Hydraulic circulation system for \textit{in situ} remediation of strippable contaminants and \textit{in situ} bioreclamation (GZB/UVB method)

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Abstract Vertical circulation flows around special screened wells, which have been used for physical (stripping) or biological \textit{in situ} aquifer remediation, are discussed. Further, these recirculating systems can be combined with any appropriate on-site remediation which involves extraction and re-infiltration into the same well. Design diagrams are presented and the advantages of these flow systems are discussed.

INTRODUCTION

An \textit{in situ} remediation method using vertical circulation flows around wells with two screen sections in one aquifer, so called "Groundwater Circulation Wells" (German: Grundwasser-Zirkulations-Brunnen, abbreviation: GZB), has become increasingly important for aquifer remediation. Originally this idea was used only for \textit{in-situ} remediation of aquifers from volatile contaminants in so called "Vacuum Vaporizer Wells" (German: Unterdruck-Verdampfer-Brunnen, abbreviation: UVB) (Herrling et al., 1991, 1992). For both the GZB and the UVB, special wells with two screen sections are employed, one at the aquifer bottom and one at the groundwater surface or below an aquitard. Within the well the groundwater is moved vertically. The contaminated water enters the well at the bottom and the stripped or treated water leaves at the top or \textit{vice versa}. An area of vertical flow circulation is created near the well. All the technologies described in this paper have been patented by IEG mbH, D-7410 Reutlingen, Germany.

\textbf{IN SITU REMEDIATION TECHNIQUES}

Physical remediation by \textit{in situ} stripping

At numerous sites in Germany, and more recently in the United States, the UVB technique have been used for \textit{in situ} groundwater remediation where the subsurface is contaminated by volatile substances, e.g. volatile chlorinated hydrocarbons, BTEX. As an alternative to conventional hydraulic redevelopment measures (pumping, off-site cleaning and infiltration of groundwater), the contaminated groundwater is stripped by air under slight vacuum in the UVB (Fig. 1(a)). Often the well is used for vapour
extraction at the same time. The contaminated air is cleaned employing activated carbon or in the case of suitable contaminants by using biofilters. Details of the UVB technique have been reported (Herrling et al., 1991, 1992).

The upper closed part of the well is maintained below atmospheric pressure by a ventilator. This lifts the water level within the well casing. The fresh air for the upper part of the well casing is introduced through a fresh air pipe: the upper end is open to the atmosphere, and the lower end terminates in a pinhole plate. The height of the pinhole plate is adjusted such that the water pressure is lower there than the atmospheric pressure. Therefore, the fresh air is drawn into the system. The reach between the pinhole plate and the water surface in the well casing is the stripping zone, in which an air bubble flow develops. The rising air bubbles produce a pump effect, which moves the water up and causes a suction effect at the well bottom. In recent wells, a separating plate and an additional pump (Fig. 1(a)) are used to reinforce the pumping effect of the air bubbles. Additionally, soil gas is drawn from the surrounding contaminated unsaturated zone at many sites. Stripped air and possibly soil gas are transported through the ventilator and across activated carbon, onto which the contaminants are adsorbed. Thus, only clean air escapes into the atmosphere. One well should be used to remediate only one aquifer (phreatic or confined) and should not connect different aquifers.

The cleaning effect of the well is based on reduced pressure, which reinforces the volatilization of contaminants from the water and, as a result of the air intermixing, their transfer to the considerable surface area of the air bubbles. The permanent vibration caused by the air bubbles also helps the volatilization process. This vibration is transmitted as compression and shear waves into sediment and fluid and presumably

![Diagram](image-url)
influences the mobility of the contaminants, even outside the well. The upward-streaming, stripped groundwater leaves the well casing through the upper screen section near the water table, which is lifted in a phreatic aquifer by the pumping process explained above and the reduced pressure. It then returns through the aquifer in an extensive circulation to the well bottom. In this way, the groundwater surrounding the well is also remediated. The artificial groundwater circulation determines the sphere of influence of a well and is overlapped with the natural groundwater flow (as described below).

In the case of DNAPL contamination, the UVB is operated upwardly as in Fig. 1(a). In the case of LNAPL, the contaminated water enters the well through the upper screen, is treated there by in situ stripping, and leaves the well through the lower screen.

**In situ bioremediation**

When the groundwater is contaminated by non-volatile substances, but which are suitable for bioremediation, the extensive circulation flow around the GZB (see Fig. 1(b)) can be used to distribute nutrients and/or electron acceptors throughout the unsaturated zone. Any water-soluble substance can be added in measured quantities while the groundwater passes the well casing. In this case the aquifer itself is used as a bioreactor. Alternately, a special bioreactor or other technologies have been installed within the well casing between the lower and upper screen in case of special

![Fig. 2](image_url) (a) In situ filter and/or reactor for sorption and/or degradation of contaminants using a groundwater circulation well (GZB), (b) on-site treatment using a groundwater circulation well (GZB).
contaminants (Fig. 2(a)). Of course, the latter in situ techniques can be directly combined with the in situ stripping for mixed contaminants, or for eliminating the biogas (e.g. CO₂, N₂) from the groundwater in the circulation. Eliminating CO₂ also prevents undesirable pH drops. In situ stripping is most suitable for the complete mixing of added nutrients with the groundwater.

When oxygen is needed for bioremediation, e.g. for hydrocarbons, O₂ saturation is attained inexpensively by in situ stripping with air (Fig. 1(a)). When the discharge through the well casing is increased, the quantity of captured groundwater flowing from upstream grows more slowly (Fig. 6(d)). It remains constant when several wells are in one line, normal to the natural groundwater flow. Thus, by intensifying the circulation flow around the UVB relative to the captured contaminated groundwater, the quantity of O₂ transferred to the contaminated water can be considerably increased.

ON-SITE REMEDIATION USING A GZB

When any on-site remediation technique is appropriate, e.g. for the elimination of dissolved heavy metals from the groundwater, the vertical circulation flow of a GZB can be utilized to advantage. The groundwater entering the well is pumped above ground, treated, and infiltrated in the same well using the other well screen (Fig. 2(b)).

Furthermore, following these ideas, the GZB can be also used as a pump or infiltration well for standard on-site remediations. In this case a partial discharge withdrawal or infiltration is taken from or added to the total discharge through the well casing (Fig. 3). There is a special ratio between the total well discharge and the extracted or infiltrated quantity of water that allows to extract or to infiltrate water without any change of head at the top of the well. This ratio has been derived numerically for confined aquifer conditions. Of course, at some distance from the well, a smooth deviation from the resting groundwater head will be found. However, in the case of low well capacity, continuous pumping can be realized at a higher rate. Infiltration can be carried out for a much greater quantity even for a small distance between the surface and the groundwater table. Furthermore, during the pump operation, the turbulent mixing of air and water in the filter gravel of the well, which often causes unwanted precipitation, can be avoided.

NUMERICAL-MODELLING INVESTIGATIONS

Flow systems of a GZB or UVB without extraction or infiltration

The vertical circulation flow around the GZB and UVB has been a matter of continuing numerical-modelling investigations (Herrling & Stamm, 1992). Up to now this has been achieved only for confined aquifer conditions, which permits the superposition of the flow fields of different wells and the natural groundwater flow; the local reduced pressure field (in case of a UVB) is neglected.

Further, density effects are ignored; only steady-state conditions are taken into account and, for estimating the capture zone, only convective transport is considered.
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The general character of the vertical circulation flow is demonstrated in Fig. 4. In a vertical longitudinal section parallel to the natural groundwater flow, streamlines mark the flow around two upward pumping GZB, their separation being made equal to the distance between stagnation point and well axis. The strong vertical circulation flow especially between the wells, which is extremely beneficial in a highly polluted area near the contamination source, is evident.

Figure 5 presents a view of the numerically calculated separating stream surfaces of nine water bodies in relation with the flow around three GZBs. They are positioned at a maximum distance normal to the natural groundwater flow so that no water can pass between the wells without having been treated. With the contaminated groundwater flowing from the left the following salient features can be clearly seen: the separating stream surfaces of the contaminated water captured by the three GZB (left), the surfaces of the water bodies having been treated and circulating around the wells (centre), and of the treated water flowing downstream (right).

Fig. 3 Groundwater circulation wells (GZB) for (a) extraction and (b) infiltration of water.

Fig. 4 Streamlines around two GZBs demonstrated in a vertical longitudinal section parallel to the natural groundwater flow.
At most remediation sites, a natural groundwater flow exists. Figure 6 shows numerical results represented in dimensionless form for the design of GZB or UVB installations under these conditions. In Fig. 6(a), the horizontal distance ($S$) of the stagnation point from the well axis is described. The ratio $S/H$ is dependent on the parameters $Q/(H^2v)$, $K_H/K_V$, and $a/H$. $Q$ denotes the vertical discharge through one well, $H$ the aquifer thickness, $v$ the natural Darcy velocity at the site, $a$ the length of the upper or lower screen section, and $K_H$ and $K_V$ the horizontal and vertical hydraulic conductivities. The location of the stagnation point is highly sensitive to the anisotropy of the aquifer.

The results of Fig. 6(b)-(d) have been calculated for an upstream distance of $5H$ from the well and for a constant ratio of $a/H = 0.25$. The results are discussed for wells that pump upward. The widths $B_T$ and $B_B$ of the upstream zone, measured at the aquifer top and bottom, are shown in Fig. 6(b). The ratios $B_T/H$ and $B_B/H$ are again dependent on the ratios $Q/(H^2v)$, $K_H/K_V$, and $a/H$. For small values of $Q/(H^2v)$, the upper part of the capture zone does not reach the top of the aquifer. This implies that for remediating a plume, a minimum well discharge ($Q$) is required. Again, the results are quite sensitive to the degree of the anisotropy.

When remediating a wide contamination plume, several wells are used in a line normal to the direction of the natural groundwater flow. The length ($D$) denotes the maximum well distance at which the contaminated groundwater cannot pass between the wells without being cleaned or treated. The ratio $D/H$ is dependent on the same parameters as before (Fig. 6(c)). When a plume of width $W$ is to be cleaned, the number ($n$) of well installations can be estimated by:

$$n = (W - B_T)/D + 1$$

When a plume is remediated, the contaminated water of quantity $Q_0$, flowing into the capture zone of a single well from upstream, is diluted with water that has already flowed through the well and circulates around it. Thus, the contaminant concentration
Fig. 6 (a) Distances ($S$) of the stagnation point from the well axis, (b) widths ($B_T$) and ($B_B$) of the upstream capture zone at the aquifer top and bottom, (c) maximum well distance ($D$) at which the contaminated groundwater cannot pass between the wells without being treated, (d) upstream discharge ($Q_0$) in the capture zone, which is diluted with the circulating water to the total well discharge ($Q$).

of the water within the well casing will be lower than in the upstream plume; near a contamination source, the situation is reversed.

Figure 6(d) illustrates the portion $Q_0$ of the total well discharge $Q$. The ratio $Q_0/Q$ is again dependent on the same parameters as the widths of the upstream capture zone. The sphere of influence of the circulation around a GZB, at sites with natural groundwater flow, is of special interest. In the direction of natural groundwater flow, this sphere has a maximum expansion of $S$ (see Fig. 6(a)) to the upstream and downstream sides. Normal to this direction, the maximum radius of the sphere of circulation is approximated by $(B_B + B_T)/4$ (Fig. 6(b)) and in the case of several wells
in one line by \( D/2 \) (Fig. 6(c)). Figure 6 can be used for the design of one GZB or a GZB field when the parameters \( K_{H}/K_{V} \) and \( Q/(H^2 v) \) can be estimated, and where \( Q \) depends on the well size and on the additional pump. For an irregular well field, a layered aquifer, or special critical cases, additional numerical calculations can be performed.

**Flow system of a GZB with groundwater extraction or infiltration**

Presently, numerical results are only available for the case of absence of natural groundwater flow and for confined aquifer conditions. When a GZB (Fig. 3(a)) is used to split the vertical well discharge \( (Q) \), pumped from the lower screen section, into an extracted quantity \( (Q_{E}) \) and an amount \( (Q_{C}) \), infiltrated in the upper screen section and generating the circulation flow around the well, it is possible to avoid any change of heads at the well top for a special ratio of \( Q_{E}/Q_{C} \). This ratio is only dependent on \( K_{H}/K_{V} \) and \( a/H \). Figure 7(a) demonstrates for \( a/h = 0.25 \), \( Q_{E} \) can be about two to three times of \( Q_{C} \) depending on the aquifer anisotropy.

For this special ratio of \( Q_{E}/Q_{C} \), the decrease of the head at the well bottom (no change of the heads at the well top) is \(-\Delta h\) (Fig. 7(b)). In a dimensionless description, \( \Delta h/H \) is dependent on the parameters \( Q_{E}/(H^2 K_{H}) \), \( K_{H}/K_{V} \), and \( a/H \) (Fig. 7(b): \( a/H = 0.25 \)). An important check of cavitation below the packer can be carried out using this diagram.

In the case of infiltration of a quantity \( (Q_{i}) \) in a GZB (Fig. 3(b)), the ratio \( Q_{i}/Q_{C} \) can be taken from the diagram of Fig. 7(a) as well, when no change of heads is demanded at the well top. In this case, \( Q \) leaves the GZB through the lower screen and \( Q_{C} \) enters the well through the upper screen. The increase of head \( \Delta h \) at the well bottom can be estimated from Fig. 7(b).

At some distance \( (r) \) from the well axis, a maximum head deviation \( (f) \) from the resting water level will result at the aquifer top. The dimensionless parameter \( r/H \) is dependent on \( K_{H}/K_{V} \) and \( a/H \), and \( f/H \) (negative for groundwater extraction and positive for infiltration) depends on \( Q_{E}/(H^2 K_{H}) \), \( K_{H}/K_{V} \) and \( a/H \). Figures 7(c) and 7(d) present results for \( a/H = 0.25 \).

**ADVANTAGES OF A GZB AND UVB**

The technologies presented, in particular the vertical circulation flow, offer many advantages, especially when compared with a standard pump and treat system. In addition to the advantages explained above, these are:

(a) For wells operating upward, no lowering of the heads appears;
(b) even at low well capacity, remediation operation is continuous;
(c) less permeable, horizontal layers are penetrated vertically;
(d) the remediation of the groundwater takes place down to the aquifer bottom;
(e) the groundwater flow regime is influenced only locally in case of no partial discharge withdrawal or infiltration;
(f) in a closed air circulation of a UVB unwanted pH increases and the involved precipitation process can be avoided;
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(a) $a / H = 0.25$

(b) $a / H = 0.25$

Fig. 7 (a) Ratio $Q_E/Q_C$ and $Q_f/Q_C$, (b) head changes $\Delta h$ at the well bottom, (c) distance $r$ from the well axis with maximum head deviation $f$, and (d) maximum head deviation $f$.

(g) the presented in situ technology avoids waste-water discharge and groundwater extraction.

Acknowledgements The authors gratefully acknowledge IEG mbH, D-7410 Reutlingen (Germany), for financially supporting these investigations. Further, B. Bernhardt, IEG mbH, inventor and patent holder of the GZB and UVB method, and E. J. Alesi, IEG
Technologies Corp., Charlotte, North Carolina 28217 (USA), are thanked for many helpful discussions.

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