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Short communication

Containment wells to form hydraulic barriers along site boundaries

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ABSTRACT

In the field, aquifer remediation methods include pump and treat procedures based on hydraulic control systems. They are used to reduce the level of residual contamination present in the soil and soil pores of aquifers. Often, physical barriers are erected along the boundaries of the target (aquifer) site to reduce the leakage of the released soil contaminant to the surrounding regions. Physical barriers are expensive to build and dismantle. Alternatively, based on simple hydraulic principles, containment wells or image wells injecting clear water can be designed and built to provide hydraulic barriers along the contaminated site boundaries. For brevity, only one pattern of containment well system that is very effective is presented in detail.

The study briefly reports about the method of erecting a hydraulic barrier around a contaminated region based on the simple hydraulic principle of images. During the clean-up period, hydraulic barriers can considerably reduce the leakage of the released contaminant from the target site to surrounding pristine regions. Containment wells facilitate the formation of hydraulic barriers. Hence, they control the movement of contaminants away from the site that is being remedied. However, these wells come into play, only when the pumping operation for cleaning up the site is active. After operation, they can be filled with soil to permit the natural ground water movement. They can also be used as monitoring wells.

1. Introduction

Contamination of soil can result in subsequent contamination of aquifers due to the transport of pollutants through soil pores. Aquifer contamination can be reduced by a number of traditional methods. These include in situ pump and treat schemes that form part of the hydraulic control systems. Pump and treat schemes rely on aqueous mobilization or dissolution of the sorbed contaminant. When the contaminant is a non-aqueous phase liquid (NAPL), surfactant-enhanced pump and treat schemes can be used for in situ reduction of aquifer site contamination. While treating a target-contaminated site, released contaminant may cross the site boundaries. Physical barriers reduce leakage and also prevent spreading of external intruding contaminant plumes into uncontaminated regions. Hydraulic barriers too can be effective in reducing leakage across boundaries of the contaminated sites.

Using USGS MOC simulation, Satkin and Bedient [1] have published studies on 7 well patterns to remediate a contaminant plume, considering a variety of pumping rates, hydraulic gradients and aquifer constants. Bedient et al. [2] provided an excellent review of many pump and treat schemes and pointed out that they are effective when the soil matrix has good hydraulic conductivity and the geology is not complex or heterogeneous. They rightly observe that treatment and disposal of the contaminated water removed from extraction wells may increase the cost of pump and treat schemes. Knox [3] has provided a detailed useful analysis of the transport of contaminated water under or through imperfect barriers. Wilson [4] adopted hydraulic principles [5] of discharge well and recharge well combinations (double cell systems) to form hydraulic isolation units to efficiently remove pollutants from contaminated aquifers. Keeley [6] presented a comprehensive review of pumping strategies to decontaminate non-ideal aquifer conditions including anisotropy and heterogeneity. Ozbilgin and Powers [7] demonstrated that extraction wells and recharge trenches effectively retarded contaminant plume advancement.

More recently, physical barrier augmented pump and treat schemes have been shown to be effective in capturing NAPL contaminants in both homogeneous and non-homogeneous systems [13] and in non-homogeneous systems [8]. Cunningham et al. [9] used the recirculation well pair formed by a discharging well (sink) and a recharging well (source) set up normal to the groundwater flow direction to act as a hydraulic barrier to the flow of contaminated water. They showed that the recirculation zone between the wells acts as a bioreactor. Their study provides guidelines to choose the design parameters for optimum well performance. Earlier, it

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Nomenclature

c	half spacing between real well and its containment well (Fig. 1a and b)
d	soil particle (mean) diameter
f_i	factor defining well type =1 for source and −1 for sink
K	aquifer transmissivity
L	length of target site
m	absolute value of source or sink constant
n	total number of operating wells in system (including injecting and extracting wells)
q	source or sink strength
Q	total flow = $n \times q$ (recharge and extracting wells)
R	Reynolds number
s	groundwater ambient pressure gradient
u	velocity component in x direction
v	velocity component in y direction
V	local groundwater flow velocity
W	width of target site
x, y	rectangular coordinates of a position
x_i, y_i	rectangular coordinates of well locations in system

Greek letters

ν	kinematic viscosity
Φ	potential function
Ψ	stream function

Subscripts

i	defining a well in system
(i, j)	matrix location of grid points

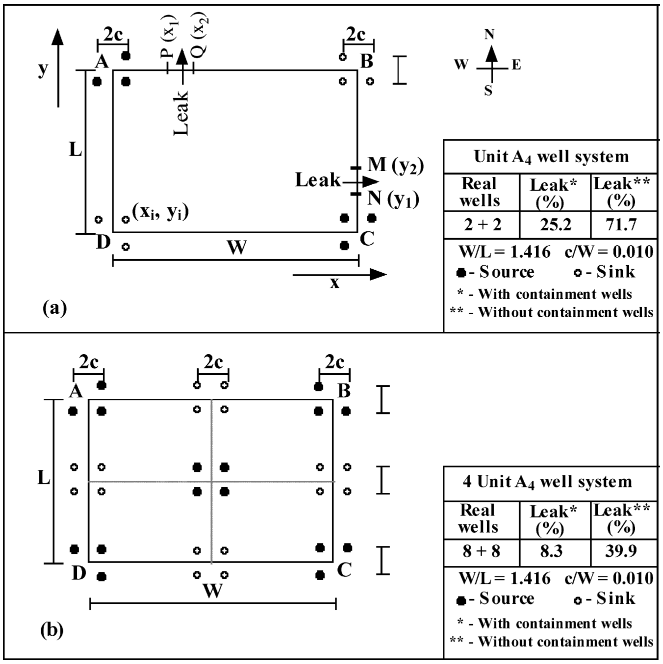
was shown that the hydraulic barrier created by such a well system could be used as an alternative to permeable reactive barriers [14]. Luo et al. [10] used multiple injection–extraction well systems to create a flow field comprising an inner cell, an outer cell and transition zones to analyze the hydraulic performance of the system and derive the flow fractions in the different zones.

In the present study, the effectiveness of two simple clear water containment systems (hydraulic barriers) based on the simple hydrodynamic principle of images is demonstrated. For brevity, only one of the efficient well patterns is described in detail to show its effectiveness of erecting hydraulic barriers by containment (image) wells in limiting the leakage of contaminant from the (aquifer) site that is remedied. In the field, the physical counterpart of the theoretical barrier imposed by the image well is the barricade (wall) that comes to play due to the well system. In practice, the containment well that generates the barrier denotes the theoretical image well of the hydraulic model.

2. Basic relations

A recharge well or an injecting well is a source (Fig. 1a and b). In the vicinity of an injecting well, one can provide another injecting well of equal strength. It is termed as the containment well. When both these wells are operating, the perpendicular bisector of the line connecting them forms a hydraulic barrier. This principle can also be applied to extracting wells (sinks in Fig. 1a and b).

To illustrate the containment (image) well concept, consider the contaminated (aquifer) site ABCD of length L and width W (Fig. 1a). For purposes of reference, let DA denote the North direction (Fig. 1a) and let corner D be the origin. A simple but arbitrarily configured containment well system termed as “unit A_4 well system” denoting the 4 wells inside the (aquifer) site ABCD is considered (Fig. 1a). At corners of ABCD, 2 additional injecting wells (sources) or 2 extracting wells (sinks) are provided outside ABCD. The following assumptions are made to develop the unit A_4 well system.



Unit A_4 well system		
Real wells	Leak* (%)	Leak** (%)
2 + 2	25.2	71.7

W/L = 1.416 c/W = 0.010
● - Source ○ - Sink
* - With containment wells
** - Without containment wells

4 Unit A_4 well system		
Real wells	Leak* (%)	Leak** (%)
8 + 8	8.3	39.9

W/L = 1.416 c/W = 0.010
● - Source ○ - Sink
* - With containment wells
** - Without containment wells

Fig. 1. Containment well systems for target site ABCD. (a) Unit A_4 well system for target site. (b) 4 Unit A_4 well system for target site.

(1) The soil matrix of the aquifer is saturated and is relatively porous, homogeneous and isotropic.
(2) The contaminant distribution in ABCD is uniform.
(3) Flow is steady and two-dimensional.
(4) Surfactants added to the injected water do not affect the hydraulic properties of water significantly.
(5) An impermeable barrier exists at the bottom of the aquifer.
(6) Wells fully penetrate the aquifer.
(7) Non-reactive advective transport is simulated and hydrodynamic dispersion is neglected.
(8) Higher velocities imply higher contaminant removal during the cleaning process.
(9) All operating wells (injecting and extracting) are of equal strength.

The streamline pattern for each individual well (sink or source) is known. As the governing equation for the flow is linear, principles of superposition yield streamline patterns. For a source (Fig. 1a) of strength q at (x_i, y_i) with a source constant $m = q/2\pi$, the stream function Ψ_i is,

$$\Psi_i = m \tan^{-1}\frac{(y-y_i)}{(x-x_i)} \tag{1}$$

Velocity components u and v in the x and y directions for this well are,

$$u = \frac{\partial \Psi}{\partial y} = f_i m \frac{(x-x_i)}{(x-x_i)^2+(y-y_i)^2},$$

$$v = -\frac{\partial \Psi}{\partial x} = f_i m \frac{(y-y_i)}{(x-x_i)^2+(y-y_i)^2} \tag{2}$$

Here, $f_i = 1$ for each source and −1 for each sink.

Based on the above well-known concepts [11,12] leakage out of a strip MN of width $y_2 - y_1$ fixed at $x = W$ along the boundary CB is,

$$\text{Leak}_{[y_2-y_1]} = \Delta\Psi|_{y_1}^{y_2} = \int_{y_1}^{y_2} u\mathrm{d}y = \int_{y_1}^{y_2} \frac{\partial\Psi}{\partial y}\mathrm{d}y$$

$$= f_i m \int_{y_1}^{y_2} \frac{(x-x_i)}{(x-x_i)^2 + (y-y_i)^2}\mathrm{d}y$$

$$= f_i m \tan^{-1}\left(\frac{y-y_i}{x-x_i}\right)|_{y_1}^{y_2} \tag{3}$$

Similarly, for boundary AB, leakage out of strip PQ of width $x_2 - x_1$ is,

$$\Delta\Psi|_{x_1}^{x_2} = f_i m \tan^{-1}\left(\frac{x-x_i}{y-y_i}\right)|_{x_1}^{x_2} \tag{4}$$

For each of the n wells in the system that are operational, the well strength will be m. Here, $m = q/2\pi = Q/2\pi n$. The analytical solution for the stream function Ψ given in Eq. (1) yields the value of Ψ at all (x, y) site locations, considering the effects of all wells. Thus,

$$\Psi = \frac{Q}{2\pi n}\left[\sum_{1}^{n} f_i \tan^{-1}\left(\frac{y-y_i}{x-x_i}\right)\right] \tag{5}$$

The potential function Φ related to pressure head h [11] is given by Eq. (6).

$$\Phi = \frac{Q}{2\pi n}\left[\sum_{1}^{n} f_i \ln[(x-x_i)^2 + (y-y_i)^2]\right] = -Kh \tag{6}$$

2.1. Well units

Fig. 1b denotes four of the unit A_4 well system that are located in site ABCD. W/L was set as 1.416 arbitrarily. Even here (Fig. 1b), two corner containment wells are present at each corner of the individual unit A_4 well system as in Fig. 1a. The small distance between the well and its (image) containment well is $2c = 0.02W$. Large values of $2c/W$ limit the number of individual well units that can be placed in a given site.

2.2. Streamline pattern, pressure head and velocity distribution

A rectangular grid system consisting of $\Delta x = 0.05W$ and $\Delta y = 0.05L$ was chosen to compute the flow out of the site boundaries. Eqs. (5) and (6) directly provide the values of Ψ and Φ at any grid point (x, y) to draw the streamline pattern. After getting the Φ values from Eq. (6), the differences $\mathrm{d}\Phi$ of the Φ values between adjacent grid points are computed. For a point (1, 1) and its adjacent point (1, 2),

$$\mathrm{d}\Phi|_{1,1\text{ to }1,2} = \Phi_{1,2} - \Phi_{1,1} \tag{7}$$

Using Eq. (8), $\mathrm{d}\Phi s$ can be transformed [11] to differences in pressure head $\mathrm{d}h$.

$$\mathrm{d}h|_{1,1\text{ to }1,2} = -\frac{1}{K}\mathrm{d}\Phi|_{1,1\text{ to }1,2} \tag{8}$$

Here, K = transmissivity that depends on the permeability of the soil. Pressure differences $\mathrm{d}h$ between grid points are obtained after a reference pressure head of 10 units was arbitrarily assigned to the N-W corner of the grid system. Using known pressure head differences between adjacent grid points, all pressure heads are computed. Pressure heads are normalized by pressure head value at the site center.

Eq. (2) yields u and v at grid points. To ensure that Darcy's law is respected, the Reynolds number $R = Vd/\nu$ should not exceed unity [11]. Here, d = mean soil particle diameter, V = mean flow velocity and ν is the kinematic viscosity of water.

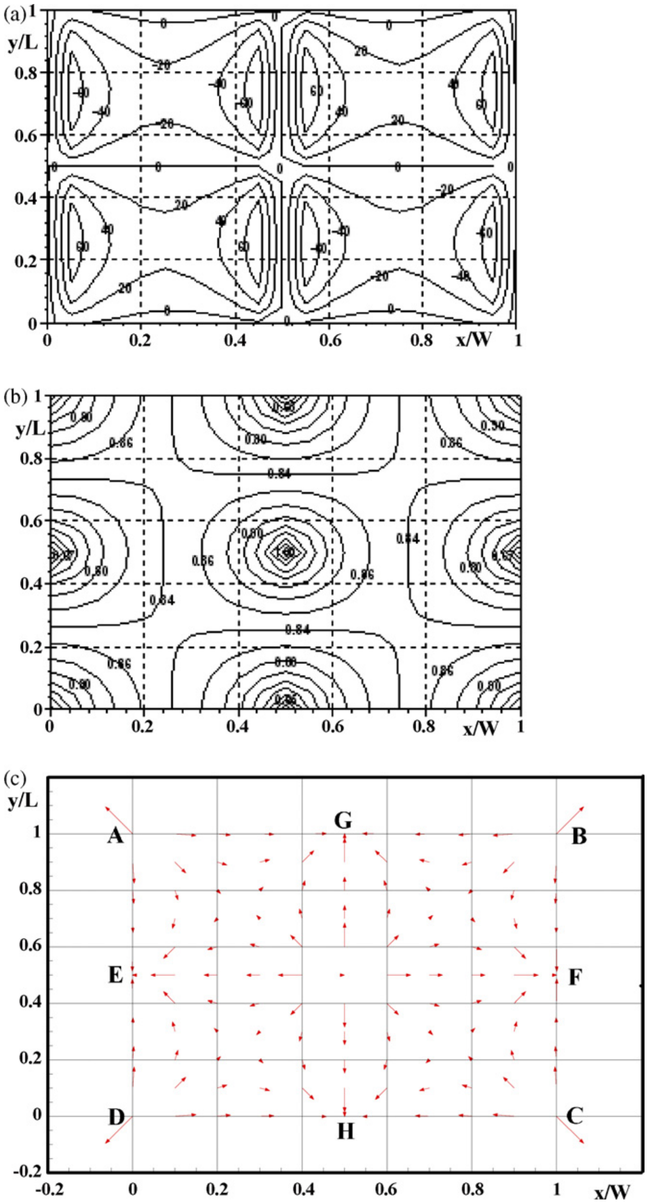


Fig. 2. (a) Flow characteristics for 4 unit A_4 well system with containment wells-Streamlines, (b) flow characteristics for 4 unit A_4 well system with containment wells—pressure head distribution, and (c) flow characteristics for 4 unit A_4 well system with containment wells—velocity vector plot.

3. Analysis of results

3.1. Well systems

Computations indicated that a unit A_4 well system of containment wells (Fig. 1a) reduces leakage from 72% to 25%. For the 4-unit A_4 well system (Fig. 1b), the leakage is 40% without containment wells. With containment wells, this leakage gets drastically reduced to 8%. Hence, more details for only the 4-unit A_4 well system (Fig. 1b) are given below.

3.2. Streamline pattern, pressure and velocity distribution for four unit A_4 well system (Fig. 1b)

Fig. 2a–c show that the flow distribution (Fig. 2a) is nearly even, except in the small regions at the center of each of the 4 individual units and the regions adjacent to the boundaries. Generally, the distance between pressure head contours are nearly the same in regions close to the central lines and the boundaries of the site indicating that the pressure gradients are nearly constant (Fig. 2b). This is also indicative of the even distribution of the flow since velocity is directly linked to pressure gradient. Only in the small regions around the centers (Fig. 2b) of the four individual unit A_4 well system, the spacing between the streamlines is larger. Hence, the velocities and pressure gradients are smaller. Decontamination may be less effective in these regions.

The velocity vector plot (Fig. 2c) includes a small region outside the target site. It shows that a small leakage (2%) occurring out of each of the site boundaries is essentially through very small gaps at corners A, B, C and D. Along the bisector of lines joining external containment wells at corners such as A, velocities normal to the bisectors cancel out, while the velocities along the bisector add up. Hence, the three corner sources induce large outward velocities through the corner gaps. As these gaps are narrow, outward flow at each corner is still small (2%). Adjacent to boundaries, the velocity vectors are nearly parallel to them. Hence, only a small amount (2%) of clear water from the containment wells enters the site through a site boundary such as AB. Streamlines in these small boundary regions are closely spaced (Fig. 2a). Still, they do not cross each other, except at well centers (singular points). Since the injected flow volume is equal to the extracted flow volume within the site, the clear water entering the site is equal to the contaminated water leaving the site. The small portion of the clear water entering ABCD (8%) does not excessively add to the disposal cost of extracted contaminated water. In other applications, where site outlines are different, performance of different well configurations may be studied to get an optimal site-specific well system. For the present site ABCD too, many well configurations (ex: 16 unit A_4 well system) are feasible. However, the simple 4-unit A_4 well system itself was quite effective in blocking leakage. Hence, only the performance of unit A_4 well system (Fig. 1a) and the 4-unit A_4 well (Fig. 1b) system results are reported.

If two wells operate in isolation, the bisector of the line connecting them will be a perfect barrier. As many wells are present in the 4-unit A_4 well system, a small component normal to all bisectors exists and hence, the leakage is not zero. To include the ground water flow effect, in Eq. (5), one adds the additional stream function corresponding to the magnitude and direction of the ground water velocity V. Ground water velocity depends on aquifer characteristics (soil particle characteristics, hydraulic gradient and viscosity of water). Knowing the magnitude and direction of V, a stream function denoting it can be easily incorporated in Eq. (5) to include effects of ground water flow.

The surfactant should be introduced with the flow of water through the injecting wells located within the target site boundaries. Thus, for the 4-unit A_4 well system (Fig. 1b), surfactant can be introduced at the eight operating injecting wells (sources) within ABCD. Clear water is injected through the eight other corner-injecting wells (containment wells) outside ABCD. They are also sources. The remaining 8 wells outside ABCD near bisectors of site ABCD are extraction wells (containment wells). They are sinks.

4. Conclusions

Containment wells that create hydraulic barriers are shown to reduce the leakage of released contaminants out of the target site boundary. For instance, the 4-unit A_4 well system reduces leakage from 40% to 8%. Though only 1 well pattern is analyzed in detail, the procedure can be easily applied to other containment well patterns, as the superposition principle is both simple and elegant.

Knowing the soil permeability characteristics and the prevailing hydraulic gradient, the ground water flow velocity vector can be formulated easily. Hence, the corresponding stream function can be added on to the stream function of the well system chosen for the site (Eq. (5)). This yields the combined effect of the well system and groundwater flow. Compared to the cost of erecting physical barriers around the site, constructing containment well system is relatively simple and inexpensive.

To restore ground water flow after the site is restored, unlike physical barriers, one need not dismantle the hydraulic barriers. Following the site clean-up task, the containment wells can be used as monitoring wells to obtain water samples. Alternatively, these wells can be filled easily with the soil.

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