Research Paper

Numerical Simulation of Water Table Drawdown due to Groundwater Pumping in a Contaminated Aquifer System at a Shooting Test Site, Pocheon, Korea

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Research Highlights

- A pump and treat remediation method has been proposed in the shooting test site.
- Before and during groundwater pumping in a contaminated aquifer, groundwater flow was simulated, calibrated, and predicted.
- Simulations show that the distribution and properties of the geologic media have significant effects on the groundwater depression zone.

ABSTRACT

The study area has been contaminated with explosive materials and heavy metals for several decades. For the design of the pump and treat remediation method, groundwater flow before and during groundwater pumping in a contaminated aquifer system was simulated, calibrated, and predicted using a generalized multidimensional hydrological numerical model. A three-dimensional geologic formation model representing the geology, hydrogeology, and topography of the aquifer system was established. A steady-state numerical simulation with model calibration was performed to obtain initial steady-state spatial distributions of groundwater flow and groundwater table in the aquifer system before groundwater pumping, and its results were illustrated and analyzed. A series of transient-state numerical simulations were then performed during groundwater pumping with the four different pumping rates at a potential location of the pumping well. Its results are illustrated and analyzed to provide primary reference data for the pump and treat remediation method. The results of both steady-state and transient-state numerical simulations show that the spatial distribution and properties of the geologic media and the topography have significant effects on the groundwater flow and thus depression zone.

Keywords : contaminated aquifer system, groundwater pumping, groundwater drawdown, pumping and treat remediation, numerical simulation

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1. Introduction

In modern times, as the performance and destructive power of the weapons used in a war increases, many countries have been operating a large number of explosive or artillery fire and shooting test field sites to develop and test these weapons. These sites have been in operation for several decades, and there is a high probability that the contamination has been in progress for a long period of time. These test field sites have already been reported to be contaminated with explosive compounds such as TNT (trinitrotoluene), RDX (Royal Demolition Explosive), and HMX (High Melting Explosive) and heavy metals such as Cd, Cu, and Pb (Best *et al.*, 1999; Chen *et al.*, 2000; Cao *et al.*, 2003; Dermatas *et al.*, 2006; Ryu *et al.*, 2007). TNT and RDX are harmful substances that can damage the human body when exposed and classified as a possible human carcinogen (weight of evidence for cancer Group C) by USEPA (2016). HMX is also harmful while it is not classifiable as to human carcinogenicity (WOE Group D) (USEPA, 2016). On the other hands, heavy metals are also harmful materials and act as human body risk factors through various pathways such as oral, inhalation, and dermal exposure (USEPA, 2007). These toxic compounds and metals generally pollute the soil in the test field sites due to unexploded or incomplete oxidation (Brannon and Pennington, 2002; Cao *et al.*, 2003). Besides, they are likely to be dissolved or eroded during heavy rainfall and can migrate into surface or subsurface water environments (Cao *et al.*, 2003; Abadin *et al.*, 2012).

The pump and treat remediation method is an effective countermeasure to treat soluble pollutants that have spread over a wide area or penetrated the groundwater aquifer system (USEPA, 1996; 2007). This method is a technique that extracts the contaminated groundwater from the aquifer, removes pollutants through various treatments (e.g., precipitation, coagulation, reduction, distillation, membrane separation, and biological reaction), and finally re-injects the treated groundwater into the aquifer or discharges it into a river or lake. This method is widely used because it can be applied to not only a small site but also a large-scale site. It is also highly adaptable for removing soluble pollutants on the explosive or artillery fire and shooting

test field sites mentioned above. In order to effectively utilize the pump and treat remediation method, it is necessary to design an optimal pumping well and operation schemes based on a deep understanding of groundwater flow in the actual complicated aquifer system (USEPA, 1996). In such a design procedure, numerical modeling can be used as an effective and practical tool because it can predict the critical groundwater pumping rate and the extent of the influenced area due to groundwater pumping under various hydrological conditions and scenarios.

This study aims to analyze groundwater flow before and during groundwater pumping in an aquifer system and to evaluate the impact of groundwater pumping on the aquifer system and depression zone of groundwater table as a contaminant catchment for the pump and treat remediation method. To achieve these objectives, the geologic and hydrogeologic settings of an aquifer system considered in this study and its geologic formation model, material properties, and boundary conditions are described. Groundwater flow before and during groundwater pumping in the unsaturated complicated aquifer system is simulated, calibrated, and predicted using the generalized multidimensional hydrological numerical model. The impact of groundwater pumping and the fate of the depression zone in the aquifer system are also suggested from a series of transient-state numerical simulations.

2. Study Area

2.1. Location and environment

The aquifer system considered in this study is located in the Pocheon area, Gyeonggi Provinces, Korea. The modeling domain is surrounded by a ridge of the Jongja Mountain up to about 445 m high above the mean sea level from the north to the east, forming a watershed (groundwater divide), while the low-lying alluvial and colluvial plains are facing the Hantan River to the south, and an unnamed small stream to the west (Fig. 1).

The aquifer system includes one of the largest explosion and shooting field test sites, named the Darakdae Training Field. The site has been used as a military test facility for US and ROK military forces for several decades after the end of the Korean War. A recent study has reported that

Fig. 1. Satellite image map of the study area with the modeling domain.

the site area has been contaminated with explosive materials such as TNT, RDX, and heavy metals (Ministry of National Defense, Korea, 2002). Among these pollutants, water-soluble materials are likely to cause water pollution in the Imjin River water system through the Hantan River, resulting in problems in the supply of agricultural and domestic water in the lower region. Among the countermeasures for removing such water-soluble contamination, a pump and treat remediation method has been proposed. Thus, a series of three-dimensional numerical simulations of groundwater flow has been seriously requested to evaluate the extent of contaminant catchment and to design the optimal pumping rates. From May to August 2013, the groundwater levels at seven monitoring wells were measured eight times in the study area (Corporation of Moum and Naum, 2013). During the same period, the falling head test, slug test, and pumping test were conducted. Their average and range were used in the model calibration.

2.2. Geologic and hydrogeologic settings

The aquifer system is geologically composed of the Quaternary sediments (i.e., alluvial and colluvial sediments, topsoil, and weathered rocks) underlain by the Quaternary

basalt, the Cretaceous clastic sedimentary rocks and tuff, and the Devonian sedimentary rocks in descending order (Korea Institute of Geoscience and Mineral Resources, 2008). All rocks before the Cretaceous are highly consolidated and partly metamorphosed, and thus they can be regarded hydrologically as a bedrock. The basalt erupted in the Quaternary, and since it flowed and filled at the lower area and valleys, it is narrowly distributed along the present river and stream. Generally, a basalt rock mass has higher hydraulic conductivity when it has several fractures such as sheeting and vertical joints or clinker structure, which are formed during a cooling period (Domenico and Schwartz, 1990; Kulkarni *et al.*, 2000). The upper part of the bedrock and basalt consists of a weathered zone with various thicknesses, and sediments cover it. Depending on the mechanism and cause of their forming, the sediments are classified into the following three types: alluvium, colluvium, and topsoil.

3. Methods

3.1. Numerical model

The hydrological numerical model used in this study is COFAT3D (Kim and Yeh, 2004), which has been developed from 3DFEMFAT (Yeh *et al.*, 1994). 3DFEMFAT is one of the most widely used finite element models to simulate a variety of density-dependent groundwater flow and advective-dispersive single-component solute (i.e., salt) transport phenomena due to various causes in saturated-unsaturated heterogeneous and anisotropic porous geologic media. It is also implemented as 3DFEMWATER in GMS (Groundwater Modeling System) developed by the Environmental Modeling Systems, Incorporated (<http://www.ems-i.com>). COFAT3D (Kim and Yeh, 2004) is a generalized multidimensional hybrid Lagrangian-Eulerian finite element model and can simulate density-dependent groundwater flow and advective-dispersive multicomponent solute transport in saturated-unsaturated heterogeneous and anisotropic porous, fractured, and fractured porous geologic media (i.e., intact rock matrices or soils, individual joints, and jointed rock masses, respectively). COFAT3D can also simulate precipitation-evapotranspiration-infiltration-seepage processes and calculate rates and amounts of groundwater and solutes, which are discharged into or recharged from arbitrary structures such as wells and tunnels, using the so-

called element cluster technique.

3DFEMFAT was successfully verified through different groundwater flow and solute transport problems, including groundwater pumping, by comparing the simulated groundwater level with the analytic solution and benchmarking with the results of other numerical models (Yeh *et al.*, 1994; Yeh, 1999). COFAT3D was validated through the seawater intrusion problem in the lab-scale sandbox by comparing the simulated groundwater table and seawater interface with the measured values in the analog model (Kim, 2006). In a fluvial aquifer system, three-dimensional simulation of groundwater flow and land deformation was performed and validated by comparing the simulated hydraulic head and vertical displacement with the measured values at the three monitoring points using COWADE123D, which has the same numerical implementation for ground-

water flow with COFAT3D (Kihm *et al.*, 2007). COFAT3D also has been applied to several field-scale problems, including groundwater pumping (Oh and Kim, 2008; Park *et al.*, 2008; Cho and Kim, 2009; Park *et al.*, 2012; Park *et al.*, 2015; Lee and Kim, 2015). COFAT3D is quite suitable for evaluating the impact on the aquifer system due to groundwater pumping.

3.2. Numerical Modeling Setup

The lateral sides (boundaries) of the modeling domain as a watershed are determined considering the mountain ridges (from the north to the east), the Hantan River (the south), and the unnamed stream (the west) (Fig 1). The top sides of the modeling domain are horizontally irregular with topography. The bottom side of the modeling domain is horizontally flat and located at a depth of 100 m below

Fig. 2. Three-dimensional geologic formation models of the aquifer system with (a) bedrock and basalt overlain by (b) weathered zone, and (c) topsoil, alluvium, and colluvium, and (d) three-dimensional finite element mesh. The vertical coordinate axis z is exaggerated twice.

the mean sea level. A three-dimensional geologic formation model representing the geology, hydrogeology, and topography of the aquifer system is established considering the boundaries mentioned earlier (Fig. 2). The topography is based on the digital elevation map (National Geographic Information Institute, 2016). The two hard rocks (i.e., basalt and bedrock; Fig. 2a) and weathered zone (Fig. 2b) are included in the three-dimensional geologic formation model. The alluvium, colluvium, and topsoil are also included in the geological formation model considering their irregular thickness and lateral extent from a statistical analysis of borehole test results (Corporation of Moum and Naum, 2013) (Fig. 2c). The three-dimensional geologic formation model is then transformed into a three-dimensional finite element mesh, which is discretized into 73,437 hexahedral elements with 80,850 nodes (Fig. 2d).

The material properties of the six geologic media (i.e., bedrock, basalt, weathered zone, alluvium, colluvium, and

topsoil) are obtained from a variety of geological surveys and hydrogeological tests, as well as the literature. The porosity is obtained from several literatures (Morris and Johnson, 1967; Davis, 1969; Istok, 1989). The saturated hydraulic conductivity is obtained from the field hydrological tests (Corporation of Moum and Naum, 2013) and the literature (Domenico and Schwartz, 1998). It is statistically analyzed, and the geometric mean and range of the six geologic media are used as initial guess and limitation values for the calibration process. The compressibility of the geologic media is obtained from the literature (Freeze and Cherry, 1979). The compressibility of water is set equal to $4.40 \times 10^{-10} \text{ m}^2/\text{N}$, and the dynamic viscosity of water is set equal to $1.124 \times 10^{-3} \text{ kg/m/s}$ (Freeze and Cherry, 1979). The constitutive relationships suggested by van Genuchten (1980) are employed in this study to consider the changes in the unsaturated hydraulic properties (i.e., degree of water saturation and relative hydraulic conductivity)

Table 1. Material properties of the geologic media

Property	Bedrock	Basalt	Weathered rock	Topsoil	Colluvium	Alluvium
Porosity of rock matrix [dimensionless] ⁽¹⁾	0.05	0.10	0.15	0.35	0.30	0.43
Saturated hydraulic conductivity [m/s] ⁽²⁾						
Minimum value	5.99×10^{-9}	4.00×10^{-7}	1.03×10^{-7}	-	1.02×10^{-6}	-
Maximum value	1.05×10^{-7}	2.00×10^{-2}	2.18×10^{-5}	-	9.21×10^{-6}	-
Geometric mean (initial value)	2.50×10^{-8}	8.94×10^{-5}	3.34×10^{-6}	1.23×10^{-5}	3.43×10^{-6}	8.25×10^{-5}
Final value (after calibration)	1.05×10^{-7}	1.75×10^{-5}	8.67×10^{-6}	1.23×10^{-5}	9.21×10^{-6}	8.25×10^{-5}
Compressibility [m^2/N] ⁽³⁾	1.00×10^{-10}	1.00×10^{-10}	1.00×10^{-9}	1.00×10^{-8}	1.00×10^{-8}	1.00×10^{-8}
Residual water saturation S_{wr} [dimensionless] ⁽⁴⁾	1.94×10^{-1}	2.32×10^{-1}	1.81×10^{-1}	1.59×10^{-1}	2.56×10^{-1}	1.05×10^{-1}
van Genuchten's unsaturated hydraulic parameters						
α_v [m^{-1}] ⁽⁴⁾	0.50	1.90	3.60	7.50	5.90	14.50
n_v [dimensionless] ⁽⁴⁾	1.09	1.31	1.56	1.89	1.48	2.68

(1) The porosity of the bedrock is an average value of the fractured crystalline rock (Davis, 1969), the porosity of the basalt is the highest value of the basalt (Istok, 1989), the porosity of the weathered rock is the highest value of the fractured igneous and metamorphic rocks (Istok, 1989), the porosity of the topsoil is an average value of the silt (Morris and Johnson, 1967), the porosity of the colluvium is an average value of the gravel (Istok, 1989), and the porosity of the alluvium is an average value of the fine sand (Morris and Johnson, 1967).

(2) Two values of bedrock's hydraulic conductivity are measured by the falling head test in the BH-5 and BH-6 (Corporation of Moum and Naum, 2013). Six values of weathered rock's hydraulic conductivity are measured by the falling head test and slug test in the BH-2 and BH-3, and the pumping test in the BH-6. Seven values of colluvium's hydraulic conductivity are measured by the falling head test in the BH-2 and BH-3. The hydraulic conductivity of the topsoil and alluvium is measured by the falling head test in the BH-8 and in the BH-9, respectively. The hydraulic conductivity of the basalt is obtained from the range and a geometric mean of the permeable basalt in the work of Domenico and Schwartz (1998).

(3) The compressibility of the bedrock and basalt is a geometric mean of the sound rock, the compressibility of the weathered rock is a geometric mean of the jointed and weathered rock, and the compressibility of the topsoil, colluvium, and alluvium is a geometric mean of the sand and silt sediments in the literature (Freeze and Cherry, 1979).

(4) The residual water saturation and unsaturated hydraulic parameters of the geologic media are obtained from the values of soil in the literature (Carsel and Parrish, 1988), which has the most similar hydraulic conductivity with each media.

by unsaturated water flow. The residual water saturation S_{wr} and van Genuchten's unsaturated hydraulic parameters α_v and n_v of the geologic media are obtained from Carsel and Parrish (1988) considering their saturated hydraulic conductivity values. The material properties and their details are described in Table 1.

Along the lateral boundaries, a no-flow boundary condition is assigned considering the groundwater divide (watershed). Along the top boundary, a variable precipitation-infiltration-seepage flow boundary condition (Huyakorn *et al.*, 1986; Yeh, 1987, 1999) with the net precipitation rate (difference between the precipitation and the evapotranspiration) is applied. The net precipitation rate is set equal to 10.0% (i.e., 153 mm/year) of the annual average precipitation rate of 1,530 mm/year in the Pocheon area (Korea Meteorological Administration, 1998-2012) considering evapotranspiration. Along the top boundary below the Hantan River and stream, a fixed hydraulic head boundary condition is applied to take into account its water level. Along the bottom boundary, a no-flow boundary condition is assigned considering the deeper impermeable bedrock.

4. Results

4.1. Steady-state numerical simulations (before groundwater pumping)

In this study, a series of trial-and-error steady-state numerical simulations without groundwater pumping is performed during the model calibration by comparing the average measured groundwater levels at seven monitoring

wells (Corporation of Moum and Naum, 2013) with the simulated groundwater levels at the corresponding nodes. Model calibration procedure started from the geometric mean of the saturated hydraulic conductivity. The conductivity was repeatedly adjusted to minimize the RMSE (Root Mean Square of Error) between the observed and simulated values of groundwater level. The results of the model calibration are plotted in Fig. 3, and calibrated values of the saturated hydraulic conductivity and unsaturated parameters are summarized in Table 1. As shown in Fig. 3, the RMSE is improved from 9.71 m to 2.77 m through the model calibration. Although the spatial distribution of the observations is limited compared to the entire modeling domain and their elevations are concentrated in a specific area, the simulated groundwater level meets within the scope of observed groundwater level in all boreholes except the BH-4.

The initial steady-state spatial distributions of groundwater table in the aquifer system before groundwater pumping are illustrated in Fig. 4. The isosurface of the pressure head is steeply curved along the valley and the ridge due to the topography (Fig. 4a). The isosurface of the hydraulic head is vertically erected in the southwestern plain area, whereas it lies horizontally in the northeastern mountain area due to unsaturated hydraulic responses (i.e., reduction of hydraulic conductivity under unsaturated zone) (Fig. 4b). The groundwater generally flows perpendicular to the isosurface of the hydraulic head. Thus, its distribution shown in Fig. 4b indicates that the vertical flow of the groundwater is dominant (i.e., recharge dominant) in the

Fig. 3. Comparison of measured and simulated groundwater levels at the monitoring wells (a) before and (b) after model calibration. The error bars indicate the standard deviation of measured groundwater levels for each well.

Fig. 4. Initial steady-state spatial distributions of (a) pressure head and (b) hydraulic head on three-dimensional viewpoint, and groundwater table (i.e., zero reference pressure head) elevation on (c) plane view and (d) enlarged around the borehole BH-5. In Fig. 4(c), the square with black solid lines refers to the area boundary of Fig. 4(d), and the square with black dashed lines refers to the area boundary of Fig. 6.

mountain area under an unsaturated condition, whereas the horizontal flow dominant (i.e., transport dominant) in the plain area under a saturated condition. Groundwater flows from the mountain ranges toward the central plain and then discharges to the Hantan River along the southwestern boundary (Fig. 4c). In the west area of the border between the basalt and bedrock, the gradient of the groundwater table is relatively weaker than that of the east area of the border (Fig. 4d). The groundwater table is lower on the basalt area. This contrast of groundwater table is due to the relatively higher saturated hydraulic conductivity of the

basalt than that of the bedrock. Similarly, the difference in groundwater table gradient is shown over the boundary between topsoil (northeastern part) and colluvial sediments (southwestern part) (Fig. 4d).

It clearly shows that the spatial distribution (i.e., lateral extent and thickness) and properties (i.e., saturated hydraulic conductivity) of the geologic media, especially the basalt, as well as the topography have significant effects on the spatial distributions of groundwater flow in the aquifer system before groundwater pumping.

4.2. Transient-state numerical simulations (after groundwater pumping)

For optimal design and operation schemes of the pumping well in the pump and treat remediation method, desirable pumping rate, and groundwater table depression and its extent under given hydraulic conditions must be predicted and evaluated. Thus, in order to obtain transient-state spatial distributions of groundwater table in the aquifer system after groundwater pumping, a series of transient-state numerical simulations are performed, and their results are illustrated in Figs. 5 and 6.

Considering the field hydrological data, contamination measurements, and numerical simulation result mentioned above, a new pumping well for the pump and treat remediation method is proposed at 10 m northwest from the BH-6 borehole. The screen interval of the well is from 15 m to 19 m depth from the ground, and it penetrated the boundary between the bedrock and weathered zone. The maximum pumping rates of the pumping well are calculated with zero reference pressure head, because groundwater pumping is impossible if the reference pressure head at the bottom of the screen interval is negative. The amount of groundwater flowing through the screen interval of the pumping well is calculated by the element cluster technique, and its temporal change is illustrated in Fig. 5a. The pumping rate increases sharply in the early period, because a pressure difference between the wellbore and aquifer is abruptly applied. Then, the pumping rate gradually decreases and finally reaches about 8 m³/day until 5 years due to gradual compensation of the pressure

difference. It means that the maximum pumping rate is 8 m³/day under given conditions. Thus four equally incremental pumping rates, which are less than or equal 8 m³/day, such as 2, 4, 6, and 8 m³/day (Cases 1 to 4) are also assigned at the pumping well.

The temporal changes in pressure head during groundwater pumping with the four pumping rates are plotted in Fig. 5b. The pressure head decreases rapidly in the early period, gradually decreases, and then reaches its final steady-state condition until 5 years. The maximum drawdown of the pressure head is 3.52 m for Case 4 (8 m³/day). For all the cases, the final steady-state value of the drawdown of the pressure head is linearly proportional to the pumping rate.

The spatial distribution of drawdown of the groundwater table after 5 days is illustrated in Fig. 6. As the pumping rate increases, the extent of the groundwater table depression increases. Generally, when the aquifer subject to groundwater pumping is composed of highly homogeneous materials, the groundwater table descends with a concentric shape named the cone of depression. In contrast, Fig. 6 shows a very irregular and complicated shape of the groundwater table depression zone. For the case of maximum pumping rate (Case 4), the shape of the depression zone is similar to that of a general cone of depression in the vicinity of the pumping well, whereas it becomes more irregular and complicate as further away from the pumping well (Fig. 6d). The depression zone about 70 m apart from the pumping well in the west-southwest direction appears like a crescent moon shape. In this area, the thickness of the colluvium is relatively thin, and thus the bedrock with a lower

Fig. 5. Temporal changes in (a) maximum available pumping rate under 0.0 pressure head and (b) pressure head during groundwater pumping with the four pumping rates.

Fig. 6. Spatial distributions of groundwater table drawdown in the aquifer system after 5 days since groundwater pumping starts with the pumping rate of (a) 2 m³/day for Case 1, (b) 4 m³/day for Case 2, (c) 6 m³/day for Case 3, (d) 8 m³/day for Case 4.

saturated hydraulic conductivity has a more significant influence than the colluvium.

The depression zone also shows sharp boundaries in the southwest and northeast, respectively. The southwest boundary is related to the geologic boundary between more permeable basalt and less permeable bedrock. The northeast boundary is related to the geologic boundary between

more permeable topsoil and less permeable colluvium.

It also clearly shows that the spatial distribution (i.e., lateral extent and thickness) and properties (i.e., saturated hydraulic conductivity) of the geologic media have significant effects on the spatial distributions of groundwater flow and thus depression zone of groundwater table in the aquifer system after groundwater pumping.

5. Conclusions

The study area has one of the largest explosion and shooting field test sites in Korea and has been contaminated with explosive materials and heavy metals for several decades. For the study area, a pump and treat remediation method has been proposed for mitigating pollutions. Thus, prediction and assessment of change in the groundwater table due to the pump and treat remediation method, based on an in-depth understanding of groundwater flow and aquifer systems, have been earnestly requested. In this study, using a generalized multidimensional hydrological numerical model, groundwater flow before and during groundwater pumping in a contaminated and unsaturated aquifer system were simulated, calibrated, and predicted.

The aquifer system is composed of the Quaternary sediments (i.e., alluvial and colluvial sediments, topsoil, and weathered rocks) underlain by the Quaternary basalt, the Cretaceous clastic sedimentary rocks and tuff, and the Devonian sedimentary rocks in descending order. A three-dimensional geologic formation model, which represents the geology, hydrogeology, and topography of the aquifer system, was established.

A steady-state numerical simulation with model calibration was performed first to obtain initial steady-state spatial distributions of groundwater flow and groundwater table in the aquifer system before groundwater pumping. A series of trial-and-error calibrations by comparing the groundwater levels and their ranges measured at seven monitoring wells with those simulated were performed.

A series of transient-state numerical simulations was then performed using the above-mentioned initial steady-state spatial distributions as initial conditions to obtain spatial and temporal distributions of groundwater flow and depression zone in the aquifer system during groundwater pumping with the four different pumping rates. The numerical simulation results were analyzed to provide primary reference data for optimal design and operation schemes of the pumping well in the pump and treat remediation method.

The results of both steady-state and transient-state numerical simulations show that the spatial distribution (i.e., lateral extent and thickness) and properties (i.e., saturated hydraulic conductivity) of the geologic media, as well as the topography, have significant effects on the spatial

distributions of groundwater flow and thus depression zone of groundwater table in the aquifer system before and during groundwater pumping.

Therefore it may be concluded that the procedure of numerical modeling prediction and its results presented in this study can be utilized as reasonable and practical guidelines or methodologies for design and establishment of the pumping well in the pump and treat remediation on the aquifer system consists of irregular and complicated geologic media and hydrological environments.

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