Capture-Zone Type Curves: A Tool for Aquifer Cleanup

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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. 300.68(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 contamnation has been eliminated, one has to choose the least expensive alternative for capturing the plume.

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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 should the wells be sited so 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. The following development is based on 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

$$y = \pm \frac{Q}{2BU} - \frac{Q}{2\pi BU}\tan^{-1}\frac{y}{x} \qquad (1)$$

where B = aquifer thickness (m), Q = well discharge rate (m^3/sec), and U = regional flow velocity (m/sec). One may note that the only parameter in

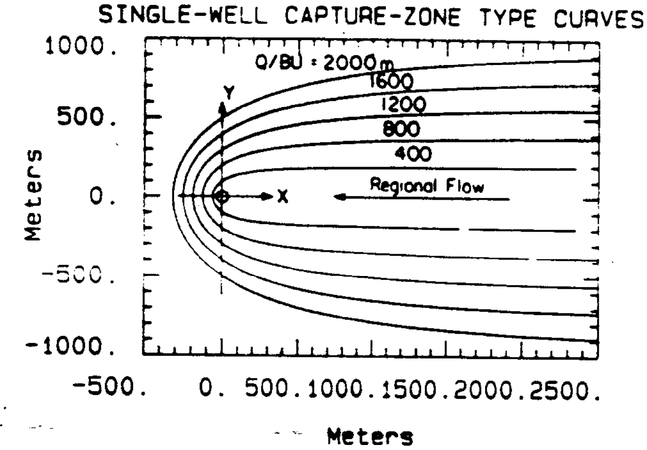

Fig. 1. A set of type curves showing the capture zones of a single pumping well located at the origin for various values of (Q/BU).

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

$$y_D = \pm \frac{1}{2} - \frac{1}{2\pi}\tan^{-1}\frac{y_D}{x_D} \qquad (2)$$

where $y_D = BUy/Q$, dimensionless, and

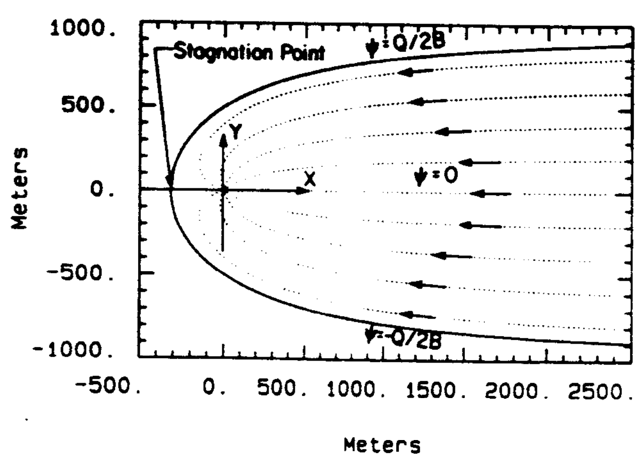

Fig. 2. The paths of some water particles within the capture zone with (Q/BU) = 2000, leading to the pumping well located at the origin.

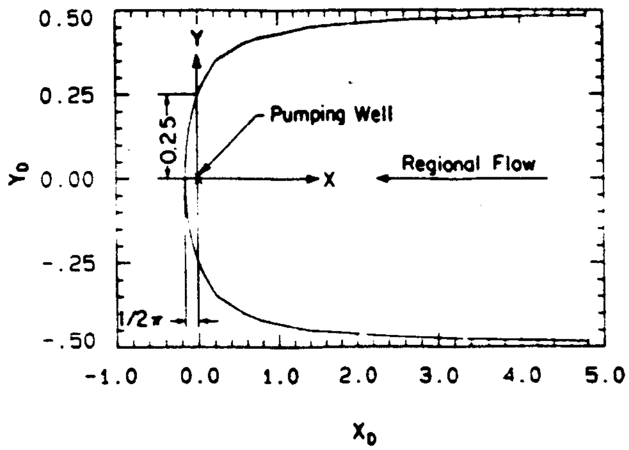

Fig. 3. Nondimensional form of the capture-zone type curve for a single pumping well.

$x_D = BUx/Q$, 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

$$W = Uz + \frac{Q}{2\pi B}[\ln(z - id) + \ln(z + id)] + C \quad (3)$$

where z is a complex variable which is defined as $x + iy$ and $i = \sqrt{-1}$.

The velocity potential ϕ and stream function ψ for such flow system are the real and imaginary parts of W in equation (3) which can be written as

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

$$\psi = Uy + \frac{Q}{2\pi B}\{\tan^{-1}\frac{y-d}{x} + \tan^{-1}\frac{y+d}{x}\} \quad (5)$$

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:

$$\frac{dW}{dz} = U + \frac{Q}{2\pi B}\left(\frac{1}{z - id} + \frac{1}{z + id}\right) = 0 \quad (6)$$

The roots of equation (6) are given by

$$z = \tfrac{1}{2}\left(-\frac{Q}{\pi BU} \pm \sqrt{[Q^2/(\pi BU)^2] - 4d^2}\right) \quad (7)$$

When $2d > Q/\pi BU$, that is, the distance between the two wells is larger than $Q/\pi BU$, 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

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

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

Note that only when $2d \gg Q/\pi BU$ the coordinates of these two stagnation points become approximately $[-(Q/2\pi BU), d]$ and $[-(Q/2\pi BU), -d]$. When $2d > Q/\pi BU$, 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 $Q/\pi BU$, then both roots of equation (6) are equal and real such that

$$z_1 = z_2 = -\frac{Q}{2\pi BU} \quad (8)$$

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

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

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

and

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

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 of $[-(Q/\pi BU), 0]$. When $2d < Q/\pi BU$, 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

$$2d \leq \frac{Q}{\pi BU} \quad (9)$$

The optimum condition is achieved at the limit when $2d = Q/\pi BU$ 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

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

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) also can be written in nondimensional form as

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

where $y_D = BUy/Q$, dimensionless; and $x_D = BUx/Q$, dimensionless.

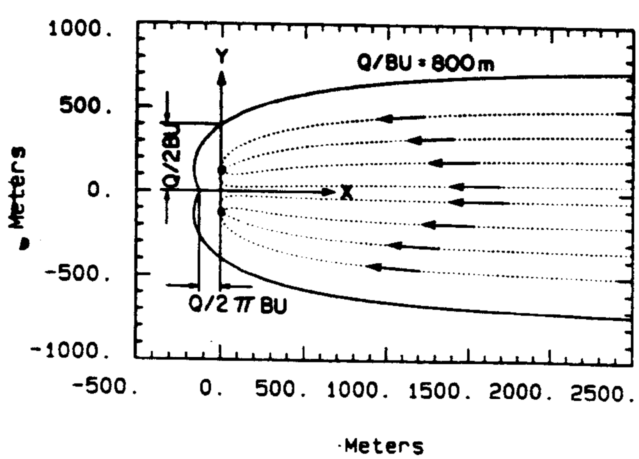

Fig. 4. Capture zone of two pumping wells properly located to prevent any leakage from the space between the two wells.

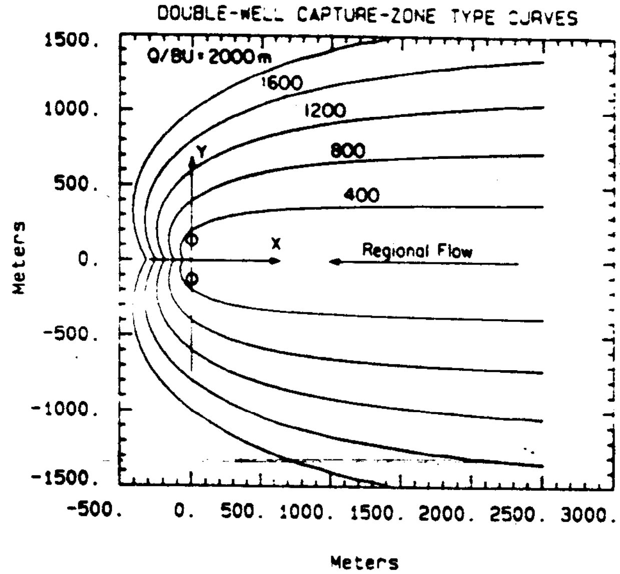

Fig. 5. A set of type curves showing the capture zones of two pumping wells located on the y-axis for various values of (Q/BU).

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

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

The velocity potential ϕ and the stream function ψ for this flow system are given by

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

$$\psi = Uy + \frac{Q}{2\pi B}\left(\tan^{-1}\frac{y}{x} + \tan^{-1}\frac{y-d}{x} + \tan^{-1}\frac{y+d}{x}\right) \quad (14)$$

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:

$$\frac{dW}{dz} = U + \frac{Q}{2\pi B}\left[\frac{1}{z} + \frac{1}{z - id} + \frac{1}{z + id}\right] = 0 \quad (15)$$

Equation (15) may be written as

$$z^3 - \frac{3z^2}{A} + d^2 z - \frac{d^2}{A} = 0 \qquad (16)$$

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

$$D = d^2 \left(\frac{d^4}{27} - \frac{d^2}{3A^2} + \frac{1}{A^4} \right) \qquad (17)$$

It can be shown easily 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 appraoching the x-axis. Such that for $d = (2\sqrt[3]{2})\,Q/2\pi BU$ the position of stagnation points are

$$z_1 : (-1.54\frac{Q}{2\pi BU}, 0),\ z_2 : (-0.73\frac{Q}{2\pi BU}, 1.9\frac{Q}{2\pi BU}),$$

$$z_3 : (-0.73\frac{Q}{2\pi BU}, -1.9\frac{Q}{2\pi BU}).$$

The value of $d = (2\sqrt[3]{2})\,Q/2\pi BU$ 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 $3Q/2\pi BU$ 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

$$y + \frac{Q}{2\pi BU}\left(\tan^{-1}\frac{y}{x} + \tan^{-1}\frac{y-d}{x} + \tan^{-1}\frac{y+d}{x}\right) = \pm\frac{3Q}{2BU} \qquad \ldots\ldots (18)$$

where $d = \sqrt[3]{2}\,Q/(\pi BU)$. Since d is only a function of (Q/BU), it is apparent that once again equation

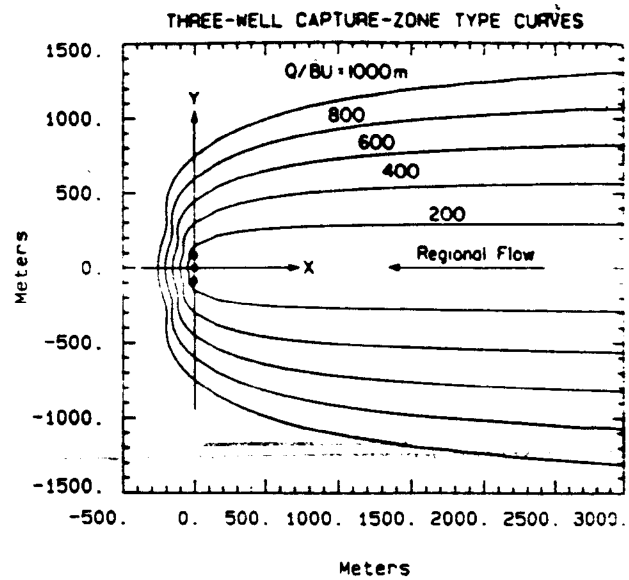

Fig. 6. A set of type curves showing the capture zones of three wells all located on the y-axis for various values of (Q/BU).

(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 $\sqrt[3]{2}\,Q/\pi BU$ from the origin.

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

$$y_D + \frac{1}{2\pi}\left[\tan^{-1}\frac{y_D}{x_D} + \tan^{-1}\frac{y_D - (\sqrt[3]{2}/\pi)}{x_D} + \tan^{-1}\frac{y_D + (\sqrt[3]{2}/\pi)}{x_D}\right] = \pm\frac{3}{2} \qquad (19)$$

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. (1) 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. (2) The equation of the dividing streamlines for the case of n pumping wells can be written down by comparing the corresponding equations for one, two, and three pumping wells:

Table 1. Some Characteristic Distances in Flow Regimes for One, Two, and Three Pumping Wells Under a Uniform Regional Ground-Water Flow

Number of pumping wells	Optimum distance between each pair of pumping wells	Distance between dividing streamlines at the line of wells	Distance between streamlines far upstream from the wells
one	-	$\frac{Q}{2BU}$	$\frac{Q}{BU}$
two	$\frac{Q}{\pi BU}$	$\frac{Q}{BU}$	$\frac{2Q}{BU}$
three	$\frac{\sqrt{2}\,Q}{\pi BU}$	$\frac{3Q}{2BU}$	$\frac{3Q}{BU}$

$$y + \frac{Q}{2\pi BU}\{\tan^{-1}\frac{y-y_1}{x} + \tan^{-1}\frac{y-y_2}{x} \ldots + \tan^{-1}\frac{y-y_n}{x}\} = \pm\frac{nQ}{2BU} \qquad (20)$$

where $y_1, y_2, \ldots y_n$ are y-coordinates of pumping wells 1, 2, . . . , 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 1.2 Q/(πBU) 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

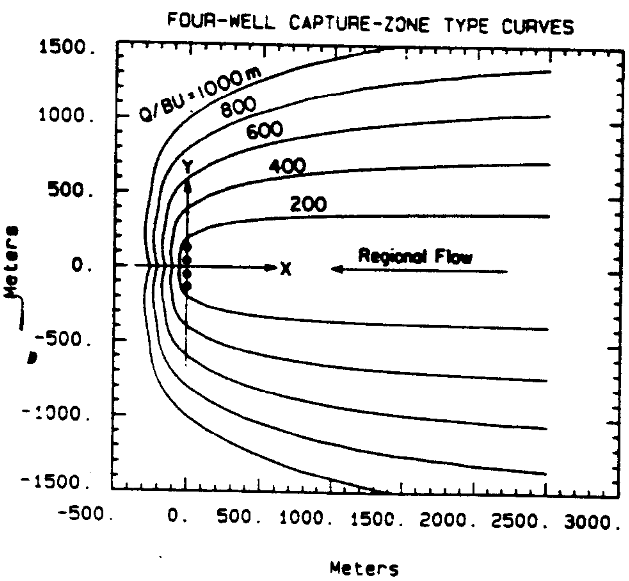

Fig. 7. A set of type curves showing capture zones of four pumping wells, all located on the y-axis for several values of (Q/BU).

parameter (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., Q/BU value) chosen. Once the type curve is selected, the optimum distance between each pair is d = 1.2 Q/(πBU).

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 (1) the cost is minimum, (2) the maximum concentration of a contaminant in the aquifer at the end of the operation does not exceed a given value, and (3) the operation time is minimized. To insure that the above conditions are satisfied, one has to answer those questions which were posed in the Introduction.

The exact solution to this problem could be quite complex and site-specific. However, the following simple procedure could be useful for many cases and could avoid common errors.

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. Further 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 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

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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 the 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 into 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 also can 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, 3×10^{-5}; and permissible drawdown at each well, 7 m.

Suppose we want 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

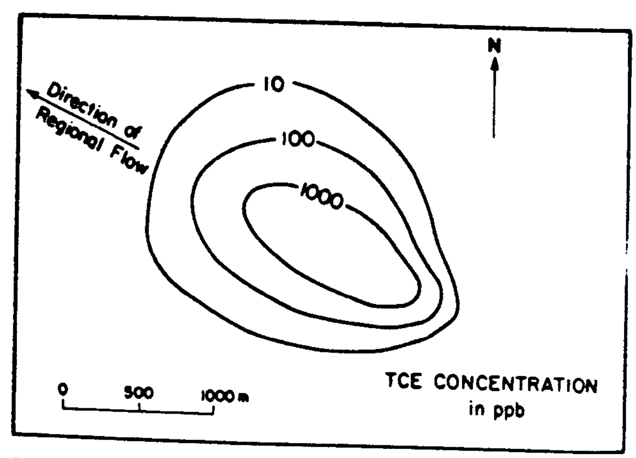

Fig. 8. Observed TCE concentration distribution.

calculate their rate of discharge, using the procedure given above. Figure 8 includes the contour line of 10 ppb. The area within this curve identifies the zone where the TCE concentration is above 10 ppb that should be captured and treated. Direction of ... regional flow is also shown in this figure. The ... of this map is identical to that of Figure 1. Superposition of this map on Figure 1 and matching the direction of flow indicate 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:

$$U = Ki = (10^{-4} \text{ m/s})(0.002) = 2.0 \times 10^{-7} \text{ m/sec} \quad (21)$$

Therefore, the corresponding discharge rate of the well is

$$\left(\frac{Q}{BU}\right) BU =$$

$$(2500 \text{ m})(10 \text{ m})(2 \times 10^{-7} \text{ m/sec}) = 5 \times 10^{-3} \text{ m}^3\text{/sec} \quad \ldots\ldots (22)$$

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

$$\Delta h = \frac{2.3Q}{4\pi KB} \log \frac{2.25KBt}{r_w^2 S} \quad (23)$$

where Δh = drawdown in the aquifer (m); Q = pumping rate (m^3/sec); K = hydraulic conductivity (m/sec); B = aquifer thickness (m); t = time e[laps]ed since the start of pumping (sec); r_w = effective well radius (m); and 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):

$$2d = \frac{Q}{\pi BU} = 382 \text{ m} \quad (24)$$

and drawdown at each of these two wells is obtained from

$$\Delta h = \frac{2.3Q}{4\pi KB} \left\{\log \frac{2.25KBt}{r_w^2 S} + \log \frac{2.25KBt}{(2d)^2 S}\right\} \quad (25)$$

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

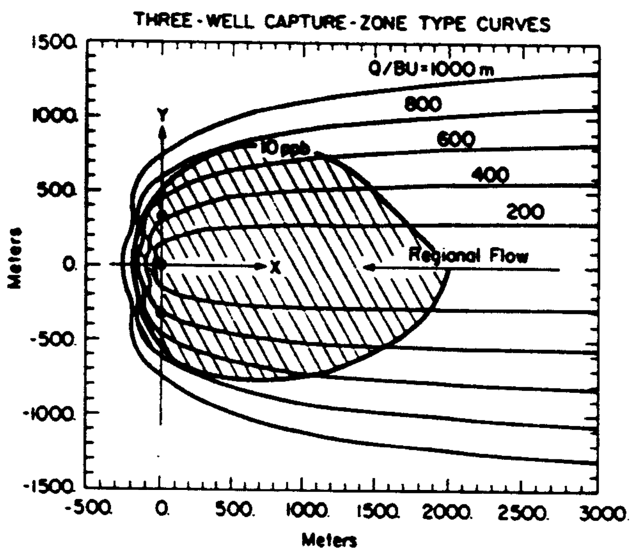

Fig. 9. The 10-ppb contour line of TCE at the matching position with the capture-zone type curve of (Q/BU) = 800.

three-well capture-zone type curves at the matching position. The area within the contour line has been crosshatched for clarity.

The rate of discharge for each pumping well is

$$Q = 800(10)(2 \times 10^{-7}) = 0.0016 \text{ m}^3/\text{sec}$$

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 are 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, these features can be 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.

Although this technique minimizes the cost of aquifer cleanup, it does not necessarily minimize 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 shortened substantially 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 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 the 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 soltuions have been presented which give the position of 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 selection

of the optimum number, location, and discharge rate for the pumping wells. The criteria for such recommendations include minimizing the cost, avoiding degradation of the water quality beyond the selected zone, and achieving the goal that the ...mum 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 fresh water while reducing the aquifer cleanup time.

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