Date Received for Clearance Process (MM/DD/YYYY)
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A. Information Category

- [ ] Abstract
- [ ] Journal Article
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B. Document Number SGW-35756, Rev. 0

C. Title
WATER-LEVEL BAROMETRIC RESPONSE ANALYSIS FOR THE LIQUID EFFLUENT RETENTION FACILITY MONITORING WELLS

D. Internet Address

E. Required Information (MANDATORY)

1. Is document potentially Classified? (•) No ( ) Yes
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   ADC Required (Print and Sign) (•) No ( ) Yes Classified
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3. Export Controlled Information (•) No ( ) Yes OUO Exemption No. 3
4. UCNI (•) No ( ) Yes
5. Applied Technology (•) No ( ) Yes
6. Other (Specify) _____

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F. Complete for a Journal Article

1. Title of Journal

G. Complete for a Presentation

1. Title for Conference or Meeting _____
2. Group Sponsoring _____
3. Date of Conference _____
4. City/State _____
5. Will Information be Published in Proceedings? ( ) No ( ) Yes
6. Will Material be Handed Out? ( ) No ( ) Yes

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ADMINISTRATIVE DOCUMENT PROCESSING AND APPROVAL

DOCUMENT TITLE:	OWNING ORGANIZATION/FACILITY:
WATER-LEVEL BAROMETRIC RESPONSE ANALYSIS FOR THE LIQUID EFFLUENT RETENTION FACILITY MONITORING WELLS	Soil and Groundwater Remediation
Document Number: SGW-35756	**Revision/Change Number:** 0

DOCUMENT TYPE *(Check Applicable)*

☐ Plan ☒ Report ☐ Study ☐ Description Document ☐ Other

DOCUMENT ACTION ◉ New ○ Revision ○ Cancellation

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DOCUMENT CONTROL

Does document contain scientific or technical information intended for public use? ◉ Yes ○ No

Does document contain controlled-use information? ○ Yes ◉ No

("Yes" requires information clearance review in accordance with HNF-PRO-184)

DOCUMENT REVISION SUMMARY

NOTE: Provide a brief description or summary of the changes for the document listed.

REVIEWERS Others

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APPROVAL SIGNATURES

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RELEASE / ISSUE

DEC 27 2007

DATE:

STA: 15

HANFORD RELEASE

ID: 20

SGW-35756
Revision 0

WATER-LEVEL BAROMETRIC RESPONSE ANALYSIS FOR THE LIQUID EFFLUENT RETENTION FACILITY MONITORING WELLS

Document Type: TR Program/Project: SGW

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Fluor Hanford, Inc.

Date Published
December 2007

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

Project Hanford Management Contractor for the
U.S. Department of Energy under Contract DE-AC06-96RL13200

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Release Approval Date

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EXECUTIVE SUMMARY

A barometric response analysis was performed in the Liquid Effluent Retention Facility (LERF) groundwater monitoring wells 299-E26-10 (downgradient) and 299-E26-11 (upgradient). The goal of this analysis was to assess the effect that barometric pressure fluctuations may have had on the results of an earlier trend-surface analysis performed to determine the magnitude and direction of the hydraulic gradient at the LERF.

Pressure transducers were installed in downgradient well 299-E26-10 and upgradient well 299-E26-11 during April 2007 to measure well water-level elevations (additional wells were used in the trend-surface analysis, but they had either gone dry or were not accessible). Data were collected at an hourly frequency until the end of July. Hourly barometric pressure measurements for the 200 East Area were obtained from Pacific Northwest National Laboratory. Multiple regression was used to analyze the well water-level responses to barometric pressure fluctuations. The water-level response characteristics indicated that the aquifer is unconfined at well 299-E26-10 and confined at well 299-E26-11. In addition, the response for well 299-E26-11 was consistent with a leaky confined aquifer.

Barometric pressure effects were removed from the time-series water-level measurements using deconvolution, and temporal trends that were not fully evident in the original measurements were revealed. At well 299-E26-10, the water-level elevation increased during late April, declined slightly through late June, and then increased significantly during July. At well 299-E26-11, the water-level elevation was stable from late April into May, and then declined steadily through July. Previous work has indicated that water levels in the 200 East Area respond to discharges at the Treated Effluent Disposal Facility (TEDF) and may also respond to long-term changes in Columbia River stage. Effluent discharges to the TEDF were significantly higher during June 2007 than in previous months, which likely explains the increasing water-level trend observed at well 299-E26-10.

Two sets of trend-surface analysis results were considered in this work; one including upgradient well 299-E26-11 (reported gradient of 9.5×10^{-4} at 257 degrees azimuth) and one without this well (reported gradient of 1.1×10^{-4} at 243 degrees azimuth). Two analyses had been performed because well 299-E26-11 has a water-level elevation about 1 m higher than the downgradient

wells. The observed variability in well water levels due to barometric pressure fluctuations during the monitoring period was approximately 0.05 m at well 299-E26-10 and approximately 0.08 m at well 299-E26-11. This level of variability would not have affected the trend-surface analysis results that included well 299-E26-11, because the observed variability is much smaller than the 1-m water-level elevation difference between the wells. The trend-surface analysis results excluding well 299-E26-11 may have been affected by barometric pressure fluctuations. The reported gradient of 1.1×10^{-4} equates to a water-level elevation difference of 0.06 m across the study area, which is comparable to the level of variability due to barometric pressure fluctuations. This variability would be more important if there are significant changes to barometric pressure during the time period in which a set of water-level measurements is collected, or if there are variations in the vadose zone transmission characteristics across the LERF site. Two characterization wells are planned to be installed at the LERF during fiscal year 2008. If these wells are completed as monitoring wells, it is recommended that additional trend-surface analyses be performed that will account for temporal barometric pressure fluctuations so that average long-term groundwater flow conditions may be more directly determined.

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LIST OF TERMS

ETF	Effluent Treatment Facility
LERF	Liquid Effluent Retention Facility
RCRA	*Resource Conservation and Recovery Act of 1976*
TEDF	Treated Effluent Disposal Facility

METRIC CONVERSION CHART

Into Metric Units			Out of Metric Units		
If You Know	*Multiply By*	*To Get*	*If You Know*	*Multiply By*	*To Get*
Length			**Length**		
inches	25.4	millimeters	millimeters	0.039	inches
inches	2.54	centimeters	centimeters	0.394	inches
feet	0.305	meters	meters	3.281	feet
yards	0.914	meters	meters	1.094	yards
miles	1.609	kilometers	kilometers	0.621	miles
Area			**Area**		
sq. inches	6.452	sq. centimeters	sq. centimeters	0.155	sq. inches
sq. feet	0.093	sq. meters	sq. meters	10.76	sq. feet
sq. yards	0.0836	sq. meters	sq. meters	1.196	sq. yards
sq. miles	2.6	sq. kilometers	sq. kilometers	0.4	sq. miles
acres	0.405	hectares	hectares	2.47	acres
Mass (weight)			**Mass (weight)**		
ounces	28.35	grams	grams	0.035	ounces
pounds	0.454	kilograms	kilograms	2.205	pounds
ton	0.907	metric ton	metric ton	1.102	ton
Volume			**Volume**		
teaspoons	5	milliliters	milliliters	0.033	fluid ounces
tablespoons	15	milliliters	liters	2.1	pints
fluid ounces	30	milliliters	liters	1.057	quarts
cups	0.24	liters	liters	0.264	gallons
pints	0.47	liters	cubic meters	35.315	cubic feet
quarts	0.95	liters	cubic meters	1.308	cubic yards
gallons	3.8	liters			
cubic feet	0.028	cubic meters			
cubic yards	0.765	cubic meters			
Temperature			**Temperature**		
Fahrenheit	subtract 32, then multiply by 5/9	Celsius	Celsius	multiply by 9/5, then add 32	Fahrenheit
Radioactivity			**Radioactivity**		
picocuries	37	millibecquerel	millibecquerel	0.027	picocuries

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1.0 INTRODUCTION

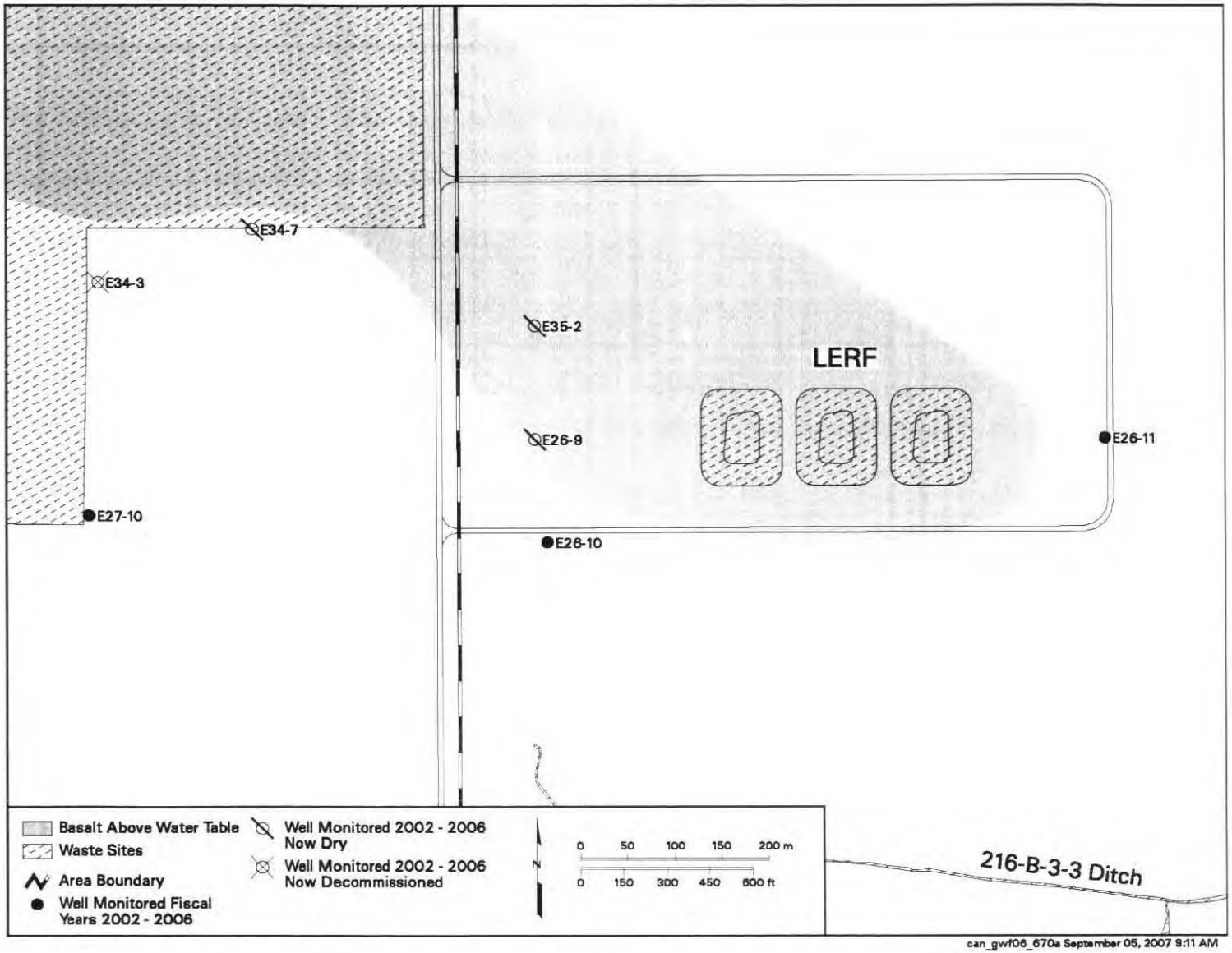
The Liquid Effluent Retention Facility (LERF) at the Hanford Site is a *Resource Conservation and Recovery Act of 1976* (RCRA) treatment, storage, and/or disposal unit that serves as a temporary holding area for liquid effluents prior to treatment at the Effluent Treatment Facility (ETF). The aquifer beneath the LERF occurs within glaciofluvial sand and gravel of the Hanford formation which overlies basalt bedrock, and the depth to water ranges between 60 m and 70 m. The water-table elevation exhibits a long-term decline in response to the curtailment of effluent discharges to ground associated with the change in the Hanford Site mission from nuclear materials production to environmental cleanup. Groundwater monitoring of the unconfined aquifer began at the LERF in 1990. Since that time, the water-table elevation has declined below the top of basalt bedrock beneath parts of the facility (i.e., the unconfined aquifer is dewatering). Many of the LERF wells have gone dry and are no longer useable.

In February 2004, a groundwater evaluation plan ("Liquid Effluent Retention Facility and 200 Area Effluent Treatment Facility, and Approved Modifications," Attachment 34 in *Hanford Facility Resource Conservation and Recovery Act Permit, Dangerous Waste Portion Revision 8* [Ecology 2004]) was developed for the LERF to assess the feasibility of continued groundwater monitoring at the facility. As part of this evaluation, the plan called for determining the groundwater-flow characteristics of the unconfined aquifer, including an assessment of barometric pressure fluctuations in the LERF monitoring wells and the potential for these fluctuations to affect hydraulic gradient and groundwater-flow direction determinations. Hydraulic properties and groundwater-flow conditions at the LERF were assessed previously in *Results of Detailed Hydrologic Characterization Tests – Fiscal Year 2003* (PNNL-14804). Hydrologic testing was conducted in two of the LERF wells: 299-E26-10 and 299-E26-11 (Figure 1). The hydraulic conductivity was found to be higher at well 299-E26-10 (36.2 m/day from a constant-rate pump test) than at well 299-E26-11 (5.53 to 7.34 m/day from slug tests).

A trend-surface analysis was also performed to assess the groundwater-flow direction using water-level measurements collected between 1997 and 2003 (PNNL-14804). The wells used in the trend-surface analysis were 299-E26-9, 299-E26-10, 299-E26-11, 299-E27-10, 299-E34-3, 299-E34-7, and 299-E35-2 (Figure 1). It was found that inclusion of wells 299-E26-11 and 299-E34-7 had a significant effect on the trend-surface analysis results. Well 299-E26-11 has a water-level elevation approximately 1 m higher than the other wells, and the water-level elevation data for well 299-E34-7 are consistently lower than the water-table elevation over much of the 200 East Area. It is suspected that the wellbore at 299-E34-7 is significantly deviated from vertical, which causes the measured depth to water to be larger than the true vertical depth to water. PNNL-14804 calculated an average hydraulic gradient magnitude of 9.5×10^{-4} and a flow direction of 257 degrees azimuth (west-southwest) when omitting well 299-E34-7 from the analysis, and 1.1×10^{-4} with a flow direction of 243 degrees azimuth (southwest) when omitting both wells. The trend-surface analysis results that had included well 299-E34-7 are deemed to be biased by the low water-level elevation in this well and are not considered further.

The purpose of the present work is to assess water-level responses to barometric pressure fluctuations at the LERF monitoring wells to determine the effect that such fluctuations may have had on the trend-surface analysis results. This document discusses the barometric response analysis that was performed at the LERF wells.

Figure 1. Well Locations at the Liquid Effluent Retention Facility.



2.0 THEORETICAL BACKGROUND[1]

Well water levels typically respond to changes in barometric pressure. The relationship is an inverse one: increases in barometric pressure cause a decline in the well water-level elevation, and vice versa. To understand why this occurs, the concept of total head must be defined.

Total head at a point location in an aquifer is a measure of the total potential energy available to induce water flow in the aquifer, and it consists of both pressure and gravitational components. The pressure component is the absolute pressure at the measurement point, and the gravitational component is usually denoted as the height of the measurement point above an arbitrary datum (e.g., mean sea level). Thus, the total head can be expressed as the sum of the elevation of the measurement point and the total pressure at that point:

$$H_{tot} = \frac{P_{tot}}{\rho \cdot g} + z \qquad \text{(Equation 1)}$$

where H_{tot} is the total (freshwater) head (L), P_{tot} is the total pressure (M L^{-1} T^{-2}), ρ is the density of freshwater (M L^{-3}), g is the acceleration of gravity (L T^{-2}), and z is the elevation of the measurement point (L). The term $P_{tot} / (\rho \cdot g)$ expresses the total pressure as an equivalent freshwater head having units of length (L).

2.1 TOTAL HEAD AND BAROMETRIC PRESSURE CHANGES FOR UNCONFINED AQUIFERS

For an unconfined aquifer (with a negligible vertical hydraulic gradient), the total pressure in Equation 1 is due to the height of the water column above the measurement point and the atmospheric pressure at the water table:

$$P_{tot} = P_a + h_w \cdot \rho \cdot g \qquad \text{(Equation 2)}$$

where P_a is the atmospheric pressure (M L^{-1} T^{-2}) and h_w is the height of the water column above the measurement point (L). Substituting into Equation 1 gives

$$H_{tot} = \frac{P_a}{\rho \cdot g} + h_w + z \qquad \text{(Equation 3)}$$

The quantity, $h_w + z$, is known as the hydraulic head, so Equation 1 can be expressed for an unconfined aquifer as

$$H_{tot} = \frac{P_a}{\rho \cdot g} + H_{hyd} \qquad \text{(Equation 4)}$$

where H_{hyd} is the hydraulic head (L). Thus, the total head at a particular point in an unconfined aquifer is the sum of the hydraulic head at that location and the barometric pressure head. Total

[1] Information for this section was derived from "The Theory of Ground-Water Motion" (Hubbert 1940); "On the Flow of Water in an Elastic Artesian Aquifer" (Jacob 1940); "Barometric Fluctuations in Wells Tapping Deep Unconfined Aquifers" (Weeks 1979); *Groundwater* (Freeze and Cherry 1979); "Identifying and Removing Barometric Pressure Effects in Confined and Unconfined Aquifers" (Rasmussen and Crawford 1997); *Effects of Barometric Fluctuations on Well Water-Level Measurements and Aquifer Test Data* (PNNL-13078); and "Considering Barometric Pressure in Groundwater Flow Investigations" (Spane 2002).

head is the parameter that determines groundwater flow in an aquifer. Hydraulic head is typically used to ascertain groundwater flow conditions with the assumption that the barometric pressure at the water table (P_a) is constant across a given study area (i.e., hydraulic head is assumed to be directly proportional to total head). As is explained later, this assumption may not always be true.

Consider two measurement points associated with a well completed in an unconfined aquifer: point A within the saturated screened interval and point B at an equivalent horizon adjacent to the well in the aquifer. The total head at point A ($H_{tot(A)}$) is the sum of the water-level elevation in the well ($H_{hyd(A)}$) and the atmospheric pressure at the water-level surface converted to an equivalent freshwater head ($P_{a(A)} / [\rho \cdot g]$). Similarly, the total head at point B ($H_{tot(B)}$) is the sum of the hydraulic head in the aquifer ($H_{hyd(B)}$) and the atmospheric pressure at the water table converted to an equivalent freshwater head ($P_{a(B)} / [\rho \cdot g]$). At equilibrium,

$$H_{tot(A)} = H_{tot(B)} \qquad \text{(Equation 5)}$$

and, therefore,

$$\frac{P_{a(A)}}{\rho \cdot g} + H_{hyd(A)} = \frac{P_{a(B)}}{\rho \cdot g} + H_{hyd(B)} \qquad \text{(Equation 6)}$$

Barometric pressure represents a blanket stress applied evenly at land surface over a large area. Consider what happens if that pressure instantaneously declines by an amount equivalent to one unit of freshwater head. This reduced pressure is immediately propagated through the wellbore to the water-level surface in the well (assuming an open well [i.e., the well cap is not airtight]), but does not propagate immediately through the vadose zone. Due to airflow resistance in the vadose zone, a time lag occurs before the barometric pressure at the water table begins to decline. Therefore, immediately after the barometric pressure decline, there will be an imbalance in the total head at points A and B, with the total head at point A being one unit-less:

$$\left(\frac{P_{a(A)}}{\rho \cdot g} - 1\right) + H_{hyd(A)} < \frac{P_{a(B)}}{\rho \cdot g} + H_{hyd(B)} \qquad \text{(Equation 7)}$$

The imbalance in total head (i.e., a gradient) induces a flow of water from the aquifer through the screen into the well. This occurs until the water level in the well increases by one unit and the equality of total heads is re-established. Assuming that water transmits easily into the well (i.e., wellbore storage effects are not significant), this process would happen rapidly so there would essentially be no time lag between the barometric pressure change and the initial well water-level response. By this mechanism, the water level in a well fluctuates in response to barometric pressure changes to maintain the equilibrium of total heads between the well and the adjacent aquifer. Eventually, the barometric pressure change will migrate through the vadose zone and change the air pressure at the water table. This will also result in a total head imbalance and the well water level will adjust to maintain the total head equilibrium. In addition, it is apparent from Equation 6 that whenever there is a difference in air pressure between the well and the aquifer water table, the water-level elevation in the well will be different than the actual water-table elevation in the surrounding aquifer. Thus, the only time a well water-level elevation equals the water-table elevation in the aquifer is when the air pressures are equal (i.e., a state of equilibrium exists).

2.2 TOTAL HEAD AND BAROMETRIC PRESSURE CHANGES FOR CONFINED AQUIFERS

The situation for confined aquifers is different. As mentioned previously, the total head at a point in an aquifer can be expressed as the sum of the elevation of the measurement point and the total pressure at that point (Equation 1). The pressure in a confined aquifer is due to the height of the water column above the measurement point (i.e., the vertical distance to the confining layer) and the weight of the overlying material including the atmosphere. This weight is supported partly by the aquifer water and partly by the aquifer skeleton, but only the part supported by the water adds to the total pressure. Thus, the total pressure at a point location in a confined aquifer is given by

$$P_{tot} = P_a + \sigma_g - \sigma_e + h_w \cdot \rho \cdot g \qquad \text{(Equation 8)}$$

where σ_g is the stress due to the weight of the overlying geologic units and soil moisture ($M\ L^{-1}\ T^{-2}$) and σ_e is the weight of the overlying material supported by the aquifer skeleton (i.e., effective stress). The quantity $P_a + \sigma_g$ is referred to as the total stress. Thus, the total head at a point location in a confined aquifer can be expressed as the sum of the measurement point elevation, the height of the water column above the measurement point, and the portion of the total stress borne by the aquifer water (i.e., total stress less effective stress):

$$H_{tot} = \frac{P_a + \sigma_g - \sigma_e}{\rho \cdot g} + h_w + z \qquad \text{(Equation 9)}$$

Like before, consider two points: point A inside the well screen and point B at an equivalent horizon in the aquifer. The total head in the well is given by

$$H_{tot} = \frac{P_a}{\rho \cdot g} + h_{w(A)} + z_{(A)} \qquad \text{(Equation 10)}$$

where $h_{w(A)}$ is the height of the water column above point A (L), and $z_{(A)}$ is the elevation of point A (L). At equilibrium,

$$H_{tot(A)} = H_{tot(B)} \qquad \text{(Equation 11)}$$

and, therefore,

$$\frac{P_a}{\rho \cdot g} + H_{hyd(A)} = \frac{P_a + \sigma_g - \sigma_e}{\rho \cdot g} + h_{w(B)} + z_{(B)} \qquad \text{(Equation 12)}$$

because $h_{w(A)} + z_{(A)}$ is the hydraulic head in the well.

For a confined aquifer, changes in the atmospheric pressure load at the surface are transmitted instantaneously to the aquifer (through the overlying vadose zone skeleton and confining unit) as a change in total stress. Thus, for confined aquifers, a unit decrease in atmospheric pressure (equivalent to one unit of freshwater head) causes an instantaneous decrease in total head in the aquifer. However, the total head decrease in the aquifer is not equal to one unit, because the total stress is not entirely supported by the aquifer water (some is supported by the effective stress on the aquifer skeleton [σ_e]). For example, if 50% of the total stress change is borne by the aquifer water and 50% by the aquifer skeleton, then the total head in the aquifer (point B) would decrease by one-half unit. Because the total head in the well (point A) would decrease by one unit, there is a resulting imbalance in total heads between the aquifer and the well:

$$\left(\frac{P_a}{\rho \cdot g} - 1\right) + H_{hyd(A)} < \frac{(P_a - 1 \cdot \rho \cdot g) + \sigma_g - (\sigma_e - 0.5 \cdot \rho \cdot g)}{\rho \cdot g} + h_{w(B)} + z_{(B)} \quad \text{(Equation 13)}$$

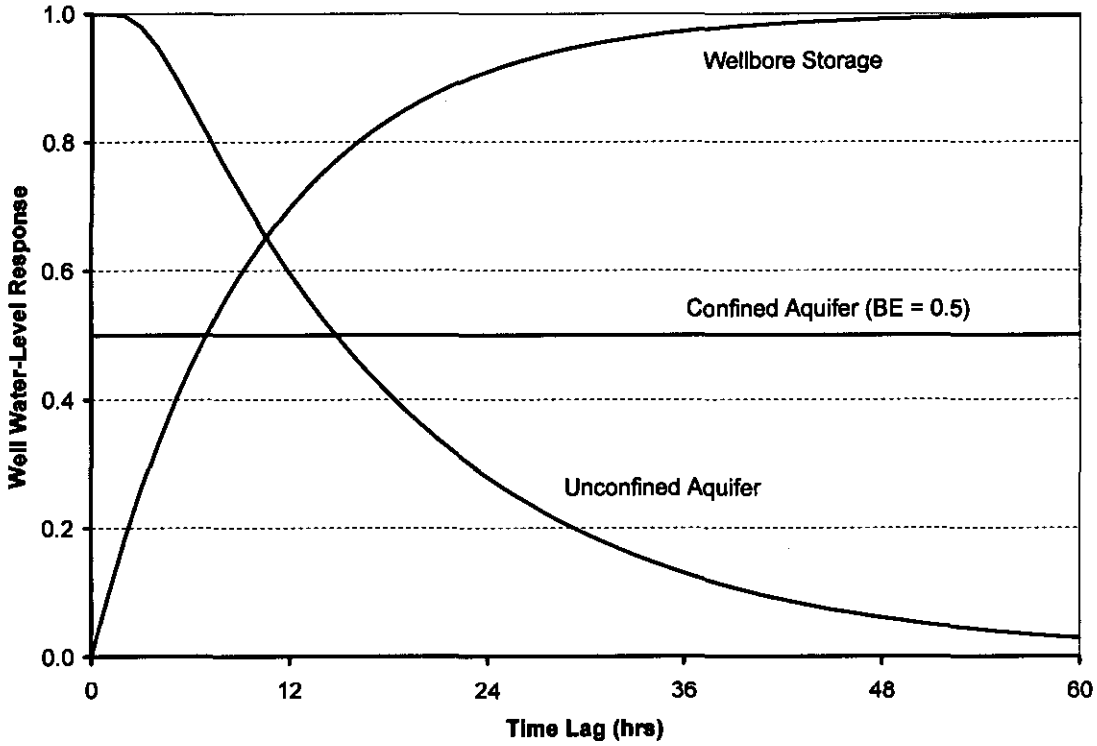
Similar to an unconfined aquifer, this imbalance in total heads induces a flow of water from the aquifer into the well until the total heads are again in equilibrium. For this example, the water level in the well would increase by one-half unit instead of one unit like in the unconfined aquifer example. The ratio between the water-level change in the well and the atmospheric pressure change is known as the barometric efficiency (*BE*) and is a direct measure of the proportion of the total stress change borne by the aquifer skeleton (and 1 – *BE* is a measure of the proportion borne by the aquifer water). Barometric efficiencies usually fall in the range of 0.20 to 0.75 (Freeze and Cherry 1979). Unlike an unconfined aquifer, as the barometric pressure change migrates through the vadose zone, the total head in a confined aquifer does not change. Thus, there is no further water-level response in a confined aquifer to an instantaneous change in barometric pressure.

2.3 CHARACTERISTIC BAROMETRIC RESPONSE FUNCTIONS

The response of the well water level to changes in barometric pressure was briefly described in the previous sections but is more completely explained in this section. Three characteristic cases by which the water level in a well may respond to changes in barometric pressure have been described in the literature: an unconfined aquifer case, a confined aquifer case, and a wellbore storage or skin effects case. Rasmussen and Crawford (1997) provided characteristic well water-level response curves to a step change in barometric pressure for the unconfined, confined, and wellbore storage cases. These response curves are shown in Figure 2. Spane (2002) provided similar curves for both well water-level response and total head response and extended the wellbore storage case to include skin effects.

As discussed previously for the unconfined aquifer case, a step decrease in barometric pressure would propagate instantaneously through the open wellbore but would be transmitted slower through the vadose zone to the water table due to airflow resistance in the vadose zone. This causes an immediate water-level increase in the well to maintain the equilibrium of total head between the well and the aquifer. As the decline in barometric pressure migrates through the vadose zone and reaches the water table, the total head in the aquifer will slowly decrease. The well water level will respond by decreasing slowly so as to maintain the total head equilibrium. This process will continue until the barometric pressure decrease is fully transmitted to the water table, at which time the well water level will have returned to its original position. Thus, the characteristic well water-level response curve for an unconfined aquifer demonstrates a time-lag dependence on a barometric pressure change: an immediate response to the barometric pressure change is followed by a slow return to the original water level (Figure 2). The rate at which the water level recovers depends on the vertical pneumatic diffusivity of the vadose zone, which depends on the intrinsic permeability of the vadose zone, the soil gas properties, and the vadose zone thickness.

Figure 2. Characteristic Well Water-Level Responses to an Instantaneous One Unit Change in Barometric Pressure (after Rasmussen and Crawford 1997).



It was also discussed previously that for a confined aquifer, a step decrease in barometric pressure would propagate instantaneously through the wellbore as well as to the aquifer, and the well water level would respond according to the barometric efficiency. There is no time-lag dependence associated with this response. The barometric pressure change will slowly migrate through the overlying sediments to the confining unit, but this merely changes the manner in which the load is transmitted to the aquifer; the total load due to the barometric pressure decrease does not change. Thus, the characteristic well water-level response curve for a confined aquifer consists of a constant response equal to the barometric efficiency (Figure 2).

The third case is that of wellbore storage or skin effects. Wellbore storage is a function of the well volume and aquifer characteristics and refers to the ease (or difficulty) by which water can move between the well and the aquifer through the well screen and filter pack. Well skin refers to the altered formation around the wellbore damaged during the well installation process, and which has different hydraulic properties than the surrounding undamaged formation. Wellbore storage or skin effects act to delay the equilibration of total head between the aquifer and the well. Figure 2 shows a theoretical water-level response associated with wellbore storage effects. The initial response is no water-level change followed by a slowly changing water level over time in response to a step change in barometric pressure. A skin effects response would be similar. The wellbore storage or skin effects response does not constitute a stand-alone case, but instead modifies the ideal response of either the unconfined or confined cases.

As stated by Rasmussen and Crawford (1997), "The effects of barometric pressure on water levels can be used diagnostically to identify whether an aquifer is confined or unconfined, whether borehole storage or skin effects are significant, or to determine the air [vertical pneumatic] diffusivity of the unsaturated zone near the well." This is accomplished by analyzing a time series of well water-level elevations and barometric pressure data to determine the water-level response to a step change in barometric pressure. This response curve is then compared with the characteristic response curves in Figure 2 to determine whether an aquifer is confined or unconfined and to assess wellbore storage or skin effects.

As stated previously, even though total head is the parameter that governs groundwater flow, hydraulic head (as observed in wells) is typically used to determine the hydraulic gradient and groundwater flow direction with the assumption that it is directly proportional to total head. However, as stated by Spane (2002), this assumption may not be realistic in areas exhibiting variable vadose zone characteristics. For an unconfined aquifer, changes in the vertical pneumatic diffusivity of the vadose zone across a study area results in different barometric response characteristics for different wells. Thus, the relationship between hydraulic head in a well and total head in the aquifer may vary from well to well. In addition, the barometric pressure may change during the time in which the measurements are being collected, and this would introduce more variability into the data. Furthermore, variable pneumatic diffusivities will lead to differences in total head across a study area in response to barometric pressure changes. This may produce measurable, temporal changes in groundwater flow conditions, particularly in low-gradient areas. Therefore, to determine long-term, average groundwater flow conditions, the effect of barometric pressure fluctuations may need to be accounted for. This is accomplished by determining the barometric response function for each well and using that response to remove the effects of barometric pressure changes from the water-level data.

2.4 DETERMINATION OF BAROMETRIC RESPONSE FUNCTIONS

The first step in determining a well-specific barometric response function is to determine the quantitative relationship between total head and barometric pressure. This is accomplished using multiple regression on time-series measurements for total head and barometric pressure. The regression equation is given by Rasmussen and Crawford (1997) as:

$$H_{tot}(t) = \beta_0 + \beta_1 t + \Delta u_0 B(t) + \Delta u_1 B(t-1) + \ldots + \Delta u_n B(t-n) \qquad \text{(Equation 14)}$$

where $H_{tot}(t)$ is the total head (L) at time t, β_0 is the offset coefficient (L), β_1 is the linear trend coefficient (L/T), Δu_n are the barometric response coefficients for time lags of 0 to n (L/L), and $B(t - n)$ are the barometric pressure measurements for time lags of 0 to n expressed as equivalent freshwater heads (L). Once the barometric response coefficients are determined, the response function to an instantaneous unit change in barometric pressure is found using the following equation (Rasmussen and Crawford 1997):

$$u(\tau) = \sum_{i=0}^{\tau} \Delta u_i \qquad \text{(Equation 15)}$$

where u is the total head response to an instantaneous unit change in barometric pressure as a function of the time lag (τ). Thus, for a time lag of zero, $u(0) = \Delta u_o$; for a time lag of one, $u(1) = \Delta u_o + \Delta u_1$, and so on. The well water-level response is $1 - u(\tau)$. The maximum time lag (n) is chosen such that the total head response curve (for an unconfined aquifer) goes to one (or the well water-level response curve goes to zero).

2.5 REMOVAL OF BAROMETRIC PRESSURE EFFECTS

Barometric pressure does not change in discrete steps, but instead varies continuously. The total head (or well water level) also varies continuously in response to barometric pressure variations. The relationship between total head and barometric pressure is expressed using a convolution integral:

$$\Delta H_{tot}(t) = \int_{\tau=0}^{t} u(\tau) \cdot B(t-\tau) d\tau \qquad \text{(Equation 16)}$$

where ΔH_{tot} is the change in total head from an arbitrary starting time of $t = 0$, and τ is the time lag between a differential barometric pressure change and the associated total head response. This equation essentially applies the barometric response function to each differential change in barometric pressure (i.e., the barometric pressure change over an infinitesimally small time step) and sums the results to compute the net change in total head for a particular time. Since the barometric response function (u) is empirically derived and the barometric pressure (B) varies arbitrarily with time, there is no analytical solution to Equation 16 and this integral must be analyzed numerically. The following equation is a numerical approximation of Equation 16 (modified from Rasmussen and Crawford 1997):

$$\Delta H_{tot}(t) = \sum_{\tau=0}^{n} u(\tau) \cdot \Delta B(t-\tau) \qquad \text{(Equation 17)}$$

where n is the chosen maximum time lag and ΔB is the change in barometric pressure (equivalent freshwater head) over successive time steps. Equation 17 is used to determine the change in total head (or well water level) in response to a time series of barometric pressure changes. The change in total head can then be subtracted from the observed total head values (i.e., deconvolved) to produce a time series of total heads where barometric pressure effects have been removed (i.e., the time series of total head that would have occurred if the barometric pressure were constant). This technique of analyzing and removing barometric pressure effects is known as multiple regression/deconvolution.

3.0 METHODOLOGY

The multiple regression/deconvolution technique described above was used to assess barometric pressure fluctuations at the LERF monitoring wells. Four of the seven wells used for the trend-surface analysis in PNNL-14804 have since gone dry (299-E26-9, 299-E34-3, 299-E34-7, and 299-E25-2), and one well (299-E27-10) is in a radioactive contamination area. Thus, only wells 299-E26-10 and 299-E26-11 were available for this study. Well 299-E26-10 is a downgradient LERF monitoring well screened across the water table to approximately 0.5 m into the uppermost basalt flow, the Elephant Mountain basalt. The aquifer thickness at well 299-E26-10 (from the water table to basalt) is only 0.9 m. Well 299-E26-11 is an upgradient well with a 1.7-m screen entirely within the Elephant Mountain basalt flow top. The water level occurs 1.0 m above the top of the screen.

Wells 299-E26-10 and 299-E26-11 were instrumented with pressure transducers and data loggers to collect a time series of well water-level elevations. Data collection began on April 12, 2007, at hourly intervals and continued until the end of July 2007. Manual water-level measurements were taken periodically to assess transducer accuracy. Hourly barometric pressure measurements were obtained from Pacific Northwest National Laboratory for the 200 East Area meteorological tower (station #6), located in the northeastern portion of the 200 East Area. The pressure transducer measurements were collected at the top of each hour to coincide with the barometric pressure measurements.

The water-level barometric response function for each well was calculated using Equations 14 and 15 with 1-hour time steps after converting the barometric pressure measurements to equivalent freshwater heads. The response functions were initially calculated using the time-series data from April 15, 2007, through May 30, 2007. However, after removing the barometric effects from the water-level data, it was found that temporal fluctuations were evident in the water levels for well 299-E26-10 during April, and the water-level data had shifted by approximately 0.02 m on May 7, 2007. In addition, small water-level data shifts were also noted for well 299-E26-11 on April 23, 2007, and again on June 25, 2007. These shifts may be due to a slight repositioning of the transducers in the wells. The final barometric response functions were computed using the time-series data from May 15, 2007, through June 24, 2007, to avoid any effect the temporal fluctuations or data shifts may have on the response curve results.

Prior to performing the multiple-regression analysis using Equation 14, a linear regression was performed on the water-level elevation data over the May 15, 2007, to June 24, 2007, time period for each well. The results showed water-level decline rates of 0.08 m/yr for well 299-E26-10 and 0.17 m/yr for well 299-E26-11. Using these rates, the water-level data were detrended prior to calculating the total head values used in Equation 14. Linear regression was also performed on the barometric pressure data, but no significant trend was found. The detrended water-level elevations were then added to the observed barometric pressures to obtain the total head time series used in Equation 14. By using detrended water-level elevations with no trend observed in the barometric pressure data, the linear trend coefficient (β_1) in Equation 14 was essentially zero.

The barometric response functions were calculated using Equation 15. Experimentation with different lag times showed that 60 hours was sufficient to represent the response functions. An assessment of the confined or unconfined nature of the aquifer and the significance of wellbore storage or skin effects was then made by comparing the response functions to the characteristic functions shown in Figure 2. Finally, Equation 17 was employed, using 1-hour time steps, to remove the barometric pressure effects from all the transducer data allowing for a comparison between the corrected and uncorrected well water-level elevations.

4.0 RESULTS AND DISCUSSION

The time series of well water-level elevations and barometric pressures for wells 299-E26-10 and 299-E26-11 (shown in Figures 3 and 4, respectively) indicate that water levels in both wells respond to changes in barometric pressure (i.e., declines in pressure correlate with increases in well water-level elevation, and vice versa). Long-term temporal trends are evident in the water-level data. At well 299-E26-10, the water level appears to be slowly declining through the end of June, followed by an increasing trend during July. The overall trend at well 299-E26-11 is

a decline with no increasing trend distinguishable during July. It is also apparent that the water-level fluctuations are larger in well 299-E26-11 than in well 299-E26-10. The barometric pressure fluctuated over a range of 0.23 m (equivalent freshwater head) during the study period, while the well water-level elevations fluctuated over ranges of 0.05 m for well 299-E26-10 and 0.08 m for well 299-E26-11.

The calculated barometric response function for well 299-E26-10 (Figure 5) ranges from approximately 0.2 for short time lags to less than 0.05 at 60 hours. This response function does not agree very well with the theoretical curves shown in Figure 2. The decline in the response function over time, approaching zero, is indicative of an unconfined aquifer response. However, the response for short time lags is nowhere near unity. This observation might be interpreted as being due to significant wellbore storage or skin effects, which would act to delay the well water-level response to changes in barometric pressure. If this were the case, however, the initial response should be an increase at the short time lags transitioning later into a decline. In addition, PNNL-14804 reported on detailed hydrologic testing conducted in this well and no mention was made of wellbore storage or skin effects being present, even though the methodology employed should have detected such effects. It was noted that this well rapidly recovers from a slug withdrawal test (90% recovery within 7 seconds), which is inconsistent with the presence of significant wellbore storage or skin effects.

Figure 3. Time Series of Well Water-Level Elevations at Well 299-E26-10 and Barometric Pressure in the 200 East Area, Spring and Summer 2007.

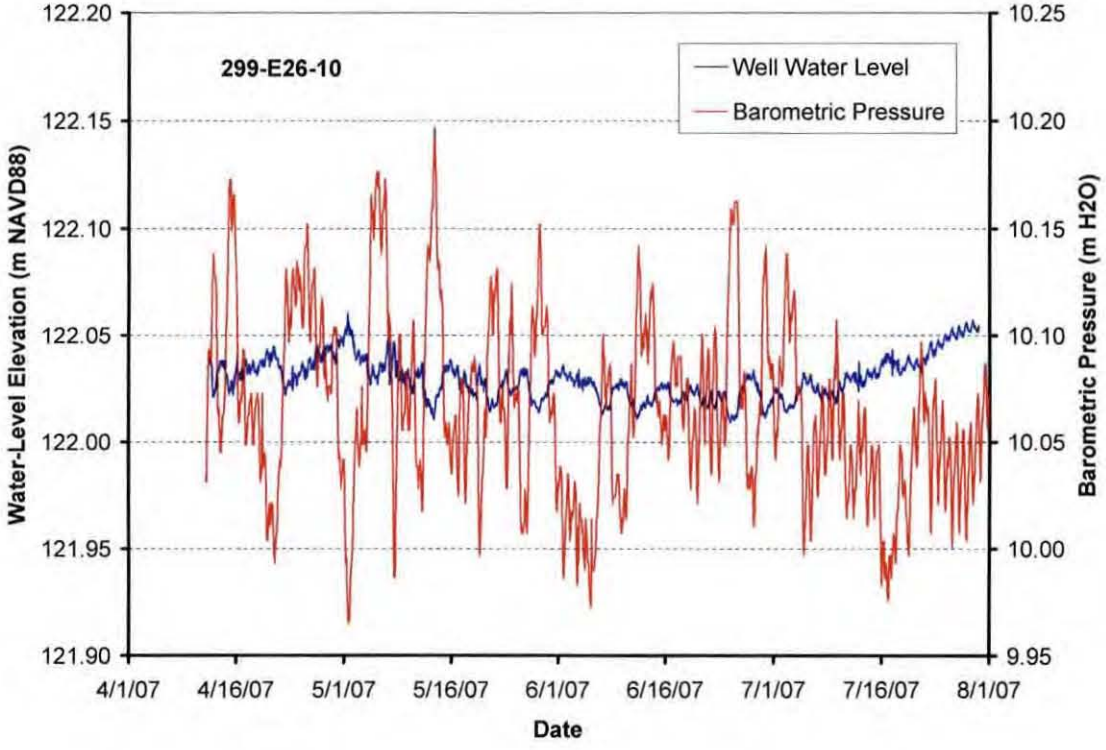


Figure 4. Time Series of Well Water-Level Elevations at Well 299-E26-11 and Barometric Pressure in the 200 East Area, Spring and Summer 2007.

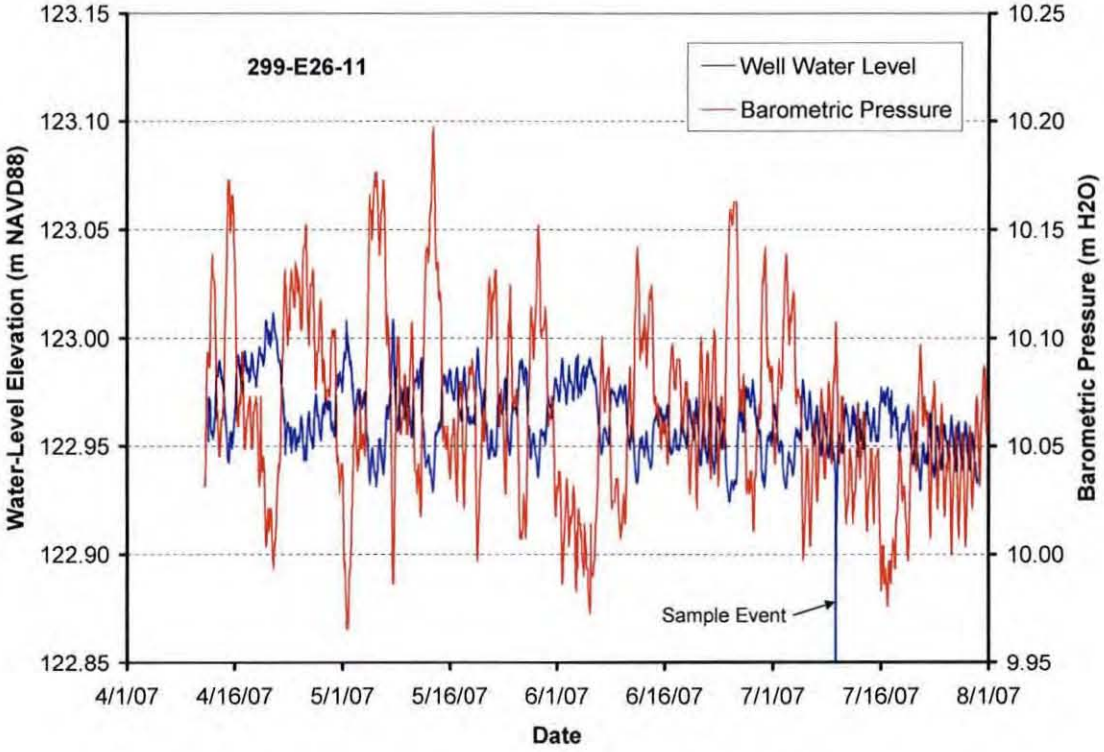
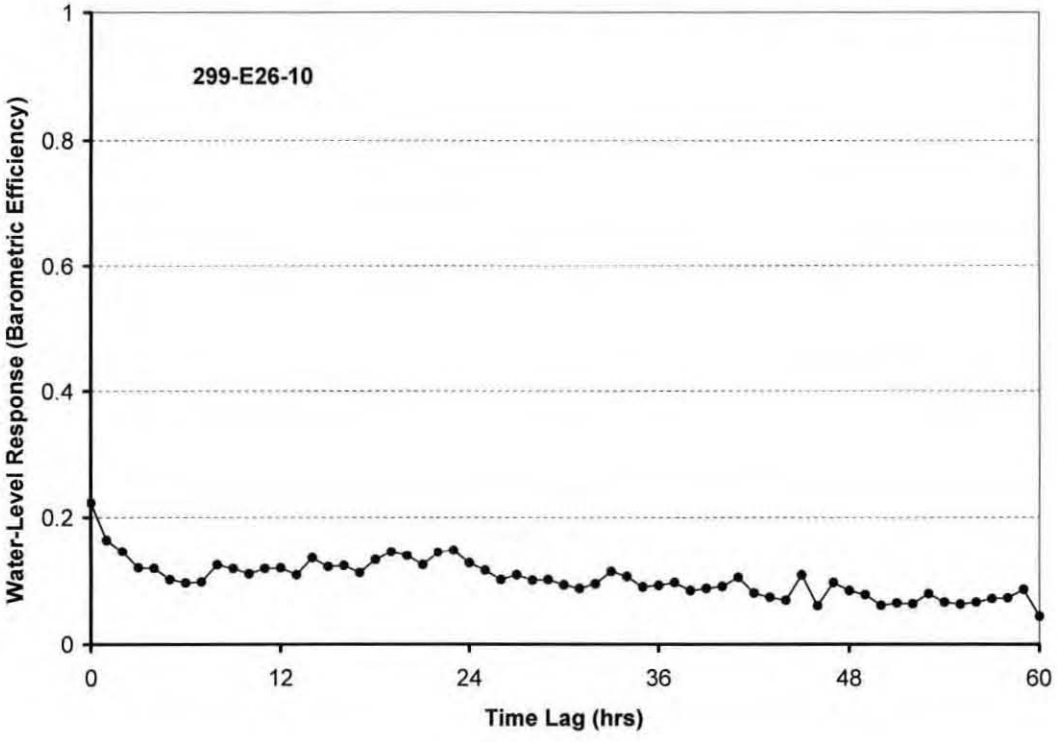


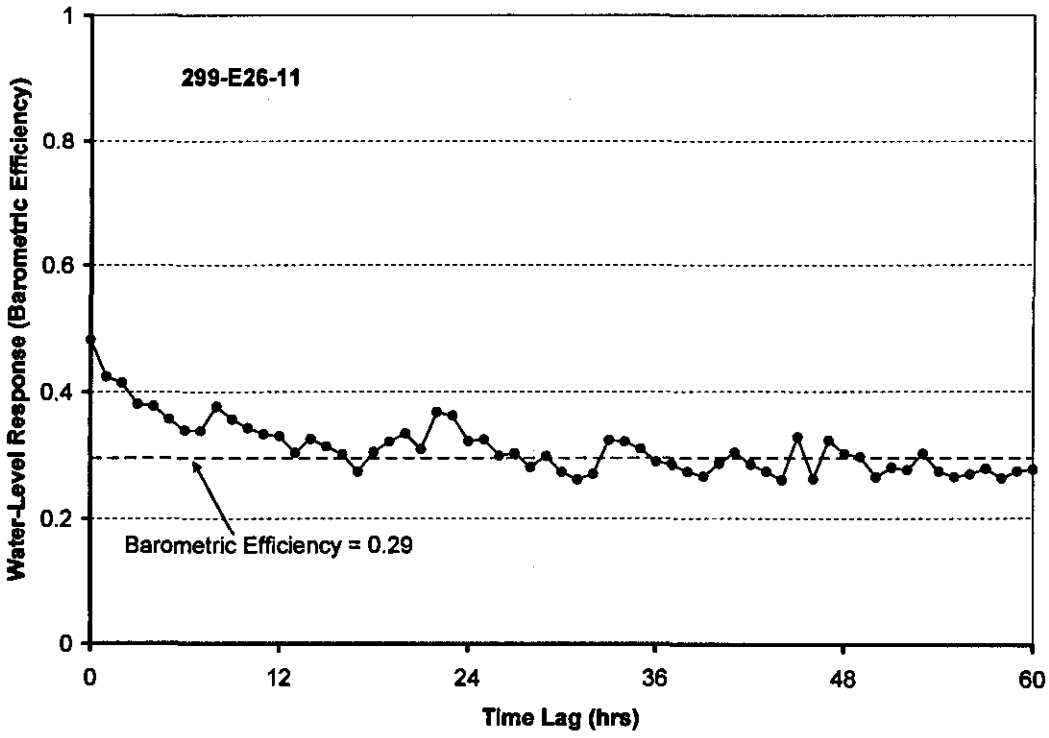
Figure 5. Water-Level Barometric Response Function for Well 299-E26-10.



The most likely explanation for the initial small barometric response at well 299-E26-10 is that changes in atmospheric pressure are being propagated quickly from the wellbore to the vadose zone through the unsaturated portion of the well screen above the water table (F. A. Spane, personal communication). Well 299-E26-10 has a 4.8-m screen, but the aquifer is adjacent to only the lower 1.4 m. Thus, most of the well screen is adjacent to the unsaturated sediments above the aquifer. This allows the wellbore to act as a short circuit for the transmission of the barometric pressure change to the vadose zone. In this case, a unit change in barometric pressure results in less than a unit difference in air pressure between the wellbore and the vadose zone above the water table immediately surrounding the well, which leads to a smaller initial water-level change.

The barometric response function for well 299-E26-11 (Figure 6) shows a decline from approximately 0.5 to approximately 0.3 during the first 12 hours and then remains relatively constant thereafter. This response also does not agree precisely with the theoretical curves in Figure 2. However, since the response function does not approach zero, it is clear that the aquifer at this location occurs under confining conditions. This conclusion is supported by observations of the well water level made during drilling in 1990. Water was first encountered beneath a mud layer and the water level then rose approximately 2.4 m up the borehole, indicating that the water was under pressure. The borehole log recorded by the well site geologist indicated that "the aquifer may be partially confined" (*Borehole Completion Data Package for the Liquid Effluent Retention Facility* [WHC-MR-0235]). Over the interval from 12 to 60 hours, the response curve averages 0.29, which is interpreted to be the long-term barometric efficiency.

Figure 6. Water-Level Barometric Response Function for Well 299-E26-11.



The initial decline in the response function at well 299-E26-11 is opposite to what would be expected if wellbore storage or skin effects were significant; this would result in an initial increase in the response function. The best explanation for the decline is that the aquifer is a leaky confined aquifer (F. A. Spane, personal communication). For a leaky confined aquifer, the confining layer is much less permeable than the aquifer material, but not impermeable (Freeze and Cherry 1979). As with a confined aquifer, the stress due to the atmospheric pressure change propagates immediately to the aquifer confining unit through the vadose zone skeleton. Some of this stress is borne by the aquifer skeleton and some by the aquifer water. In a leaky confined aquifer, however, some of the load due to the pressure change is eventually transferred from the aquifer skeleton to the water, once the pressure change migrates through the pore space of the leaky confining layer. This results in a decline of the barometric efficiency over time (recall that barometric efficiency is a direct measure of the amount of the total stress change borne by the aquifer skeleton).

Equation 17 was used to remove the effects of barometric pressure fluctuations from the time series of well water-level elevations (when applying this equation to well 299-E26-11, the response function was assumed to continue indefinitely beyond 60 hours at a constant value of 0.29, the long-term barometric efficiency). The results show features of the data that were not evident otherwise. For well 299-E26-10, a 0.02-m shift in the transducer measurements on May 7, 2007, is evident in the corrected water levels, but is masked by barometric pressure fluctuations in the original measurements (Figure 7). The corrected water levels for well 299-E26-10 show an increasing trend during late April and early May, followed by a slow decline through June, and then an increasing trend of about 0.04 m during July. Previous work has shown that the water-table elevation in the 200 East Area responds to effluent discharges at the Treated Effluent Disposal Facility (TEDF) (located about 3 km southeast of the LERF) and may also respond to long-term changes in Columbia River stage (*The 2002-2003 Fluctuation of the Water-Table Elevation in the 200 East Area and Vicinity: Evaluation of Potential Causes* [PNNL-SA-49780]). Discharges to the TEDF were significantly higher during June 2007 than in previous months, which likely explains the increasing water-level trend observed during July.

Similar features are visible in the corrected water levels for well 299-E26-11 (Figure 8). A 0.02-m shift in the transducer data occurred on April 23, 2007, which was not apparent in the original water levels. Another shift in the data of about 0.01 m occurred on June 25, 2007. From late April to early May, the water-level trend is stable. This is followed by a declining trend throughout the remainder of the study period. The increasing water-level trend during July at well 299-E26-10 was not seen at well 299-E26-11.

No attempt was made to estimate the vertical pneumatic diffusivity of the vadose zone at the LERF. More theoretical work is needed to address the water-level barometric response characteristics for wells screened across the water table or completed in leaky confined aquifers, before the response functions from such wells could be used to determine the vertical pneumatic diffusivity.

Figure 7. Water-Level Elevations in Well 299-E26-10 Before (Blue) and After (Green) Removal of Barometric Pressure Effects.

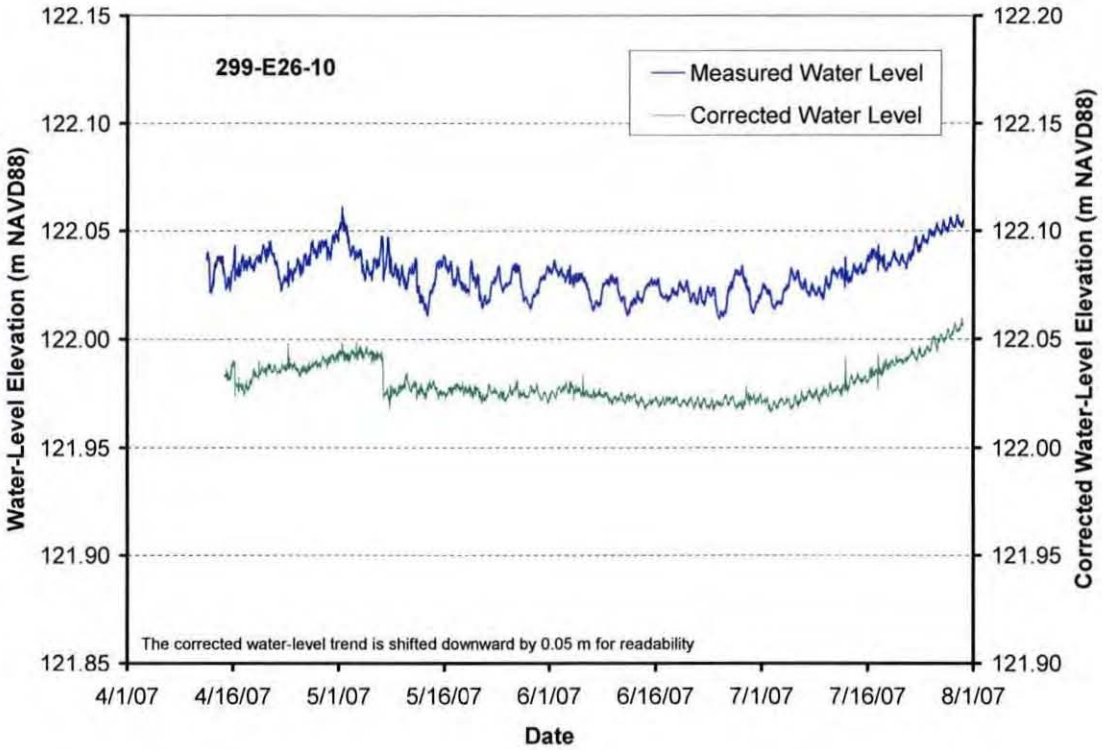
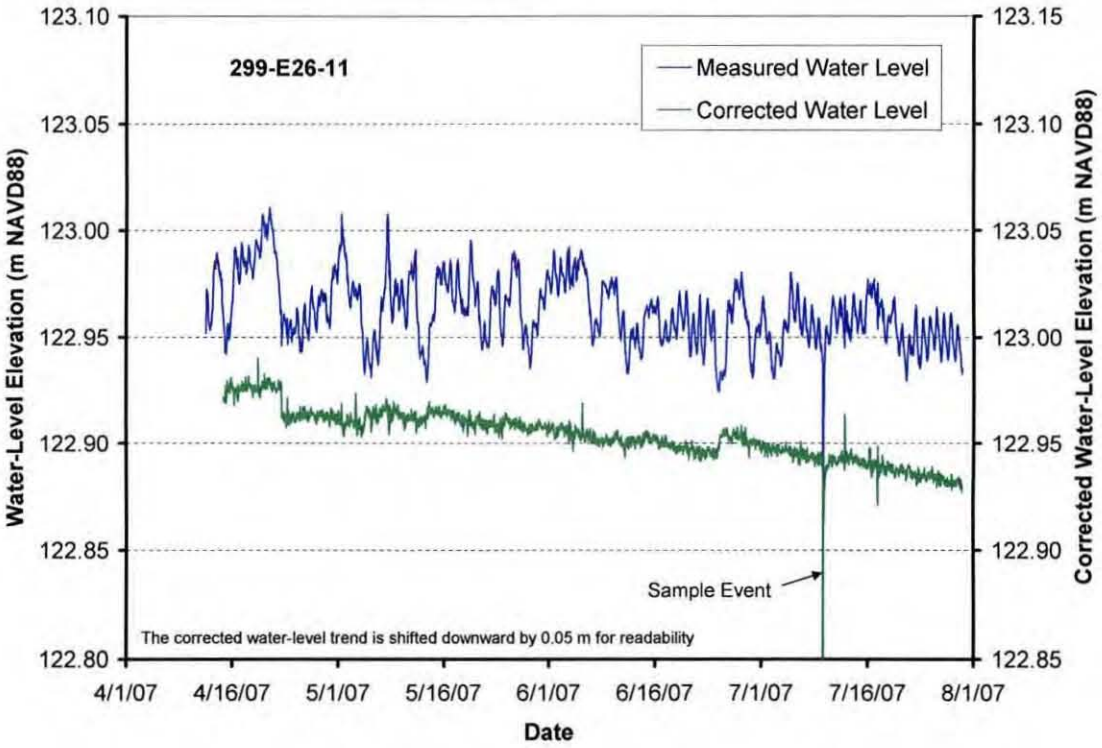


Figure 8. Water-Level Elevations in Well 299-E26-11 Before (Blue) and After (Green) Removal of Barometric Pressure Effects.



4.1 POTENTIAL EFFECTS OF BAROMETRIC PRESSURE FLUCTUATIONS ON THE TREND-SURFACE ANALYSIS

As previously described in Section 1.0, a trend-surface analysis was performed on water-level elevations collected from seven wells in the LERF vicinity between 1997 and 2003 to determine the magnitude and direction of the hydraulic gradient (PNNL-14804). Two wells were found to have a significant effect on the trend-surface results: well 299-E34-7, which is suspected to be significantly deviated from vertical; and well 299-E26-11, which has a water-level elevation approximately 1 m higher than the other wells. Two hydraulic gradient results were presented in Section 1.0, one including well 299-E26-11 (gradient of 9.5×10^{-4} at 257 degrees azimuth) and one without this well (gradient of 1.1×10^{-4} at 243 degrees azimuth). Both results excluded well 299-E34-7.

Barometric pressure fluctuations are not expected to have affected the trend-surface result that included well 299-E26-11. The range of water-level elevation response to barometric pressure changes was found to be approximately 0.05 m in well 299-E26-10 and approximately 0.08 m in well 299-E26-11. This variability is much smaller than the 1-m water-level elevation difference observed between well 299-E26-11 and the other wells used in the trend-surface analysis. Thus, differences in the well water-level elevations of up to 0.08 m between wells will not affect the trend-surface results. This conclusion assumes that the variability observed in wells 299-E26-10 and 299-E26-11 is representative of the other wells used in the trend-surface analysis. Time-series water-level elevation measurements for 10 wells at Low-Level Waste Management Area 1 (located in the northwest corner of the 200 East Area) indicate a variability of 0.05 to 0.10 m, which closely matches the variability observed at the LERF. This conclusion is also supported by the results in PNNL-14804, where trend-surface analyses were performed separately on seven sets of water-level measurements (when including well 299-E26-11) with very consistent results (the standard deviation of the gradient direction was only 3.5 degrees and the standard deviation of the gradient magnitude was more than an order of magnitude lower than the average).

The trend-surface analysis result that excluded well 299-E26-11 may have been affected by barometric pressure fluctuations. The reported gradient was 1.1×10^{-4}, and the wells used to obtain that result are approximately 500 m apart in the downgradient direction. This results in a water-table elevation difference across the study area of 0.06 m, which is within the range of variability observed in the time-series water-level data. In addition, there was much greater variability in the trend-surface results when omitting well 299-E26-11 from the analysis. The trend-surface analysis was performed on four data sets, and the gradient direction ranged from 192 to 257 degrees azimuth with a standard deviation of 35.1 degrees, and the standard deviation of the gradient magnitude differed from the average by less than a factor of two (PNNL-14804). This variability could well have been caused, at least in part, by barometric pressure fluctuations.

Two characterization wells are planned to be installed at the LERF during fiscal year 2008. If these wells are completed as monitoring wells, they would then be available for use in performing another trend-surface analysis to confirm the results of PNNL-14804. It is recommended that a barometric response analysis be performed on the new wells and barometric effects be removed from the water-level data prior to performing the trend-surface analysis. This would enable a more direct determination of long-term average groundwater flow conditions (Spane 2002).

5.0 CONCLUSIONS

The water-level elevation in wells 299-E26-10 and 299-E26-11 at the LERF respond to changes in barometric pressure. The variability in well water-level elevations was found to be approximately 0.05 m at well 299-E26-10 and approximately 0.08 m at well 299-E26-11. The water-level barometric response function for well 299-E26-10 indicated that the aquifer is unconfined. However, the water-level response is subdued in this well because the unsaturated portion of the well screen above the water table acts to quickly equilibrate air pressure differences between the atmosphere and the vadose zone surrounding the well.

The water-level barometric response function for well 299-E26-11 demonstrated that the aquifer in the Elephant Mountain flow top at this location occurs under confining conditions. Furthermore, the specific shape of the response function suggests that the aquifer may be best described as a leaky confined aquifer. The long-term barometric efficiency for this well was found to be 0.29.

The trend-surface results in PNNL-14804 that included well 299-E26-11 in the analysis were not affected by barometric pressure fluctuations because the variability in the well water-level elevations is much smaller than the relief of the interpreted water table. Barometric pressure fluctuations probably did contribute to the variability of the trend-surface results when well 299-E26-11 was excluded from the analysis. In this case, the variability of well water-level elevations is approximately the same as the interpreted water-table relief. If this variability differs from well to well due to varying vadose zone characteristics, then accounting for barometric pressure fluctuations may be important when determining groundwater flow conditions at the LERF. If two new characterization wells (due to be installed at the LERF during fiscal year 2008) are completed as groundwater monitoring wells, then another trend-surface analysis can be performed in which barometric fluctuations are accounted for allowing for a more direct determination of long-term groundwater flow conditions.

6.0 ACKNOWLEDGMENTS

Thanks are extended to Frank Spane of Pacific Northwest National Laboratory for his help with the multiple regression/deconvolution technique, for helping to interpret the barometric response functions calculated for the wells used in this study, and for technical review. Thanks are also due to Robert Edrington and Reed Simpson for collecting the water-level data, Michelle Riffe for text processing and editing, and Susan Davis for administrative support.

7.0 REFERENCES

Ecology, 2004, "Liquid Effluent Retention Facility and 200 Area Effluent Treatment Facility, and Approved Modifications," Attachment 34 in *Hanford Facility Resource Conservation and Recovery Act Permit, Dangerous Waste Portion Revision 8*, 04-05-015, Permit No. WA7890008967, Washington State Department of Ecology, Olympia, Washington.

Freeze, R. A., and J. A. Cherry, 1979, *Groundwater*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

Hubbert, M. K., 1940, "The Theory of Ground-Water Motion," in *Journal of Geology* 48(8):785-944.

Jacob, C. E., 1940, "On the Flow of Water in an Elastic Artesian Aquifer," in *Transactions of the American Geophysical Union* (21):574-586.

PNNL-13078, 1999, F. A. Spane, Jr., *Effects of Barometric Fluctuations on Well Water-Level Measurements and Aquifer Test Data*, Pacific Northwest National Laboratory, Richland, Washington.

PNNL-14804, 2004, F. A. Spane, Jr., and D. R. Newcomer, *Results of Detailed Hydrologic Characterization Tests – Fiscal Year 2003*, Pacific Northwest National Laboratory, Richland, Washington.

PNNL-SA-49780, 2006, J. P. McDonald, *The 2002-2003 Fluctuation of the Water-Table Elevation in the 200 East Area and Vicinity: Evaluation of Potential Causes*, Pacific Northwest National Laboratory, Richland, Washington.

Rasmussen, T. C., and L. A. Crawford, 1997, "Identifying and Removing Barometric Pressure Effects in Confined and Unconfined Aquifers," in *Ground Water* 35(3):502-511.

Resource Conservation and Recovery Act of 1980, 42 U.S.C. 6901, et seq.

Spane, F. A., 2002, "Considering Barometric Pressure in Groundwater Flow Investigations," in *Water Resources Research* 38(6):14-1 – 14-18.

Weeks, E. P., 1979, "Barometric Fluctuations in Wells Tapping Deep Unconfined Aquifers," in *Water Resources Research* 15(5):1167-1176.

WHC-MR-0235, 1990, L. A. Doremus and A. W. Pearson, *Borehole Completion Data Package for the Liquid Effluent Retention Facility*, Westinghouse Hanford Company, Richland, Washington.

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