Comparative Economic Analysis
Vertebrae™ Horizontal Nested Well System versus Vertical Extraction Wells

1 | INTRODUCTION

This report summarizes the process and results obtained from an economic analysis comparing the installation cost of the Vertebrae™ horizontal nested well system to a vertical well groundwater pump and treat system such as might be installed at a gas station, terminal, or small manufacturing plant. The purpose of the analysis is to help decision makers gain an understanding of the potential value that could be realized from the installation of the Vertebrae™ at a given site. The results indicate that for a small site such as a gas station the average the installation cost for the Vertebrae™ system is approximately 15% less than that of a standard vertical well system. For larger sites, such as terminal or manufacturing plant; the average savings is on the order of 57%.

This is a preliminary evaluation that considers only the cost required to install a system to begin treatment operations, and not full life cycle costs. Given the efficiencies associated with horizontal wells, operational flexibility of the horizontal nested well system, and the ability to use the Vertebrae system for investigation and remediation, it is anticipated that the life-cycle savings associated with the Vertebrae™ system will be substantial when compared with traditional vertical well systems.

2 | VERTEBRAE™ DESCRIPTION AND BENEFITS

Although this report is focused on economics, it is important to briefly describe the Vertebrae™ system and its associated benefits since they have a considerable effect on the economics in both the short and long term. The Vertebrae™ system represents an extension and improvement on horizontal well installation techniques used for purposes of remediation.

Horizontal wells offer many advantages over vertical wells because of the increased formation contact area that can be achieved with horizontal well bores. This increased contact area is especially valuable when dealing with soils consisting of finer grain materials and those having low vertical to horizontal permeability ratios. Another significant advantage of horizontal wells it that they can be placed directly under surface structures such as above ground storage tanks or manufacturing buildings where the largest volume of released contaminants often occurs. At the present time horizontal wells are most often used to treat contamination by the injection of reagents or by dual-phase fluid extraction.

The traditional horizontal well design involves a well screen interval that extends throughout most of the horizontal bore. The primary disadvantage of the traditional design is that it does not address the problem of preferential flow paths that result from the heterogenous nature of the subsurface environment (i.e., (mixtures of sand, silt, clay and fill materials). These preferential flow paths prevent the homogenous delivery of reagents to the impacted soils. They also limit the extraction of fluids from all soils encountered by the wellbore. Thus, coarse gained soils with higher permeabilities receive the greatest amount of treatment while fine grained low permeability soils receive minimal treatment. This problem exists with vertical wells as well, and is one of the reasons for the long durations associated with pump and treat operations. It also explains the rebound of dissolved concentrations of contaminants in groundwater after pump and treat operations are ceased.

The Vertebrae™ design makes use of segmented and isolated well screens that are individually piped to the surface. This design overcomes the influence of preferential flow paths and allows for substantial flexibility of operation, both in the introduction of reagents and in the dual-phase extraction of fluids.

The Vertebrae™ design also enables the use of the system for assessment of contaminant distribution. This is done by collecting water and/or air samples from the segmented zones. The result is a more detailed delineation of contamination under surface structures than can be obtained by traditional methods. Therefore, this design introduces additional life cycle cost savings since the system used for additional site assessment is available for immediate use as a remediation technology.

3 | ANALYSIS METHODOLOGY

It is well known within the remediation industry that site characteristics such as the type of surface structures, the soil types, depth to groundwater, and depth to bedrock can vary considerably from one site to another. In addition, labor rates and equipment cost are somewhat location specific. To account for this variability and uncertainty, this analysis makes use of Monte Carlo simulation.

Monte Carlo simulation replaces fixed cost estimates for completing various implementation tasks with probability distribution functions (PDFs). PDFs describe the range of cost values that are possible for the various implementation tasks as well as the probability of taking given values within the range. During the simulation, the input PDFs are repeatedly sampled and the total cost based on the sum of these sampled costs is repeatedly calculated. Each input sampling and calculation event is referred to as an iteration. For this analysis, the small and large site simulations involved 5,000 iterations.

4 | MODEL INPUTS

There are a number of different types of PDFs than can be used to represent a range of values based on the application type. A common and popular PDF used for purposes of cost estimating is the Program Evaluation and Review Technique (PERT) distribution. This distribution is popular for two reasons. The first is that the parameters used to shape this distribution are minimum, most likely and maximum estimates. The second is the distribution can take on the shape of a normal distribution (often referred to as the bell curve) or a lognormal distribution which can be skewed to the left or right based on the numerical difference (or distance) between the three input values. Normal and lognormal PDFs are commonly found to be associated with economic parameters (e.g. home values, automobile prices, and construction cost) as well as environmental parameters (e.g., soil hydraulic conductivity and porosity).

The process of estimating model inputs began with identifying relevant cost components for the Vertebrae™ system and the vertical well systems that would be used at both the small and large sites. Additional assumptions were made regarding the size as the small and large sites. The small site was assumed to be approximately one acre in size, with features that might be found at a gas station or historical dry cleaner operation. The larger site was assumed to be two to five acres in size with features similar to a terminal or manufacturing plant.

Once the cost components were identified, minimum, most likely and maximum cost estimates were developed for each component of Vertebrae™ and the vertical well systems. These estimates are based on a combination of information found in RS Means cost manuals, online research of supplier costs, and expert judgement. In a number of cases, the minimum, most likely and maximum component costs are based on a detailed breakout of unit costs and the number of units estimates. This is best demonstrated by way of example.

Exhibit 1 shows the estimated minimum, most likely and maximum estimates for each of the cost components of the vertical well extraction system for the small site. These estimates assume that the minimum system will include two extraction wells, the most likely system three extraction wells, and a maximum system five extraction wells.

Cost Component	Minimum	Most Likely	Maximum
Design	$ 5,000	$ 20,000	$ 50,000
Extraction Wells with Pumps	$ 11,000	$ 31,500	$ 92,000
Trenching	$ 2,500	$ 12,000	$ 40,000
Piping	$ 1,000	$ 3,000	$ 12,500
Electrical	$ 1,000	$ 6,000	$ 20,000
Concrete	$ 9,000	$ 36,000	$ 135,000
Startup	$ 10,000	$ 15,000	$ 20,000

Exhibit 1 Small site vertical well system cost component estimates

Exhibit 2 shows the detailed cost breakout used to estimate the minimum, most likely and maximum values for the Extraction Wells with Pumps cost component shown in Exhibit 1.

		Cost Per Unit			Number of Units		
Line Item	Units	Minimum	Most Likely	Maximum	Minimum	Most Likely	Maximum
Driller Mob	$/Each	1,000	1,500	2,500	1	1	1
Drilling	$/Lf	25	35	50	10	15	30
Well Casing	$/LF	15	20	30	5	10	15
Field Labor	$/hr	75	150	225	8	24	32
Screen	$/LF	28	40	60	4	5	10
Pump	$/Each	3,500	5,000	8,000	1	1	1

Exhibit 2 Detailed cost breakout for vertical well system

For those wishing to verify the values as found in Exhibit 1 using the information contained in Exhibit 2, it is important to note that the values in Exhibit 2 are on a per well basis. In addition, the costs found in Exhibit 1 are rounded up to the nearest thousand dollars. For example, the $11,000 minimum cost found in Exhibit 1 is calculated by multiplying the minimum costs for drilling, well casing, field labor, screen and pump by their associated minimum number of units. These products are then summed and multiplied by the minimum number of wells for the small system, which is two. The minimum mobilization cost is then added to this result, since there is one mobilization regardless of the number of wells drilled. The final result is then rounded up to the nearest thousand. The same process is used to calculate the $92,000 maximum Extraction Wells with Pumps cost but, in this case, the assumed maximum number of wells is five.

Exhibit 3 presents the PDF that represents the cost of the Extraction Wells with Pumps cost component for the small site vertical well system based on the values presented in Exhibit 1. This distribution indicates that the mean (probability weighted average) for installing vertical Extraction Wells with Pumps at the small site is $38,000. One standard deviation below this mean is estimated at $23,000 and one standard deviation above is estimated $52,000. In addition, Exhibit 3 indicates that the 90% confidence interval is from $17,000 to $64,000. This means that there is a 90% chance that the cost to installing vertical Extraction Wells with Pumps at a given small site is within the range of $17,000 to $64,000.

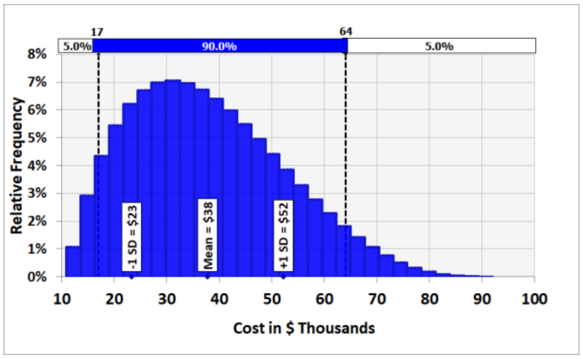

Exhibit 3 PDF for Extraction Wells with Pumps cost component of small site vertical well system

Exhibit 4 shows the estimated minimum, most likely and maximum estimates for each of the cost components of the vertical well extraction system for the large site. These estimates assume that the minimum system will include seven extraction wells, the most likely system nine extraction wells, and a maximum system eleven extraction wells. The process of estimating these values is the same as that described above pertaining to the estimate of the cost of the Extraction Wells and Pumps for the small site. The detailed cost breakouts and PDFs have been omitted for purposes of brevity.

Cost Element	Minimum	Most Likely	Maximum
Design	$ 6,000	$ 32,000	$ 100,000
Extraction Wells with Pumps	$ 36,000	$ 91,500	$ 200,500
Trenching	$ 3,000	$ 19,200	$ 80,000
Piping	$ 1,200	$ 4,800	$ 25,000
Electrical	$ 1,200	$ 9,600	$ 40,000
Concrete	$ 10,800	$ 57,600	$ 170,000
Startup	$ 12,000	$ 24,000	$ 40,000

Exhibit 4 Large site vertical well system cost component estimates

Exhibit 5 shows the estimated minimum, most likely, and maximum estimates for the components of the Vertebrae™ well systems. This table was developed based on installation of a single well system consisting of seven to eleven screened well segments. These segments were assumed to have a minimum, most likely and maximum lengths of ten, fifteen and twenty feet respectively. Lastly, segments were assumed to have minimum, most likely and maximum spacings of ten, fifteen and twenty feet respectively. The Vertebrae™ does not require the installation of subsurface pumps. This analysis is focused on in-ground system placement costs and does not include the costs of surface equipment. Therefore, surface equipment costs are not included in either the vertical well system estimates or the Vertebrae™ estimates.

Since the Vertebrae™ system does not include subsurface pumps the electrical cost component is not included in Exhibit 5. Also, since the Vertebrae™ system is installed beneath structures and paving and does not make use of piping trenches to connect the various wells to a central collection location, trenching, piping and electrical cost components are omitted. The build cost component represents the cost to prefabricate the Vertebrae™ system that is delivered to the site and used to place the screened well segments along with their conductor pipes within the horizontal well bores.

Cost Component	Min	Most Likely	Max
Design	$2,500	$3,000	$4,000
Build	$24,000	$30,000	$81,000
Drill/Install	$61,697	$68,552	$85,690
Develop/Complete	$13,506	$16,883	$30,389

Exhibit 5 Vertebrae™ system cost component estimates

The cost estimates included in Exhibit 5 were developed by EN Rx engineers based on their experience in installing such systems at a variety of locations.

Given the design assumptions associated with Exhibit 5, this same system works equally well for both the small and large site. This is because of the of the large contact area and efficiencies associated with horizontal wells. In other words, the Vertebrae™ system typically employed at small sites provides the treatment capacity of a much larger vertical well system. To imagine how this can be, one need only consider the total length of well screen that will be in contact with the formation. The single well system represented by Exhibit 5 could have as much as 220 feet of total screened interval (11 screened sections with each section having a length of 20 feet). The effect of the system is further enhanced by the fact that surface structures such as tanks, pump stations, and builds will not prevent the positioning of the well boring directly beneath source areas and in the center of contaminant plume. Therefore, for the purpose of this analysis the potential costs for implementing the vertical well systems at both the small and large site will be compared to the potential cost of the Vertebrae™ having the cost components as outlined in Exhibit 5.

5 | ECONOMIC MODELING RESULTS

This section summarizes results obtained from Monte Carlo simulation models developed for evaluating and comparing the installation cost of the Vertebrae™ horizontal nested well system to a vertical well groundwater pump and treat system for a typical small and large site as described in the model input section. The results include model output PDF graphs and descriptive statistics comparing the two systems as applied to the two site types.

The output PDF graphs provide a visual means of comparing the potential range of costs for implementing the two systems as well as the likelihood of taking on various costs within that range. The descriptive statistics provide more detailed numerical data regarding the likely cost of implementing the two systems.

5.1 | Small Site Economic Analysis Results

Exhibit 6 presents the output PDFs associated with vertical extraction wells and the Vertebrae™ systems. The mean cost of each system is reported along with the PDFs. Since the PDF represents a range of cost, it is helpful to have one number that represents this range. This mean value accomplishes this task. The mean is the probability weighted average of all values contained within the PDF. It is an unbiased estimator and the best value to use when comparing the potential cost of the two systems. Using this information, we can say on average it will cost $129,000 to implement the Vertebrae™ System at a small site and $151,000 to implement a vertical well extraction system. Therefore, we can estimate the Vertebrae™ system on average will cost $22,000 less than vertical well system, a savings of approximately 15%.

The difference in the mean cost of implementing the two systems at a small site may not seem substantial. However, the shape of the PDFs indicates that there is much more uncertainty associated with the vertical wells. This is evident by noticing the somewhat flattened and spread-out shape of the vertical well system PDF. By comparison the Vertebrae™ system PDF is much more peaked up and extends across a smaller range.

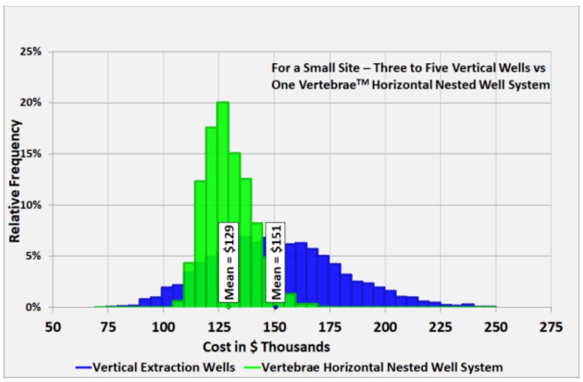

Exhibit 6 Small site output PDFs comparing Vertebrae™ system and vertical extraction wells

Exhibit 7 presents the output descriptive statistics applied to the small site. The mean values, which have already been discussed, are the same as those presented in Exhibit 6. The standard deviation measures the dispersion of the data. As seen Exhibit 4 the cost data for the vertical extraction well system is more dispersed. This is why the standard deviation for the vertical well extraction system at $29,000 is more than double that of the Vertebrae™ system, which is $11,000. The mode is the value calculated most often during the simulation. It is the value associated with the highest bar in the PDFs presented in Exhibit 6. Although, like the mean, it is a measure of central tendency, it does not account for the full range of costs and should not be used for comparing alternatives.

The probability percentiles provide an indication that the cost will be less than or equal to a given value. For example, the 90% probability percentile for the small site vertical extraction systems is $189,000. This means that there is a 90% chance that the small site vertical extraction system can be installed for less than or equal to $189,000

Statistic	Vertebrae™ Well System	Vertical Extraction Wells
Mean	$129,000	$151,000
Std Deviation	$11,000	$29,000
Mode	$127,000	$139,000
10% Percentile	$117,000	$115,000
50% Percentile	$128,000	$149,000
90% Percentile	$144,000	$189,000

Exhibit 7 Small site output descriptive statistics comparing Vertebrae ™ system and vertical extraction wells

5.1 | Large Site Economic Analysis Results

Exhibits 8 and 9 present the large site output PDFs and descriptive statistics associated with the Vertebrae™ system and vertical extraction wells.

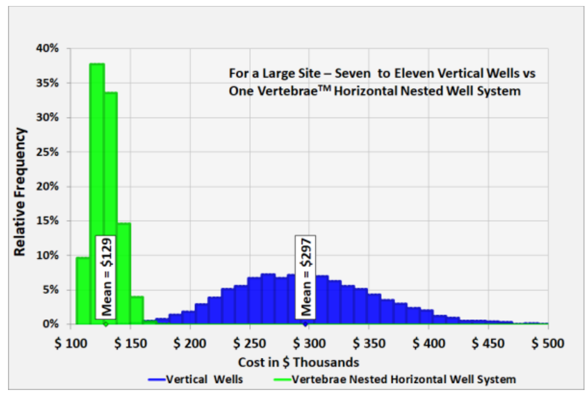

Exhibit 8 Large site output PDFs comparing Vertebrae™ system and vertical extraction wells

Statistic	Vertebrae™ Well System	Vertical Extraction Wells
Mean	$129,000	$297,000
Std Deviation	$11,000	$59,000
Mode	$127,000	$251,000
10% Percentile	$117,000	$224,000
50% Percentile	$128,000	$294,000
90% Percentile	$144,000	$376,000

Exhibit 9 Large site output descriptive statistics comparing Vertebrae™ system and vertical extraction wells

These results indicate that the Vertebrae™ system on average will cost $168,000 less than vertical well systems, a savings of 57%. Recall that because of contact area and operational efficiencies that same Vertebrae™ well system was assumed for both the small and large sites. Based on these results, it can be said that when applied to small sites the Vertebrae™ system provides an additional $168,000 in value in improved performance. Additional analysis is required; however, this preliminary analysis indicates the potential for substantial life cycle savings.