PREDICTING YIELD AND OPERATING BEHAVIOR OF A HORIZONTAL WELL

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ABSTRACT

The major purpose for using a horizontal well is to increase reservoir contact and thereby enhance the productivity of the well. As technology has advanced, drilling techniques for installing horizontal wells that were previously restricted to the petroleum industry have found their way to the water industry. Since the mid-1980s, horizontal directional drilling techniques have been used to install horizontal wells for environmental remediation of groundwater contamination.

Previous studies on the performance and behavior of horizontal wells have generally been restricted to theoretical analyses or small scale subsurface remediation projects. This paper presents the methodology used to select the design parameters and predict the yield for a 1,220 foot long, 12-inch diameter full scale test horizontal well. Performance and operating data from a 13 day pumping test are also presented.

INTRODUCTION

In some geologic environments, the thickness of the water bearing formation, or aquifer, may not be sufficient to supply the required volume of water to a system of vertical wells, even though the aquifer is hydraulically connected to a nearby surface water body. A typical example occurs in a river valley where thin alluvial deposits overlie bedrock. Even though the hydraulic conductivity of the sediment is excellent, the transmissivity is severely limited because the deposits are so thin.

In the hydrogeologic situation described above, significant volumes of water can be obtained using well screens orientated horizontally within the aquifer. These horizontally orientated well screens have historically been referred to as infiltration galleries. Infiltration galleries consist of one or more horizontally laid screens placed in the permeable alluvial materials either adjacent to a water body or beneath its bed. A significant quantity of water may be pumped from an infiltration gallery because the hydraulic conductivity of the natural material is so high that recharge from the adjacent body of water is substantial.[1]

The city of Des Moines, Iowa is located at the confluence of the Des Moines and the Raccoon Rivers. The valley formed by the Raccoon River consists of alluvial deposits approximately 30 feet thick. The alluvial deposits are located on top of a formation of bedrock and include a layer of relatively coarse glacial outwash approximately 15 feet to

20 feet thick. To optimize the volume of water available from a relatively thin alluvial aquifer such as this, a horizontally orientated collection system is required.

In the mid-1880s, the initial segments of an infiltration gallery were constructed within these alluvial deposits adjacent to the Raccoon River to serve as the water supply for the city of Des Moines. This infiltration gallery consisted of two foot long sections of 48-inch diameter precast concrete pipe separated by ¼ - inch steel spacers. The gallery was installed using open cut trenching techniques. Coarse material excavated from the trench was reclaimed and used as backfill material. The initial segment of infiltration gallery constructed was 1,000 feet long. As the population of Des Moines and the demand for water increased, the infiltration gallery was extended to provide a raw water supply for the original water treatment plant. The last extension of the infiltration gallery occurred in 1932.

Today, the infiltration gallery at Des Moines has a total length of 3.28 miles and yields from 10 to 20 million gallons of raw water per day (MGD). The yield from the infiltration gallery supplements a surface raw water supply from the Raccoon River and the Des Moines River to meet the Des Moines Water Works' average day demand of 45 MGD.

In the early 1990s, the Des Moines Water Works recognized that to continue to provide a reliable quantity of water to an expanding base of central Iowa water consumers, a second water treatment plant was needed. This second water treatment plant would also be located along the Raccoon River, approximately ten miles west of the existing treatment plant and infiltration gallery. The capacity of this proposed second water treatment plant was 25 MGD.

The site of this proposed second water treatment plant was within the same Raccoon River valley as the original water treatment plant. It was not surprising, therefore, when it was found that even though the hydraulic conductivity of the sediment was excellent, the transmissivity would be severely limited because, again, the alluvial deposits were relatively thin. Some type of horizontally orientated well screens, similar to an infiltration gallery, would be required for the raw water collection system.

Des Moines Water Works was aware of existing trenchless technology with which long lengths of pipe, or well screens, could be installed horizontally without the need for excavation. This was seen as a possible means to install a system of horizontally orientated well screens, or horizontal wells, within the coarser alluvial deposits. These horizontal wells could then possibly serve as a means to collect raw water for the proposed water treatment plant.

BACKGROUND ON HORIZONTAL WELLS

Horizontal wells have historically been most prevalent in the petroleum industry. The major purpose for using a horizontal well in the petroleum industry is to increase reservoir contact and thereby enhance the productivity of the well over that of a conventional vertical well.[2]

In the late 1980s, advancements in trenchless technology, especially in horizontal directional drilling technology, resulted in a dramatic increase in the number of horizontal wells in the petroleum industry. These advancements also allowed horizontal directional drilling techniques to emerge as an innovative method for monitoring and delivering remediation technologies to contaminated subsurface locations.[3] As a result, horizontal wells became more appealing for air sparging, soil venting, and groundwater extraction applications.

Horizontal wells are more attractive than conventional vertical wells for environmental remediation of groundwater contamination for many of the same reasons horizontal wells are preferred over vertical wells in the petroleum industry. Some of these reasons include:

1. Greater reservoir contact with the well screen increases the productivity of the well.
2. Geometry of the reservoir production zone or the groundwater contamination zone is conducive to greater access with a horizontal well than a series of vertical wells.
3. Access to groundwater contamination zones with vertical wells are often hindered by obstacles such as buildings, paved surfaces, or other topographical obstructions.

Des Moines Water Works wanted to determine if a system of horizontal wells, installed using trenchless technology, was feasible as a raw water collection system. A single test horizontal well was proposed for testing and evaluation purposes. To design a test horizontal well, however, a methodology for determining the required length of a horizontal well or for predicting yield from a horizontal well was needed.

LITERATURE REVIEW

From the petroleum industry in 1986, Joshi[4] developed an equation for calculating the steady state oil productivity of a horizontal well that took into account reservoir anisotropy and well eccentricity (i.e., horizontal well location other than mid-height of the reservoir). Joshi summarized several solutions available in literature to predict the steady state flow of oil in a horizontal well.[2,4,5]

In 1992, Beljin and Losonsky[6] presented an equation developed by Joshi[2,4,5] as a means to estimate drawdown for a horizontal well used for groundwater recovery. Beljin and Losonsky summarized Joshi's work as follows:

> While a vertical well drains a cylindrical volume, a horizontal well of length *L* drains an ellipsoid. The zone of influence is elliptical, with endpoints of the well constituting the foci of the ellipse as shown in Figure 1a and 1b.

Figure 1a. Drainage area of a well based on a circular zone of influence.[6]

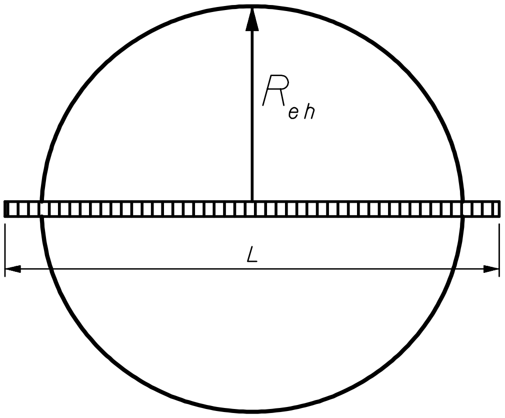
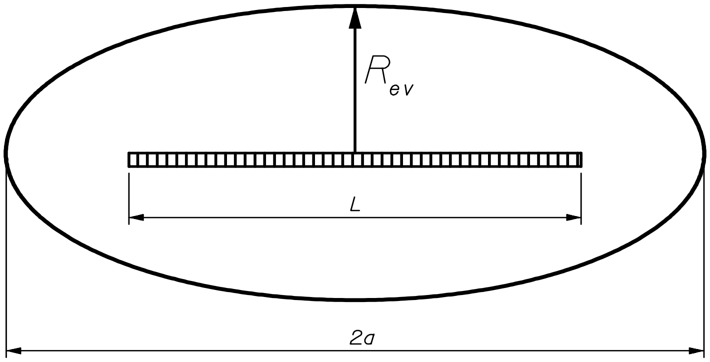


Figure 1b. Drainage area of a well based on an elliptical zone of influence.[6]



The area of drainage of the ellipse, A_e, is:

$$A_e = \pi R_{ev} a \qquad \textit{(Equation 1)}$$

In which R_{ev} is the effective drainage radius of the vertical well in the same aquifer, and "a" is half the major axis of the ellipse.

$$a = \sqrt{\left(\frac{L}{2}\right)^2 + R_{ev}^2} \qquad \textit{(Equation 2)}$$

To compare the drainage area of a horizontal well with that of a vertical well, the drainage radius of the horizontal well, R_{eh}, measured in the plane that contains the well, is defined such that the corresponding circular area A_c equals the elliptical drainage area A_e of the well.

$$A_e = A_c = \pi R^2_{eh} \qquad \textit{(Equation 3)}$$

Combining equations 1, 2, and 3 and solving for "*a*" results in

$$a = \left(\frac{L}{2}\right)\left[0.5 + \sqrt{0.25 + \left(\frac{2R_{eh}}{L}\right)^4}\,\right]^{0.5} \qquad \textit{(Equation 4)}$$

Beljin and Losonsky then provided a generalized formula, based on Joshi's work, for estimating steady-state flow from a horizontal water well located in the center of a vertical aquifer plane.

$$Q_h = \frac{2\pi KB\,\Delta s}{\log\left[\dfrac{a + \sqrt{a^2 - \left(\dfrac{L}{2}\right)^2}}{\dfrac{L}{2}}\right] + \left(\dfrac{B}{L}\right)\log\left[\dfrac{B}{2r_w}\right]} \qquad \textit{(Equation 5)}$$

Where:

Q_h = Flow rate
Δs = Drawdown
L = Length of horizontal well
r_w = Well radius
K = Hydraulic conductivity
B = Aquifer thickness
log [ ] = Natural log, $\log_e$[ ]
a = ½ major axis of the drainage ellipse
β = conductivity contrast, $(K_h/K_v)^{1/2}$
K_h = Horizontal hydraulic conductivity
K_v = Vertical hydraulic conductivity

Beljin and Losonsky[6] noted Equation 5 was only valid for isotropic, homogenous, and confined aquifers.

For a horizontal well located off-center of the vertical aquifer plane, Beljin and Losonsky again used Joshi's work to modify Equation 5 to become

$$Q_h = \frac{2\pi K_h B \Delta s}{\log\left[\dfrac{a+\sqrt{a^2 - \left(\dfrac{L}{2}\right)^2}}{\dfrac{L}{2}}\right] + \left(\dfrac{\beta B}{L}\right)\log\left[\dfrac{\left(\dfrac{\beta B}{2}\right)^2 + \beta^2\ \delta^2}{\dfrac{\beta B r_w}{2}}\right]} \qquad \textit{(Equation 6)}$$

Where δ is the distance the well is off-centered in the vertical aquifer plane. Joshi called this term, δ, well eccentricity.[4]

Joshi demonstrated in petroleum production applications that if the horizontal well was sufficiently long as compared to the reservoir height, the well could be located anywhere in the vertical plane without significant loss of productivity. Joshi stated that, in general, a horizontal well's performance was not significantly affected by eccentricity as long as the well is located between ± 25% from the reservoir center; i.e., $\delta < \pm B/4$. [2,4]

It was realized by the author that the work completed by Joshi[2,4,5], and the subsequent work by Beljin and Losonsky[6], was for horizontal wells located in confined aquifers. Driscoll, however, has proposed that some equations used to predict drawdown for confined aquifers can be applicable for unconfined aquifers. This is provided drawdown is small in relation to aquifer thickness.[1]

Equation 6 provided Des Moines Water Works with a basis for determining the required length of a test horizontal well given a specific yield. The test horizontal well would be used to:

1. Evaluate the feasibility of using a system of horizontally directional drilled wells as a raw water collection system.
2. Confirm the applicability of Equation 6 for predicting yield for the Des Moines Water Works situation. Since the Des Moines Water Works application involved an unconfined aquifer, drawdown would be held small in relation to aquifer thickness.

DESIGN OF THE HORIZONTAL TEST WELL

For design of any well, whether vertical or horizontal, a hydrogeological investigation is necessary to identify aquifer characteristics. Included in this investigation are pump tests to quantify hydraulic conductivity of the aquifer, soil borings to determine location of bedrock and aquifer thickness, and grain size distribution analyses of the aquifer material to assist in selection of the well screen.

Data gathered from pump tests and soil borings conducted within the proposed well field were used as a basis for selecting the values for the parameters used in Equation 6.

Following is a discussion of how the data that were obtained from the pump tests and soil borings were applied and used in Equation 6.

Drawdown, Δs

To maximize drawdown and yield, the test horizontal well needed to be installed within the aquifer at the lowest elevation possible. Soil boring information obtained during the hydrogeological investigation showed elevation 798 to be the optimum location for the horizontal well. This elevation provided a minimum of two to three feet of freeboard above the bedrock. Samples obtained from soil borings also showed the coarser glacial outwash material was located at or near this elevation.

It was stated earlier that Equation 6 applied to horizontal wells located within confined aquifers. It was also stated that some equations used to predict drawdown for confined aquifers can be applicable to unconfined aquifers. Drawdown, however, should be held small in relation to aquifer thickness.

The aquifer in which the test horizontal well would be located consisted of a relatively coarse layer of glacial outwash between 15 feet and 20 feet thick. Design drawdown, therefore was restricted to between four feet and five feet.

Well radius, r_w

In order to encourage flow contribution from the distal end of the well screen from the pump, it was desirable to limit headloss along the well screen. A maximum headloss of four feet along the well screen was considered as acceptable. With a desired flow rate, Q_h , in the range of 1,800 to 2,000 gpm, a 12-inch diameter well screen was required to limit the well screen head loss to four feet.

Aquifer thickness, B

The relatively coarse layer of glacial outwash, located on top of the boundary layer of bedrock, was between 15 feet and 20 feet thick. Yield from the test horizontal well was calculated from equation 6 for several values of aquifer thickness. This will be discussed and illustrated later in this paper.

Hydraulic conductivity, K, K_h, K_v, β

The hydrogeologic investigation included multiple rate step drawdown tests and constant rate tests at three locations within the proposed well field. This testing was conducted to determine hydraulic conductivity values. Test results showed hydraulic conductivity values that ranged from 4,500 gpd/ft^2 to 7,500 gpd/ft^{2}for the well field. The hydraulic conductivity, *K*, for the well field was conservatively estimated to be 4,500 gpd/ft^2.

Because of the coarseness of the aquifer material, the conductivity contrast, sometimes referred to as permeability anisotropy variable, $\beta = K_h/K_v^{1/2}$, was assumed to be 3.16.

One-half, ½, major axis of the drainage ellipse, a, and R_{ev}

Using data gathered from the constant rate pumping test, the effective drainage radius of a vertical well, R_{ev}, was determined to be 200 feet. Using Equations 2, 3, and 4, "*a*", one-half the major axis of the drainage ellipse, was then determined and was found to vary for different horizontal well lengths, *L*.

Well eccentricity, δ

Well eccentricity is the distance the well is off-centered from the vertical aquifer plane.[4] Based on soil borings to determine the location of bedrock and the proposed centerline elevation of the horizontal well, well eccentricity, δ, was estimated to be 4 feet.

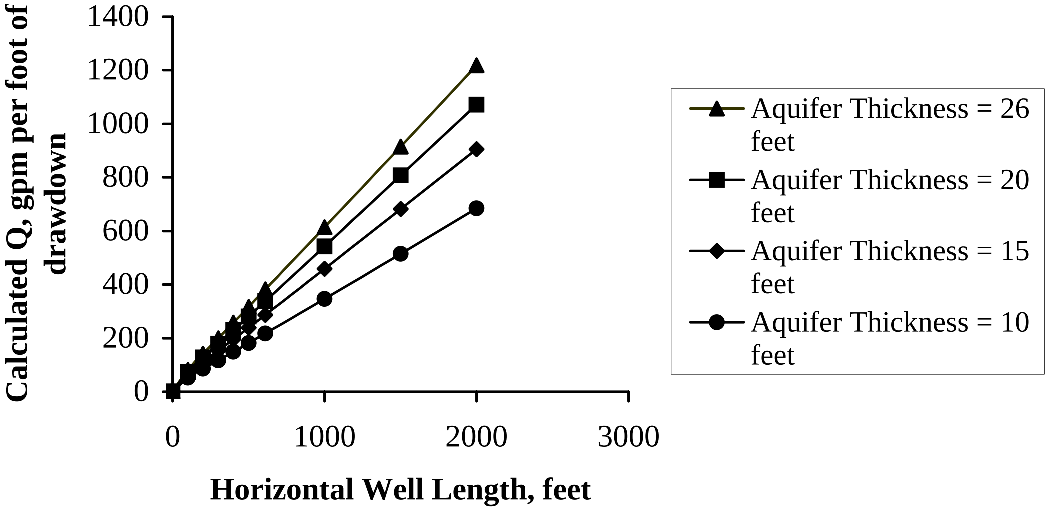
In summary, the values selected for the variables contained in Equation 6 are summarized in Table 1.

Table 1. Values of variables determined from hydrogeologic investigation and used with Equation 6.

Q_h ,flow rate = Calculated from Equation 6
L, length of horizontal well (See Figure 2) = Selected various values
Δs, drawdown = 1 foot
R_{ev}, drainage radius of a vertical well = 200 feet
r_w , well radius = 0.5 feet
K, hydraulic conductivity = 4,500 gpd/ft^2
B, aquifer thickness (See Figure 2) = 26 feet, 20 feet, 15 feet, and 10 feet
a, ½ major axis of the drainage ellipse = Varies for different values of *L*
K_h , horizontal hydraulic conductivity = 4,500 gpd/ft^2
K_v , vertical hydraulic conductivity = 450 gpd/ft^2
β, conductivity contrast, $(K_h/K_v)^{1/2}$ = 3.16
δ = well eccentricity = 4 feet

Figure 2 presents the calculated flowrate per foot of drawdown, *Q*, versus horizontal well length, *L*, from Equation 6 using the values from Table 1, above. The flowrate per foot of drawdown presented in Figure 2 is for various aquifer thickness.

Figure 2. Calculated flowrate per foot of drawdown, *Q*, versus horizontal well length, *L*, from Equation 6.



It was desirable to obtain 1,800 gpm to 2,000 gpm as a yield from the test horizontal well while limiting drawdown to between four and five feet. Based on Figure 2, a horizontal well length of 1,220 feet would be predicted to yield approximately 500 gpm per foot of drawdown. At four feet of drawdown, yield would be predicted to be approximately 2,000 gpm. The length of the test horizontal well was, therefore, established as 1,220 feet.

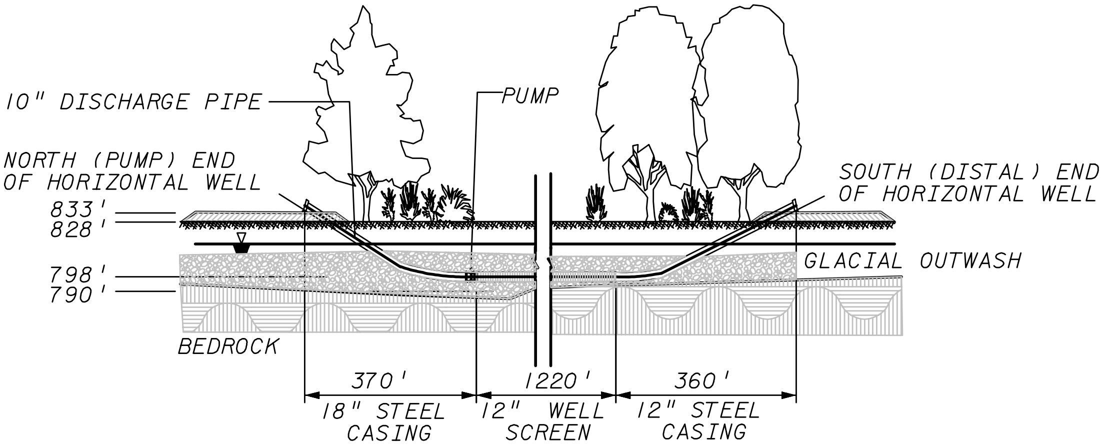
HORIZONTAL WELL PERFORMANCE TESTING

In March 1998, Des Moines Water Works installed 1,220 feet of 12-inch diameter stainless steel, pipe-based, well screen using horizontal directional drilling technology. The slot size opening of the well screen was 0.050 inches.

The north end, or pump end, of the test horizontal well included 370 feet of 18-inch diameter riser pipe constructed of Schedule 40 carbon steel. An 18-inch by 12-inch reducer provided the transition from the 18-inch riser pipe to the 12-inch well screen. The south end, or distal end of the test horizontal well, included 360 feet of 12-inch diameter riser pipe also constructed of Schedule 40 carbon steel.

The well screen was orientated horizontally within the glacial outwash portion of the alluvial aquifer with a centerline elevation of 798. In plan view, the test horizontal well was orientated parallel with the Raccoon River between 70 feet and 100 feet from the bank of the river. Figure 3 illustrates the profile of the test horizontal well.

Figure 3. Profile of test horizontal well including summary of information obtained from hydrogeologic investigation.

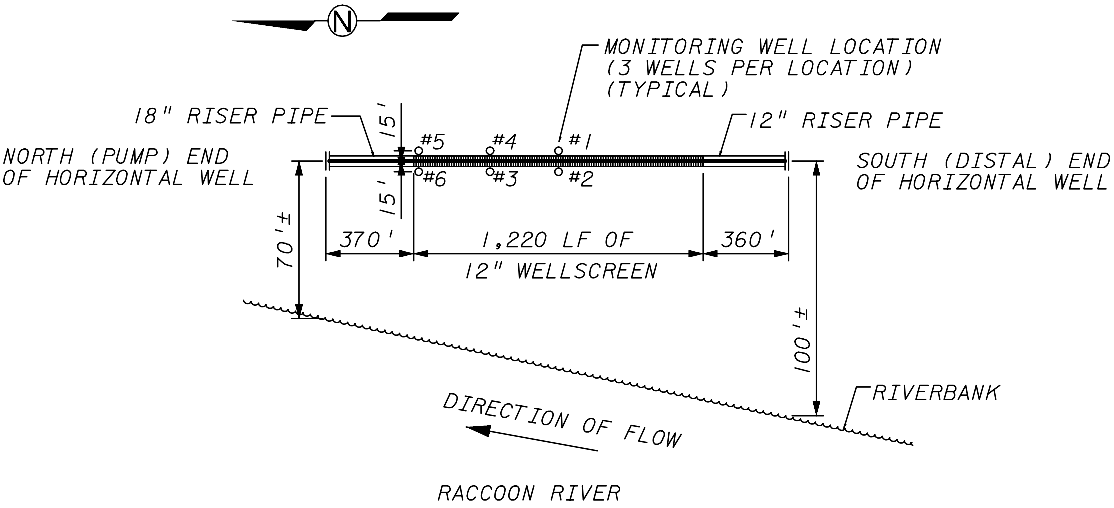


A two stage Ingersoll-Dresser Model 12HH220 submersible pump was used as the test pump. The impellers were trimmed to provide 2,200 gpm at 70 feet of total dynamic head. The pump was driven by a 50 horsepower Pleuger/Ingersoll-Dresser Model M10 electric motor. The pump was located approximately 340 feet into the 18-inch diameter casing pipe. This was approximately 20 feet to 30 feet from the beginning of the 12-inch diameter well screen. Discharge piping consisted of 340 feet of 10-inch diameter Schedule 80 PVC pipe from the pump to the ground surface.

The pump test for the test horizontal well was conducted over 13 days, from January 14, 1999 until January 27, 1999. Flow rate was constantly monitored and recorded with an eight-inch turbine meter. Actual flowrate throughout the pumping test was 1,800 gpm. Drawdown data from seven monitoring locations were logged every 15 minutes using automatic data logging equipment.

Six monitoring wells were installed using a 4.25-inch hollow stem auger drill. They were located 15 feet along both sides of the test horizontal well toward the pump end of the well. The monitoring wells were drilled to bedrock and consisted of 2-inch diameter PVC pipe that was screened at the end. A seventh monitoring location was within the 12-inch diameter casing at the south, or distal, end of the well. Layout of the six monitoring wells is shown in Figure 4.

Figure 4. Plan view of monitoring wells.

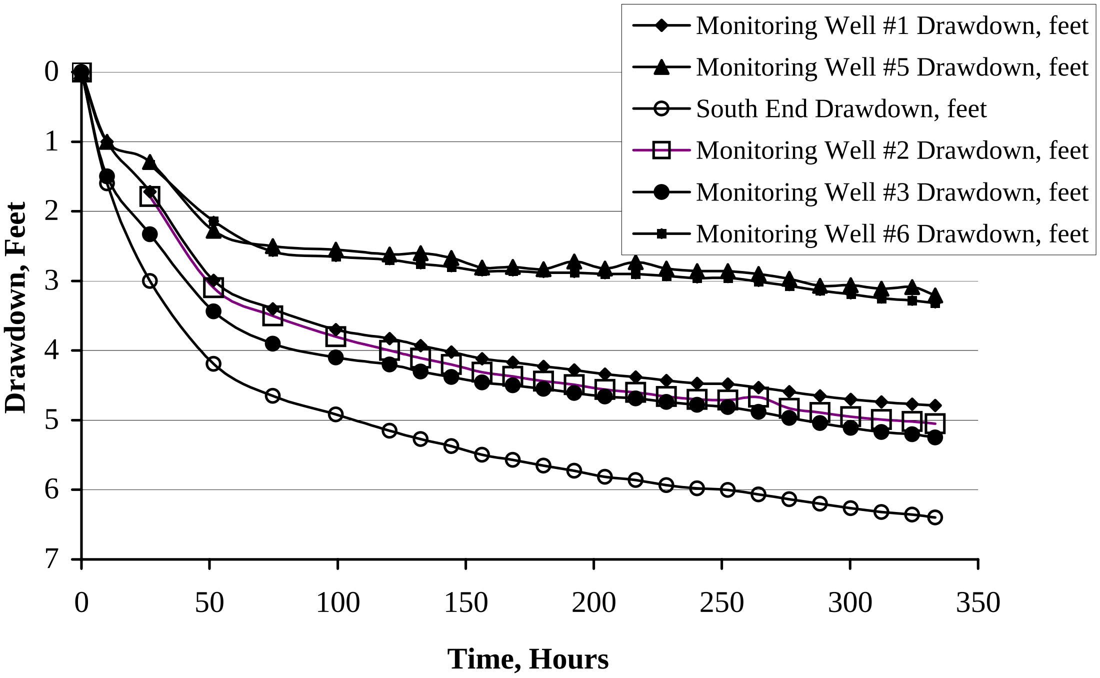


Drawdown measurements were obtained using submersible precision pressure transmitters/transducers that generated a 4 – 20 mA signal proportional to water depth. One pressure transmitter/transducer was inserted into each monitoring well. Pressure readings related to water depth in the monitoring well were transmitted throughout the pump test to the data logging equipment.

RESULTS

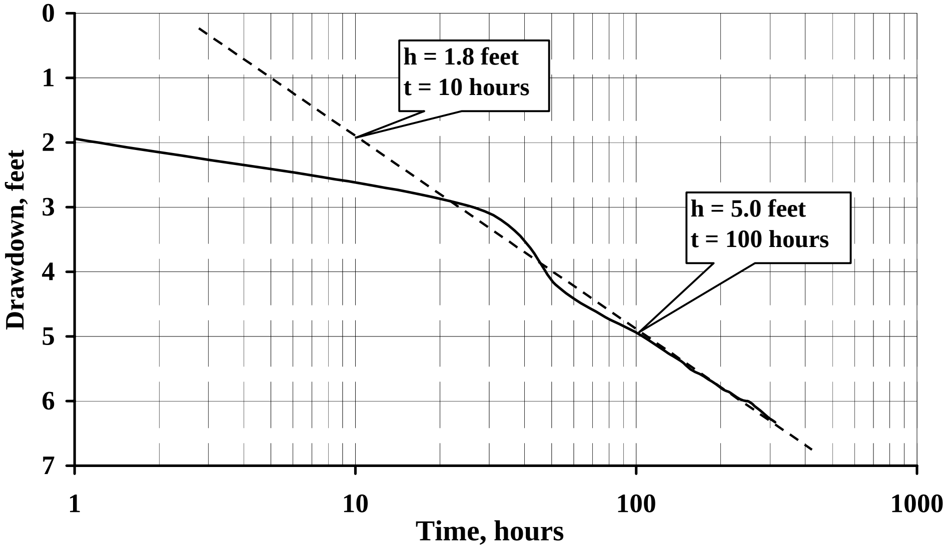
Figure 5 graphically presents the drawdown data obtained at five of the six monitoring wells throughout the pump test. Monitoring well #4 did not properly log data and is not included with the data presented in Figure 5. Figure 5 does include drawdown data obtained from the south, or distal, end of the test horizontal well.

Figure 5. Graphical comparison of drawdown at monitoring wells during pumping test of test horizontal well.



Driscoll summarizes a methodology referred to as the modified non-equilibrium equation or the modified Theis method. This methodology can be used to calculate the coefficient of transmissivity from the slope of a semi-log plot of time versus drawdown. Figure 6 presents the drawdown from the south, or distal, end of the test horizontal well in a semi-logarithmic plot of time versus drawdown.

Figure 6. Semi-logarithmic plot of time versus drawdown at south end of test horizontal well.



According to Driscoll[1],

$$T = \frac{264\,Q}{\Delta s} \qquad \textit{Equation 7}$$

where

T = coefficient of transmissivity, in gpd/ft
Q = pumping rate, in gpm
Δs = slope of time versus drawdown graph expressed as the change in drawdown between any two times on the log scale whose ratio is 10 (one log cycle)

Using a Δs value of 3.2 feet from Figure 6, the coefficient of transmissivity, T, is calculated as

$$T = \frac{264Q}{\Delta s} = \frac{264(1{,}800\text{ gpm})}{5.0\text{ feet - }1.8\text{ feet}} = \frac{264(1{,}800\text{ gpm})}{3.2\text{ feet}} = 148{,}500\text{ gpd/ft}$$

Hydraulic conductivity, K, is transmissivity, T, divided by the aquifer thickness, B, which is between 15 feet and 20 feet. Therefore, using 20 feet as B

$$K = \frac{T}{B}$$

$$K = \frac{148{,}500\text{ gpd/ft}}{20\text{ feet}}$$

$$K = 7{,}425\text{ gallons per day/ft}^2$$

This value for hydraulic conductivity is significantly larger than the 4,500 gpd/ft^2 used in Table 1 and with Equation 6 for the determination of well screen length. It should be noted, however, that this value is close to the higher end of the range of hydraulic conductivity values (7,500 gpd/ft^2) that were determined during the multiple step and constant rate tests. These tests were conducted during the hydrogeologic investigation mentioned earlier in this paper.

CONCLUSIONS

Following are some conclusions that can be made from the data collected from the test horizontal well and presented in Figure 5 and Figure 6:

1. The magnitude of drawdown increased the further the distance along the well screen from the pump. The greatest drawdown was observed at the south, or distal, end of the horizontal well.

2. Since drawdown increased with distance along the well screen from the pump, it can be concluded the distal end of the horizontal well contributed significantly to the overall yield from the horizontal well.
3. Computations based upon the semi-logarithmic plot of time versus drawdown for the south end of the horizontal well yielded a hydraulic conductivity, *K*, of 7,425 gpd/ft^2 for an aquifer thickness of 20 feet. This is very close to the upper range of hydraulic conductivity values determined from the pumping tests performed during the hydrogeologic investigation.
4. Recharge from the Raccoon River was not evident after 13 days of continuous pumping at a rate of 1,800 gpm. This was despite the horizontal well being within 100 feet of the Raccoon River. It must be concluded, therefore, that all water that had been pumped during the 13 day test had come from storage within the aquifer.
5. The semi-logarithmic plot of time versus drawdown for the south end of the test horizontal well shown in Figure 6 confirms recharge from the Raccoon River had not occurred after 13 days of continuous pumping at a rate of 1,800 gpm. The slope of the data line would approach zero if a recharge boundary had been encountered during the pumping test.
6. The lack of evidence that recharge occurred illustrates the claim that horizontal wells have enhanced productivity over conventional horizontal wells. This is due to the increased reservoir contact horizontal wells have over vertical wells. It is doubtful a vertical well would have been able to produce 1,800 gpm for 13 days from the same aquifer without the benefit of recharge.
7. Equation 6 was useful for determining the length of horizontal well needed to produce a given yield. Actual drawdown, however, exceeded the target drawdown of four to five feet.
8. At this time, it appears Equation 6 presents a reasonable means for predicting the performance of a horizontal well. This is despite the apparent shortcoming in predicting drawdown for Des Moines Water Works' test horizontal well during the pumping test.

SUMMARY

Horizontal wells provide the advantage of increased reservoir contact and enhanced productivity over traditional vertical wells. This was shown with the Des Moines Water Works' test horizontal well. In a shallow alluvial aquifer, the test horizontal well produced 1,800 gpm continuously for 13 days without the benefit of recharge. As technology advances in the area of horizontal directional drilling, horizontal wells have the potential to be attractive in the future as a water resource.

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