawdown at each of these two wells, we should add the drawdowns of both wells at the position of each well. The optimum distance between these two wells is obtained from equation (9):

$$2d = \frac{Q}{xBU} = 382m$$

(24)

and drawdown at each of these two wells is obtained from

$$\Delta h = \frac{2.3Q}{4\pi KB} \left\{ \log \frac{2.25KBt}{r_o^2S} + \log \frac{2.25KBt}{(2d)^2S} \right\}$$

(25)

Substituting for $2d$, the drawdown after one year becomes 6.57 m. Generally, the well losses for small discharge rates such as 0.0024 m$^3$/sec are small. However, if the amount of well losses together with the calculated drawdown 6.57 m become larger than the assumed maximum allowable drawdown of 7 meters we have to examine the possibility of using three pumping wells.

Superposition of the 10 ppb contour line with the three-well capture zone type curves (Figure 6) gives a matching parameter of $Q/BU = 800$. Figure 9 shows the 10 ppb contour line of TCE on the three-wells capture zone type curves at the matching position. The area within the contour line has been cross hatched for clarity.

The rate of discharge for each pumping well is

$$Q = 800 \left( 10 \times 2 \times 10^{-7} \right) = 0.0016 \text{ m}^3/\text{sec}$$
Fig. 9. The 10-ppb contour line of TCE at the matching position with the capture-zone type curve of \((Q/BU) = 800\).
Drawdown in the middle well is the sum of the drawdowns of the two lateral wells in that well plus its own drawdown, which amounts to 5.7 m. If we are convinced that the total drawdown is less than 7 m or field tests indicate that, then our optimum number of wells is three and the rate of discharge from each one is 0.0016 m³/sec. One of these wells is on the origin and the other two at (0, ± 320) as shown in Figure 9.
DISCUSSION

The method introduced in this paper is intended to provide guidance to proper siting of extraction wells and to determine their appropriate rates of discharge for cleaning aquifers contaminated with hazardous chemicals. It is important to note that the theory was developed based on the assumption that the aquifer is confined, homogeneous, and isotropic. Obviously for aquifers consisting of impermeable clay lenses and high conducting flow channels, this technique may give erroneous results. For example, in some fluvial aquifers highly permeable channels can easily carry away the contaminants at a much faster rate than the general average regional flow. If the field investigation has clearly identified such a channel system one can easily adapt this method to take it into consideration. However, very often these features can be easily missed during typical site investigations. Therefore, it is recommended that some array of monitoring wells be constructed downstream and beyond the capture zone of the extraction wells. These wells should be continuously monitored during the cleanup operation to insure that such channeling does not exist.

Another point which should be discussed here is the fact that although this technique minimizes the cost of aquifer clean up, it does not necessarily minimise the operation time. Once we choose the minimum pumping rate it takes a long time to extract all of the contaminated ground water. In the example described above the total volume of contaminated water within the 10 ppb contour is about 5.16 million cubic meters (MCM). The rate of discharge from all three wells is 0.0048 m³/sec which is about 414.7 m³/day. Therefore, ignoring biodegradation and adsorption, the total period required to remove 5.16 MCM of contaminated water at the above rate is about 34 years. This is, of course, based on the assumption that no water with concentration below 10 ppb is extracted by the wells. Our investigation using RESSQ (Javandel, et al., 1984) shows that it takes about 48 years to extract the total volume of contaminated water presently located within the 10 ppb contour. This period could be substantially shortened if we reinject the treated water back into the aquifer at an appropriate location upstream from the extraction wells.
To avoid mixing the highly contaminated water with the surrounding water, it is often beneficial to consider one or more extraction wells in the high concentration zone of the plume. The technique described here could be used to site these wells.

Extraction wells are assumed to penetrate and be open over the total thickness of the aquifer. If the wells are partially penetrating the aquifer, the cleanup is rather effective at elevations corresponding to the screened zone and is subject to error in the elevations corresponding to the nonpenetrated zone of the aquifer. In other words contaminants located in the nonpenetrated zone may not be totally captured if the extraction wells are only partially penetrating. Obviously, if the plume is located only at the upper or lower part of the aquifer then partially penetrating extracting wells are beneficial.

The method is based on two-dimensional flow systems which implies that the aquifer is confined. For unconfined aquifers the solution is more complex. However, if the amount of drawdown relative to the total saturated thickness of the aquifer is small, the error is not expected to be large.

**SUMMARY**

Optimum design of cleanup operation for a contaminated aquifer is an important task for the people in charge of such activities as well as for the regulatory agencies responsible for enforcing the requirements set by law and the National Contingency Plan. An important part of such task is capturing the contaminated water and pumping it to surface. Rigorous analytical solutions have been presented which give the position of the stagnation points and optimum distances between pumping wells to avoid any escape of contaminated water between the wells. Equations for the dividing streamlines defining the capture zone of the pumping wells from the rest of the aquifer are also presented. A series of capture-zone type curves for one, two, three and four pumping wells are given. A procedure is recommended to facilitate the selection of the optimum number, location and the discharge rate for the pumping wells. The criteria for such recommendations include minimizing the cost, avoiding further degradation of the water quality beyond the
selected zone, and achieving the goal that the maximum concentration of a contaminant in the aquifer at the end of operation does not exceed a given value. In case that the treated water needs to be returned to the aquifer, a procedure is suggested for siting recharge wells. This is based on the capture-zone technique which avoids mixing of the treated water with the fresh water while reducing the aquifer cleanup time.
EDGEMENT

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Review Comments On Operable Unit Feasibility Study For The
North Hollywood Well Field Area Of The North Hollywood -
Burbank NPL Site, San Fernando Valley Groundwater Basin

Introduction

The Operable Unit Feasibility Study (OUFS) was reviewed
from the perspective of determining an optimum groundwater
pumping system to 1) contain the contaminated body of water
and thereby prevent its spread and 2) pump the maximum volume
at the minimum cost. EPA designed an extraction well field
to compare with the well field suggested in the OUFS with the
method reported by Javendal and Tsang (1986); simulations to
test pumping efficiency and travel time distribution were
run with the computer code RESSQ (American Geophysical Union
Water Resources Monograph #10, 1984). Additional benefits
derived from the simulations include an analysis of the
efficiency of the pumping field proposed in the OUFS and a
suggestion of what data must be collected in greater detail
to assure success of the clean up plan.

Background

Javendal and Tsang (1986, copy of paper attached)
demonstrate that the minimum pumping rate necessary to contain
a contaminant plume is achieved by a line of extraction wells
located normal to the direction of the ambient groundwater
velocity field. They derive type curves to calculate the pumping rate based on the ratio \( Q/vb \), where \( Q \) is the pumping discharge rate, \( b \) is the aquifer thickness and \( v \) is the average velocity of groundwater flow in the aquifer. This is essentially the strength of the sink in the flow field and has dimension of length. The necessary information to accurately apply the type curves is 1) the direction and velocity of ambient groundwater flow, and 2) aquifer thickness. Because the clean up efforts are located in the uppermost, unconfined aquifer of a multiaquifer system, it is important to determine at least the following: 1) saturated thickness of the unconfined aquifer in both lateral and transverse directions and 2) saturated hydraulic conductivity for the unconfined aquifer. Also, it is important to determine the effect of pumping deeper, confined aquifers on the unconfined aquifer. It defeats the clean up effort if pumping the underlying aquifer induces such a leakage rate as to spread the contamination deeper into the system.

Both the type curve approach and RESSQ are rigorously defined only for confined, uniform (isotropic, homogeneous) aquifers. Thus the unconfined aquifer must be pumped at a discharge rate such that the response of the aquifer is reasonably similar the response of a confined aquifer. Bear(1979, *Hydraulics Of Groundwater*) suggests that so long
as the drawdown in the unconfined aquifer is small relative to its saturated thickness, that the Dupruit assumptions can be applied to Darcy's law at the well and drawdown caused by the pumping well can be estimated. If the aquifer is grossly heterogeneous or anisotropic than the velocity must be transformed into a "uniform" coordinate system. This further emphasizes the importance of detailed analysis of the local groundwater velocity.

EPA Analysis

EPA analysis indicates that four extraction wells may be sufficient to contain and extract the plumes. Figure 1 shows a map of the landmarks used for locating wells and the contamination plumes and a local coordinate system. Figure 2 shows the disturbance of the uniform flow field resulting from pumping the 4 EPA wells located just downgradient of the two plumes of contamination. Figure 3 shows the location of the two contaminant plumes of immediate concern and that the four "EPA extraction" wells will capture the plume. The location of each well and the outline of the plumes were taken from the OUFS. The uniform flow field assumes that the angle the velocity vector makes with the horizontal x axis is 315°, the aquifer is 33 m thick and the average groundwater velocity (q/n) is 150 m/yr. Figures 4 through 6 show the sensitivity of varying the direction of velocity vector.
This analysis suggests that the four wells when pumping 33.9 m$^3$/hr (150 gpm) may be adequate to capture the plumes. Figure 7 shows the location and capture zone of the eight LADWP wells (suggested in the OUFS) when pumping m$^3$/hr (250 gpm). Figure 8 shows the movement likely effect of these well on the movement of the contaminant. Assuming the numerical values of the parameters used in the simulations are reasonable, then the EPA wells will capture the plume while pumping approximately 600 gpm. The LADWP wells will result in the extraction of contaminated water but must pump 2000 gpm.

The RESSQ code contains an algorithm to calculate the travel time of a streamline from source until captured by a well. Assuming the numerical values of the parameters are reasonable it will take a maximum of 8.3 years for the last of the contamination to enter the EPA extraction wells. However, if the wells are located as in the OUFS and pumped at a rate of 2000 gpm, it will still take more than 20 years for the last of the contaminant to be captured. Thus pumping (with the proposed well field arrangement) at a greater discharge will not capture more of the plume more quickly, but actually results in mixing a larger volume of uncontaminated water with the contaminated water.

To "speed up" the clean-up process, it is suggested that injection wells be placed up-gradient of the pumping wells and that approximately 250 gpm be returned to the flow
field. The travel time is reduced to approximately 4.5 years

**Summary**

The actual well field design must incorporate site specific data to assure the plan is successful. However, based on simulations combining RESSQ and the type curve approach EPA suggests the following must be accurately known:

1) **Magnitude and direction of the local groundwater flow field.** This includes the rate of leakage between the unconfined aquifer and the underlying confined aquifers. This must be known to quantify the effect of the uniform flow field on the capture zone and to be certain that pumping the deeper aquifers does not induce contaminated water from the upper, contaminated aquifer into the lower, uncontaminated aquifers.

2) **Sustainable yield of the unconfined aquifer and the relative rate of drawdown along the line of extraction wells.** This must be known to plan the pumping rate and to be sure all model simulations are reasonable.

3) **Aquifer thickness and saturated hydraulic conductivity.** Spatial trends should be quantified if at all possible. This must be known to verify a simulation model.

4) **Monitor wells down-gradient of the pumping wells to assure that the minimum rate pumping field captures all the contaminated water.**
Figure 2. Capture Zone For The Four EPA Extraction Wells, Angle Of Velocity Vector Equals 315°.
Figure 1

© Location of LADWP Wells
+ Location of EPA Wells
Figure 4: Capture Zone Created By Four Pumping Wells If The Velocity Vector Is Oriented 300°. Note That All The Contaminant Is Not Captured.
Figure 5 Capture Zone Created By Four Pumping Wells If The Velocity Vector Is Oriented 335°.
Figure 6  Capture Zone Created By Four Pumping Wells If The Velocity Vector Is Oriented 310°
Figure 7: Capture Zone For The Eight LADWP Wells.
Figure 8: Outline of TCE Plume Superimposed Upon The Eight Well Capture Zone.
Figure 3 Outline Of TCE Plume Superimposed Upon The Four Well Capture Zone.