Comparison of Vented and Absolute Pressure Transducers for Water-Level Monitoring in Hanford Site Central Plateau Wells

Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management

Contractor for the U.S. Department of Energy
under Contract DE-AC06-08RL14788

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Executive Summary

Automated water-level data collected using vented pressure transducers deployed in Hanford Site Central Plateau wells commonly display more variability than manual tape measurements in response to barometric pressure fluctuations. To explain this difference, it was hypothesized that vented pressure transducers installed in some wells are subject to barometric pressure effects that reduce water-level measurement accuracy. Vented pressure transducers use a vent tube, which is open to the atmosphere at land surface, to supply air pressure to the transducer housing for barometric compensation so the transducer measurements will represent only the water pressure. When using vented transducers, the assumption is made that the air pressure between land surface and the wellbore is in equilibrium. By comparison, absolute pressure transducers directly measure the air pressure within the wellbore. Barometric compensation is achieved by subtracting the wellbore air pressure measurement from the total pressure measured by a second transducer submerged in the water. Thus, no assumption of air pressure equilibrium is needed. In this study, water-level measurements were collected from the same Central Plateau wells using both vented and absolute pressure transducers to evaluate the different methods of barometric compensation. Manual tape measurements were also collected to evaluate the transducers.

Measurements collected during this study demonstrated that the vented pressure transducers over-responded to barometric pressure fluctuations due to a pressure disequilibrium between the air within the wellbores and the atmosphere at land surface. The disequilibrium is thought to be caused by the relatively long time required for barometric pressure changes to equilibrate between land surface and the deep vadose zone and may be exacerbated by the restriction of air flow between the wellbore and the atmosphere due to the presence of sample pump landing plates and well caps. The disequilibrium is likely limited to wells screened across the water table (i.e., open to the deep vadose zone) where the depth to water is large or a low-permeability layer occurs in the vadose zone. Such wells are a pathway for air movement between the deep vadose zone and land surface and this sustains the pressure disequilibrium between the wellbore and the atmosphere for longer time periods.

Barometric over-response was not observed with the absolute pressure transducers because barometric compensation was achieved by directly measuring the air pressure within the well. Users of vented pressure transducers should be aware of the

over-response issue in certain Hanford Site wells and ascertain if it will affect the use of the data. Pressure disequilibrium between the well and the atmosphere can be identified by substantial air movement through the wellbore. In wells exhibiting pressure disequilibrium, it is recommended that absolute pressure transducers be used rather than vented transducers for applications that require precise automated determinations of well water-level changes in response to barometric pressure fluctuations.

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1 Introduction

The Hanford Site is a U.S. Department of Energy installation occupying approximately 1,500 km² (580 mi²) in south-central Washington State (Figure 1). From the 1940s to the 1980s, the site was used to produce plutonium for national defense. The current mission for the Hanford Site is waste management and environmental cleanup. Groundwater monitoring is performed at the site to support environmental cleanup and meet requirements of the *Atomic Energy Act of 1954*; the *Resource Conservation and Recovery Act of 1976*; and the *Comprehensive Environmental Response, Compensation, and Liability Act of 1980*.

Groundwater monitoring activities at the Hanford Site commonly include the use of vented, submersible pressure transducers for automated water-level monitoring in groundwater wells. Through experience, it has been discovered that the barometric-pressure-induced, apparent well water-level fluctuations indicated by vented pressure transducers installed in some Hanford Site wells are typically greater than actual water-level fluctuations determined using measuring tapes. For example, vented pressure transducers were installed in several wells at Low-Level Waste Management Area 1 (a burial ground in the northwest corner of the 200 East Area) from late 2005 until early 2007, and periodic manual water-level measurements were also collected using measuring tapes. The measurements for well 299-E28-27 during 2005 are shown in Figure 2. There was poor agreement between the tape measurements and the corresponding transducer measurements (differences up to 3.1 cm), and the variability of the transducer data was much larger than the variability of the tape measurements. The standard deviations of the data (after removing the linear declining trends) were 1.76×10^{-3} for the tape measurements and 1.44×10^{-2} for the corresponding transducer measurements, which is an order of magnitude difference (statistically significant at the 5 percent level of significance). Thus, it was hypothesized that vented pressure transducers installed in some wells are themselves subject to barometric pressure effects that reduce water-level measurement accuracy. To test this hypothesis, a study was conducted to evaluate the effect of barometric pressure fluctuations on vented pressure transducers installed in two Hanford Site wells.

The Hanford Site is located within the Pasco Basin, a structural depression in the Columbia Plateau physiographic province. The Columbia Plateau is a sequence of Miocene-age basalt flows that form the bedrock beneath the site. Anticlinal ridges occur to the north, west, and south of the site where the basalt is exposed at land surface, and the site is bordered on the north and east by the Columbia River (Figure 1). The stratigraphy beneath the site consists of unconsolidated to semiconsolidated sediments overlying basalt. In ascending sequence, the sediments consist of the following: (1) silt, sand, and gravel of the Miocene-Pliocene Ringold Formation; (2) the fine-grained Cold Creek unit; (3) sand and gravel of the Pleistocene-age Hanford formation; and (4) Holocene surficial deposits. Much of the Hanford formation consists of cataclysmic flood deposits from glacial lake outbursts at the end of the last ice age. These deposits formed several bars, including the Cold Creek bar extending from the northwest into the central portion of the site, resulting in a region of elevated topography referred to as the Central Plateau (Figure 1). The 200 East and 200 West Areas, where plutonium-separation activities occurred, are located on the Central Plateau. The 100 Area (reactors) and 300 Area (fuel fabrication facilities) are not on the Central Plateau but instead are located along the Columbia River.

Figure 1. Hanford Site Map and Study Area Features

Figure 2. Vented Transducer and Water-Level Measurements at Well 299-E28-27

An unconfined aquifer occurs beneath much of the site within the Hanford and Ringold sediments, and a water table map is provided in Figure 3. The Ringold Formation lower mud unit forms the base of the unconfined aquifer beneath much of the central portion of the site, but where absent, basalt bedrock forms the aquifer base. Natural recharge to the unconfined aquifer occurs primarily by precipitation infiltrating along the anticlinal ridges to the west and south and from upgradient agricultural activities. Groundwater generally flows from west to east across the site and discharges to the Columbia River. Depths to the water table range from zero along the shore of the Columbia River to over 100 m (328 ft) in portions of the Central Plateau. Depths to water are generally greater on the Central Plateau than elsewhere onsite.

The study was conducted in two wells located within and near the 200 East Area. Much of the unconfined aquifer beneath this area occurs within a paleochannel filled by the highly conductive Hanford formation sediments. A flow divide occurs beneath the 200 East Area; some of the water flowing in from the west moves toward the north through Gable Gap and some moves toward the southeast. Because of the flow divide and the highly transmissive aquifer, the water table beneath the 200 East Area has a relief of only a few centimeters over a horizontal distance of approximately 4 km (2.5 mi). Thus, highly accurate water-level measurements are required to determine groundwater flow directions in this area.

Figure 3. Hanford Site Water Table Map, March 2010

2 Background and Methodology

This chapter provides background information describing how pressure transducers work and how barometric compensation is achieved. Understanding transducer design allows a hypothesis to be formulated regarding why vented pressure transducers may be affected by barometric pressure changes and also allows for development of a methodology for testing this hypothesis.

2.1 Pressure Transducers and Barometric Compensation

Pressure transducers indirectly measure water level by measuring pressure due to an overlying fluid column. At a point of measurement beneath the water surface in a well, the total pressure consists of two components: (1) water pressure, and (2) atmospheric pressure at the water surface. Both of these result from fluid density, height of the fluid column above the point of measurement, and the acceleration of gravity. To use a pressure transducer for water-level monitoring, some method of barometric compensation must be used to account for the atmospheric pressure component so only the water pressure component will be measured.

The most common type of pressure transducer used for water-level monitoring is the strain gage transducer (*Use of Submersible Pressure Transducers in Water-Resources Investigations* [Freeman et al., 2004]). This device employs a flexible membrane that changes shape as the pressure changes. Electrical resistors, usually in the form of a Wheatstone bridge, are attached to the membrane. The resistance in the bridge changes as the membrane changes shape (i.e., under strain), which results in a different voltage within the bridge proportional to the pressure change. To collect a pressure reading, a data logger supplies a reference voltage (or amperage) to the bridge, and the voltage difference within the bridge is measured and converted to a pressure reading using calibration parameters.

Vented transducers compensate for barometric pressure by using a vent tube that supplies atmospheric pressure to the transducer housing. The membrane experiences pressure on one side due to atmospheric pressure and water pressure, while the reference side experiences only the atmospheric pressure supplied by the vent tube. In effect, this method mechanically subtracts the atmospheric pressure component of the total pressure so the membrane deforms only due to the water pressure (i.e., gage pressure). The other end of the vent tube is at land surface, so the assumption is made that air pressure at land surface, as supplied through the vent tube, represents air pressure at the water surface inside the well.¹

The membrane in an absolute pressure transducer experiences the sum of air pressure and water pressure on one side but has a vacuum on the reference side of the membrane. In this case, the deformation of the membrane is due to the total pressure at the point of measurement. Barometric compensation is achieved by using two transducers: one transducer submersed beneath the water surface, and one transducer located within the air column just above the water surface. The pressure caused solely by the water is calculated by subtracting the two pressures. No assumption is needed regarding the equivalence of air pressure between the well and the atmosphere because the air pressure in the well is measured directly.

2.2 Hypothesis

The pressure measured by a vented transducer can be represented as shown in Equation 1:

$$P_v = P_w + P_b - P_a \quad (\text{Equation 1})$$

¹ An air pressure difference exists between the land surface and the water surface in the well due to the elevation difference between the two locations. This difference is automatically accounted for because the air pressure will also increase inside the vent tube with depth below land surface.

where:

- P_v = pressure measured by a vented transducer
- P_w = water pressure at the probe depth
- P_b = air pressure in the wellbore at the water surface
- P_a = atmospheric pressure supplied to the transducer housing through the vent tube

It is clear from Equation 1 that if $P_b \neq P_a$, then $P_v \neq P_w$. This situation may occur in wells screened across the water table where the vadose zone is thick or the pneumatic diffusivity is low, perhaps due to a low-permeability layer in the vadose zone. The thick vadose zone and/or low diffusivity retards barometric pressure changes at ground surface from reaching the water table quickly. The well screen adjacent to the vadose zone above the water table allows the wellbore to provide a pathway for air movement between land surface and the deep vadose zone, which in turn sustains the air pressure difference between the atmosphere and the wellbore because of the time required for the pressure to equilibrate between the deep vadose zone and land surface.

Additional factors that could affect the pressure imbalance include the rate of barometric pressure change and the ease with which air can move between the wellbore and the atmosphere. Because of the time lag associated with a thick and/or low diffusivity vadose zone, higher rates of barometric pressure change will result in a greater difference between P_b and P_a in Equation 1, and this will cause a larger difference between P_v and P_w . Also, most Hanford Site wells have a sample pump installed that is supported by a landing plate on the outermost casing. The landing plate usually has one or two access ports that allow equipment (e.g., measuring tapes or transducers) to be lowered into the well. These access ports are typically less than 1 in. in diameter. Furthermore, the well cap overlaps the outermost casing and may fit tightly against the casing. Both the well cap and pump landing plate restrict the free flow of air between the well casing and the atmosphere and this may exacerbate any air pressure differences.

These factors may cause atmospheric pressure changes to be attenuated and time-lagged within the wellbore. Water levels in wells respond to atmospheric pressure changes. In most wells, the relationship is inverse; when barometric pressure declines, well water levels increase, and vice versa (*Groundwater* [Freeze and Cherry, 1979]). Consider the case where a barometric pressure decline results in an increase in well water-level elevation. An attenuated, lagged, air-pressure response in the wellbore would manifest as a higher barometric pressure at the water surface than is being supplied to the transducer housing through the vent tube (i.e., $P_b > P_a$ in Equation 1). In this case, the net pressure measured by the transducer would be equal to the water pressure plus the pressure difference between the air in the vent tube and the air in the well; this would cause a higher water level being determined than had actually occurred (i.e., it follows from Equation 1 that if $P_b > P_a$, then $P_b - P_a > 0$ and $P_v > P_w$). Note that the direction of the water-level response indicated by the vented transducer is as expected, as the barometric pressure declined and the water-level reading increased; however, the increase would be an over-response. A similar process would occur in reverse for barometric pressure increases causing water-level declines (i.e., if $P_b < P_a$, then $P_b - P_a < 0$ and $P_v < P_w$). Thus, it was hypothesized that barometric pressure changes that propagate nearly instantaneously to the transducer housing through the vent tube may be attenuated and time-lagged within the wellbore causing vented transducer readings to over-respond to barometric pressure fluctuations.

2.3 Methodology

Because absolute pressure transducers measure the barometric pressure directly above the water surface, if barometric pressure changes at ground surface are attenuated and time-lagged within the wellbore, this should be indicated by differences in water table elevations determined by absolute pressure transducers

and vented transducers. Also, water levels determined by absolute pressure transducers should be more accurate and more consistent with manual tape measurements than water levels determined with vented transducers. This was tested by installing both absolute and vented pressure transducers for comparison in two Central Plateau wells in and near the 200 East Area: well 299-E33-34 (northwestern 200 East Area at Low-Level Waste Management Area 1), and well 699-37-47A (southeast corner of the 200 East Area, near the Plutonium-Uranium Extraction [PUREX] Cribs) (Figure 1). The two wells have depths to water of 72 and 98 m (237 and 320 ft), respectively, and both are screened across the water table (see Appendix A for well construction diagrams). The absolute transducers used were the Model 3001 Levellogger[®] Gold and the Model 3001 Barologger[™] Gold, both manufactured by Solinst.² Each of these devices is a transducer and data logger combined into a single probe. The Levellogger is optimized to measure water pressure, whereas the Barologger is optimized for air pressure measurements. The Levellogger has a range of 5 m (16.4 ft) of water (~7.1 psia) above normal atmospheric pressure, while the Barologger has a range of 1.5 m (4.9 ft) of water (~2.1 psia) above normal atmospheric pressure. Within the wells, the Levellogger was submersed in the water while the Barologger was installed just above the water surface. Barometric compensation was achieved by subtracting the Barologger readings from the Levellogger readings. The vented transducers used were Drück[®] Model PDCR 1830-8388, 5 psi submersible pressure transducers connected to Campbell[®] Scientific CR800 series data loggers. In addition to the transducer measurements, periodic manual measurements were collected from both wells using a measuring tape. Both sets of transducer measurements were indexed to elevations by minimizing the square of the differences between the transducer data and the manual measurements.

The three sets of water-level measurements collected from each well (vented transducer data, absolute transducer data, and manual measurements) were statistically compared for consistency. If the hypothesis is correct that vented transducers over-respond to barometric pressure fluctuations in the study wells, the variability of the absolute transducer data would be both significantly less than the vented transducer data and comparable to the variability of the tape measurements. After removing any long-term linear trends, the standard deviations of the data sets were compared statistically using the *F*-distribution at the 5 percent level of significance with the null hypothesis that the standard deviations were equal. The results of the tests are given as *p*-values, which is the probability that an observed difference in standard deviations could be due solely to random chance. Where the *p*-value is less than 0.05, the null hypothesis of equal standard deviations is rejected and it is concluded that the standard deviations are different. Where the *p*-value is greater than 0.05, insufficient evidence is available to reject the null hypothesis.

3 Results and Discussion

This chapter presents the results of comparing the absolute and vented transducers in two Central Plateau wells. The implications of the findings are also discussed, particularly in regard to the use of pressure transducers to determine the barometric water-level response characteristics of wells.

² Model 3001 Levellogger[®] Gold is a registered trademark and the Model 3001 Barologger[™] Gold is a trademark of Solinst Canada Ltd., Georgetown, Ontario, Canada.

³ Drück[®] is a registered trademark of Drück Limited, Groby, Leicester, Great Britain.

⁴ Campbell[®] is a registered trademark of Campbell Scientific Inc., Logan, Utah.

3.1 Transducer Comparison Results

The transducer data and manual measurements collected from wells 299-E33-34 and 699-37-47A are shown in Figures 4 and 5, respectively. It is apparent that the vented transducer measurements exhibited more variability than both the absolute transducer measurements and the manual measurements. To compare the variability in the data sets, the slight decreasing linear trend was removed so only the variability around that general trend was compared. The ranges of the detrended data sets are shown in Table 1. The vented transducer data had a range approximately five times greater than the absolute transducer measurements at well 299-E33-34 and approximately three times greater at well 699-37-47A. The range of the manual measurements was similar to the absolute transducer measurements at well 299-E33-34 and half the range of the absolute transducer measurements at well 699-37-47A.

The differences between the vented transducer measurements and the absolute transducer and manual measurements were statistically significant. Comparison of the vented and absolute transducer measurements yielded p -values of 0.000 for both wells (i.e., less than 0.05, so the null hypothesis of equal standard deviations was rejected). Comparison of the manual measurements to the vented transducer measurements also yielded low p -values of 0.038 and 0.031 for wells 299-E33-34 and 699-37-47A, respectively. Comparison of the manual measurements to the absolute transducer measurements yielded higher p -values of 0.236 and 0.263 for the two wells. Because these values are greater than 0.05, the null hypothesis of equal standard deviations could not be rejected. These results are consistent with the hypothesis that the vented transducer measurements over-responded to barometric pressure changes.

Figure 4. Transducer and Manual Water-Level Measurements at Well 299-E33-34

Figure 5. Transducer and Manual Water-Level Measurements at Well 699-37-47A

Table 1. Range of the Detrended Transducer and Manual Measurements

Data Set	Range (m)
299-E33-34	
Vented transducer data	0.093
Absolute transducer data	0.019
Manual measurements	0.014
699-37-47A	
Vented transducer data	0.179
Absolute transducer data	0.054
Manual measurements	0.027

The installation of the Barologgers in the wellbores allowed for a comparison between the air pressure in the wells and the atmospheric pressure. As discussed in Section 2.2, barometric pressure changes should be attenuated and time-lagged within the boreholes due to the thick vadose zone and/or low diffusivity combined with the restriction of air movement past the pump landing plate and well cap. This was assessed by comparing the barometric pressure measurements from meteorology station #6 (located in the 200 East Area [Figure 1] and operated by Pacific Northwest National Laboratory [PNNL]) to the Barologger measurements of air pressure within the wellbores. The difference in elevation between station #6 and the water level in the wells was accounted for by applying an offset to the station #6 measurements so the mean of the measurements equaled the mean of the Barologger measurements. The results are shown in Figures 6 and 7 for 299-E33-34 and 699-37-47A, respectively. As expected, the magnitude of the air pressure changes in both wellbores was slightly less than at station #6, and the wellbore measurements were offset later in time than the station measurements.

Figure 6. Comparison of Elevation Adjusted Barometric Pressure Measurements from 200 East Area Station #6 and Downhole BaroLogger in Well 299-E33-34

Figure 7. Comparison of Elevation Adjusted Barometric Pressure Measurements from 200 East Area Station #6 and Downhole Barologger in Well 699-37-47A

The difference in air pressure between the wellbores and the atmosphere was used to predict the vented transducer measurements using the absolute transducer measurements. This was done by adding the difference between the Barologger measurements and the elevation adjusted station #6 barometric pressure measurements to the absolute transducer measurements (see Equation 1, where P_w is the time series of absolute transducer water-level measurements, P_a is the time series of elevation corrected barometric pressure measurements from station #6, and P_b is the time series of Barologger measurements). The results are shown in Figures 8 and 9, which compare the actual and predicted vented transducer measurements. The two data sets agree very closely for both wells, and this agreement is shown by the similar statistical parameters in Table 2 (the offset between the actual and predicted measurements at well 299-E33-34 [Figure 8] can be attributed to differences in matching the absolute and vented transducer measurements to the manual water-level measurements). This demonstrates unequivocally that differences between the vented and absolute transducer measurements are almost entirely due to air pressure differences between the wellbores and the atmosphere. The slight differences that remain may be due to instrument noise or transducer drift.

Figure 8. Comparison of Actual and Predicted Vented Transducer Measurements at Well 299-E33-34

Figure 9. Comparison of Actual and Predicted Vented Transducer Measurements at Well 699-37-47A

**Table 2. Comparison of Actual and Predicted
Vented Transducer Measurements**

Well Name/ Parameter	Actual Measurements	Predicted Measurements
299-E33-34		
Range (m)	0.093	0.092
Standard deviation (m)	0.0166	0.0167
699-37-47A		
Range (m)	0.174	0.183
Standard deviation (m)	0.0292	0.0284

3.2 Discussion

The over-response of vented transducers in Central Plateau wells to barometric pressure fluctuations has consequences for certain uses of vented transducer data but probably has no effect on other uses. Section 3.2.1 describes how the over-response may affect the determination and use of well water-level, barometric response functions. Section 3.2.2 addresses issues related to the use of vented transducers for long-term monitoring, and evaluates the effects of vent tube blockage. Section 3.2.3 discusses the effect that attenuated, time-lagged air pressure responses in wellbores would have on determinations of total head.⁵

3.2.1 Barometric Response Functions

Measurements from pressure transducers can be used to adjust manual water-level measurements for barometric pressure effects. Such adjustments may be made to determine the long-term, average hydraulic gradient unaffected by short-term barometric pressure effects (“Considering Barometric Pressure in Groundwater Flow Investigations” [Spaine, 2002]; PNNL-13078, *Effects of Barometric Fluctuations on Well Water-Level Measurements and Aquifer Test Data*). In “Identifying and Removing Barometric Pressure Effects in Confined and Unconfined Aquifers” (Rasmussen and Crawford, 1997), a method is described for performing these adjustments, in which a water-level, barometric response function is determined by multiple regression and is then used to remove barometric pressure effects from water-level measurements by deconvolution. The response function describes the well water-level response to an instantaneous unit change in atmospheric pressure. A response function is determined by analyzing time-series data of water-level and barometric pressure measurements to derive a regression equation. This equation is used to predict the cumulative water-level change at a given time step resulting from a series of barometric pressure changes over the previous n time steps, where n is chosen to result in a good prediction. The needed time-series of water-level data is usually obtained using pressure transducers.

The transducer response functions to barometric pressure changes determined for wells 299-E33-34 and 699-37-47A are shown in Figures 10 and 11, respectively, using both the vented and absolute transducer measurements with barometric pressure measurements from 200 East Area Station #6. These functions

⁵ Total head is the sum of hydraulic head (i.e., water-level elevation) and the atmospheric pressure at the water surface.

were determined using the MRCX software developed by PNNL (PNNL-19775, *Guide to Using Multiple Regression in Excel [MRCX v. 1.1] for Removal of River Stage Effects from Well Water Levels*). For each well, the vented response function shows a larger magnitude response than the absolute response function, a result consistent with an over-response in the vented transducer measurements. These functions will yield different adjustment values when applied to a given water-level measurement, and because the vented transducer measurements are not representative of the actual water-level fluctuations in the well, use of the vented response function will not yield suitable adjustments of manual measurements. This is demonstrated in Figures 12 and 13, which show the original and barometric-adjusted absolute transducer measurements, along with the original and adjusted manual measurements using both response functions. For well 299-E33-34 (Figure 12), the adjusted manual measurements are closer to the adjusted transducer measurements when the absolute transducer response function is used instead of the vented response function. The same is generally true for measurements at well 699-37-47A (Figure 13), although the manual measurements for this well are not as accurate so the adjustments are also not a good.

Barometric response functions can also be used to estimate the vadose zone pneumatic diffusivity, a key parameter for describing the rate at which a barometric pressure change will migrate through the vadose zone to the water table.

Figure 10. Barometric Response Functions for Well 299-E33-34

Figure 11. Barometric Response Functions for Well 699-37-47A

Figure 12. Absolute Transducers and Manual Water-Level Measurements at Well 299-E33-34 Adjusted for Barometric Pressure (BP) Fluctuations

Figure 13. Absolute Transducers and Manual Water-Level Measurements at Well 699-37-47A Adjusted for Barometric Pressure (BP) Fluctuations

It might be concluded that it would be more appropriate to use the absolute transducer response function instead of the vented transducer response function to determine diffusivity. However, diffusivities can only be properly determined using wells open only below the water table (i.e., are not open at all to the vadose zone). Wells open to the vadose zone act as pathways for air flow; in effect, such wells provide a short-circuit for the movement of air between land surface and the deep vadose zone. Thus, the response functions determined for wells 299-E33-34 and 699-37-47A represent the combined diffusivity of the vadose zone, well effects, and transducer effects in the case of the vented transducer response functions. Thus, neither response function would provide a representative estimate of the vadose zone diffusivity. However, it may still be possible to determine changes in the vadose zone diffusivity (e.g., due to moisture content changes) by comparing changes to either response function generated over different time periods.

For wells screened entirely below the water table, it is expected that either a vented transducer or absolute transducers will yield similar water-level fluctuations in response to barometric pressure changes.

As stated in Section 2.2, the over-response of the vented transducers in the Central Plateau wells is likely limited to wells screened across the water table (i.e., wells that are at least partly open to the vadose zone). This condition allows for the wellbore to be a pathway for air movement between land surface and the deep vadose zone, which in turn allows for air pressure differences between the wellbore and the land surface to be sustained longer due to the time required for the pressure in the deep vadose zone to equilibrate. For wells screened entirely below the water table and having no open interval adjacent to the vadose zone, a pathway for air movement through the wellbore would not exist and, thus, no substantial pressure difference would exist between the air in the wellbore and at land surface. Without a pressure difference, transducer over-response is not expected to occur. In this case, response functions generated

using either vented transducers or absolute transducers should be similar, and either response function could be used to determine a vadose zone pneumatic diffusivity.

Barometric response functions can also be used diagnostically to determine whether an aquifer is confined or unconfined and whether the water-level response in a well is affected by wellbore storage or skin effects (Rasmussen and Crawford, 1997, PNNL-13078; Spane, 2002). Each of these conditions results in a response function having a characteristic shape, as shown in Figure 14 (the skin effects response would extend the time delay of the wellbore storage model [PNNL-13078]). While shown separately in Figure 14, the wellbore storage/skin effects response is always superimposed on the other responses. The vented transducer response functions in wells 299-E33-34 and 699-37-47A (Figures 10 and 11) resemble the unconfined aquifer characteristic response, but as stated previously, are of larger magnitude than the actual water-level responses. Thus, it is theoretically possible that wellbore storage/skin effects might be masked by the over-response of the vented transducers, although this did not occur during in the study because wellbore storage/skin effects were not observed in the absolute transducer response functions.

Another type of response was observed in the absolute transducer response function for well 699-37-47A that was not evident in the vented transducer response function. It is commonly stated in the scientific literature that the response of a well water level to a barometric pressure change is inverse (i.e., increases in barometric pressure cause declines in well water levels, and vice versa). For an unconfined aquifer, however, this assumes that the water table elevation remains constant, which is not always the case.

Figure 14. Characteristic Well Water-Level Barometric Response Functions

The absolute transducer response function for well 699-37-47A (Figure 11) is less than zero between time lags of approximately 10 to approximately 50 hours, indicating a positive correlation between barometric pressure changes and well water levels during this time. This phenomenon is caused by the displacement of water within the aquifer due to areal differences in the vadose zone thickness and/or pneumatic diffusivity, as was theorized by Spane (2002). If an increase in barometric pressure migrates faster through the vadose zone to the water table elsewhere as compared to the vicinity of well 699-37-47A, the water table elevation near the well would have to increase to maintain the total head equilibrium in the highly transmissive aquifer. The opposite would occur for a barometric pressure decline. This effect causes a component of the response function to exhibit a positive correlation with air pressure changes (i.e., a response function less than zero). It appears that the over-response of the vented transducers prevented this displacement effect from being observed in the vented transducer response function.

3.2.2 Use of Vented Transducers

The issue with vented transducers in Central Plateau wells screened across the water table is one of over-response only to barometric pressure fluctuations. This will not affect the use of vented transducers for long-term, water-level monitoring or aquifer testing because barometric pressure effects can be removed from the data (as explained in Section 3.2.1). For instance, the vented pressure transducers in wells 299-E33-34 and 699-37-47A are long-term installations. Figures 15 and 16 show the original and barometric-adjusted, vented transducer data collected from these wells from August 2008 through March 2011. Both data sets are useful for determining long-term trends in the water table elevation and for providing information on the effect of stressors to the aquifer. These data sets clearly indicate the long-term decrease in the 200 East Area water table elevation resulting from the curtailment of effluent discharges to ground in the mid-1990s, and they also show water table fluctuations caused by discharges to the nearby Treated Effluent Disposal Facility (peaks in July 2009, June 2010, and October/November 2010).

A potential problem with barometric compensation of vented transducers is a blocked vent tube, and it might be hypothesized that such a condition would explain the transducer over-response identified during this study. However, examination of Equation 1 (Section 2.2) indicates that an over-response condition cannot occur from either a partially or fully blocked vent tube. For the case of a fully blocked vent tube, P_a in Equation 1 would be a constant, and erroneous transducer readings would be common because it would be a rare condition that $P_b = P_a$. Measurements from the absolute transducers used in this study indicated that the initial water-level response was less than the barometric pressure change within the wellbores of both wells. Thus, changes in wellbore air pressure were larger in magnitude than changes in water pressure (i.e., $|\Delta P_b| > |\Delta P_w|$). Under this condition, it follows from Equation 1 that for a fully blocked vent tube (i.e., P_a a constant), increases in air pressure will cause higher transducer water-level readings, and air pressure decreases will result in lower transducer water-level readings, which is opposite of the observations made during this study. Even in the limiting case where the water level change is equal in magnitude to the wellbore air pressure change (i.e., $|\Delta P_b| = |\Delta P_w|$), there would be no change in the vented transducer readings.

Figure 15. Vented Transducer and Manual Water-Level Measurements at Well 299-E33-34 from August 2008 Through March 2011

Figure 16. Vented Transducer and Manual Water-Level Measurements at Well 699-37-47A from August 2008 Through March 2011

In the event of a partial vent tube blockage, the pressure in the vent tube would be slow to equilibrate with air pressure changes. Thus, the pressure in the vent tube would be attenuated and time-lagged, the same as in the wellbore. Three conditions should be considered: (1) the vent tube pressure equilibrates faster than the wellbore pressure, (2) the vent tube pressure equilibrates at the same rate as the wellbore pressure, and (3) the vent tube pressure is slower to equilibrate than air pressure in the wellbore. The first condition is similar to an open vent tube in that the wellbore air pressure is attenuated and time-lagged compared to the vent tube pressure. Thus, an over-response would still be observed but would be smaller in magnitude than if the vent tube was fully open. The over-response would still be a result of the attenuated, time-lagged air pressure in the wellbore. For the second condition, $P_b = P_a$ all of the time and the vented pressure transducer readings would accurately reflect the water level in the well. For the third condition, the pressure in the vent tube would be attenuated and time-lagged compared to the air pressure in the wellbore (i.e., $|\Delta P_b| > |\Delta P_a|$). Upon examination of Equation 1 with this condition, and knowing that changes in wellbore air pressure can be larger in magnitude than changes in water pressure (i.e., $|\Delta P_b| > |\Delta P_w|$) or equal in magnitude (i.e., $|\Delta P_b| = |\Delta P_w|$), the vented transducer readings would either under respond to barometric pressure changes (i.e., $|\Delta P_v| < |\Delta P_w|$) or would respond in the opposite sense than expected (i.e., $\Delta P_v \propto -\Delta P_w$). Note that in no case would a partially or fully blocked vent tube cause the over-response condition observed during this study.

This study only considered Central Plateau wells screened across the water table. The thick vadose zone beneath the Central Plateau is an important factor causing a relatively long time lag before the gas pressure at the water table equilibrates with air pressure changes, which sustains the air pressure difference between the wellbore and the land surface for longer times. It is expected that vented transducer over-response would either not occur or would be much less in magnitude in areas where the vadose zone is not as thick (e.g., 100 Area), unless there is a substantial barrier to air movement in the vadose zone.

3.2.3 Total Head Determinations

Total head is the sum of hydraulic head (i.e., the water-level elevation in a well or the water table elevation in an aquifer) and barometric pressure head (i.e., the air pressure at the water surface in a well or the air pressure at the water table expressed as an equivalent water column height). Total head is the parameter that governs groundwater flow (Rasmussen and Crawford, 1997; PNNL-13078; Spane, 2002). When hydraulic heads are used to determine the hydraulic gradient and groundwater flow, the assumption is made that air pressure at the water table (or at the water surface in the wells) is uniform throughout the study area. This study demonstrated that the air pressure in Central Plateau wells screened across the water table is commonly in disequilibrium with the air pressure at land surface (Figures 6 and 7). Therefore, the determination of total head in Central Plateau wells is not as simple as adding the barometric pressure measurements from a nearby meteorology station (e.g., station #6 in the 200 East Area) to the measured water-level elevations in the wells. Instead, the air pressure in the wellbores must either be specifically measured by an absolute pressure transducer, or the quantitative relationship between the wellbore air pressure and the barometric pressure at the meteorology station must be established to allow the wellbore air pressure to be estimated from the station measurements. Because absolute pressure transducers are commonly installed in Central Plateau wells for only short time periods, the approach of estimating the wellbore air pressures will be used most often when converting water-level measurements to total head values.

The process of estimating the air pressure in the wellbores and calculating total head is demonstrated for wells 299-E33-34 and 699-37-47A. The quantitative relationship between the station #6 barometric pressure measurements and the air pressure in the wells at the water surface (as measured by the downhole Barologgers) was determined by multiple regression using the MRCX software

(PNNL-19975). This was performed using the “original data” option in the software, which uses a regression equation of the following form (PNNL-19975) (Equation 2):

$$P_b(t) = \alpha + \beta_0 P_m(t) + \beta_1 P_m(t - 1) + \beta_2 P_m(t - 2) + \cdots + \beta_n P_m(t - n) \quad (\text{Equation 2})$$

where:

- P_b = air pressure in the wellbore at the water surface at some time t
- α = offset coefficient
- β_x = regression coefficients
- P_m = meteorology station barometric pressure measurements as a function of time
- n = maximum time lag chosen to result in a good prediction of the wellbore air pressure

A maximum time lag of 72 hours yielded very good predictions for both wells 299-E33-34 and 699-37-47A, and the results of the regression are shown as response functions in Figure 17. Nearly full responses to an instantaneous unit change in barometric pressure occurred after approximately 24 hours in well 299-E33-34 and approximately 48 hours in well 699-37-47A.

Total heads for both wells using both the estimated wellbore air pressures and the elevation adjusted station #6 barometric pressure measurements for comparison are shown in Figures 18 and 19 for representative 2-week time periods. The total head differences are the same as the air pressure differences shown in Figures 6 and 7, which compared the wellbore air pressure measurements to the elevation adjusted station #6 barometric pressure measurements. Total head differences ranged up to 0.020 m (0.79 in.) for well 299-E33-34 and 0.077 m (3.03 in.) for well 699-37-47A over the 2-week periods shown. Because the water table elevation varies by only a few centimeters in the 200 East Area, these differences are significant when determining groundwater flow directions. However, differences in meteorology station and wellbore air pressures may not be significant in areas with larger hydraulic gradient magnitudes. Thus, the need for using wellbore air pressures to calculate total head will need to be evaluated on a site-specific basis. In addition, the presence of substantial wellbore storage/skin effects will need to be determined for each well in which total heads are to be calculated. As noted in PNNL-13078, the approach of calculating total head by summing the water-level elevation and the air pressure is valid only in wells that do not exhibit a delayed head response due to wellbore storage/skin effects.

Figure 17. Wellbore Air Pressure Response Functions for Wells 299-E33-34 and 699-37-47A

Figure 18. Total Head Comparison in Well 299-E33-34

Figure 19. Total Head Comparison in Well 699-37-47A

4 Summary and Recommendations

This chapter summarizes the findings of the study and provides recommendations for users of pressure transducer data. Recommendations are also provided for expanding this study to other well/vadose zone conditions.

4.1 Summary

Data collected during this study demonstrated that in response to barometric pressure changes, vented pressure transducers installed in Hanford Site Central Plateau wells screened across the water table yield water-level measurements that fluctuate to a larger degree than actual water-level changes in the wells. Analysis of the data demonstrated that the over-response of vented pressure transducers was caused by pressure disequilibrium between the air within the wellbores and the atmosphere at land surface. The disequilibrium was attributed to a thick vadose zone and/or low diffusivity and the resulting long lag time required for air pressure changes to equilibrate between land surface and the water table. This condition is probably exacerbated by sample pump landing plates and well caps installed on the wells that restrict the flow of air between the wellbores and the atmosphere.

The implications of vented transducer over-response were explored. It was concluded that barometric response functions determined from time-series, water-level data collected using vented transducers are not representative of the actual well water-level response, but instead reflect the combination of vadose zone pneumatic diffusivity, well effects, and transducer effects. Only time-series measurements collected with absolute transducers yielded response functions representative of the actual well water-level response. It was also shown that certain diagnostic features of barometric response functions may be masked by vented transducer over-response, such as displacement effects and perhaps wellbore storage/skin effects. It was also emphasized that vented transducers are still useful for long-term

monitoring and hydrologic testing because barometric effects, including transducer over-response, can be removed from the data by multiple regression/deconvolution. Finally, the air pressure disequilibrium between the wellbores and the atmosphere as related to total head calculations were discussed, and it was demonstrated that total head could be calculated using wellbore air pressure values estimated from measurements at a nearby meteorology station.

4.2 Recommendations

Care should be exercised when selecting the type of pressure transducer to be deployed for a specific application, or when analyzing previously collected pressure transducer data. Users of pressure transducer data should be aware of the over-response of vented pressure transducers to barometric pressure fluctuations when this equipment is installed in certain Hanford Site wells, especially Central Plateau wells screened across the water table. Users of vented pressure transducers will need to ascertain if transducer over-response will occur (or has occurred) during application of this equipment; if so, users will need to determine if the over-response will affect use of the data. Wells exhibiting pressure disequilibrium can be identified by substantial air movement through the wellbores. In wells exhibiting the pressure disequilibrium, it is recommended that absolute pressure transducers be used whenever actual well water-level barometric response characteristics need to be determined, such as when adjusting manual water-level measurements for barometric pressure fluctuations or when using barometric response functions for diagnostic purposes. Some users may elect to deploy absolute transducers for all applications in wells exhibiting pressure disequilibrium to avoid the transducer over-response issue entirely.

This study examined the limitations of data collected using vented pressure transducers installed in Central Plateau wells screened across the water table, but it should be extended to other Hanford Site settings. It was hypothesized that vented transducer over-response would not occur in Central Plateau wells screened entirely below the water table, but this should be confirmed by actual data collection. Furthermore, the over-response issue should be studied in wells located where the vadose zone is not as thick, such as in the 100 Area.

5 References

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Appendix A

Well Construction Diagrams for Wells 299-E33-34 and 699-37-47A

Well 299-E33-34

WELL CONSTRUCTION AND COMPLETION SUMMARY			
Drilling Method: Cable tool Drilling Fluid Used: 200 W Water Driller's Name: G. Lydin Company: Kaiser Engineers Date Started: 02Jan90	Sample Drive barrel Method: Hard tool Additives Used: None Lic Nr: Not documented Company Location: Hanford Date Complete: 23Apr90	WELL NUMBER: 299-E33-34 TEMPORARY WELL NO: E10-MW7 Hanford Coordinates: N/S N 46,796 E/W W 55,065 State NAD83 N 137,740.72m E 573,104.63m Coordinates: N 451,956 E 2,240,140 Start Card #: Not documented T R S Elevation Ground surface: 630.39-ft (Brass cap)	
Depth to water: 225.6-ft Mar90 (Ground surface) 228.7-ft 25Jun93 GENERALIZED Geologist's STRATIGRAPHY Log Sl=slightly			
0-10: Muddy sandy GRAVEL 10-20: Sandy GRAVEL 20-35: SAND 35-40: Gravelly SAND 40-75: Sl gravelly SAND 75-80: SAND 80-90: Sl gravelly SAND 90-120: SAND 120-125: Sl gravelly SAND 125-140: SAND 140-160: Gravelly SAND 160-175: SAND 175-195: Sl muddy SAND 195-200: Muddy SAND 200-205: Gravelly SAND 205-215: Sandy GRAVEL 215-225: Muddy sandy GRAVEL 225-230: (No recovery) 230-237: Muddy sandy GRAVEL 237-240: SAND 240 : BASALT	<div style="display: flex; flex-direction: row-reverse;"> <div style="width: 10%; text-align: right; padding-right: 5px;"> Elevation of reference point: [633.33-ft] (top of casing) Height of reference point above [2.94-ft] ground surface Depth of surface seal [3.0-19.8-ft] Type of surface seal: Cement grout to 19.8-ft, has concrete 4x4-ft x 6-in surface pad extending 3-ft into annulus 4-in ID stainless steel casing, +0.5-219.0-ft Hole diameter, 0-147.0-ft, 11-in nominal 147.0-240.0-ft, 9-in nominal Bentonite crumbles, 19.8-212.4-ft, 8-20-mesh -in Volclay tablets 212.4-216.6-ft Silica sand pack, 216.6--239.3-ft, 20-40-mesh 4-in stainless steel screen, 219.0-239.3-ft, #10-slot w/channel pack Fill ~239.3-240-ft Borehole drilled depth: [240.0-ft] </div> <div style="width: 90%; border-left: 1px solid black; border-right: 1px solid black; position: relative;"> <!-- Diagram content represented by the image alt --> </div> </div>		
Drawing By: RKL/2E33-34.ASB Date : 13Sep93 Reference : WHC-MR-0205			

Well 299-E33-34 (cont'd.)SUMMARY OF CONSTRUCTION DATA AND FIELD OBSERVATIONS
RESOURCE PROTECTION WELL - 299-E33-34

WELL DESIGNATION : 299-E33-34
 CERCLA UNIT : 200 Aggregate Area Management Study
 RCRA FACILITY : Low Level Burial Grounds, WMA-1
 HANFORD COORDINATES : N 46,796 W 55,065 [19Apr90-200E]
 LAMBERT COORDINATES : N 451,956 E 2,240,140 [HANCONV]
 N 137,740.72m E 573,104.63m [19Apr90-NAD83]
 DATE DRILLED : Apr90
 DEPTH DRILLED (GS) : 240.0-ft
 MEASURED DEPTH (GS) : Not documented
 DEPTH TO WATER (GS) : 225.6-ft, 20Mar90;
 228.7-ft, 13Sep93
 CASING DIAMETER : 4-in stainless steel, +0.5-219.0-ft;
 6-in stainless steel, +2.9--0.5-ft
 ELEV TOP CASING : 633.33-ft, [19Apr90-200E]
 ELEV GROUND SURFACE : 630.39-ft, Brass cap [19Apr90-200E]
 PERFORATED INTERVAL : Not applicable
 SCREENED INTERVAL : 219.0-239.3-ft, 4-in #10-slot stainless steel w/channel pack
 COMMENTS : FIELD INSPECTION, 25Jan93;
 4 and 6-in stainless steel casing.
 4-ft by 4-ft concrete pad, 4 posts, 1 removable.
 Capped and locked, brass cap in pad with well ID.
 Not in radiation zone.
 OTHER:
 AVAILABLE LOGS : Geologist, driller
 TV SCAN COMMENTS : Not applicable
 DATE EVALUATED : Not applicable
 EVAL RECOMMENDATION : Not applicable
 LISTED USE : LLBG monthly water level measurement, 24Apr90-25Jun93;
 CURRENT USER : WHC ES&M w/l monitoring and RCRA sampling,
 WHC ER characterization
 PUMP TYPE : Hydrostar
 MAINTENANCE :

Well 699-37-47A

0534480

WELL SUMMARY SHEET			Boring or Well No. 699-37-47A (B2822)	
			Sheet 1 of 2	
Location <u>200 East Area, SE Corner</u>		Project <u>RCRA/W152</u>		
Prepared By <u>JW Lindberg</u> (Sign/Print Name)	Date <u>11/4/96</u>	Reviewed By <u>BA Williams</u> (Sign/Print Name)	Date <u>11/22/96</u>	
CONSTRUCTION DATA		Depth in Feet	GEOLOGIC/HYDROLOGIC DATA	
Description	Diagram		Graphic Log	Lithologic Description
0'-3' Concrete with 6" stainless steel protective casing.		10		Eolian Silty Sand 0'-3'
3'-19' Surface seal (neat cement)		20		Hanford fm. 3'-285' Dark Gray
		30		3'-50' Sand with occasional pebbles
		40		
		50		50'-110' gravelly sand
		60		
		70		
10 3/4" Temporary Casing 0.0-306.3' (carbon steel)		80		
		90		
		100		
8 5/8" Temporary Casing 0.0 to 525.5' (carbon steel)		110		110'-165' Sand, med.-coarse grained
		120		
		130		
4" stainless steel casing (Permanent)		140		140'-146' pebbles
		150		
		160		
		170		165'-245' Sand, occasional pebbles
		180		
		190		
		200		
		210		
		220		
		230		
		240		
		250		245'-295' Gravelly Sand, coarsening downward
		260		
		270		
		280		
		285		Ringold fm. upper Ringold unit
		290		
Bentonite Pellets (1/4") 304.5'-306.0'		300		285'-310' Silty Sand, Grades Downward
Sandpack Interval 340.8'-304.5' 10/20 Sand		310		to unit E, Olive Brown
Static Water Level 312 ft		312		Ringold fm. Unit E 310'-367'

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Well 699-37-47A (cont'd)

WELL SUMMARY SHEET			Boring or Well No. 699-37-47A	
			Sheet 2 of 2	
Location <u>200 East Area, SE Corner</u>		Project <u>RCRA/W152</u>		
Prepared By <u>JW Lindberg</u> <small>(Sign/Print Name)</small>	Date <u>11/4/96</u>	Reviewed By <u>[Signature]</u> <small>(Sign/Print Name)</small>	Date <u>11/22/96</u>	
CONSTRUCTION DATA		Depth in Feet	GEOLOGIC/HYDROLOGIC DATA	
Description	Diagram		Graphic Log	Lithologic Description
Stainless Steel Screen 338.7'-308.7' 20 slot		330		Unit E 310'-367' Sandy Gravel
Slough (formation) 358.0'-340.8'		340		Dark Gray
Bentonite Pellets (1/4") 365'-365'		350		
		360		
		370		Ringold Fm, lower mud unit
		380		367'-412' Sandy silt, tr. clay.
Cement Grout 365.0'-410.0'		390		Gray (lt. gray when dry).
		400		
		410		Ringold Fm, unit A and lower mud
		420		unit mixed. 412'-437.5'
Silica Sand 525.5'-410.0'		430		dark gray to brown for fines
		440		Ringold Fm, unit A Sandy Gravel
		450		437.5' - 516' Dark Olive Gray
		460		
		470		475'-480' fine sand gray-brown
		480		
		490		
		500		
		510		
		520		516' to TD
hole TD = 525.5'		530		Basalt, Elephant mtn. Member
				TD = 525.5' Black

B.2

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