AN OVERVIEW OF *IN SITU* VERTICAL GROUNDWATER CIRCULATION WELL TECHNOLOGIES

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INTRODUCTION

Vertical groundwater circulation well (GCW) technology has been used in Europe since 1986 and in the U.S. since 1992 for numerous groundwater and soil treatment applications [8]. Today, GCW-based technologies are being applied to a growing number of sites in an attempt to affect *in situ* source management and treatment of organic and/or inorganic constituents of interest (COI) in the dissolved phase. New system designs have also proved effective under full-scale field conditions for enhancing the recovery of non-aqueous-phase liquids.

However, not all of these installations have met the remedial goals or design expectations. Our experience suggests these system “failures” were due to inappropriate selection, design, installation or performance monitoring of the GCW systems. Given the continued interest in the potential usefulness of GCW technologies, it is becoming increasingly important to understand some of the benefits and limitations inherent to the systems.

Toward this end, it is instructive to understand the principles and theories behind the operation of GCW systems. With this information, the potential usefulness of the technology for a specific site can be more accurately assessed, the most appropriate GCW system can be selected, and the proper monitoring network for validating system efficacy can perhaps be established.

PRINCIPLES OF GCW OPERATION

Vertical GCW systems commonly focus on creating *in situ* vertical groundwater circulation cells by drawing groundwater from an aquifer formation through one screen section of a double-screened well and discharging it through the second screen section (Figure 1). This circulation commonly occurs from the top of the formation to the bottom (herein termed “standard flow”). Under standard flow conditions, groundwater is moved upward inside the remediation well. Groundwater flow upward through the GCW can be achieved via an airlift effect, or, as is the case with the UVB technology (see below), it can be induced via an in-well groundwater circulation pump. The circulation cell flow path thus encompasses groundwater flowing from the upper part of the treatment zone into the lower part of the GCW well.

In a reverse circulation mode, the flow of groundwater within the GCW well is downward via the aid of an in-well groundwater pump (*i.e.*, water flows from the bottom of the aquifer formation in a torroidal upward pattern, or from the top of the GCW to the bottom). In the reverse circulation mode, water in the lower half of the aquifer moves away from the well while water in the upper half of the aquifer moves toward the well.

In both the standard and reverse flow modes of operation, groundwater is circulated around the central GCW, but none is removed from the aquifer. Thus, induced differences in potentiometric head establish and maintain the 3-dimensional circulation cell in an ellipsoidal area around the circulation well [5, 8]. The majority of the groundwater captured by the circulation cell circulates a number of times through the GCW before being released downgradient. As such, water serves as the *in situ* carrier bringing COI from throughout the capture zone to the GCW system were it is treated and then discharged back into the formation. The vertical and horizontal circulation flow patterns force water to move through the entire aquifer portion within the circulation cell thus improving COI mobilization by forcing flow through less permeable formation and lenses.

With natural groundwater flow, the total amount of water circulating around a GCW will consist of a) upgradient water being captured, and b) groundwater being re-circulated. The relationship of a:b is typically 15:85, respectively [5]. Thus, of the total volume of groundwater being circulated in the cell at any time, 15% represents upgradient, potentially impacted water. An equal portion of groundwater will exit the circulation cell in the downgradient release zone. As discussed below, these flow dynamics and dimensions of the capture zone, circulation cell, and release zone can be mathematically calculated for a specific site and used as design aids based on numerical simulations of the groundwater hydraulics.

COMMERCIALLY AVAILABLE GCW SYSTEMS

Vertical GCW technologies are commercially available through a variety of equipment vendors. These include:

1. Density Driven Convection (DDC) Wells, Wasatch Environmental, Salt Lake City, UT (801) 972-8400;

2. NoVOCs:EG&GEnvironmental,Pittsburgh, PA (412) 920-1341; and

3. Unterdruck Verdampfer Brunnen (UVB) and Coaxial Groundwater Sparging (CGS): IEG Technologies Corp., Charlotte, NC (704) 599-4818.

Each of these systems has unique benefits (and disadvantages) inherent to the design, hence they each enjoy some degree of patent protection (Table 1). For example, both the DDC and NoVOCs systems operate under positive pressure to circulate water via an airlift effect. Alternatively, the UVB system utilizes a vacuum blower enhanced by an in-well pump to support groundwater flow, and the CGS system combines positive and negative pressure in the same well.

POTENTIAL ADVANTAGES OF GCW SYSTEMS

Depending in large part on site-specific hydrogeological conditions presented below, and other site parameters, an *in situ* remedial approach employing GCW technology could potentially offer the following advantages:

1. Enhanced groundwater treatment and accelerated remediation time due to the ability of the GCW system to create vertical and horizontal components of groundwater flow;
2. Simultaneous treatment of the saturated zone and unsaturated zone;
3. Simultaneous treatment of organic COI (stripping, accelerated *in situ* biodegradation) and removal of inorganic COI (physical removal via ion exchange);
4. *In situ* treatment without groundwater removal from the subsurface;
5. Very low energy requirements; and
6. More cost-efficient treatment when compared to conventional pump-and-treat.

GCW MODE OF ACTION

Each GCW system combines biotic and abiotic processes to affect COI removal or destruction of COI:

<u>*In situ* soil flushing</u>: Movement of groundwater in a circular mode is realized through vertical groundwater circulation. The circulating groundwater constantly transports the newly dissolved COI to the well, wherein they are removed thus clean groundwater is released back into the aquifer. The radius of influence of each GCW is very site specific, but for the UVB and NoVOCs systems, it has been shown to range between 3- and 5-times the thickness of the saturated zone being treated. For the DDC and CGS systems, the ratio is often closer to 1:1.

<u>Physical stripping</u>: In-well aeration yields *in situ* stripping of VOCs from groundwater. Physical stripping is achieved under either positive pressure (DDC, NoVOCs), vacuum (UVB technology), or both (CGS).

<u>Accelerated biodegradation</u>: In-well aeration also results in the addition of oxygen to the groundwater that is returned to the aquifer and circulated throughout the formation. Combined with the overall mixing effect, this serves to enhance the rate and extent of *in situ*, aerobic biodegradation of susceptible organic COI. The catabolic activity of the resident microflora can be further stimulated through the addition of rate-limiting inorganic nutrients to the circulating groundwater.

ENHANCED MODE OF ACTION: SYSTEM MODIFICATIONS

The design and patent of the UVB technology allows for unique engineering modifications to effect treatment of inorganic COI and recalcitrant organics. For example;

In-well bioreactors: aerobic, *in situ* bioreactors integrated with the UVB system have proved effective, under field conditions, in accelerating the rate and extent of biodegradation of high-molecular-weight polycyclic aromatic hydrocarbons [6], chlorinated solvents [4], and pesticides [3].

Immobilization: For the removal of inorganic COI not subject to physical stripping or biodegradation (*i.e.*, dissolved heavy metals), their removal from circulating groundwater is accomplished through the integration of an ion exchange matrix or a fixed-film reactor. Induced groundwater circulation constantly supplies the remediation well with new mobilized dissolved metals that need to be extracted from the groundwater before it is released back into the aquifer.

Stacked cells: In situations where the thickness of the saturated zone is large (*e.g.*, >60 feet) or the flow of groundwater is too great for the GCW to yield effective treatment, stacked circulation cells can be accommodated by the UVB system. For example, using three screen sections within the same GCW (upper, middle and lower), groundwater enters the GCW well through the middle screen section that is positioned strategically within the impacted aquifer. After treatment, clean groundwater is pumped to and discharged from the upper and lower screen sections. Thus, two stacked circulation cells are created: 1) an upper circulation cell (standard-flow), and 2) a lower circulation cell (reverse-flow).

MODELING GCW EFFICACY

Successful application of GCW technology requires that its zone of influence (ZOI) be known and predicted prior to installation. Various mathematical models, which rely on the input of accurate geologic and hydrogeologic data, exist to estimate the ZOI of these treatment systems.

Aquifer Parameters

The site-specific aquifer parameters clearly exert the greatest influence on GCW operation and efficacy. The following are typical of those factors considered important in the proper selection and design of a GCW system:

1. COI type and concentration;
2. COI plume dimensions;
3. Vertical saturated thickness of the aquifer containing COI;
4. Depth to groundwater;
5. Seasonal fluctuation in depth;
6. Groundwater flow direction;
7. Remedial objectives;
8. Average expected COI load;
9. Aquifer type (confined, unconfined);
10. Horizontal hydraulic conductivity (Kh);
11. Vertical hydraulic conductivity (Kv);
12. Hydraulic gradient;
13. Groundwater flow velocity;
14. Aquifer porosity;
15. Geology (boring logs, presence of confining layers); and
16. Inorganic elements (Ca, Mg, Fe, Mn).

Engineering and Design Parameters

The hydraulic influence of a GCW system also depends on a number of engineering and design parameters specific to a given application. Specifically,

1. Internal groundwater pumping rate;
2. Length of screen sections;
3. Distance between screen sections; and
4. Well diameter.

Mathematical Modeling

For each GCW system, a unique, site-specific hydraulic zone of influence will be established. Given the information above, a number of mathematical modeling programs can be employed to predict this complicated response. Dr. Bruno Herrling and colleagues [5] developed the first such program. Throughout the years, this program has been continually modified based on the results of literally hundreds of full-scale field installations, such that it often provides the most accurate prediction of GCW flow dynamics.

The following estimations, assumptions and simplifications are often used for the purpose of modeling the hydraulic zone of influence for a site-specific GCW configuration:

1. The aquifer thickness is constant;

2. The aquifer is under confined conditions;
3. The aquifer structure is assumed radially homogeneous to hydraulic conductivity;
4. Multiple horizontal layers may be used that are anisotropic and have only one vertical and one horizontal conductivity;
5. The local below-atmospheric pressure field near the well is neglected;
6. Density effects are neglected;
7. The computations assume steady-state conditions; and
8. Only convective transport is considered.

Modeling Results

Results of Herrling's modeling of site conditions offers values for various hydraulic parameters of the GCW systems (see Figure 2 for example):

1. The upstream and downstream stagnation points (S) = 53 ft;
2. The bottom width of capture zone (Bb) = 170 ft;
3. The top width of capture zone (Bt) = 24 ft;
4. Effective hydraulic radius of influence (r) = 48 ft;
5. The distance D (maximum spacing between GCW systems); and
6. Circulation time (that required for a unit volume of water to move from the outflow zone of the well through the zone of influence of the GCW system, and back into the inflow zone of the well).

GCW DESIGN AND CONSTRUCTION

Considering the modeling data above, the most appropriate GCW system and design configuration can be selected for a specific site. Once selected, factors associated with well installation and construction need to be carefully considered because they have a significant influence on the *in situ* operation of the systems.

These factors include:

1. Drilling method;
2. Selection of screen materials;
3. Placement of screen sections;
4. Well development; and
5. Air flow and water flow

PERFORMANCE MONITORING

As with any advanced or emerging technology, it is often necessary to invest additional time and resource into the establishment of a monitoring network that clearly documents that the system is operating as designed. In many cases, such a network is not properly established, thus leading to uncertainty regarding system efficacy. In other cases, the network is established, but the sampling locations are not based on the hydraulics associated with the GCW influence.

Establishment of Monitoring Network

Considering the GCW dynamics presented in Figure 2, it is obviously essential to understand the 3-dimensional, ellipsoidal flow dynamics and general principals behind GCW operation prior to selecting the vertical and horizontal placement of performance monitoring wells. A typical configuration of monitoring wells entails replicate sampling points located upgradient, cross-gradient and/or down-gradient of the groundwater circulation cell, with points located both inside and outside the hydraulic zone of influence [6]. For a GCW containing only two screen sections, each of these performance monitoring wells should be nested and screened appropriately to allow for discrete groundwater sampling of upper and lower zone of influence. In addition, it is often useful to equip each GCW system with 2-inch annular piezometers, individually screened at each location of the GCW screens. For GCW systems designed with more than two screen sections (*i.e.*, stacked cells), or for multiple GCW systems designed to have overlapping ZOI (*i.e., in situ* biocurtain), the establishment of a proper monitoring network becomes more complicated.

Performance Monitoring Parameters

A number of physical, chemical and/or biological parameters can be measured on various substrates in an effort to better characterize the operation and performance of a GCW system. For example, general monitoring of GCW operation may include physical measurement of:

- Groundwater flow rate, temperature, and cumulative volume;
- Air flow rate, temperature, and relative humidity; and
- Packer pressure (if appropriate); and

Intermittent monitoring of the various chemical parameters in system influent and effluent can be used to assess treatment efficacy of a GCW system:

- Off-gas (COI)
- Groundwater influent (COI, DO, pH)
- Groundwater effluent (COI, DO, pH)

Intermittent monitoring of a variety of physical and chemical parameters in groundwater monitoring wells positioned strategically around a GCW system can be useful in further determining system efficacy:

- DO
- pH
- COI analysis
- Piezometric head

Data Interpretation

The ability of a GCW system to effectively remove COI from groundwater is relatively easy to establish. This is done by comparing change in COI concentration in groundwater samples from:

- GCW influent
- GCW effluent
- Groundwater upgradient
- Groundwater downgradient
- Off-gas

Through these measurements, GCW system stripping efficiency can be calculated, and a pseudo-mass balance of COI can be obtained.

Physical Validation of Flow Dynamics

In addition to COI removal, physical validation of modeled hydraulic parameters is often useful to field validate system efficacy. These data can help validate theoretical predictions of flow fields, and the zone of influence of a GCW installed at a specific site. There are at least three ways in which this can be determined: pressure transducers, dye tracers, and *in situ* flow sensors.

Pressure Transducer Testing

Pressure transducers can be employed to provide physical measurements of changes in piezometric head to yield a detailed, 3-dimensional picture of pressure heads induced by the GCW system. Ideally, pressure transducers are installed in the natural formation since using transducers in piezometers may create disturbances from flow through the sand pack and the well screens. However, the head changes between two points in an aquifer separated by greater than 20 ft can be significant. Thus, when measuring relative changes in hydraulic head (between deep and shallow), transducers can be used in the piezometers. All transducers must be equilibrated with a barometer before installation and during operation, and surveyed to a common datum (*e.g.*, top of the GCW well flange).

Dye Tracer Studies

Dye traces provide evidence of hydraulic connection between points of dye injection and dye recoveries in an aquifer [1, 7]. However, dye traces do not provide the information necessary to quantify the dynamics, and the boundaries of flow fields generated around the well. The success of a dye tracer test depends on the flow path, and the ability of groundwater to travel from the dye injection point to the dye recovery point. This is determined by conducting the dye tracer study using a network of strategically located groundwater monitoring wells around the treatment system [4].

In Situ Groundwater Flow Sensors

More recently, *in situ* permeable flow sensors have been used which use a thermal perturbation technique to measure the three-dimensional groundwater flow velocity vector [2]. This technique overcomes the sensitivity limitation of the pressure transducer test by measuring the flow vector and not the pressure head. However, this technique can provide erroneous results in areas where heat sinks exist in the aquifer.

Pressure Transducer Case Study

Mathematical modeling of a GCW ZOI at an installation in south central Florida [6] involved calculation of a radially symmetric flow field using a Galerkin finite element method with linear shape functions and triangular elements. The natural horizontal flow field was then superimposed on a rectangular three-dimensional grid by interpolating and adding the respective velocity vectors. Specifically, the radially symmetric model consisted of 5000 finite elements with 2877 nodes. Mathematical modeling of the system predicted that a 120 ft diameter ZOI would be created by the GCW system at a flow rate of 8 gpm.

In an attempt to physically validate modeled values, a grid of twelve transducers was installed in the vicinity of the treatment well at radial distances of 10, 20, and 30 ft from the treatment well at two depths of 12 ft and 22 ft below ground surface. Changes in pressure heads created by the treatment system were measured at groundwater flow rates in the range of 1 to 3 gpm (the aquifer would not sustain flow at 8 gpm). Measurable changes in piezometric heads were recorded at all locations. Piezometric head data from the upgradient transducers at recirculation flow rate of 2 gpm are shown in **Figure 3**. The established flow fields around the well were consistent with the standard circulation mode of operation of the GCW in that the shallow aquifer water seemed to flow away from the UVB well, while in the deep aquifer water seemed to flow towards the UVB well. These data validated that a three-dimensional circulation cell with a radius of 20 to 40 ft was established around the UVB well.

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FIGURE 3

Piezometric Heads Around UVB-400
Blower and Pump ON, Q = 2 gpm
Transducer Test, KII - Gainesville