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Flow simulation of a system of groundwater circulation well and pumping well for NAPL site remediation

J. Stamm, T.I. Eldho & M. Scholz
Institute for Hydromechanics, University of Karlsruhe, D-76128, Karlsruhe, Germany

Abstract

Groundwater circulation wells (in German, Grundwasser Zirkulation Brunnen, GZB) have been established as an in-situ flushing method for the remediation of volatile contaminants in groundwater. Here the operation of a GZB with three well screens and numerical modeling of a field operating system of GZB and pumping well, for the remediation of volatile contaminants is presented. The GZB is used for the removal of volatile contaminants in a highly industrial polluted region and a pumping well is provided at the downstream of the GZB in order to capture the existing contaminants in the downstream which is recharged into the GZB. A three-dimensional super position model coupled with finite element method is used to analyze the flow pattern between GZB and pumping well. The flow pattern for different quantities of circulation and pumping is also presented.

Introduction

Many of the potentially contaminated groundwater sites are affected by compounds that form non-aqueous phase liquids (NAPL) like TCE, PCBs, gasoline, etc. from industries. There is an urgent need for reliable, efficient and cost effective methods for preventing and remediating these contaminants from groundwater. Groundwater circulation wells (GZB) have been established as an efficient in-situ method for the remediation of volatile contaminants in groundwater. Their hydraulic flow field permits physical and biological remediation of the saturated as well as unsaturated subsurface region. The GZB is designed to remove volatile organic contaminants from groundwater by transforming the contaminants from the aqueous phase to gaseous phase and subsequently treating the resulting air stream through

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carbon adsorption units. Herrling and Stamm[1] presented a detailed report on the various aspects of groundwater circulation well operations, numerical simulations and applications. This paper is concerned with the study of the operation of a GZB with three screens and numerical modeling of a field operating system of GZB and pumping well, for the remediation of volatile contaminants.

Operation of the GZB

Here the operation of a GZB with three screen sections and the related circulation flow for the removal of volatile contaminants is described. GZB with more than two screen sections are used to create multiple circulation cells for thick aquifers with low natural gradient and density driven DNAPL migration throughout the thickness with more or less contaminant distribution over the depth. Use of more screens creates smaller circulation cells, intensify insitu flushing and shortens the flow time. Fig. 1. describes a typical GZB with three screen sections. In GZB in Fig. 1, the contaminated water enters through the middle screen section and leave through the upper and lower screen sections. In the aquifer, two circulation cells are created and air flow is introduced to strip the volatile contaminants.

Fig. 2 shows the longitudinal cross section of the flow pattern for a GZB with three screens in a natural gradient. The flow pattern is presented for a homogeneous anisotropic aquifer with 30 m thickness and a circulation of

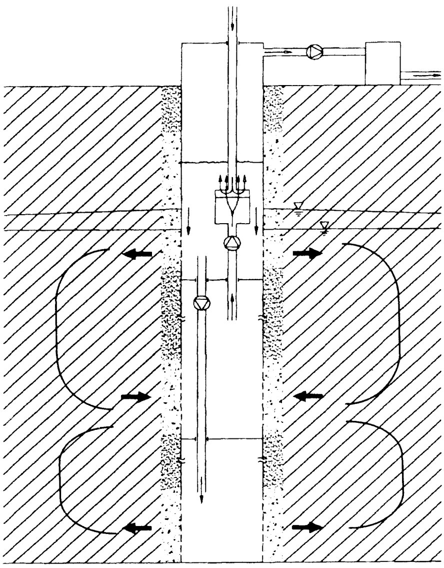

Figure 1: Groundwater circulation well with three screen sections

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50 m^3/h. The horizontal permeability is 5.4×10^{-4} m/s and anisotropy of the aquifer is 6 (K_h/K_v). The velocity of natural groundwater flow is 0.1 m/day and effective porosity is 0.2. The stagnation points are indicated as S.

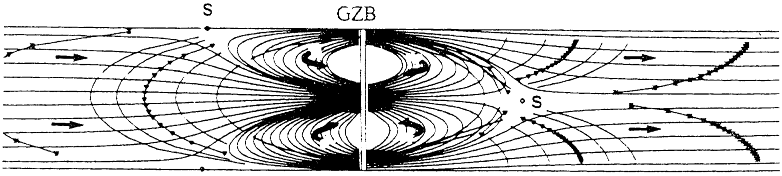

Figure 2: Cross section of flow for GZB with three screens with stream lines, isochrones and stagnation points (S) for 50 m^3/h circulation

Numerical model

For the effective installation and operation of the GZB, the radius of influence and hence the capture zone of the GZB should be found out. For a GZB, the radius of influence mainly depends on different parameters of: horizontal and vertical hydraulic conductivities, aquifer thickness (H), natural flow gradient (v), total well discharge (Q) and well screen lengths (a). To estimate the radius of influence and the capture zone of a GZB, a three-dimensional superposition model coupled with finite element method has been developed (Stamm[2]). The partial differential equation governing the radial symmetric flow around a groundwater circulation well can be expressed in cylindrical coordinates as (Bear[3]),

$$\frac{\partial}{\partial r}\left(2\pi r K_r \frac{\partial h}{\partial r}\right) + \frac{\partial}{\partial z}\left(2\pi r K_z \frac{\partial h}{\partial z}\right) = 0 \qquad (1)$$

where h is the piezometric head and K_r and K_z are the hydraulic conductivities in radial symmetric and vertical directions. Generally used boundary conditions are (Bear[3]):

$$h - \bar{h} = 0; v_i n_i + \bar{v} = 0 \qquad (2)$$

where v_i is the velocity vector, n_i is the unit vector normal to the boundary and $\bar{h}$ and $\bar{v}$ denote prescribed head and velocity values. Fig.3 shows the flow domain and boundary conditions.

The three-dimensional flow field for the described aquifer conditions with GZB is obtained by superposition of a horizontal uniform flow field, computed in a vertical cross section, representing the natural groundwater

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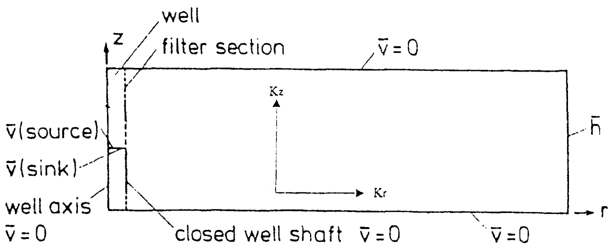


Figure 3: Radial symmetric flow domain and boundary conditions

flow and radial symmetric flow fields. The superposition of the different flow fields (Verrujit[4]) has been realized on a simple rectangular three-dimensional discretization with variable grid distances by interpolating and adding the respective velocity vectors (Stamm[2]). The numerical computation of the radial symmetric flow has been performed using a Galerkin finite element method with linear shape function and triangular elements (Pinder and Gray[5]). A particle tracking method has been used to calculate the capture zone by a large number of stream lines. For the computation of each stream line, the path of a particle is integrated in the 3-dimensional velocity field using an explicit Euler method with small integration steps. The numerical results for the capture zone are verified with analytical solutions and field measurements at an experimental field site in Karlsruhe-Knielingen, Germany (Stamm[2]).

Case study

Here the interaction of the flow fields of a GZB with three filter screens and a pumping well, for the in-situ remediation of a NAPL contaminated plume is presented as a case study. The remediation site is located in the valley of river Rhine in south Germany. The groundwater in the site is contaminated by chlorinated hydrocarbons (mainly TCE and PCE) from a laundry near to GWM8. The aquifer where the contamination is observed is unconfined in nature, made up of a mixture of sand and gravel of various sizes. For the remediation of the whole contaminant plume, a number of GZBs (SBR) have been installed in the site. The contamination extended GZB5 before it was installed and the operation started. To monitor the movement of plume and the remediation process, number of monitoring wells have been installed. Fig. 4 shows the position of the contaminated plume, groundwater circulation wells (GZBs or SBR) and the monitoring wells.

In the present study, the flow around GZB5 (in Fig. 4) and the flow behavior between GZB5 and the monitoring well GWM16 is analyzed. The plume is extended beyond the capture zone of the GZB5 and to remediate it, the monitoring well GWM16 which is located 55 m downgradient of GZB5 is used as pumping well to capture this plume. The contaminated water pumped by GWM16 is recharged into GZB for remediation. So the GZB is used as a partially recharge well. At the investigation site, the aquifer can be considered as single layered with an average horizontal permeability (K_h) of $6x10^{-4}$ m/s. The anisotropy (K_h/K_v) is assumed as 10. The groundwater gradient observed is 0.03% and the natural groundwater flow velocity subsequently is $1.8x10^{-7}$ m/s. The effective porosity of the aquifer (n_e) is 0.2. The concentration of chlorinated hydrocarbon in the vicinity of GZB5 is observed to be around 20,000 µg/l.

Here a GZB with three screen sections is used. The lengths of the three screen sections are: upper screen length (a_T) = 4.8 m, middle screen length (a_M) = 4.2 m and lower screen length (a_L) = 3.2 m. The mean diameter of the GZB is 400mm. The height of the GZB is 21.8 m and steady water level

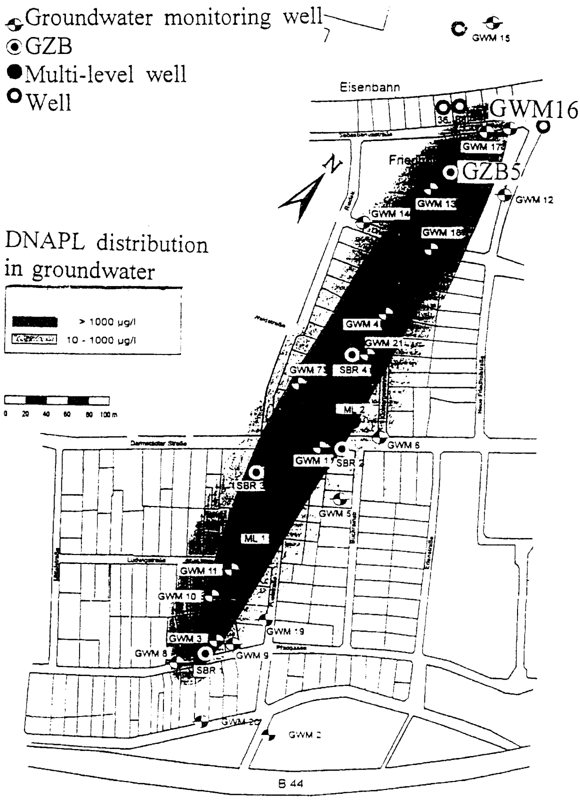


Figure 4: Contaminated site with the remediation wells (GZB) and monitoring wells (GWM) positions.

in the aquifer is 18.2 m. The flow simulation for the GZB and the pumping well is done using the numerical model described earlier. The radial symmetric flow calculation around the GZB is done by finite element method using 4182 linear triangular elements and 2215 nodes. The superpositioning of the different flow fields is done by considering a three-dimensional block of size 170mx200mx18.2m, which take care all flow features including the pumping well (GWM16). It is discretized into rectangular grids on which the radial symmetric FEM grid is positioned for the radial symmetric calculations.

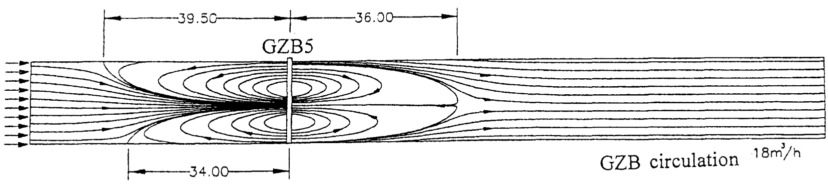
Analysis of flow around GZB5 without pumping activity in GWM 16

To determine the radius of influence of the GZB and hence the capture zone, initially numerical analysis is done without considering the downgradient pumping well (GWM16) for well circulations of Q_1= 18 m^3/h and Q_2= 15 m^3/h. Fig. 5 show the stream lines in the longitudinal section of the flow through the GZB, respectively for 18 m^3/h and 15m^3/h. With a variation of 3 m^3/h in well discharge, capture zone differs approximately by 3%. As clear from Fig. 5a, the maximum length of the capture zone of the GZB in the downstream direction is 36 m for 18 m^3/h discharge.

Analysis of flow around GZB5 with pumping in GWM 16

Here the combined flow field of the GZB and the pumping well (GWM16) is considered in the analysis. Two cases of circulation rates in GZB (Q_1 = 18 m^3/h and Q_2 = 15 m^3/h) are considered with two different pumping rates in

a)



b)

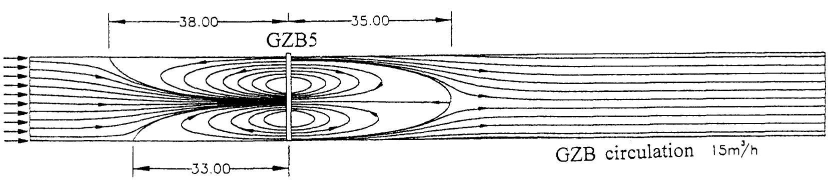
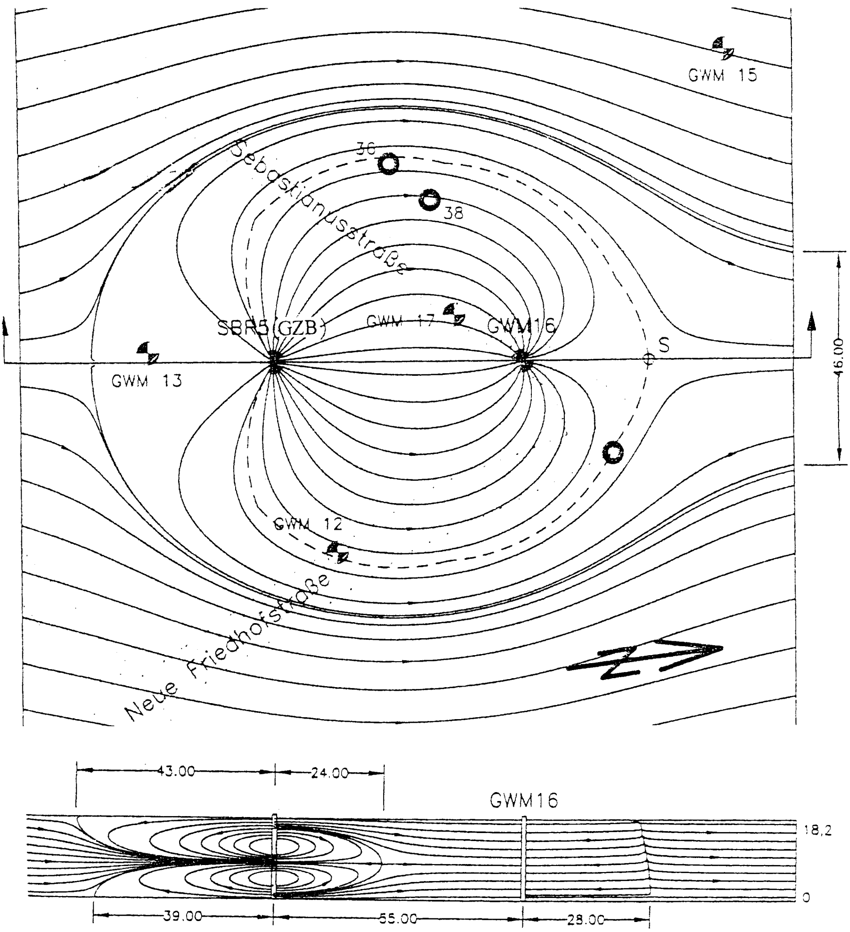


Figure 5: Flow pattern around GZB for: a) Q_1=18 m^3/h and b) Q_2=15 m^3/h

a)



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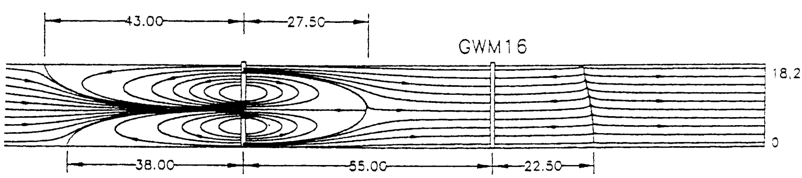

Figure.6. Flow between GZB5 and GWM16 for a) $Q_1 = 15\ m^3/h$ (pumping in GWM16 = 3.0 m^3/h) ; b) $Q_2 = 18\ m^3/h$ (pumping in GWM16 = 2.2 m^3/h)

GWM16 (2.2 m^3/h and 3 m^3/h). Fig. 6a shows the plan and elevation of the flow pattern for 15 m^3/h circulation rates, including the capture zone of the

GZB and pumping well and the stagnation points. Fig. 6b shows the elevation of the flow pattern for 18 m^3/h circulation rates. As in Fig. 6b, with a circulation of 18 m^3/h (including the recharge from pumping well) and a pumping of 2.2 m^3/h, the stagnation point is at 22.5 m beneath the pumping well and the plume is completely captured. Comparing with Fig. 5a, the upstream capture zone is enlarged by about 5m. As in Fig. 6a, with a circulation of 15 m^3/h and with pumping rate of 3 m^3/h, only a small reduction in capture zone of about 5% to the corresponding circulation of 18 m^3/h is observed while the downstream stagnation point of the pumping well increased by 5.5 m. Hence, for the present case, a circulation of 15 m^3/h and a pumping rate of 3 m^3/h would be sufficient to capture all contaminated plume in the process of remediation.

Conclusions

The operation and flow simulation of a GZB with three screen sections is presented. For the flow simulation, a three-dimensional superposition model based on finite element method for radial symmetric flow has been used. This model is found to be very efficient in the simulation of complex GZB flow fields. The effect of a pumping well in the circulation well field is analyzed for a field case study. A pumping well which pumps and recharges to the circulation well is found to be effective in increasing the capture zone of the GZB which are required for the remediation of a contaminant plume, without disturbing vertical circulation flow field. Hence a combined GZB and pumping well system is more efficient and economical.

References

1. Herrling, B. & Stamm, J., *Numerische Untersuchungen zum Unterdruck-Verdampfer-Brunnen (UVB) und zum Grundwasser-Zirkulations-Brunnen (GZB)*, Report No. 702, Institute for Hydromechanics, University of Karlsruhe, Germany, 1993.
2. Stamm, J., *Numerische Berechnung dreidimensionaler Strömungs-vorgänge um Grundwasser-Zirkulations-Brunnen zur In-situ-Grundwasser-sanierung*, Doctoral Thesis, Institute for Hydromechanics, University of Karlsruhe, Reihe 15, Nr. 169, VDI-Verlag, Dusseldorf, 1997.
3. Bear, J., *Dynamics of Fluids in Porous Media*, Elsevier , New York, 1972.
4. Verrujit, A., *Theory of Groundwater Flow*, MacMillian, New York, 1970.
5. Pinder, G.F. & Gray, W.G., *Finite Element Simulation in Subsurface Hydrology*, Academic Press, New York, 1977.