Journal of Contaminant Hydrology, Volume 235, November 2020, Article number 103725
DOI:10.1016/j.jconhyd.2020.103725

Pump-and-Treat configurations with vertical and horizontal wells to remediate an aquifer contaminated by hexavalent chromium

Imma Bortone[1], Alessandro Erto[2]*, Armando Di Nardo[3], Giovanni F. Santonastaso[3], Simeone Chianese[3], Dino Musmarra[3]

[1]*School of Water, Energy and Environment, Cranfield University, College Road, Cranfield, United Kingdom.*

[2]*Dipartimento di Ingegneria Chimica, dei Materiali e della Produzione Industriale, Università di Napoli Federico II, 80125, Napoli, Italy*

[3]*Dipartimento di Ingegneria, Università della Campania L. Vanvitelli, Via E. Roma 29, 81031 Aversa (Ce), Italy*

* *Corresponding author. E-mail address: aleserto@unina.it (A. Erto)*

Abstract

Pump-and-treat technology is among the most used technologies for groundwater remediation. While conventional, vertical wells (VRWs) are well-known and used from long time, horizontal wells (HRWs) have been explored for remediation technologies only in last few decades. HRWs have shown to outperform vertical wells in terms of versatility, productivity and clean-up times under certain conditions.

In this paper, the efficacy of an innovative pump-and-treat (P&T) configuration for groundwater remediation obtained by adopting either VRWs or HRWs technology is comparatively tested. A 3D transient finite element model of an unconfined aquifer containing a hexavalent chromium ($Cr^{(VI)}$) contamination plume was considered to compare a single horizontal well configuration *vs* a range of spatially-optimised arrays containing vertical wells. A sensitivity analysis aimed at finding the best configuration to minimise the remediation time and the related cost is carried out by comparing different well diameters, *D*, pumping rates, *Q*, and position of wells. A comparative cost analysis demonstrates that, for the examined case-study, a single HRW achieves the clean-up goals in the same time span as for a greater number of vertical wells, but at higher price due to the excavation costs.

Keywords: pump and treat; groundwater remediation; horizontal wells; hexavalent chromium; computational fluid dynamic (CFD).

1. INTRODUCTION

Groundwater contamination is one of the most serious environmental problems. The use of pesticide in agriculture, uncontrolled waste disposals, industrial discharges, and many others have seriously altered the quality of groundwater, which is an important source of drinking water (Balthazard-Accou et al, 2019). In particular, chromium (Cr) groundwater pollution has become of high concern in the past decades, due to the relevant concentrations found both in soil and water (Oliveira, 2012).

Cr exists in several oxidation states and the most toxic and common form is hexavalent chromium, $Cr^{(VI)}$, which is also highly mobile (Shanker and Venkateswarlu, 2011). The International Agency for Research on Cancer (IARC) classes hexavalent chromium as a group 1 ("Carcinogenic to humans") (WHO, 1996). The oxidative form and transport of chromium in environmental phases is dependent on a multitude of interrelated chemical and mechanical processes, which also affect the applicability and effectivity of remediation technologies. Additional factors for consideration are the location of the site in relation to urban areas, agricultural areas or drinking water sources, also in combination with legal and financial constraints. The choice of remediation technology is therefore a case by-case decision and different parameters have to be accounted for (Yihdego and Al-Weshah, 2016a).

The pump and treat (P&T) method is one of the most popular treatments for chromium contaminated groundwater, mostly coupled with adsorption onto activated carbons as treatment step (Bortone et al, 2013; Di Natale et al, 2015). It is also the most common groundwater remediation method in general and is employed in approximately 40% of contaminated groundwater sites (EPA, 2002). P&T generally involves the extraction of polluted water from the aquifer by means of wells, and to successively treat it by means of different possible techniques in designed on-site or off-site plants. Once treated, the water from P&T can be re-injected into the same aquifer or discharged to a surface water body, in relation to the quality standards of the aquifer (EPA, 2004). The P&T approach enables large volumes of groundwater to be decontaminated quickly, in comparison to other methods, but have the disadvantages of long operation time, potential reversal of hydraulic gradient, possible spreading of contamination into sensitive receptors and ecosystems and high costs (Ko et al, 2005; Park, 2016; Yihdego and Al-Weshah, 2016b; Yihdego and Al-Weshah, 2018). Hence, it is specifically suitable for applications to severe or urgent incidents of groundwater contamination, quickly mitigating health risks and damage to the ecosystem.

Conventional P&T systems use vertical remediation wells (VRWs); however, horizontal wells (HRWs) have shown to outperform their vertical counterparts under certain conditions (Miller, 1996; Carlisle et al, 2002; Van Heest, 2013). HRWs are typically employed for the recovery of heavy oil, but have been gaining popularity also for groundwater remediation in recent years. This is chiefly due to the ability of a single horizontal well to extend its radius of influence over a large lateral range, which is particularly beneficial in sites where the spread of pollutant is extensive horizontally. Pilot tests of vapour extraction from horizontal wells at a sandy site have shown to remove up to five times as much contaminant as vertical wells (Looney et al, 1991).

The initial expenses for implementing a horizontal well is comparatively larger than the corresponding for vertical ones. However, if the scale of the operation is sufficient, this can be counterbalanced by superior performances once in operation, overall resulting in a cheaper remediation effort (Miller, 1996). HRW well screens can be hundreds of meters long and multiple VRWs with overlapping zones of influence can be needed to accomplish what a single HRW can obtain with a single zone of influence (EPA, 2017). As an example, in a pilot study of Lundegard et al (2001), was shown that 30 vertical air sparging wells achieved the same results of one horizontal well with 90 m of well screen. Furthermore, analytical studies have estimated that a single horizontal well can achieve remediation targets in one quarter of the time taken by vertical wells (DE, 1998, Sequino, 2014).

Despite the HRWs appear as very promising, in the published literature there is still a lack of knowledge about the comparative performances between vertical and horizontal wells, specifically for groundwater remediation. Hence, this study aims to compare the efficacy of vertical and horizontal wells for the remediation of chromium-contaminated groundwater. As scaling-up of pilot tests to full scale remediation is a very challenging issue, in this work a theoretical contaminant plume is considered and simulated within a shallow, unconfined aquifer, in which hexavalent chromium was considered as the sole contaminant. A finite element model using the Subsurface Flow module in Comsol Multiphysics® was constructed and used to simulate a range of vertical and horizontal well systems. Preliminary, the optimal well locations were determined, while well positioning, number of wells and pumping rate were taken as variable operating parameters. The optimisation objectives were the minimization of both the cost and remediation time, assuming a maximum value of drawdown change.

2. MATERIALS AND METHODS

The design of remediation systems (RS) is strictly dependent of the site characteristics and contaminant type. RS are generally designed after that a throughout site investigation has been completed. To achieve groundwater regulatory remedy goals and associated performance requirements, RS design follows defined criteria which can be summarised as: (i) selecting appropriate technologies for the treatment of each type of the contaminant present and appropriate methods for groundwater collection or extraction and discharge; (ii) establishing design parameters (e.g., system flow rate and influent concentrations); and (iii) considering a suitable monitoring system.

P&T systems are mostly constructed and operated to contain or prevent the migration of a define pollutant concentration to potential receptors or to remove a known contaminant mass from an aquifer to achieve selected clean-up criteria. P&T well technology can potentially have numerous design purposes options. It is not uncommon to find many wells extracting groundwater at the same time, or wells screened at different depths to maximise the overall effectiveness. The choice of geometry, positioning and number of wellbores is dependent on the site characteristics. An optimal solution is then designed to minimise technical complexity while simultaneously adhering to defined performance targets. Proper selection and design of the extraction system can guarantee a cost effectively goal achievement, by reducing capital expenses in drilling wells and long-term maintenance costs and also, in some cases, eliminating the necessity of additional remedy options such as barrier walls (Miller, 1996).

Vertical wells (VRWs) are the type of wells most commonly used for extraction systems. Normally, the vertical well is positioned in the polluted zone and pumped so that the water level is drawn down, causing the water to enter the well. HRWs are generally preferred where the ground surface above the plume is accessible, and the aquifer provides relatively high yields (> 5 m^3/day per well) and a high saturated thicknesses (> 3 m). However, VRWs are considered as the only reasonable collection method for plumes >30 m below the surface (EPA, 2005). When in the aquifer there is an inhomogeneous or patchy contamination, VRWs can be designed to focus extraction on the most contaminated areas and to reduce the amount of uncontaminated water extracted.

Over past years, horizontal wells (HRWs) have been adapted for numerous soil and groundwater remediation applications, including P&T (Miller, 1996). HRW drilling begins vertically or directionally at the ground surface and then proceeds horizontally following the depth and length of the target aquifer. Trenched or directionally-drilled are the two common types of HRWs that can be applied to remediation purposes. When compared to the vertical P&T wells, HRWs show some certain advantages. Firstly, a benefit that pertains to groundwater remediation cases in particular, is their suitability for use in sensitive settings. HRWs have been shown to allow greater contact with contamination and to access places beneath surface obstructions, where conventional vertical drilling or trenching would be undesirable or impractical (EPA, 2017).

A further advantage of the horizontal approach is the possibility to maximise the open screened area and, hence, in shallow aquifers where the contamination plume extends over a large lateral, but not vertical, range. Water pumped from the well drops the water level in the well, thereby establishing a head gradient from the aquifer toward the well, which determines the drawdown, S, of the piezometric surface (Figure 1). Each extraction well has a zone of influence, which is defined as the distance from the well centre to a point in the water level in which the gradient approaches zero. The rate of groundwater extraction determines the influent flow to the treatment system and hence is a key design variable. The number and distance of capture wells within a given flow net also affects the volume of water that the extraction system can pump.

P&T systems to capture contaminated groundwater using vertical remediation wells (VRWs) and horizontal wells (HRW) are depicted in Figure 1, assuming that a pumping rate, Q, is applied and water is drawn into the well through radial slits in a cylindrical well screen. The consequent lowering of the water table within the zone of influence of the well is described by the loss of hydraulic head, h. The hydraulic head is the distance between the aquifer floor and the water table. The height of the undisturbed water table is the sum of hydraulic head and drawdown, S.

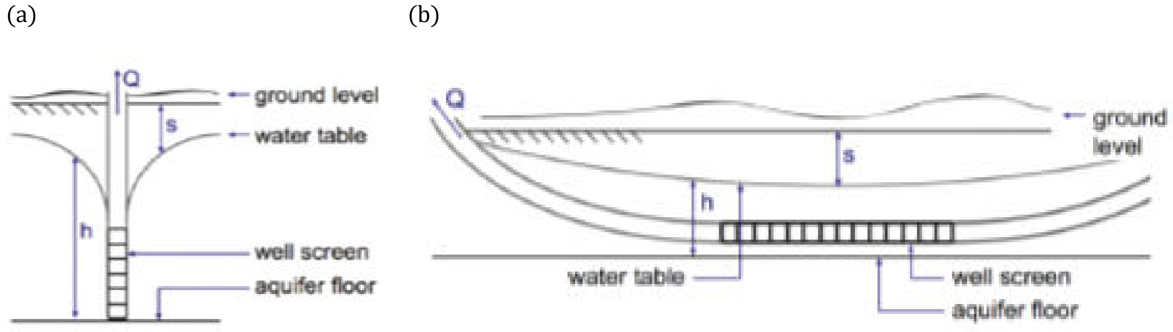

Figure 1. Comparison of scheme of (a) vertical and (b) horizontal remediation well operating with a pumping rate, Q, in an unconfined aquifer. Both wells configurations incur a surrounding hydraulic head, h, field with drawdown profile, S.

2.1 Governing equations

A 3D finite element model of the aquifer system is constructed with the use of the Subsurface Flow module in Comsol Multiphysics®. The model can be used to predict the contaminant transport and groundwater flux over time, *t* (Tabatabain, 2014).

The governing equation for the description of the dynamics of a contaminant in three dimensions (3D) with concentration, C, through the aquifer is described as follows (Fetter, 1993):

$$\frac{\partial C}{\partial t} = \nabla \cdot (D_h \nabla \mathrm{C}) - \vec{u} \nabla \mathrm{C} \tag{1}$$

Which combines the effect of advection and dispersion mechanisms. The hydrodynamic dispersion coefficient, denoted with D_h, is defined as the sum of the tensor of mechanical dispersion, D, and the molecular diffusion coefficient, D^* (Gelhar et al, 1992). The components of the mechanical dispersion tensor are:

$$\begin{aligned}
D_{xx} &= \alpha_L\, u_x^2/|\boldsymbol{u}| + \alpha_T\big((u_y^2 + u_z^2)/|\boldsymbol{u}|\big)\\
D_{yy} &= \alpha_L\, u_y^2/|\boldsymbol{u}| + \alpha_T((u_x^2 + u_z^2)/|\boldsymbol{u}|)\\
D_{zz} &= \alpha_L\, u_z^2/|\boldsymbol{u}| + \alpha_T\big((u_x^2 + u_y^2)/|\boldsymbol{u}|\big)\\
D_{xy} &= D_{yx} = (\alpha_L - \alpha_T)\, u_x u_y/|\boldsymbol{u}|\\
D_{yz} &= D_{zy} = (\alpha_L - \alpha_T)\, u_y u_z/|\boldsymbol{u}|\\
D_{xz} &= D_{zx} = (\alpha_L - \alpha_T)\, u_x u_z/|\boldsymbol{u}|
\end{aligned} \tag{2}$$

where α_L and α_T are the longitudinal and transverse dispersivities, respectively, and depend on the porosity and tortuosity of the specific soil of the aquifer. Longitudinal dispersivity can be experimentally obtained and varies with the fluid, media and contaminant characteristics (Gelhar et al, 1992), while transverse dispersivity typically follow the relationship given by Eq (3).

$$\alpha_L = 10\alpha_T \tag{3}$$

The advective flux through a porous medium, second term on the right hand side of Eq (1) is dependent on the velocity vector, $\vec{u}$ described by the Darcy's law,

$$\vec{u} = -\kappa \cdot \overline{\nabla} h \tag{4}$$

Where k is the hydraulic conductivity of the soil and $\overline{\nabla} h$ is the hydraulic head gradient vector. By coupling Eqs (1) and (2), the model can predict the profile of hydraulic head and contaminant distribution over time, enabling also to find the best well configuration and placement**.**

In Eq (1), it is assumed that no natural attenuation takes place, e.g. there is no adsorption phenomena in the aquifer.

Among the possible methodology approaches (Yihdego, 2018), the well extraction rate, cone of depression and well drawdown in an unconfined aquifer when pumping occurs at the centre of a well, can be calculated by using Darcy's equation,

$$Q = \frac{\pi k(h_1^2 - h_2^2)}{ln\frac{r_1}{r_2}} \tag{5}$$

Where r_1, r_2, h_1 and h_2 denote the radius and water head at the well and at the end of the cone of influence, respectively.

2.2 Case study

A simplified, unconfined groundwater aquifer is modelled according to the dimensions in Figure 2. The domain considered is a uniform and homogeneous porous medium of total volume equal to 15,000 m^3, with 50 m length, 30 m width and 10 m depth. It is assumed that, at the beginning of the remediation period, the domain contains a cuboid hexavalent chromium contamination plume with a uniform concentration of hexavalent chromium, $Cr^{(VI)}$, equal to 1 mg/L. As schematised in Figure 2, the total volume of $Cr^{(VI)}$ plume is equal to 1,400 m^3, which extends over an area of 200 m^2 and a depth of 7 m.

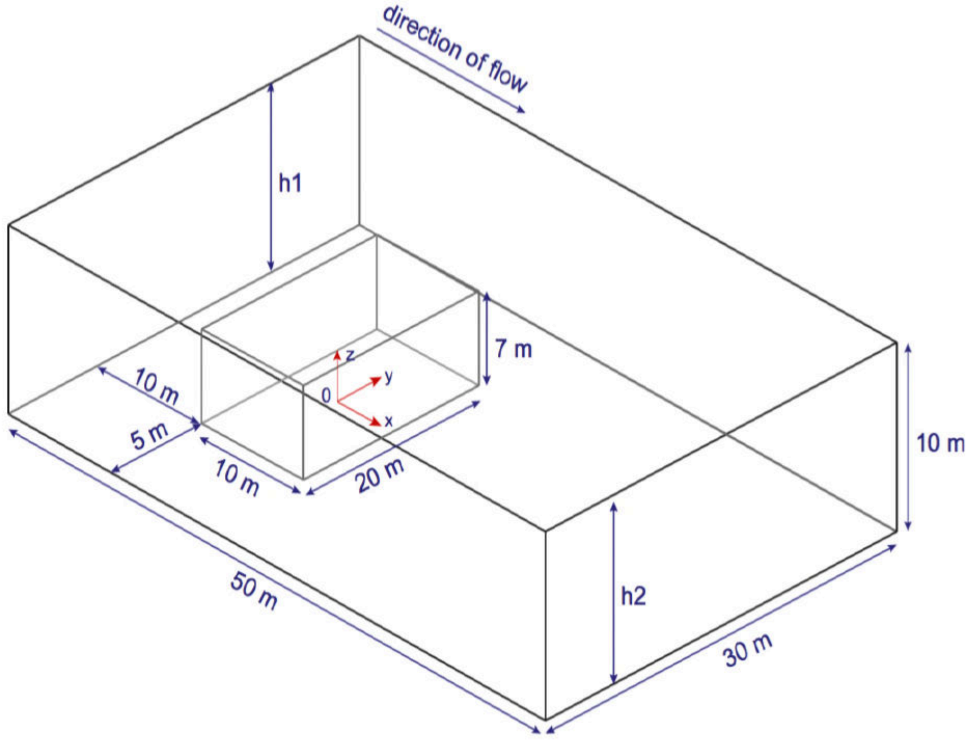

Figure 2. Schematization of the domain under consideration, with cuboid hexavalent chromium contaminant plume.

The hexavalent chromium contaminant plume has been fictitiously released into the aquifer prior to the remediation period, and there is no ongoing contaminant source. The key characteristics of the aquifer system are given in Table 1.

Table 1. Aquifer characteristics and numerical model parameters.

Case Parameters	
Hydraulic conductivity, κ	10^{-5} m/s
Porosity, ε	0.3
Hydraulic gradient, i	20%
Hydraulic head at upstream boundary, h_1	10 m
Hydraulic head at downstream boundary, h_2	9.9 m
Aquifer thickness, B	10 m
Ambient temperature	10 ˚C
Molecular diffusion coefficient, D^*	10^{-9} m^2/s
Longitudinal dispersivity, α_L	1 m
Transverse dispersivity, α_T	0.1 m
Initial concentration of $Cr^{(VI)}$ plume, C_{Cr}	1 mg/L

The computational mesh considered for the model was an extremely fine physics-controlled mesh of 836,464 domain elements with a minimum of 0.190 m. Verification of numerical accuracy was achieved through the estimation of numerical errors during the simulations. The finite element discretization was solved via considering two adaptive and iterative accuracy requirements, subject to relative and absolute tolerances: one for the time-stepping (solver) error and one for the algebraic equation (solver) error (Söderlind and Wang, 2006). The relative residual and the algebraic error estimates were verified to maintain below the order of 10^{-14}, with no recorded failures of the adaptive step-size and of the algebraic nonlinear solver.

2.3 Groundwater treatment

The contaminant mass loading can be estimated by using the well flow rate, and the cost of treatment of the extracted contaminated groundwater depends on the type of treatment used.

As treatment system, adsorption onto activated carbon is chosen. The configuration designed is a fixed-bed column in which the water pumped from the wells is fed for the elimination of the contaminant. To ensure that the adsorption limit of the column this is not exceeded, the column(s) must be sufficiently long, and regenerated sufficiently often, to assure a full and continuous remediation of the groundwater.

For simplicity it is supposed that, after pumping from the aquifer, the groundwater will enter a storage tank, which will house the entire volume of contaminated groundwater. As such, the contaminant concentration within the tank will reach a uniform value before entering the treatment column. A probe was set up to report the total mass of chromium in the domain, m_t, at each time step. Linear interpolation was then used to estimate the mass of the remaining contaminant, m_T , in the aquifer when $t=T$; that is, the time at which the regulatory threshold for hexavalent chromium, C_{ML}, equal to $5\cdot10^{-5}$ g/L (LD, 2006) has been achieved across the entire domain. The contaminant concentration inside the tank prior to treatment is therefore given by:

$$C_0 = \frac{m_0 - m_T}{QT} \tag{6}$$

where m_0, is the initial chromium mass, while m_T is the chromium mass over the time, Q is the flow rate and T is the simulation time.

To model the behaviour of the contaminant through the adsorption column, the mass transport Eq (1) must include the reactive term representing adsorption mechanisms. The Eq (1), by assuming a 1D flux through the column and taking into account the rate of adsorption within the treatment column, becomes:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial C}{\partial x}\right) - u_x\frac{\partial C}{\partial x} - \frac{\rho_b}{\epsilon_b}\frac{\partial \omega}{\partial t} \tag{7}$$

The adsorption rate ($\frac{\partial \omega}{\partial t}$), i.e. the variation of the adsorption capacity of the solid calculated as the contaminant mass adsorbed per dry weight of the activated carbon material, is a function of the dry bulk density, ρ_b , and porosity, ε_b, of the adsorbing column material, so that:

$$\frac{\rho_b}{\varepsilon_b}\frac{\partial \omega}{\partial t} = K_L A(C - C^*) \tag{8}$$

where K_L is the liquid to adsorbent mass transfer coefficient, experimentally derivable and dependent on the characteristics of the activated carbon and the groundwater (Di Natale et al, 2015). A is the external specific surface area of the adsorbent material; finally, C is the contaminant concentration in the liquid phase and C^* is the corresponding equilibrium value as a function of the solid adsorption capacity. This term can be derived from an experimental adsorption isotherm, which must be available in the same operating conditions as for the fixed-bed column.

A granular activated carbon (GAC) material has been supposed to fill the column, namely the Aquacarb 207EA^{TM} having the characteristics detailed in Table 2.

Cr$^{(VI)}$ adsorption isotherm onto the chosen activated carbon was described via a linear relationship between the liquid concentration and the adsorbed solute mass per mass of adsorbent ω.

$$\omega = K_d C \tag{9}$$

where the partitioning coefficient, K_d, was derived from the experimental data reported in Di Natale et al (2015).

Eqs (7)-(9) were solved by assuming the following initial conditions:

$$\left[\begin{array}{l} C_0 = \frac{m_0 - m_T}{QT} \\ \omega = 0 \end{array}\right. \tag{10}$$

Table 2. Characteristics of Aquacarb 207EA^{TM} for Cr$^{(VI)}$ adsorption

GAC Characteristics	
BET surface area	950 m^2 /g
Average pore diameter	26 Å
Dry bulk density, ρ_b	520 kg/m^3
Porosity, ε_b	0.4
Partitioning coefficient, K_d	7.9x10^{-7} m^3/mg
Maximum inflow speed, u_x	0.05 m/s
Retail cost	4.2 £/kg

2.4 P&T design considerations

An appropriately designed P&T system should achieve the groundwater remedy goals in a cost-effective manner for the operating life of the system.

The cost of implementing a P&T system varies dramatically, depending on case-specific conditions, such as the instillation depth, the aquifer characteristics, institutional drawdown limits as well as the choice of well materials and design.

The main assumptions considered for the design of the P&T well system are summarised in Table 3. Firstly, it was supposed that a successful configuration must be able to ensure the removal of the polluted water, where chromium concentration is above the threshold concentration C_{ML} of 5 x 10^{-5} g/L (DL, 2006) from the entire domain. Simultaneously, the well configuration must also be able to maintain a hydraulic head across the domain that satisfies a chosen drawdown criterion. In order to preserve the ecosystem dependent on the groundwater, a site-specific drawdown limit is imposed before each remediation intervention. Typically, drawdown is limited to approximately one-third of the aquifer depth, B (Gorelick et al, 1993). A widely adopted drawdown limit is 35% of the aquifer depth for the first year of pumping and 50% thereafter (GA, 2006). Based on these considerations, two drawdown criteria were considered, namely Δs_{max} = 35% and 50%. Finally, a successful well configuration must be able to achieve the Δs_{max} without exceeding a maximum pumping rate, $Q_{w,max}$.

The maximum pumping rate is based on the maximum well screen entry speeds, as well as the adherence to the inequality, $Re < 1$, which is one of the conditions for the validity of Darcy's law.

To ensure the validity of Darcy's law and laminar flow at the well screen, the maximum pumping rate per well was calculated by respecting the conditions expressed in Eq (11).

$$1 > \frac{ul}{v} \qquad \Leftrightarrow \qquad u < \frac{v}{l}. \tag{11}$$

where u and ν are the velocity and kinematic viscosity of groundwater, respectively, while *l* is the flow length.

An average grain diameter of 1 mm was assumed, based on the correlation between hydraulic head, porosity and grain size given by Zahir and Kaleel (2013).

The speed of groundwater flow through the well screen must therefore satisfy the following inequality:

$$u < \frac{1.31*10^{-3}\ \mathrm{Pa\ s}}{(10^3\ \mathrm{kg/\ m^3})(10^{-3}\ \mathrm{m})} = 1.31 * 10^{-3}\ \mathrm{m}/s \tag{12}$$

The smallest well screen considered for these purposes has an outer surface area of 3.83 m^2. The maximum water volume that may pass through an individual well per day was, therefore, equal to 430 m^3/d. The practical design criteria herein described are summarized in Table 3.

Table 3. Practical design criteria.

Design Constraints	
Maximum pumping rate per well, $Q_{w,max}$	430 m^3/d
Maximum drawdown criteria, ΔS_{max}	35%, 50%
Maximum contamination level, C_{ML}	5 mg/m^3

The costs of a P&T system account for the capital costs associated with system installation as well as the annual costs for operation and maintenance (EPA, 2005).

Different assumptions were made to compare the vertical and horizontal P&T system, in line with typical figures found in the literature (Huang and Mayer,1997; Fournier, 2002; EPA, 2017). The cost of a vertical well system, $C_{VP\&T}$, was adapted from the model by Huang and Mayer (1997), in which the costs are represented as the sum of an installation term, a pumping term, a groundwater lift term and a treatment term:

$$C_{V_{P\&T}} = a_0 n_w + a_1 n_w Q T + a_2 Q(\bar{S}/d_w)T + a_3 m_{GAC} \tag{13}$$

Where n_w is the number of wells, T is the time taken to bring the maximum contaminant concentration below the limit across the aquifer, $\bar{S}$ is the average drawdown incurred by the pumping wells and m_{GAC} is the mass of the adsorptive material used. The groundwater lift costs incorporated the drawdown effects, in which the depth of the wells, *dw*, was considered equal to the aquifer depth, B.

Differently, the cost for a horizontal P&T system, $C_{HP\&T}$, was defined as the sum of the costs associated with drilling, mobilisation, well materials, pumping, groundwater lift and treatment, as summarised in Eq (14).

$$C_{H_{P\&T}} = a_4 n_w + a_5 L_{tot} + a_6 \left(L_{scr} + L_{pipe} \right) + a_1 V + a_2 V(\bar{S}/d_w) + a_3 m_{GAC} \tag{14}$$

where V is the volume of pumped water, equal to the product of the pumping flow rate, Q, and time of simulation, T. In Eq (14), the total drilling length, L_{tot}, is expressed as a function of the well screen length, L_{scr}, the aquifer depth, B, and the z-position of the well, z_w, as follows:

$$L_{tot} = L_{scr} + 2L_{pipe} \tag{15}$$

$$L_{pipe} = \left(\frac{B - z_w}{cos\theta} \right) \tag{16}$$

Coefficient a_i with i=1,…, 6 represents the unit costs applied to estimate the $C_{VP\&T}$ and $C_{HP\&T}$ terms (Table 4).

Table 4. Operation unit costs

VRW Configuration cost		
Well Installation	a_0	4,000 £ per well
Pumping	a_1	2.35 £/m^3
Groundwater lift	a_2	0.15 £/m^4
Adsorbing column (CAG)	a_3	4.19 £/kg
HRW Configuration cost		
Well Installation	a_4	7,900 £ per well
Well Drilling	a_5	120 £/m
Well Materials	a_6	38.5 £/m
Pumping	a_1	2.35 £/m^3
Groundwater lift	a_2	0.15 £/m^4
Adsorbing column (CAG)	a_3	4.19 £/kg

The expenses associated with the installation and operation of both vertical well and horizontal well configurations are listed in Table 4 and, in particular, for each vertical well, the related installation cost was assumed as reported in Fournier (2002), while pumping and groundwater lift costs were obtained from Huang and Mayer (1997). References for the implementation costs of a horizontal well were from respectively EPA (2017) for the installation and well materials, Lehr (2004) and DT (2010) for the directional drilling costs and Huang and Mayer (1997) for the pumping and lifting costs. The HRW installation cost listed in Table 4 refers to the HRW mobilisation costs, which relate to the rig rate, costs of personnel costs/other costs for the operating company's personnel and consultants, costs associated with service companies/equipment contracts, and other consumables (NOG, 2009; EPA,2017). Generally for VRW, these costs are part of the installation costs together with drilling and material costs, as also reported in Fournier (2002). Specifically, HRW installation cost for a single well was considered 1.9 times more expensive than a VRW's, which falls within the expected 1.5 - 2.5 range suggested by Joshi (2003).

3. RESULTS AND DISCUSSION

Different P&T configurations were designed for the theoretical case study proposed in order to compare the effect of the operating parameters. The modelling results were gathered for both the vertical (VRW) and horizontal (HRW) P&T well configurations. A sensitivity analysis was carried out by varying the well diameter, D, the pumping rate, Q, and the position of wells, necessary to minimize the remediation cost and time, by accomplishing the limit drawdown, ΔS_{max}, considered.

Generally, well screen diameters commonly applied for P&T application range from 4" (1.2 m) to 12" (2.5 m) (Cohen et al., 1997). In order to avoid excessive drawdown and friction losses, a larger diameter was selected to keep the uphole inflow speed and the inflow through the well screen below 5 ft/s (1.5 m/s) and 0.1 ft/s (0.03 m/s), respectively (Driscoli, 1986). Then, in order to determine a suitable diameter for the theoretical case study, a 6" well (1.8 m), was compared with a 12" well (2.5 m) to evaluate the influence of well diameter on remediation time and drawdown.

Firstly, a single well configuration for both VRW and HRW was compared. For the VRW configuration, a single well, 10 m long, was placed at $x = 2.5$ m, $y = 0$ m and z=0 m (Figure 3a) , while the single horizontal well (HRW) was located centrally within the contamination plume, at x = 0 m, y = 0 m, and z = 0.5 m, axially parallel to the direction of flow and parallel to the aquifer floor with an initial length of 10 m (Figure 3b). A schematization of both well configurations together with an example of the aquifer hydrodynamics under the effect of a well diameter of 12" and pumping rate, Q, of 40 m^3/d is shown in Figure 3. Additionally, Figure 3 illustrates the initial contaminant plume distribution in the aquifer (black rectangle) in relation to the cone of depression created by the wells. As highlighted, under the same aquifer initial conditions and well parameters, for a single HRW configuration (with screen length of 8 m) the cone of depression is approximately the same width but twice longer than for a single VRW configuration.

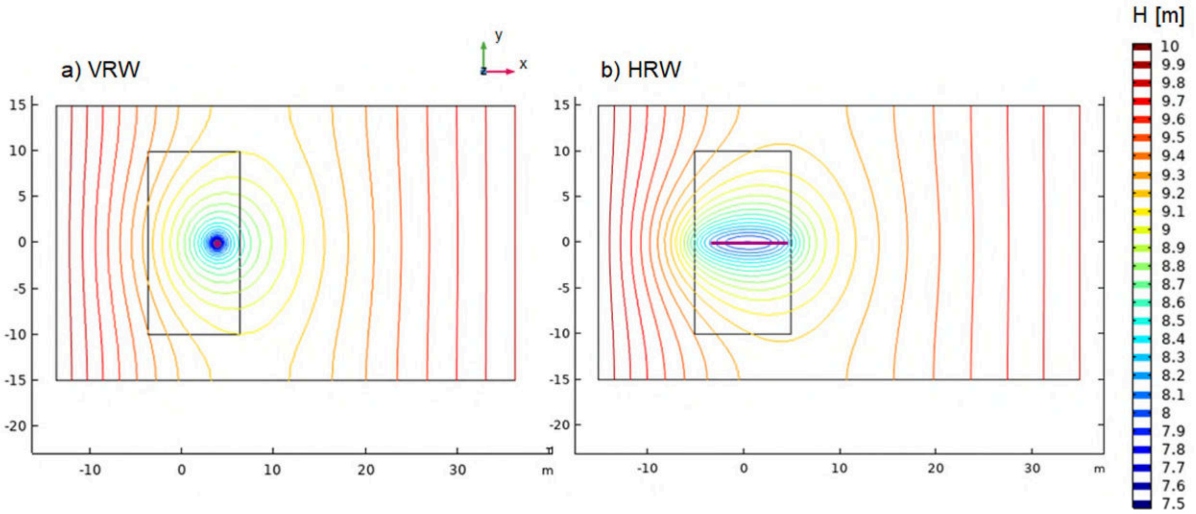

Figure 3. Schematisation of well location and aquifer hydrodynamics for (a) vertical and (b) horizontal well configuration with same well diameter (12”) and pumping rate (Q=40 m^3/d).

Figure 4 compares the results of remediation time, *T*, and drawdown, Δ*S,* for both the configurations by varying the diameter of both vertical and horizontal wells for a range of pumping rates.

As shown by Figure 4a, for the vertical well, a trivial difference in remediation time was observed between the two diameters adopted. The well with the 12” diameter was able to bring the maximum concentration to the C_{ML} across the domain between 1 and 2 days faster than the 6” diameter well, depending on the pumping rate.

While the larger diameter provided negligible benefit to remediation time, it resulted in a considerable reduction in drawdown. A drawdown difference of up to 8% was observed between the two well diameters and this difference grew with increasing pumping rate. Under the 35% drawdown limit, for example, the 6” well could be used in conjunction with a maximum pumping rate of 20 m^3 /d, to remediate the well in 125 days.

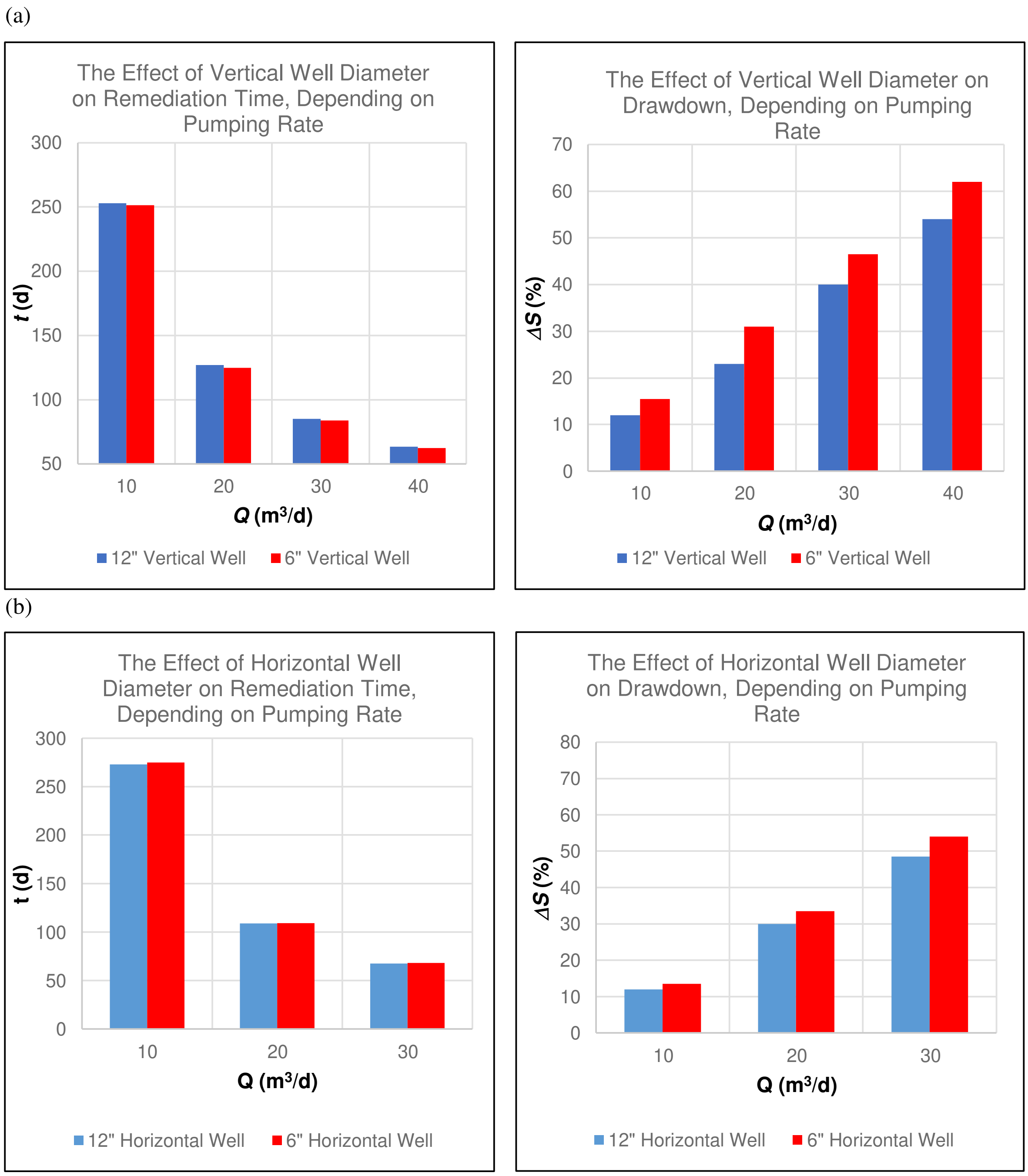

Figure 4. Comparison of remediation times between two well diameters respectively for (a) vertical and (b) horizontal wells.

The influence of diameter of the horizontal well on remediation time and hydraulic head field (Figure 4b) showed the same effects found for the vertical well. As seen from Figure 4b, the observed variation of remediation time is almost negligible for the two diameters.

Differently from the vertical well, for the HRW the time difference is negligible and the reduction in drawdown incurred by the larger well diameter is slightly smaller and it increases with pumping rate, illustrated in Figure 4b.

After having established a suitable well diameter, D=12”, other optimal parameters were defined, such as the pumping rate for the vertical well and z-positioning, length and pumping rate for the horizontal well.

For the VRW configuration, positions in the range of 0 m $\leq x \leq$ 5 m were tested, whose results are depicted in Figure 5. As shown, the vertical well performs best at approximately half way between the hotspot and the plume edge, at x = 2.5 m. This x-position corresponds to a minimum remediation time of about 102 days.

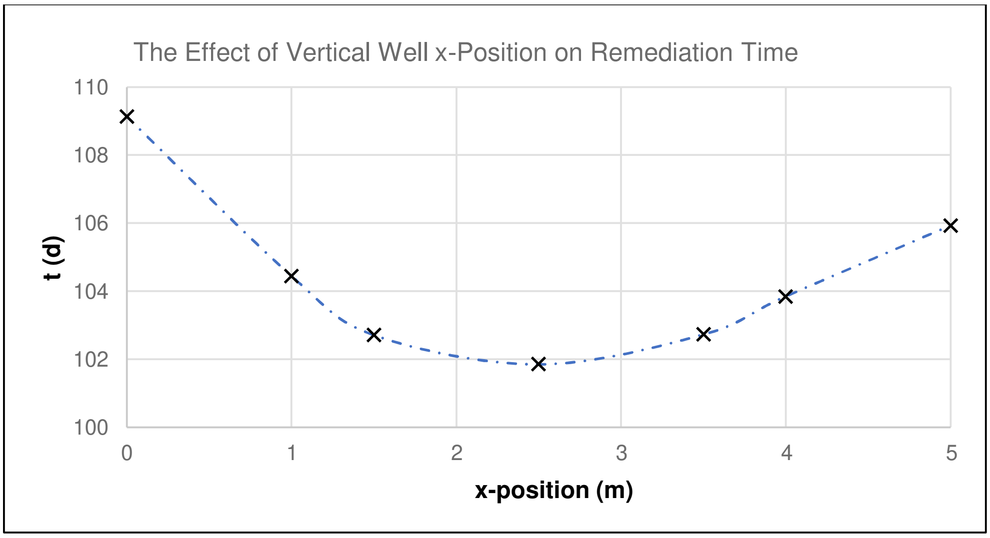

Figure 5: Single VRW configuration results of remediation time by varying x-positions of the well centre-point. Results are gathered from simulations of a single vertical well of 12” diameter and Q=25 m^3/d.

Then, increasing pumping rates were assumed, ranging from 10 to 40 m^3/d, and compared to the 35% and 50% drawdown limit taken into account, as represented in Figure 6. For the VRW configuration, the maximum pumping rates for the 35% and 50% drawdown limits resulted 25 m^3/d and 35 m^3/d, respectively.

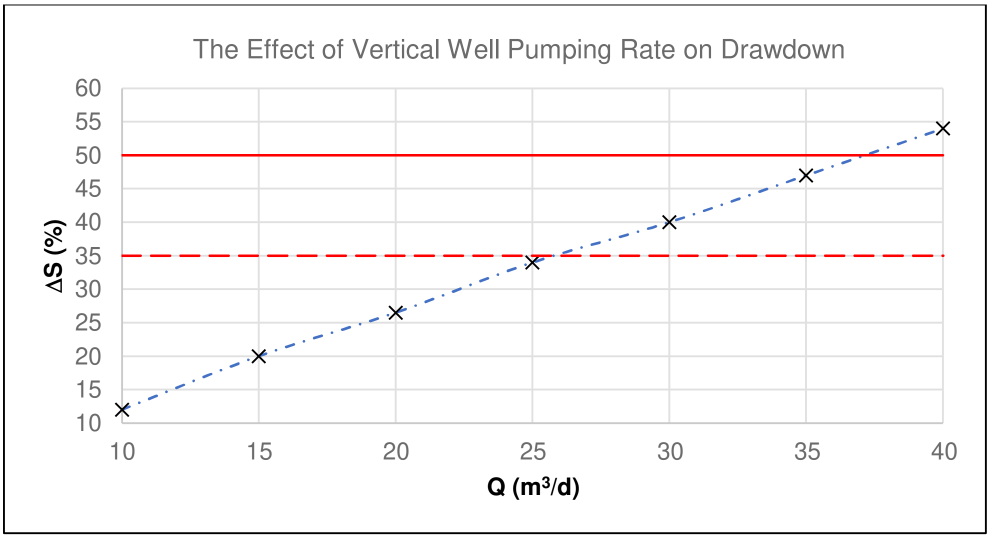

Figure 6: Single VRW configuration results of percentage drawdown between wells by varying pumping rates, Q, in case of a single vertical well of 12" diameter at (x, y) = (2.5 m, 0 m). The red lines correspond to the suggested drawdown criteria.

Subsequently, multiple well configurations, by increasing the number of vertical wells up to two, three and four were evaluated. In the following, the results of the four wells configuration, with diameter of 12" at a position of x=2.5 and y=0 m was reported in the case of VRWs (Figure 7). Once again, the influence of the inter-well spacing on the remediation time of a 4-well system was examined.

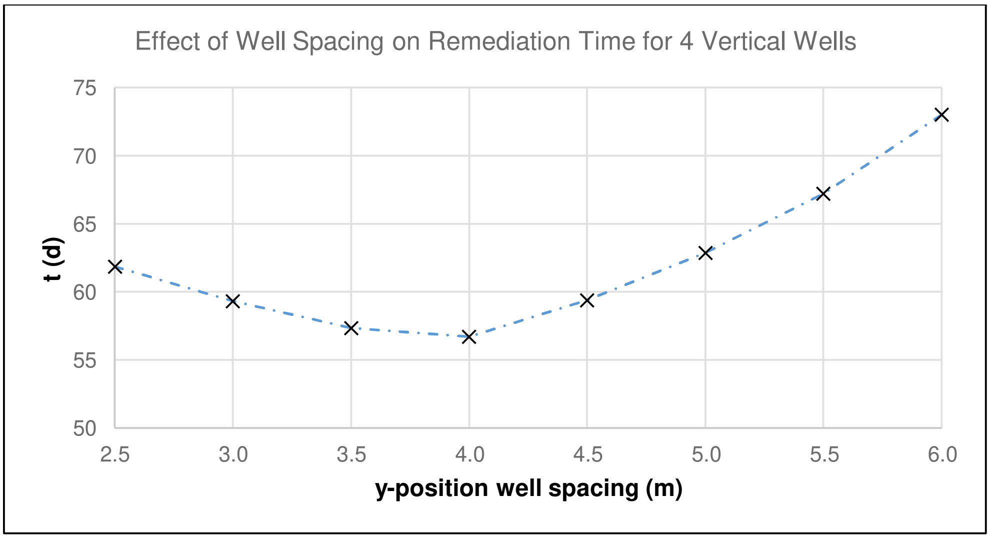

Figure 7. Multiple VRW configuration results of remediation time by varying inter-well spacing for four vertical wells of 12" diameter, placed at x = 2.5 m, y = ±2 m, ± 6 m, with a combined pumping rate Q_{tot} = 40 m^3/d. .

As illustrated in Figure 7, a well spacing of 4 m was deemed to be optimal and was consequently adopted for all the subsequent tests on the 4-wells system.

The total pumping rate for all the wells was also varied in the case of four vertical pumping wells, at intervals of $\Delta Q_{tot} = 5$ m^3/d, starting from a lower value of 25 m^3/d, until the drawdown limits of 35% and 50% were exceeded. Figure 8 illustrates the influence of the four well system on the hydraulic head field. It shows that the maximum pumping rates to satisfy the 35% and 50% drawdown criteria are 70 m^3/d and 100 m^3/d, respectively.

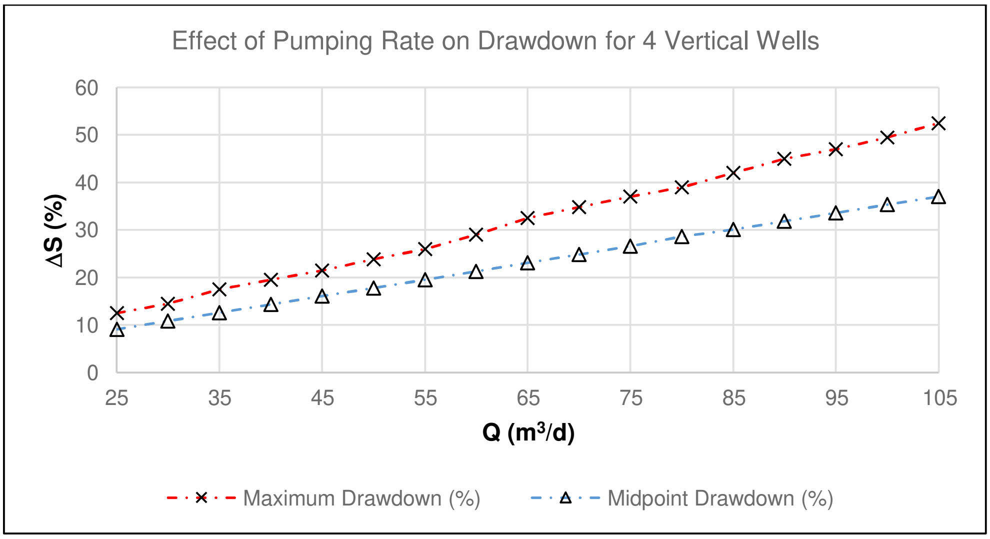

Figure 8. Multiple VRW configuration results of percentage drawdown by varying the pumping rate and the hydraulic head between four 12” diameter vertical wells, placed at x = 2.5 m, y = ±2 m, ±6 m.

An ideal well placement was explored also in the case of HRW P&T configuration, trying to minimise both drawdown and remediation time. For the horizontal well, a suitable well location was determined with the aid of the data represented by Figures 9 and 10. In this case, the distance from the bottom of the aquifer, z, was considered as variable, with a range of $0 \leq z \leq$ 1.5 m. In the z-position range adopted, a positive relationship was observed between the well height and remediation time but it influenced negatively the relationship between the well height and drawdown. Accordingly, a z well position corresponding to 0.5 m was chosen for subsequent horizontal well systems, as a compromise between these two opposing tendencies.

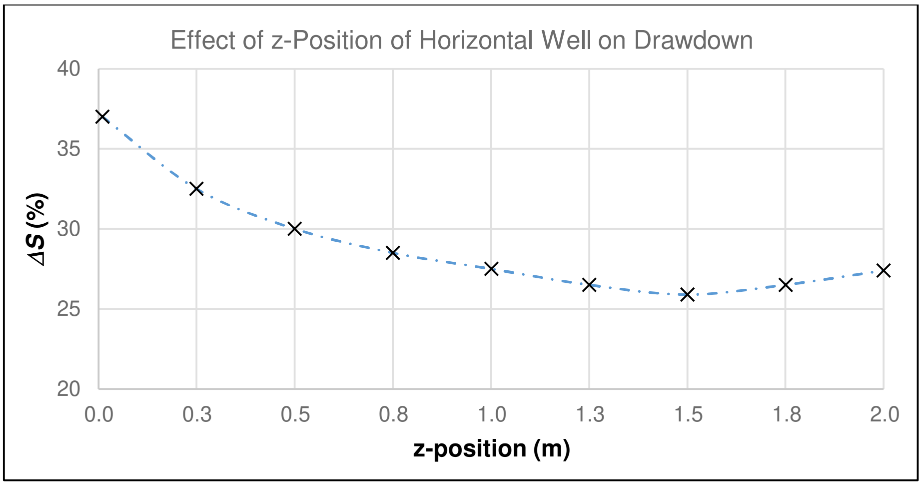

Figure 9. Relationship between the z-position of a single horizontal well and the maximum drawdown incurred, ΔS_{max}. This data set corresponds to a 10 m long, 12" diameter horizontal well, operating at a pumping rate Q = 25 m^3/d.

The second variable analysed also in the case of horizontal well was the well screen length (Figure 10). As expected, an increase in the well screen length together with the flow rate showed a shorter remediation time. However, a longer drilling distance and increased well screen materials results in a significant increment of the financial expense. Furthermore, a well screen of 10 m length showed to increase the proportion of the well screen not in contact with the plume. Consequently, the well length was changed at iterations of ΔL_{scr} = 2 m, while keeping pumping rate independent of well screen length.

As seen in Figure 10, a direct relationship between screen length and remediation time is observed. For this reason, results for which $L_{scr} \geq 10$ m were discarded. Therefore, in the case of HRW, the optimisation aimed at minimising the remediation time, and consequently minimising the well length, while adhering to drawdown targets. However, these two objectives are in opposite direction. For each of the 35% and 50% drawdown limits, the well length was incrementally decreased below 10 m until both limits had been accomplished.

The pumping rates of Q = 25, 40 m^3/d were selected to be able to compare the VRW and HRW single well configurations. With Q = 25 m^3/d, the horizontal well remediated the aquifer in 100 days while adhering to the 35% drawdown limit, with a maximum well length of L_{scr} = 8 m. The ΔS_{max} = 50% criterion was met at this L_{scr} value when Q = 35 m^3/d.

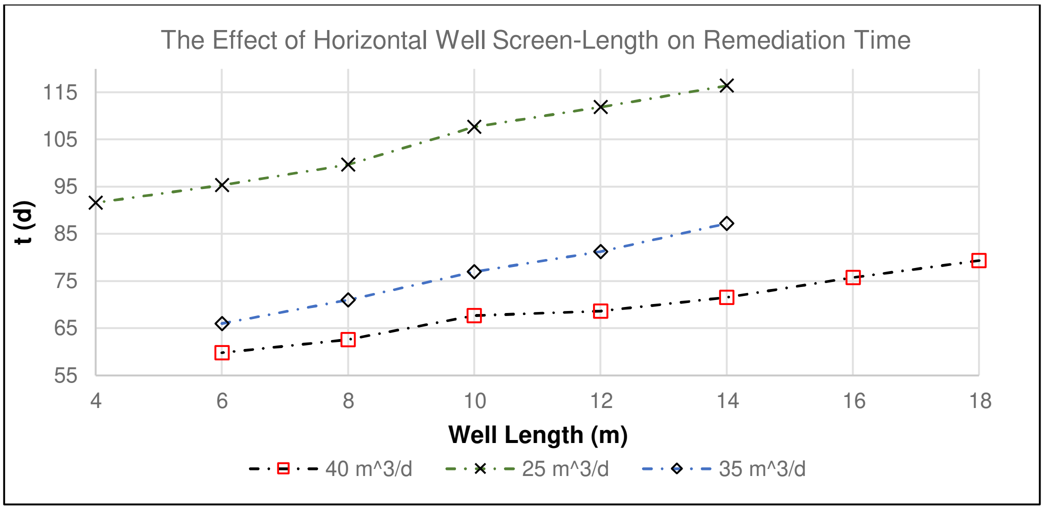

Figure 10. Relationship between the length of a single, 12” diameter horizontal well, located at z = 0.5 m, and the remediation time, t.

Furthermore, by decreasing the well length there was a reduction of the maximum pumping rate, as illustrated by Figure 11, which shows the drawdown limits in comparison to the well lengths tested. The flow rate, Q, equal to 40 m^3/d pumping rate was not able to achieve neither the drawdown criterion nor an economical well screen. A second L_{scr} value of 4 m was selected for comparison with the 8 m screen. At this screen length, the well was able to remediate the aquifer while adhering to the 30% and 50% drawdown criteria at pumping rates of 17 m^3/d and 25 m^3/d, respectively. The notable configurations for the single horizontal well are summarised in Table 4.

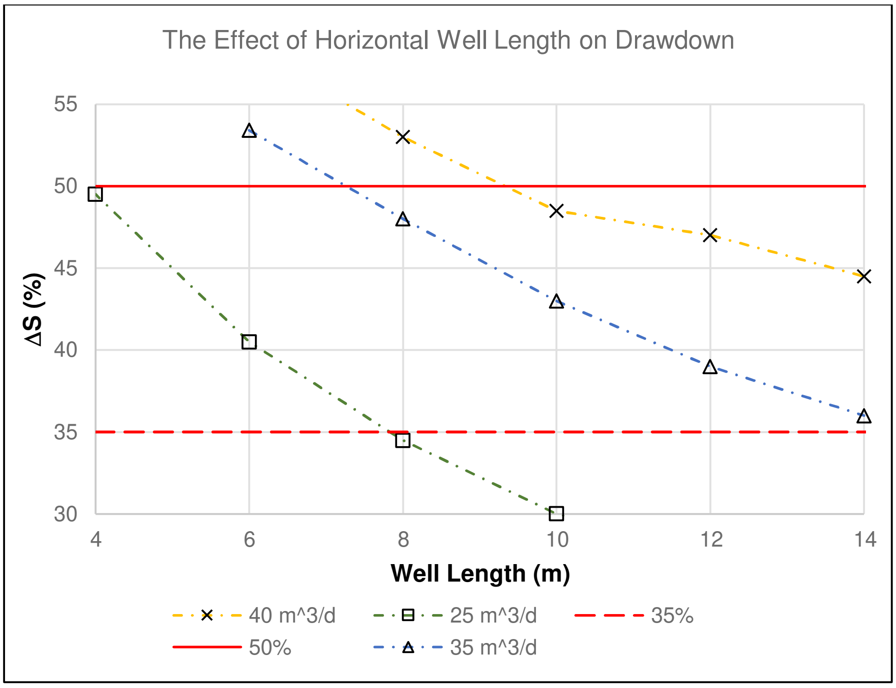

Figure 11. Relationship between the length of a single, 12” diameter horizontal well, located at $z = 0.5$ m, and the maximum drawdown incurred, ΔS_{max},

A summary of the best results obtained both for VRWs and HRWs, optimised for their respective drawdown criteria are summarised in Table 5 and 6, respectively. Specifically, the configurations that were optimised according to the 35% drawdown criterion are shown in green. Those that were optimised according to the 50% drawdown criterion are shown in orange. In particular, for each configuration, for a complete comparison, the pumping rates, Q_{tot}, remediation time, T, the contaminant concentration, C_0 (obtained from Eq (6)) and volume treated, V, we also reported.

Table 5. Summary of simulation results for a single and four vertical well of 12” diameter at a position of (x, y) = (2.5 m, 0 m ±4).

P&T Layout #	Pumping rate, ***Q*** [m^3/d]	Remediation time, ***T*** [*d*]	Drawdown, $\boldsymbol{\Delta S}$ [%]	Pumped volume, V [m^3]	Concentration, C$_0$ [mg/m^3]
Single well VRW Configurations					
V1	25	102	34.0	2,550	168
V2	35	72.9	47.0	2,550	168
Four wells VRW Configurations					
V3	25	89.6	12.5	2,240	190
V4	35	64.6	17.5	2,260	188
V5	40	56.7	19.5	2,270	188
V6	45	50.5	21.5	2,270	187
V7	55	41.4	26.0	2,280	187

V8	65	35.2	32.5	2,290	186
V9	70	30.5	34.8	2,140	199
V10	100	21.9	49.5	2,190	194

Table 6. Summary of pertinent results for a single horizontal well with 12” diameter at z = 0.5 m.

Single well HRW Configurations						
P&T layout #	**Pumping Rate, Q [m^3/d]**	**Well Length, L[m]**	**Remediation time, $T[d]$**	**Drawdown, ΔS [%]**	**Pumped volume, V [m^3]**	**Concentration, C_0 [mg/m^3]**
H1	17	4	134	34.0	2,278	188
H2	25		91.6	49.5	2,290	187
H3	25	8	99.7	34.5	2,493	172
H4	35		71.0	48.0	2,485	172

Table 5 demonstrates that, in case of VRW, the 4-wells system is able to remediate the aquifer in accord with the 35% and 50% maximum drawdown criteria in approximately 31 and 22 days, respectively. As shown in Table 6, in case of HRW, the single well with 4 m screen length reaches a drawdown of 35% in 134 days, while the single well with 8 m screen length in approximately 100 days.

3.1 P&T configuration costs

To conclude the P&T systems comparison based on vertical and horizontal well configurations, a cost analysis was carried out. Both the costs related to the pumping and treatment processes were obtained as explained in section 2.4.

For the treatment process, the contaminant concentration of the inflowing water to the treatment column varied for each well configuration, depending on the volume of groundwater extracted during the pumping period and accumulated in the extracting tank (Table 7). The configurations yielding the highest C_0 were the triple vertical well systems, for which $234 \leq C_0 \leq 241$ mg/m^3. For the treatment of the water deriving from this configuration, a 4 m activated carbon column was obtained from calculation, by using Eqs (7)-(10). The same column was checked to be able to treat the water deriving from all the tested configurations and, in all the cases, the column reached the threshold limit concentration, C_{ML}, equal 5 mg/m^3 after approximately 18 h of treatment.

With a length of L_{GAC} = 4 m, a radius, r, of 1.2 m, and a bulk density of 520 kg/m^3, the mass of the activated carbon for treatment column obtained was of approximatively 3,000 kg (Eq (17)):

$$m_{GAC} = \pi r^2 L_{GAC}\rho_b = \pi(1.2\text{ m})^2(4\text{ m})\left(520\,\frac{\text{kg}}{\text{m}^3}\right) \cong 3{,}000\text{ kg} \tag{17}$$

At a retail price of £ 4.2 per kg, the cost of treatment, not including the price of the thermal regeneration phase, amounts to £12,580.

Table 7 and 8 list the expenses obtained for the best configurations obtained both for VRWs and HRWs listed respectively in Tables 5 and 6. Also in this case, the configurations that were optimised according to the 35% drawdown criterion are shown in green while, those that were optimised according to the 50% drawdown criterion are shown in orange. VRW configuration costs have been estimated according to Eq (13), while horizontal well costs have been estimated according to Eq (14).

Table 8. Summary of estimated costs for VRW Configurations.

P&T layout	**Installation**	**Pumping**	**Lift**	**Treatment**	**Total $C_{VP\&T}$**
#	£	£	£	£	£
VRW Configuration with single well					
V1	4,000	5,980	1,300	12,580	23,860
V2		5,990	1,800		24,370
VRW Configurations with four wells					
V3	16,000	5,260	420	12,580	34,260
V4		5,310	593		34,500
V5		5,330	663		34,570
V6		5,340	733		34,650
V7		5,350	888		34,820
V8		5,380	1,120		35,100
V9		5,020	1,110		34,710
V10		5,150	1,630		35,360

Table 9. Summary of estimated costs for HRW Configurations.

P&T layout	**Installation**	**Drilling**	**Material**	**Pumping**	**Lift**	**Treatment**	**Total $C_{HP\&T}$**
#	£	£	£	£	£	£	£
HRW Configuration with single well of 4 m screen length							
H1	7,900	2,840	912	5,350	1,160	12,580	30,750
H2		2,840	758	5,380	1,700		31,320
HRW Configuration with single well of 8 m screen length							
H3	7,900	3,320	1,070	5,860	1,290	12,580	32,020
H4		3,320	758	5,840	1,790		32,500

For VRWs, both single and four wells configurations allow complying with the targets, even if with different time and comparable costs. For a single well HRW configuration, it was equally possible but the associated total costs were 1.3 times greater than those corresponding to a single VRW configuration. However, by considering the VRW configuration with four wells, the single HRW configuration allowed for a reduction of total costs equal to approximately 7.5% on average, with the same remediation results.

4. CONCLUSIONS

This study compared differing P&T configuration, by using vertical and horizontal wells for a hypothetical homogeneous aquifer polluted by hexavalent chromium. A sensitivity analysis by comparing different well diameter, D, the pumping rate, Q, and position of wells was carried out. The analysis aimed at finding the best configuration, i.e. to simultaneously minimise the remediation time and related cost of the case study, also allowing to respect a maximum drawdown, ΔS_{max}. The best P&T configuration by using vertical wells resulted when the number of wells was increased to 4, while for the horizontal well configuration, a single well allowed for the total plume removal, by also respecting the criteria adopted.

The cost analysis showed the expected disparity between the vertical and horizontal well installation expenses. However, by considering the same operating costs per well, horizontal wells can make the overall clean-up project less expensive, by reducing both the number of wells, operating costs and disruption to businesses or other activities.

It is worth noting that the costs calculated in this work might be underestimated as installation costs of both horizontal and vertical wells vary greatly depending on many site-specific factors. Certain expenses that are independent of well orientation, placement and number do not directly relate to the decision variables and have therefore been neglected for the present purposes. The model used to estimate the costs provides a preliminary estimate in order to compare the various configurations adopted. For a practical project, however, a more detailed analysis would be required.

References

Balthazard-Accou K., Emmanuel E., Agnamey P., Raccurt C. (2019). Pollution of Water Resources and Environmental Impacts in Urban Areas of Developing Countries: Case of the City of Les Cayes (Haiti). Environmental Health - Management and Prevention Practices.

Bortone I., Chianese S., Di Nardo A., Santonastaso G., Erto A., Musmarra D. (2013). A comparison between Pump & Treat technique and permeable reactive barriers for the remediation of groundwater contaminated by chlorinated organic compounds. Chemical Engineering Transaction, 32:31-36

Carlisle D., Cook D. A., Miller J. A. (2002). Successful use of an innovative horizontal/vertical well couplet in fractured bedrock to intercept a mobile gasoline plume. Groundwater Monitoring & Remediation, 22(2). 82-87.

Cohen. R. M., Mercer. J. W., Greenwald. R. M., Beljin. M. S. (1997). Design guidelines for conventional pump-and-treat systems. EPA. Ground Water Issue.

DE, U.S. Department of Energy (1998). Innovative Technology Summary Report. Horizontal Wells: Subsurface contaminants focus area. DOE/EM-0378.

Di Natale F., Erto A., Lancia A., Musmarra D. (2015). Equilibrium and dynamic study on hexavalent chromium adsorption onto activated carbon. Journal of Hazardous Materials, 281, 47-55.

DT, Directional Technologies (2010). How much does a horizontal remediation well cost. Available online at: www.directionaltech.com/how-much-does-a-horizontal-remediation-wellcost/ [accessed on 29/03/20].

Driscoli F. G. (1986). Ground Water and Wells. Johnson Division. UOP. St Paul, MN.

EPA, U.S. Environmental Protection Agency (2002). Groundwater remedies selected at superfund sites. EPA-542-R-01-022, Washington, D.C.

EPA, U.S. Environmental Protection Agency (2005). Cost-Effective Design of Pump and Treat Systems. EPA 542-R-05-008, Washington, D.C.

EPA, U.S. Environmental Protection Agency (2017). How to Evaluate Alternative Cleanup Technologies For Underground Storage Tank Sites. EPA 510-B-17-003, Washington, D.C.

Fetter C. W. (1993). Contaminant Hydrogeology. 2nd Ed. Ch. 2.6: Derivation of the Advection Dispersion Equation for Solute Transport. New Jersey: Prentice-Hall.

Fournier L. B. (2002) Directionally Drilled Horizontal Wells Offer Cost Savings and Technical Advantages over Alternative Soil and Groundwater Remediation Systems. Remediation Journal, 13(1) ,87-98.

Gelhar L.W., Welty C., Rehfeldt K. R. (1992). A critical review of data on field-scale dispersion in aquifers. Water Resource Research, 28, 1955–1974.

Gorelick S. M., Freeze R. A., Donohue D., Keely J. F. (1993). Groundwater Contamination: Optimal Capture and Contaminant. Bocaraton, Florida: Lewis Publishers.

GA, Government of Alberta (2006). Water conservation and allocation guideline for oilfield injection. Available online at: open.alberta.ca/publications/water-conservation-and-allocationguideline-for-oilfield-injection [accessed on 23/03/20].

Huang C., Mayer A. S. (1997). Pump-and-treat optimization using well locations and pumping rates as decision variables. Water Resources Research, 33(5), 1001-1012.

Joshi S. D. (2003) Cost/Benefits of Horizontal Wells, SPE 83621, Joshi Technologies International, Inc.

Ko A., Lee K., Hyun Y. (2005). Optimal groundwater remediation design of a pump and treat system considering clean-up time. Geosciences Journal, 9(1), 23-31.

Lehr J. H. (2004). Wiley's Remediation Technologies Handbook: Major Contaminant Chemicals and Chemical Groups. Appendix: Technologies with abstracts and technology costs. Wiley-Interscience, New Jersey.

LD, Legislative Decree 152/2006 (2006). Environmental Protection Code, Testo Unico Ambientale 152/2006. Available online at: https://www.camera.it/parlam/leggi/deleghe/06152dl2.htm [accessed on 29/03/20] (in italian)

Looney B. B., Hazen T., Kaback D., Eddy. C. (1991). Full-scale field test of the in situ air stripping process at the Savannah river integrated demonstration test site. WSRC-RD-91-22. Aiken, South Carolina. Westinghouse Savannah River Company.

Lundegard P. D., Chaffee B., LaBrecque D. (2001). Effective Air Delivery from a Horizontal Sparging Well. Groundwater Monitoring and Remediation, 117-123.

Miller R. R. (1996). Horizontal wells: Technology overview report. GWRTAC Series: TO-9602.

NOG, Norsk Olje and Gass (2009). Norwegian Oil and Gas Association recommended guidelines for Joint User Costs for Mobile Rigs / Drill Ships. No. 077/02, Norway.

Oliveira H. (2012). Chromium as an Environmental Pollutant: Insights on Induced Plant Toxicity. Journal of Botany, 375843, 8 pp.

Park Y.C. (2016). Cost-effective optimal design of a pump-and-treat system for remediating groundwater contaminant at an industrial complex. Geosciences Journal, 20,891–901.

Sequino M. (2014). Conquering a Busy Intersection to Install Horizontal Remediation Wells and Protect Indoor Air. 21st Annual International Petroleum Environmental Conference, October 2014, Houston, Texas.

Shanker A.K., Venkateswarlu B. (2011). Chromium: Environmental Pollution, Health Effects and Mode of Action. Encyclopedia of Environmental Health, 650-659.

Söderlind G., Wang L. (2006) Adaptive time-stepping and computational stability. Journal of Computational and Applied Mathematics, 185, 225-243.

Tabatabaian M. (2014). COMSOL® for Engineers. British Columbia Institute of Technology, pp. 254. ISBN: 978-1-938549-53-3

Van Heest G. (2013). Horizontal Wells for groundwater remediation: How a technology that revolutionised the oil industry is used to remediate groundwater. Air & Waste Management Association.

WHO, World Health Organization (1996). Guidelines for drinking-water quality. 2nd ed. Vol. 2. Health criteria and other supporting information. Geneva.

Yihdego, Y., Al-Weshah R. (2016a). Hydrocarbon assessment and prediction due to the Gulf War oil disaster, North Kuwait. Journal of Water Environment Research 89(6), 484-499

Yihdego, Y., Al-Weshah R. (2016b). Engineering and environmental remediation scenarios due to leakage from the Gulf War oil spill using 3-D numerical contaminant modellings. Journal of Applied Water Sciences 7, 3707-3718.

Yihdego, Y. (2018). Engineering and enviro-management value of radius of influence estimate from mining excavation. Journal of Applied Water Engineering and Research 6(4), 329-337.

Yihdego, Y., Al-Weshah R. (2018). Treatment of world's largest and extensively hydrocarbon polluted environment: Experimental approach and feasibility analysis. International Journal of Hydrology Science and Technology 8(2), 190-208.

Zahir I. L. M., Kaleel M. I. M. (2013). Geomorphology. Porosity, specific yield and hydraulic conductivity of granular materials. Kandy: Kurinchi Publication.