New Perspectives on Horizontal to Vertical Well Ratios for Site Cleanup

W. Richard Laton, PhD, PG, CHg
Department of Geological Sciences
California State University, Fullerton

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 seems arbitrary in that both depth of the system and hydrogeological conditions play a large role that does not seem to be considered. A better way to evaluate the cost-benefit of one system over another is to base it on the number of vertical wells per a given length of a directional well and to evaluate it more on the zone of influence of both designs through a mathematical and hydrogeological approach, such as that which is considered here.

1. INTRODUCTION

Horizontal directional drilling (HDD) can be defined as any drilling activity that deviates from the vertical. Typically, this deviation is greater than 80 degrees from the vertical. Directional or horizontal drilling is not new. The technique 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 is 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).

There are several types of boreholes associated with HDD. There are continuous boreholes, which have a starting point on the surface and end by returning to the surface, and there are blind boreholes that enter from the surface but end in the subsurface. There are several different orientations associated with blind boreholes, these are dual, stacked, trilateral, or herringbone configurations.

Within the realm of the environmental and industrial 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 it is becoming more popular, having been used for water and vapor pressure measurement and assessing water and vapor quality within the subsurface.

The use of HDD has been used at many sites for remediation or site cleanup throughout the U.S. and overseas (Concurrent Technologies Corporation, 2002). Remediation uses of HDD include pump and treat, bio-venting, and vapor extraction systems. Further, 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 also work well as part of 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. 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 pipe and screened intervals in the ground; the screens in both instances can be long or short. Boring diameters can be from inches to tens of feet and both can be sealed from the surface. Also, both vertical and HDD wells have both been used for monitoring, extraction, or injection and can both 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 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 as a natural occurring gravel (natural collapse) or pre-packed filter. Meaning that no external material is added to the well bore.

It has been proposed that HDD wells can replace many vertical wells when it comes to monitoring, extraction, or injection. The thought behind this proposal is the increased subsurface contact area with HDD wells. Since HDD wells can be placed within a single geological, hydrogeological, or contaminant zone, there is essentially an unlimited contact area. This is not the case with vertical wells. A vertical well allows a vertical section of the subsurface to be screened, but multiple vertical wells are needed to cover the same given zone or unit of interest.

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 (Wilson, Kaback & Oakley, 1990; Koenigsberg, Piatt, & Robinson, 2018; Cleveland, 1994; Zhan, 1999; Zhan & Coa, 2000; Feleccia, 2015).

In all cases the results are based upon site specific examples. In order 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 well. Such a comparison would allow for the determination of the zone of influence (capture area) for both designs and, thus, one could make direct comparisons between the two systems.

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, Piatt, & Robinson, 2018). Additional advantages of HDD wells are:

- 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 cross vertical fractures;
- Able to improve access to contaminants at sites with surface restrictions;
- Minimal security issues because 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, minimal water table fluctuation for light non-aqueous 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 pre-packed screen or natural collapse;
- Challenging to grout vis a vis segmented individual sections;
- Well development may be difficult;
- Can be affected by major water level changes; and,
- Sometimes costly.

2.3 DISCUSSION OF SPECIFIC DISADVANTAGES FOR THE USE OF HDD WELLS

The following section explains the primary issues used to discourage HDD wells from being utilized. These are problematic in that they are addressing the issues as they would relate to vertical wells rather than just HDD wells.

Screen Length and Placement: Several studies have been conducted to research stratification within vertical groundwater monitoring wells (Britt, Parker, & Cherry, 2010). This is something that typically would not be seen in an HDD well. Additionally, 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, Kaback, & Oakley, 1990). Several advancements have come about in the last decade to include the placement of multiport HDD wells (Koenigsberg, Piatt, & Robinson, 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 pre-packed screens instead of the natural collapse. This is where the natural aquifer material around the screen is used, rather than introducing external materials. Additionally, soil and water sampling are routinely collected without a well or filter pack, such as cone penetration testing (CPT), direct push, Simulprobe™, Hydropunch™, etc. These sampling technologies are routine and well accepted.

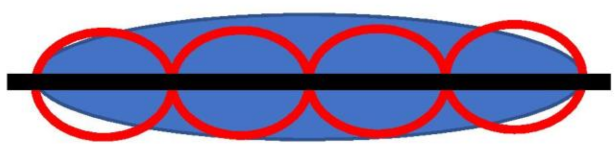
Grout Seals: In 2009, the University of Nebraska-Lincoln published a study on grout seals. Their findings concluded that all seals leak and that if above the water table, bentonite grouts will dry out and shrink (Lackey, Myers, Christopherson, & Gottula, 2009). The placement of any grout seal is always difficult. The insertion of a grout seal within an HDD well is made even more difficult due to the orientation of the pipe. Grouting techniques still need more attention to develop better methods of sealing.

Well Development: All wells need to be developed after drilling. This is performed to remove the drilling fluid introduced during the well installation and to reverse impacts to the formation resulting from the drilling process. This is typically conducted through a surging or pumping manner. However, jetting or the introduction of cutting chemicals (chemicals introduced to the well in order to break down the drilling fluids; i.e. bentonite) are used in some instances. Vertical water production wells are generally developed for over one hour per foot of screen (Driscoll, 1986). In the environmental industry, vertical monitoring wells are developed over a much shorter time interval and with much less energy. Commonly, HDD wells are developed much more intensely than their vertical well counterparts and will often take a longer time to fully develop. This is due to the issues with conductivity between the screen and formation and potential for drilling fluids to plug the formation.

3. MATHEMATICS

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; Sawyer & Lieuallen-Dulam, 1998; Losonsky & Beljin, 1992). A simpler approach is presented here that entails using 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). 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.

Figure 1

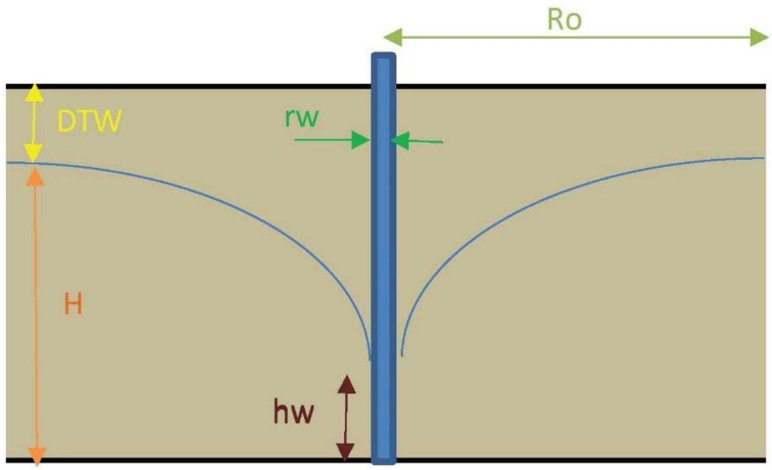


Powers (1992) provides the follow two basic equations required for this analysis:

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

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

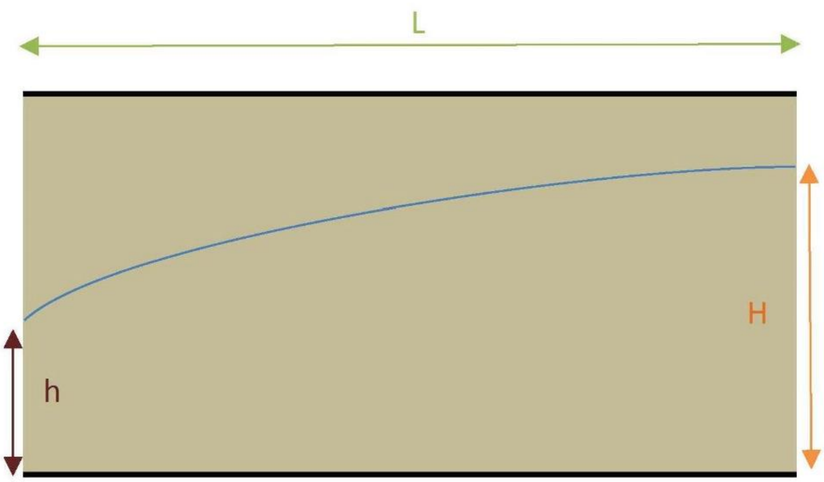
Figure 2



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

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

Figure 3



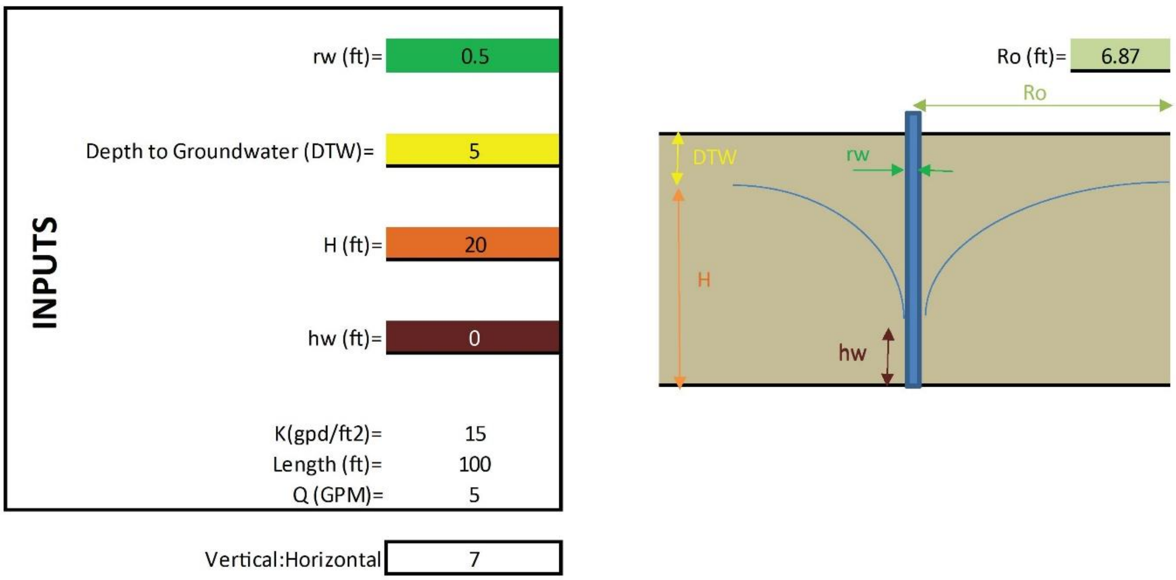
Notes: Equations are in U.S. units

- Q = discharge or pumping
- x = unit length of trench, far flow from 2 sides, use twice the indicated value
- K = hydraulic conductivity
- R_o = radius of influence
- R_w = radius of well
- H = aquifer thickness
- h = height of water column at well after pumping
- L = drawdown distance away from line source

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 vertical wells required to replace a single horizontal well.

3.1 EXAMPLE: WHAT IS THE RATIO OF VERTICAL WELLS TO THAT OF A SINGLE HDD WELL

Figure 4



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 that of what might be found 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 a 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 R_o of 6.87 feet. Thus, the ratio of vertical to horizontal wells is 7:1.

4. CONCLUSIONS

Horizontal wells are an obvious choice for remedial projects not conducive to vertical wells. The ability to conduct HDD under existing structures or not disturb active operations makes horizontal wells an excellent alternative to traditional vertical wells. However, many times, during any remedial design planning, the need to quickly determine 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. Additionally, 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.

REFERENCES

Britt, S.L., Parker, B.L., & Cherry, J.A. (2010). A downhole passive sampling system to avoid bias and error from groundwater sample handling. *Environmental Science & Technology, 44*(13), 4971-4923. doi: 10.1021/es100828u

Cleveland, T.G. (1994). Recovery performance for vertical and horizontal wells using semianalytical simulation. *Ground Water*, *32*(1), 103-107. doi:10.1111/j.1745-6584.1994.tb00617.x

Concurrent Technologies Corporation. (2002). *Horizontal environmental wells- A catalogue of horizontal environmental wells in the United States* (Report No: TS-02-01). Retrieved from: https://cluin.org/products/tins/tinsone.cfm?id=58323796&query=CHARACTERIZATION%20AND%20REMEDIATION%20OF%20A%20TCE%20SOURCE%20AREA%20USING%20ELECTRICAL%20RESISTANCE%20HEATING%20&numresults=25&startrow=551

Driscoll, F. (1986). *Groundwater and Wells.* St. Paul, Minnesota: Johnson Screens.

Farr, A. (2012, July 4). A brief history of directional drilling: The birth and development of the HDD market. *Trenchless Technology*. Retrieved from: https://trenchlesstechnology.com/brief-history-horizontal-directional-drilling/

Fileccia, A. (2015). Some simple procedures for the calculation of the influence radius and well head protection areas (theoretical approach and a field case for a water table aquifer in an alluvial plain). *Acque Sotterranee, 4*(3), 7-23. doi: 10.7343/as-117-15-0144

Forouzanfar, F., Reynolds, A.C., & Li, G. (2012). Optimization of the well locations and completions for vertical and horizontal wells using a derivative-free optimization algorithm. *Journal of Petroleum Science and Engineering, 86-87,* 272-288. https://doi.org/10.1016/j.petrol.2012.03.014

Karlsson, H. (1993). Horizontal systems technology for shallow site remediation. *Journal of Petroleum Technology*, *45*(2), 160-165. doi:10.2118/24600-PA

Koenigsberg, S.S., Piatt, E.R., & Robinson, L.I. (2018). New perspectives in the use of horizontal wells for assessment and remediation. *Remediation*, *28* (4), 45-50. doi: 10.1002/rem.21575

Lackey, S.O., Myers, W.F., Christopherson, T.C., & Gottula, J.J. (2009). Nebraska grout task force in-situ study for grout material 2001-206 and 2007 dye tests. *Conservation and Survey Division, 413*. Retrieved from: http://digitalcommons.unl.edu/conservationsurvey/413

Laton, W.R. (2006). Building Groundwater Monitoring Wells on Campus – A Case Study and Primer. *Journal of Geoscience Education*, *54*(1), 50-53.

Losonsky, G., & Beljin, M.S. (1992). Horizontal wells in subsurface remediation. Greenbelt, MD: Hazardous Materials Control Research Institute.

Mukherjee H., & Economides, M.J. (1991). A parametric comparison of horizontal and vertical well performance. *Society of Petroleum Engineers*, *6*(2), 209-216. https://doi.org/10.2118/18303-PA

Parmentier, P.P., & Klemovich, R.M. (1996). A new direction in remediation. *Civil Engineering, 66*(4), 55-57. Retrieved from https://cedb.asce.org/CEDBsearch/record.jsp?dockey=0099248

Powers, J.P. (1992). *Construction dewatering: new methods and applications -2nd edition.* Hoboken, NJ: John Wiley & Sons, Inc.

Sawyer, C.S., & Lieuallen-Dulam, K.K. (1998). Productivity comparison of horizontal and vertical ground water remediation well scenarios. *Ground Water*, *36*(1), 98-103. https://doi.org/10.1111/j.1745-6584.1998.tb01069.x

Wilson, D.D., and Kaback, D.S. (1993). *Industry survey for horizontal wells final report* (DOE Contract No. DE-AC09-89SR18035). Aiken, SC: U.S. Department of Energy.

Wilson, D.D., Kaback, D.S., & Oakley, D.B. (1990). *Horizontal environmental wells.* Paper presented at the workshop proceedings of the 1993 NGWA Outdoor Action Conference. Dublin, Ohio.

Zhan, H. (1999). Analytical study of capture time to a horizontal well. *Journal of Hydrology, 217*(1), 46-54. https://doi.org/10.1016/S0022-1694(99)00013-x

Zhan, H. & Coa, J. (2000). Analytical and semi-analytical solutions of horizontal well capture times under no-flow and constant-head boundaries. *Advances in Water Resources*, *23*(8), 835-848. doi: 10.1016/S0309-1708(00)00014-2

W. Richard Laton, Ph.D., PG, CHg, is an Associate Professor of Hydrogeology in the Department of Geological Sciences, California State University, Fullerton. This is a continuation of a career that includes years of teaching, consulting, litigation support, and management experience. Dr. Laton possesses extensive knowledge in the areas of hydrogeology, soil and water contamination, field sampling techniques, and well drilling and hydraulics. Dr. Laton received his B.A. in Earth Science from St. Cloud State University, an M.S. in Earth Science from Western Michigan University, and his Ph.D. in Hydrogeology from Western Michigan University. Email address: wlaton@fullerton.edu.

FIGURE LEGEND