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New perspectives on horizontal to vertical well ratios for site cleanup

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Abstract

Directional drilling has been used for a variety of purposes, including utilities, dewatering, and remedial activities. Using this method for site cleanup versus traditional vertical extraction wells needs to be considered based upon today's remedial challenges. Traditionally, it has been stated that a single horizontal well can substitute for up to 11 vertical wells. This "rule" is arbitrary, since length and depth of the plume, surface access, and hydrogeological conditions must be considered. A better way to evaluate the cost-benefit of a horizontal versus vertical well system is a predicted zone of influence using a mathematical and hydrogeological approach, as described herein.

1 | INTRODUCTION

Horizontal directional drilling (HDD) is a steerable and trenchless method of installing utilities and horizontal wells. Typically, this deviation is 12–30° from horizontal directional or horizontal drilling is not new. Using horizontal drains has been around for over 2,000 years. Some of the earliest examples are from Iran and North Africa (Mukherjee & Economides, 1991). The technique has been used throughout Europe for tunnels, water supply, and drainage. The oil industry began using directional drilling in the early 1940s. However, it was not until the 1980s that horizontal drilling began to gain traction in North America for both the oil and environmental industry (Wilson & Kaback, 1993).

Improvements in locating and directing the drilling bit in loose unconsolidated soils improved greatly in the 1990s. It was then that the utility companies began to utilize the technique almost exclusively. This also coincided with the onset of fiber-optic cable and two new rig manufacturing companies; Vermeer and Ditch Witch (Farr, 2012). As the technology became more accepted in the 1990s for the environmental industry, more effort was put into understanding its potential in the evolution of site monitoring and remediation (Laton, 2006).

The two primary types of well completions are continuous (double-ended) and blind (single entry). Continuous boreholes have a starting point on the surface and end by returning to the surface, blind boreholes enter from the surface and terminate below ground. There are many different orientations associated with blind boreholes, some examples are dual, stacked, trilateral, or herringbone configurations. Each of these orientations is used based on project size, geology, and desired effect.

Within the realm of the environmental and extractive and infrastructure construction industries (mining, river crossing, utilities, etc.), HDD has been used for monitoring, extraction, and injection. Wastewater has been disposed of via horizontal wells and horizontal wells also have been utilized for water supply and dewatering. Using horizontal wells for monitoring is relatively infrequent, but is becoming more popular. Horizontal wells have most commonly been used for water and vapor pressure measurement and assessing water and vapor quality within the subsurface.

HDD has been used at many sites for remediation or site cleanup throughout the United States and overseas (Concurrent Technologies Corporation, 2002). Remediation uses of HDD include the pump and treat bio-venting, and vapor extraction systems. Furthermore, horizontal wells have been used to deliver chemicals to the subsurface both in the vadose zone and beneath the water table. Additionally, they have been used for air sparge or vapor extraction within shallow groundwater systems to aid in the removal of hydrocarbons and other volatile contaminants such as certain chlorinated solvents. HDD wells can also be incorporated with permeable reactive barriers or hydraulic control systems.

2 | VERTICAL WELLS VERSUS HDD WELLS

What are the similarities between the more traditional vertical groundwater well and an HDD well? What they have in common is that both use a drilling rig to be installed (though neither rig can be interchanged with another). Also, like some vertical wells, HDD usually is conducted either with water or other drilling fluid and they both can be installed above or below the water table. There is little in the way of depth limits on the installation or drilling of the wells and both end up with a pipe and screened intervals in the ground; the screens in both instances can be long or short. Boring diameters can be from inches to several feet and both can be sealed from the surface. Also, both vertical and HDD wells have been used for monitoring, extraction, or injection and can be developed similarly. Finally, the wells can both be nested or have multiple areas of subsurface connection.

In terms of differences, most vertical monitoring wells have gravel or filter pack surrounding the well screen. This annular fill is used to aid in holding back the subsurface formation and help filter the fluid as it enters the screen. For HDD drilling, this is usually done with natural occurring gravel (natural collapse) or prepacked filter; meaning that no external material is added to the well bore.

HDD wells have often been used to replace many vertical wells when it comes to monitoring, extraction, or injection. The logic behind replacing vertical wells with HDD wells is the increased subsurface contact area with HDD wells. HDD wells tend to better mimic the geometry of elongated plumes and/or thin geologic sequences. This is not the case with vertical wells. A vertical well allows a discrete vertical section of the subsurface to be screened. Depending on the radius of influence and size of the area, multiple vertical wells may be needed to cover the same given zone or unit of interest that fewer HDD wells can treat.

Karlsson (1993), stated that a single HDD well would replace between 5 and 10 vertical wells. Parmentier and Klemovich (1996), stated it was as high as 30 and many others have attempted to quantify the number of vertical wells that a single horizontal well can replace (Cleveland, 1994; Fileccia, 2015; Koenigsberg, Piatt, & Robinson, 2018; Wilson, Kaback, & Oakley, 1990; Zhan, 1999; Zhan & Coa, 2000).

In all groundwater cases, the results are based upon site-specific examples. To fully understand this ratio, one needs to consider the following: geology, hydrogeology, depth, diameter, and purpose. A better way to understand this ratio for the purpose of planning would be to compare the number of vertical wells per lineal foot of HDD groundwater well. Such a comparison would allow for the determination of the zone of influence (groundwater capture area) for both designs and, thus, one could make direct comparisons between the two systems.

Groundwater capture area or zone of influence refers to the area surrounding the screen and how far-reaching it is. This is calculable based upon an understanding of the transmissivity, hydraulic conductivity, and storage of the formation and rate of stress (i.e., pumping). Losonsky and Beljin (1992) developed equations for both HDD and vertical well zone of influence. Their findings indicate that for a horizontal well to replace n vertical wells, its screen length must be $2n$ or greater. This was, however, not based on the hydrogeological characteristics of a potential project site.

2.1 | Advantages of HDD wells

In certain settings, there can be multiple advantages to HDD wells over vertical wells. Both HDD wells and horizontal trenches significantly increase the access (or exposure) to contaminants compared to traditional vertical wells. The geometries of HDD wells and trenches are similar. Trenches may be preferred for some applications requiring shallow surface access, while HDD wells may be preferred for deeper applications or in situations where surface access restrictions exist due to the built environment, natural obstacles, site security issues, and matters concerning access with neighbors and business disruption (Koenigsberg et al., 2018). Additional advantages of HDD wells are:

- Proper access agreements;
- The wellhead does not need to be directly over the well;
- The well can be placed under existing structures, landfills, roads, rivers, lakes, wetlands, adjacent property, etc.;
- Drilling can be conducted under an operational site, without disturbance;
- The screen orientation can coincide with the major axis of the contaminant plume;
- Increase in linear footage of well screen in contact with the contaminant zone, compared to vertical wells;
- The screen can be installed along the leading edge of a plume or at a property boundary for hydraulic control;
- The well can be used for monitoring, remediation, and/or dewatering;
- Horizontal wells can be used to intersect vertical fractures;
- Horizontal wells improve access to contaminants at sites with surface restrictions;
- Minimal security issues bec ause fewer wellheads may be required;
- Minimal surface disturbance because fewer wellheads may be required;
- Reduced operating expenses because fewer wells may be required; and,
- Able to provide access to off-site contamination to be treated by on-site operations.

2.2 | Disadvantages of HDD wells

Limitations of HDD environmental wells include a requirement for accurate drilling installation, reduced ability to intercept multiple layers in a stratified geologic setting, minimal water table fluctuation for light nonaqueous phase liquid recovery, and limited vertical influence of the well due to anisotropy. Additional disadvantages of HDD wells are:

- Potentially difficult to place gravel/filter pack, may require prepacked screen or natural collapse;
- Challenging to grout vis a vis segmented individual sections;
- Increase volume of solid waste and development water;
- Can be affected by major water level changes; and,
- May be higher cost than a series of vertical wells.

2.3 | Discussion of specific disadvantages for the use of HDD wells

The following section explains the common criticisms of HDD wells.

Screen Length and Placement: Several studies have been conducted to research stratification within vertical groundwater monitoring wells (Britt, Parker, & Cherry, 2010). It is thought that stratification is something that typically would not be encountered in HDD wells. However, it should be noted that there do exist horizontal stratigraphic changes (horizontal heterogeneity) that can impact HDD wells. In addition, HDD wells can be placed within a thin geological unit or precisely in the plume. This cannot be accomplished with vertical wells but rather only with mini piezometers. This leads to a much larger contact area for an HDD well over that of a vertical well (Wilson et al., 1990). Several advancements have come about in the last decade to include the placement of multiport HDD wells (Koenigsberg et al., 2018). This new technique of multiport HDD wells can aid in both the monitoring and remedial efforts associated with various projects. The system can be used for assessment/ monitoring (both pressure and chemistry) across a contaminant plume, while providing access points for future treatment.

Gravel Pack: the absence of an external gravel/filter pack. Many groundwater monitoring wells are installed without a gravel/filter pack (a natural collapse gravel/filter pack). Some HDD wells use prepacked screens instead of the natural collapse. This is where the natural aquifer material around the screen is used, rather than introducing external materials. In addition, soil and water samples are routinely collected without a well or filter pack, such as cone penetration testing, direct push, Simulprobe™, Hydropunch™, etc. These sampling technologies are routine and well accepted.

Grout Seals: the insertion of a grout seal within an HDD well is difficult due to the orientation of the pipe (horizontal vs. vertical). In 2009, the University of Nebraska-Lincoln published a study on grout seals associated with vertical wells. Their findings concluded that all seals leak and that if above the water table, bentonite grouts will dry out and shrink (Lackey, Myers, Christopherson, & Gottula, 2009). The placement of any grout seal (cement or bentonite) is to seal the annular space around the pipe. With an HDD pipe situated on the bottom of the drill hole, grouting around the pipe is difficult. Thus, grouting techniques for HDD wells still need more attention to develop better methods of sealing.

Well Development: the development process is required to remove the drilling fluid and fines introduced during well drilling. It is also used to remove fines from annular space and in the formation area immediately surrounding the borehole. This is typically conducted through jetting and pumping. Jchemicals into the well to clear the drilling fluids and fines from the well. Vertical water production wells are generally developed for over 1 hour (hr) per foot of the screen (Driscoll, 1986). In the environmental industry, vertical monitoring wells are developed over a shorter time interval and with less energy. Commonly, HDD wells are developed for a longer period of time, in some cases as much as 10 hr. This is due to the placement of the HDD pipe within the borehole. Because of gravity, heavier materials will fall out of solution within the drilling fluid (or from around the borehole). This makes it more difficult to develop the bottom portion of the borehole.

3 | MATHEMATICAL MODEL

The following mathematical equations are used to determine the estimated number of vertical wells needed to replace a single HDD well across a given capture area and a specific hydrogeological regime. A simplified approach to determining the ratio of horizontal wells to that of vertical wells is to look at the capture area of each. This has been addressed before with modeling and complex equations (Forouzanfar, Reynolds, & Li, 2012; Losonsky & Beljin, 1992; Sawyer & Lieuallen-Dulam, 1998). A simpler approach is presented here that entails using basic equations for radial flow in a water table aquifer for vertical wells and water table flow from a line source to a drainage trench (horizontal well). As flow to a trench mimics that of groundwater flow to a horizontal well, this approach seems reasonable. In using this simplified approach an approximate ratio of the number of vertical wells required to provide the same capture area as a single horizontal well can be calculated. (Figures 1–3).

Powers (1992) provides the following two basic equations required for this analysis:

Equation for radial flow, water table aquifer (vertical well).

$$Q_w = \frac{K\left(H^2 - h_w^2\right)}{458 ln(R_o/r_w)}$$

Equation for water table flows from a line source to a drainage trench (HDD well).

$$\frac{Q}{x} = \frac{K(H^2 - h_w^2)}{2,880L}$$

Notes: Equations are in US units

Q = discharge or pumping
x = unit length of trench, far flow from two sides, use twice the indicated value
K = hydraulic conductivity
R_o = radius of influence
r_w = radius of well
H = aquifer thickness
h_w = height of water column at well after pumping
L = drawdown distance away from line source

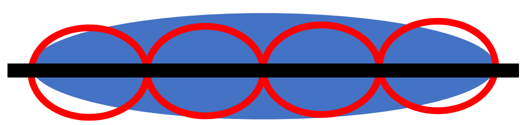

FIGURE 1 Horizontal well to vertical wells [Color figure can be viewed at wileyonlinelibrary.com]

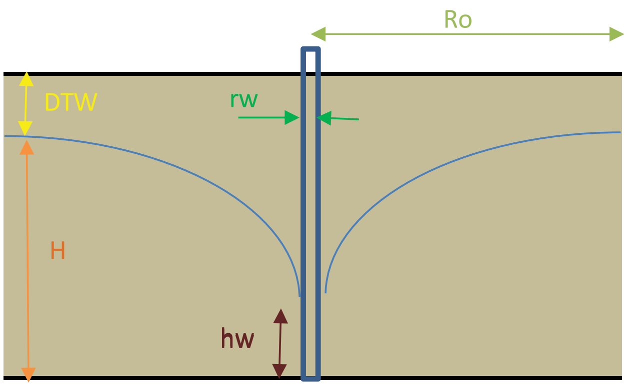

FIGURE 2 Radial flow, water table aquifer [Color figure can be viewed at wileyonlinelibrary.com]

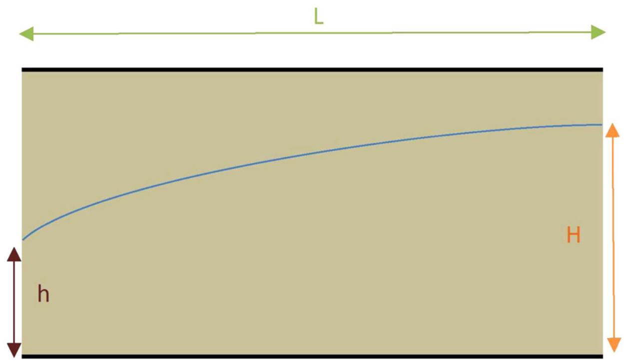

FIGURE 3 Water table flow from a line source to a drainage trench [Color figure can be viewed at wileyonlinelibrary.com]

Through the simple relationship of comparing R_o to that of L with a set pumping rate allows for the comparison of systems. Then the ratio becomes simple; by doubling the R_o and dividing it by the length of planned horizontal well produces the ratio of the number of vertical wells that can be replaced by a single horizontal well.

3.1 | Example: what is the ratio of vertical wells to that of a single HDD well

The following example illustrates how this approach can be used by looking at a basic hydrogeological problem such as one might encounter in the upper mid-west. In this example the following conditions exist for a hypothetical hydraulic barrier to intercept and capture contaminated groundwater flowing perpendicular to the barrier such as conditions at a service station where gasoline has leaked:

- Depth to groundwater: 5 feet (ft) below ground surface (bgs)
- Desired groundwater drawdown: 20 ft bgs
- Hydraulic conductivity: 15 gallons per day/square foot (2 ft/day) representing medium sand.
- Barrier length: 100 ft
- Pumping rate: 5 gallons per minute (gpm)

In this example, seven 6-inch vertical wells would be required to replace a single 6-inch 100-ft long horizontal well. This represents a vertical well R_o of 6.87 ft. Thus, the ratio of vertical to horizontal wells is 7:1 (see Figures 4 and 5)

4 | CONCLUSIONS

Under certain site conditions, horizontal wells offer several advantages to vertical wells, depending on geology and surface or near-surface structures. However, many times, during any remedial design planning, the need for a method determines the potential differences for a horizontal well system versus that of a series of vertical wells is needed. The mathematical solution explained above approximates the ratio of horizontal to vertical extraction wells and provides information to allow for a cost comparison to be performed. In

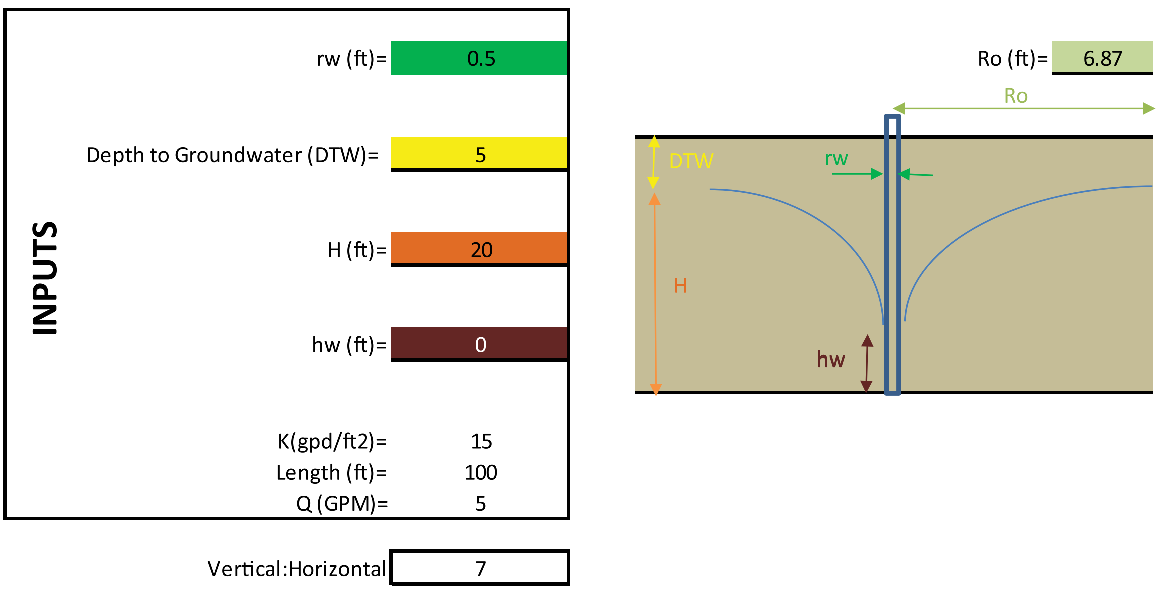

FIGURE 4 Example model input. gpm, gallons per minute [Color figure can be viewed at wileyonlinelibrary.com]

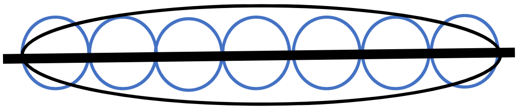

FIGURE 5 Illustrated model output [Color figure can be viewed at wileyonlinelibrary.com]

addition, by using the known hydraulic conductivity, depth to groundwater, and the desired depth of drawdown, pumping rates can be adjusted to maximize the desired outcome for remedial designs. Utilizing actual site data in the approach allows for the ability to make better decisions without the expense of conducting a full-scale groundwater flow model.

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