Considering barometric pressure in groundwater flow investigations

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[1] Water level elevation measurements in wells are commonly used as a basis to delineate groundwater flow patterns (i.e., flow direction and hydraulic gradient). Barometric pressure fluctuations, however, can have a discernible impact on well water levels. These barometric effects may lead to erroneous indications of hydraulic head within the aquifer. Total hydraulic head within the aquifer, not well water level elevation, is the hydrologic parameter for determining groundwater flow direction and hydraulic gradient conditions. For low-gradient, unconfined aquifer sites exhibiting variable vadose zone characteristics (e.g., thickness, pneumatic diffusivity), barometric pressure fluctuations can cause temporal changes in lateral flow direction and flow velocity. Discrete water level measurements used to determine the average or long-term groundwater flow conditions, therefore, may provide nonrepresentative results. Calculation of the barometric response characteristics for individual wells provides the basis to account for the temporal effects of barometric pressure fluctuations from monitor well measurements, so that average, long-term groundwater flow pattern behavior can be determined. *INDEX TERMS:* 1829 Hydrology: Groundwater hydrology; 1832 Hydrology: Groundwater transport; 1833 Hydrology: Hydroclimatology; *KEYWORDS:* barometric efficiency, barometric pressure, unconfined aquifer, confined aquifer, groundwater flow, hydraulic head

1. Introduction

[2] Groundwater flow characterization is important to accurately predict and monitor the migration of groundwater contaminants within hazardous waste locations. Accurate delineation of local groundwater flow direction and hydraulic gradient conditions within study areas of small size and/or having low-gradient conditions, however, can be particularly difficult. Natural external stresses (barometric effects, tidal or river-stage fluctuations, earth tides, tectonic events) can affect the accuracy of well water level measurements and how they are used to determine hydraulic head and to infer groundwater flow conditions within an aquifer.

[3] A number of earlier investigations have addressed these effects on aquifer response and well water level measurements. Examples include those by *Jacob* [1940], *Ferris* [1963], *Bredehoeft* [1967], *Bower and Heaton* [1978], *Hsieh et al.* [1988], and *Erskine* [1991] for confined aquifers and *Weeks* [1979], *Rojstaczer* [1988], *Rojstaczer and Riley* [1990], and *Quilty and Roeloffs* [1991] for partially confined and unconfined aquifer systems. Only recently, however, has the importance of removing external stress effects from water level measurements for wells monitoring shallow, unconfined aquifer systems been recognized for groundwater flow characterization [see *Rasmussen and Crawford*, 1997; *Spane*, 1999]. As will be discussed, external stress effects imposed by barometric fluctuations can have a significant impact on temporal groundwater flow conditions (flow velocity, flow direction) within unconfined aquifers that exhibit low hydraulic gradients and variable vadose zone properties. This is due to the areal variation in transmission of atmospheric pressure to the water table surface, which is part of the total hydraulic head parameter governing groundwater flow.

[4] This study examines the effect of barometric pressure fluctuations primarily within unconfined aquifers. The corrective methods considered, however, are applicable to confined aquifer systems exhibiting variable barometric response characteristics. Specifically, this investigation focuses on (1) effects of barometric pressure fluctuations on well measurements; (2) temporal effects of barometric pressure fluctuations on groundwater flow characteristics in low-gradient areas; and (3) barometric correction methods for determining average, long-term groundwater flow characteristics.

2. Fluid Potential and Hydraulic Head

[5] The relationship between fluid potential and hydraulic head for defining groundwater flow was first described by *Hubbert* [1940] and is commonly presented in textbooks [e.g., *Domenico and Schwartz*, 1997] as

$$\phi = gh. \tag{1}$$

[6] As indicated, fluid potential is equivalent to the product of the height of a well fluid column of known density, above a reference datum z and acceleration due to gravity. In hydrologic investigations the height of the fluid column, h_{fc}, above mean sea level is referred to as hydraulic head H. For groundwater studies, hydraulic head within unconfined and confined aquifers is normally determined by obtaining water level measurements from wells and converting these measurements to hydraulic head values. The

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"observed" hydraulic head H_o obtained from water level measurements can be expressed as

$$H_o = E - D_w, \tag{2}$$

where E is elevation of surface datum from which field measurement is made [L] and D_w is depth from surface datum to the fluid column surface within the monitoring well [L].

[7] In aquifers without significant vertical gradients, point measurements of hydraulic head can be used to construct a potentiometric (hydraulic head) map that represents the areal distribution of hydraulic potential within the aquifer. Potentiometric maps can be used to infer directions of groundwater movement, with flow occurring normal to contours of equal potential or head in systems with isotropic hydraulic conductivity. In situations where well fluid column densities vary significantly within the study area, observed hydraulic heads must be corrected to a reference density fluid prior to use in potentiometric maps. The reference density fluid normally used in hydrologic investigations is water at standard temperature and pressure conditions, with a density equal to $\sim$1.00 g/cm^3 (0.999014 g/cm^3 [*Spane and Mercer*, 1985]). The observed hydraulic head value corrected to this reference density fluid is referred to as a freshwater head, H_{fw} [*Lusczynski*, 1961; *DeWiest*, 1969].

[8] The use of observed and freshwater head for delineating groundwater flow patterns assumes that the atmospheric pressure is uniform over the area of investigation and/or the effects of atmospheric pressure variation (i.e., existing at the aquifer boundary) are insignificant in comparison with areal fluid head variations (i.e., hydraulic gradient) within the aquifer. This requirement of uniformity and relative significance of atmospheric pressure is stated in theoretical discussions pertaining to groundwater flow as presented by *Hubbert* [1940], *Jacob* [1940, 1950], *Toth* [1963, 1978], and *Freeze and Witherspoon* [1966, 1967].

[9] To define groundwater flow conditions more exactly, the atmospheric pressure at the upper aquifer boundary must be applied to the freshwater or observed hydraulic head. The total head H_t can then be expressed as either

$$H_t = H_{fw} + H_a \tag{3}$$

or

$$H_t = H_o + H_a, \tag{4}$$

where H_a is the atmospheric head component [L]. The atmospheric head component can also be calculated as an incremental value referenced to an arbitrary atmospheric pressure standard, P_{std} (e.g., the long-term average for a particular site or the standard 10.333-m atmospheric pressure head at mean sea level).

[10] While potentiometric maps are commonly used to depict steady state or pseudo steady state conditions within an aquifer, transient external stress effects imposed by barometric pressure fluctuations can exert a pronounced effect on field-measured water levels in wells that are used to develop areal, steady state head relationships. These transient effects on well measurements should be characterized and accounted for. This requires the systematic correlation of well water level measurements with observed barometric pressure fluctuations.

3. Barometric Effects Within Well/Aquifer Systems

[11] Barometric fluctuations represent an areal, blanket stress applied directly at land surface and to the open well water level surface. The manner in which a well/aquifer system responds to changes in atmospheric pressure is variable and directly related to the degree of aquifer confinement and hydraulic/storage characteristics of the well/aquifer system. *Rasmussen and Crawford* [1997] identify three conceptual models that describe the response of water level measurements in wells to barometric pressure change. These include an instantaneous well response within confined aquifers, a delayed well response within unconfined aquifers (because of the delayed transmission of barometric pressure through the vadose zone), and a delayed well response associated with well characteristics (i.e., well bore storage and well skin effects).

[12] *Rasmussen and Crawford* [1997] provide a method to distinguish the dominant response model affecting well water level measurements associated with barometric pressure change. Diagnostic plots for the three well response models are shown in Figure 1. The plots show the time lag dependence of each barometric response model associated with a unit step change in atmospheric pressure. The plots were developed by performing multiple-regression analysis of the water level response to the barometric pressure change over the time lag period, as indicated by *Rasmussen and Crawford* [1997]. As shown in Figure 1, each barometric response model has a distinguishing pattern that can be used diagnostically for response-model identification. As might be expected, composite responses can occur between the well bore storage model and either aquifer model. The barometric model patterns indicated in Figure 1 are specifically for open well water level response. Different barometric response relationships would be exhibited if total head were utilized (e.g., using equation (4)) rather than well water level elevation. Figure 2 shows the diagnostic response models for the same conditions examined in Figure 1. As shown, the instantaneous aquifer response pattern for confined aquifers is a function of 1-BE, which contrasts with the well response that is a function of barometric efficiency (BE). For unconfined aquifers, the aquifer response displays a buildup (increasing) pattern, which contrasts inversely with the decreasing well response pattern shown in Figure 1 (unconfined aquifer model). A brief discussion of the relationship between BE and each individual barometric response model is presented in sections 3.1, 3.2, and 3.3.

3.1. Confined Aquifers

[13] For confined aquifers the transmission of atmospheric pressure effects is instantaneous, i.e., to both the well and the aquifer. *Jacob* [1940] was first to define the associated barometric response change in water level within an open well that monitors a confined aquifer as the barometric efficiency:

$$\mathrm{BE} = -\gamma_{fc}(\Delta h_w / \Delta P_a), \tag{5}$$

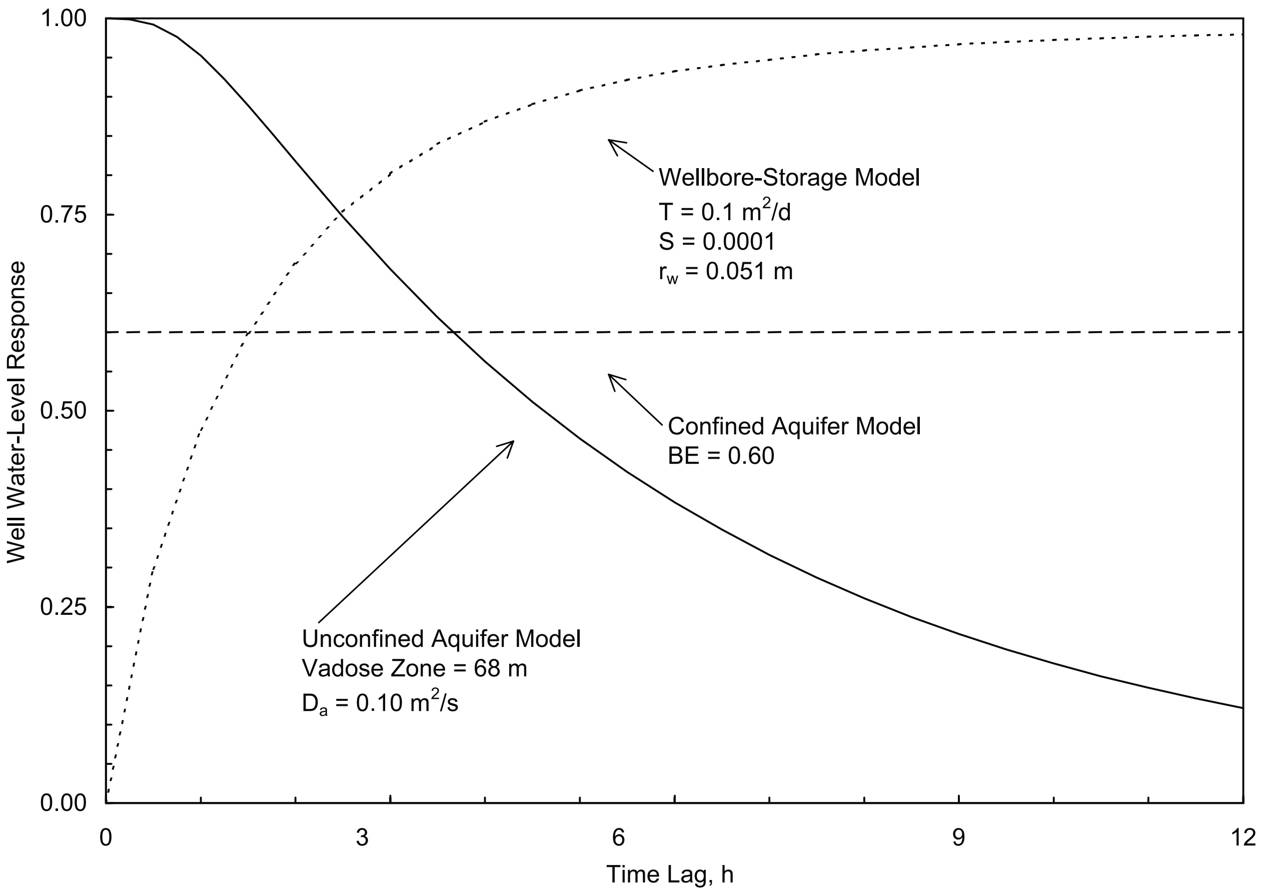

Figure 1. Well barometric pressure response models.

where γ_{fc} is the average specific weight of the fluid column in the well [F/L^3]; Δh_w is the change in elevation of the well fluid column associated with atmospheric pressure change [L]; and ΔP_a is change in atmospheric pressure [F/L^2].

[14] If no significant well bore storage or well skin effects exist, the down-hole pressure (absolute) measured within an open well is in equilibrium with the pressure in the confined aquifer, P_f, at the measurement elevation point. The aquifer pressure responds immediately to atmospheric pressure fluctuations but at a magnitude equal to the atmospheric pressure change minus the pressure change caused by the change in the fluid column elevation within the well [*Spane and Mercer*, 1985]:

$$\Delta P_f = \Delta P_a + \gamma_{fc}\, \Delta h_w \tag{6}$$

or combining with equation (5):

$$\Delta P_f = (1 - \mathrm{BE})\Delta P_a. \tag{7}$$

[15] Equations (6) and (7) indicate that the change in down-hole formation pressure represents only that portion of the atmospheric pressure change not borne by the test formation matrix. Therefore high barometric efficiencies reflect rigid test formations, while low barometric efficiencies indicate highly compressible formations. If an absolute pressure gauge is not used to obtain monitoring well measurements, total head within the aquifer can be calculated by simply adding the incremental change in atmospheric pressure from a reference value to the observed head determined from a well water level measurement.

[16] As noted by *Rasmussen and Crawford* [1997], the diagnostic barometric response pattern for a confined aquifer model is distinguished by a constant well response function for a step in pressure for all time lags (see Figure 1). This constancy in barometric response is attributed to the lack of dependence on lagged barometric response (i.e., barometric effects are applied "instantaneously" both at the well and to the aquifer system).

3.2. Unconfined Aquifers

[17] Although wells monitoring unconfined aquifers commonly respond to barometric pressure fluctuations, different mechanisms are involved than previously described for confined aquifer systems. For an unconfined aquifer the diagnostic well response to barometric pressure change is distinguished by a decreasing response pattern for increasing time lags (see Figure 1). This characteristic response pattern is caused by an imbalance in atmospheric pressure values within the well/aquifer system. This imbalance is associated with the delay in transmitting the atmospheric pressure signal through the vadose zone to the water table surface. *Weeks* [1979] states that the transmission of atmospheric pressure within the vadose zone is a direct function of its vertical pneumatic diffusivity that, in turn, is a function of the vadose zone vertical permeability, moisture content, and compressibility of contained gas. For vadose

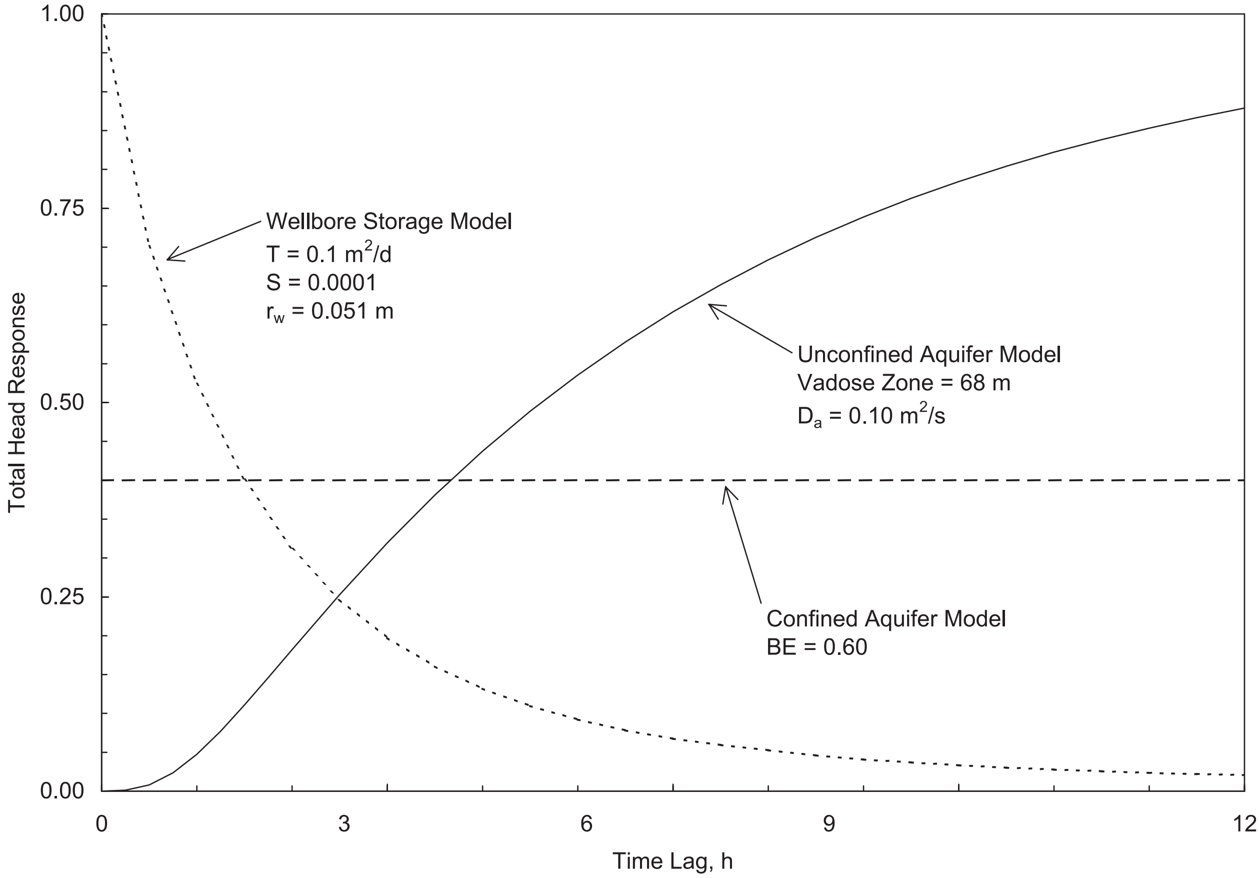

Figure 2. Total head barometric pressure response models.

zones exhibiting low pneumatic diffusivities and/or significant thickness, unconfined aquifer wells will exhibit significant water level fluctuations (i.e., apparently high barometric efficiency values) because of barometric fluctuations. This type of behavior, when viewed versus time (e.g., well water level hydrograph), appears to be very similar to confined aquifer behavior. However, when analyzed diagnostically (as shown in Figure 1) versus lagged time, the unconfined aquifer exhibits a distinctly different response pattern.

[18] To assess the magnitude of barometric effects on well water level elevations and total heads for unconfined aquifers, hourly atmospheric pressure readings measured at the Hanford Site Meteorology Station (Washington State) were examined for 1998. Atmospheric pressure changes are expressed as equivalent change in freshwater head (in meters) for direct comparison with well/aquifer measurements. During 1998 a maximum range in atmospheric pressures of 0.508 m was recorded (9.838–10.346 m of water), with the greatest variability occurring from fall through late spring due to the occurrence of frequent Pacific storms. In contrast, less variability is exhibited during the summer months and is primarily associated with diurnal heating and cooling. The mean 1998 hourly value of 10.061 m is only slightly less than the reported long-term hourly average value of 10.087 m reported by *Hoitink et al.* [1999]. The greatest daily atmospheric pressure change ever observed for the Hanford Site is reported to be 0.35 m, which is slightly less than the 0.47-m maximum daily response reported by *Landmeyer* [1996] for the southeastern United States during a late-winter cyclone event.

[19] Figure 3 shows a comparison of observed July through December 1998 hourly atmospheric pressures and simulated total head and well water level elevations. The simulations are based on the WTAB program [*Weeks*, 1979], an initial total head/water level elevation of 150 m above mean sea level, and vadose zone properties of pneumatic diffusivity, D_a, equal to 0.01 m^2/s and thickness equal to 75 m. As shown, the well water level elevation response, which exhibits considerable variability, is not equal to the total head (or water table elevation). This is due to the imbalance of atmospheric pressure that occurs within the open well versus within the surrounding aquifer. The total head within the unconfined aquifer varies directly by the amount of the atmospheric pressure change reaching the water table, which as discussed previously is a time-delayed process. On the basis of the atmospheric pressure record shown in Figure 3, a maximum well water level fluctuation of 0.454 m and a maximum 0.292-m change in total head would be expected, assuming similar barometric changes to those measured in 1998.

3.3. Well Bore Effects

[20] The discussions pertaining to barometric pressure effects within confined and unconfined aquifer systems assume that no delay occurs in equalization of pressure between the well and aquifer system. In reality, the transmission of the barometric pressure change between the well

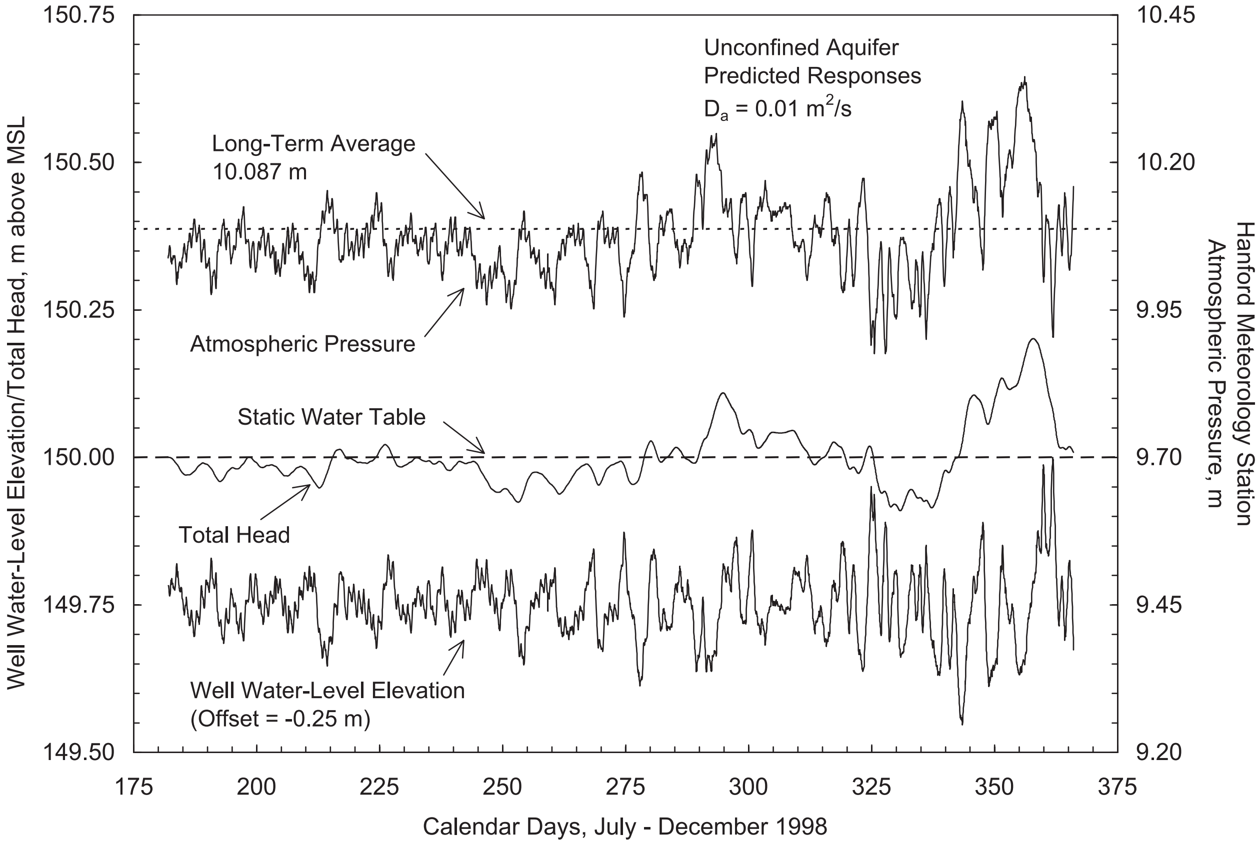

Figure 3. Predicted well water level elevation and hydraulic head response, based on Hanford Site 1998 atmospheric pressure measurements.

and aquifer is delayed because of the time required for movement of a finite volume of water between the well and the surrounding aquifer. This time delay depends on the aquifer properties (i.e., transmissivity, storativity) and existing well/borehole conditions (i.e., well bore storage and well skin effects).

[21] Because of the pressure imbalance between a well and aquifer at the instant of barometric change, previous investigators [e.g., *Furbish*, 1991] have noted that these momentary pressure imbalances can be treated as individual step changes in pressure (i.e., ΔP_a [1-BE]), which are applied at the well. These applied barometric pressure steps can be treated as individual well slug tests, which can be superimposed to provide the combined pressure response transmitted to the aquifer. *Furbish* [1991] and *Rasmussen and Crawford* [1997] used the *Hvorslev* [1951] slug test model to describe this barometric well response, based primarily on aquifer properties. However, because of the limiting assumptions of the Hvorslev model pertaining to well bore storage and elasticity of the aquifer as noted by *Butler* [1998], the analytically based *Cooper et al.* [1967] method can be used more rigorously to describe delayed barometric induced responses caused by well bore storage and/or similar models that account for both well bore storage and well skin effects [*Novakowski*, 1990; *Liu and Butler*, 1995].

[22] Figure 4 shows the diagnostic well response function for a slug test affected by well bore storage (solid lines) for a unit step change in barometric pressure. The predicted slug test/well bore response was calculated using the Kansas Geological Survey slug test model described by *Butler* [1998] and the following aquifer/well properties: transmissivity 0.01, 0.1, 1.0 m^2/d; storativity 0.0001; and well casing radius 0.051 m. As indicated in comparing Figures 1 and 4, the well bore response function is distinctly different than the instantaneous/constant pattern exhibited by a confined aquifer and opposite that exhibited by an unconfined aquifer model. The delayed well bore response is a function solely of the aquifer and well properties, with lower aquifer transmissivity values significantly increasing the delayed nature (time lag) of the well response function. For most common well/aquifer conditions (no skin effects), no observable time lag would be expected for transmissivity values greater than $\sim$10 m^2/d (i.e., >95% of the well bore effect is dissipated within 5 min). Increasing well bore radius and decreasing aquifer storativity also cause increases in time lag.

[23] Well skin/damage effects cause an extension in the time delay associated with well bore storage. This additional delay for the well bore storage/response patterns is also shown in Figure 4 (dashed lines), using a positive skin factor of +6.2. For illustrative purposes, a positive skin of +6.2, based on the standard finite thickness skin relationship presented by *Earlougher* [1977], is equivalent to a damaged zone having a reduced hydraulic conductivity equal to one tenth that of the aquifer, extending an additional well bore radius from the well (r_{skin} = 0.102 m, r_w = 0.051 m).

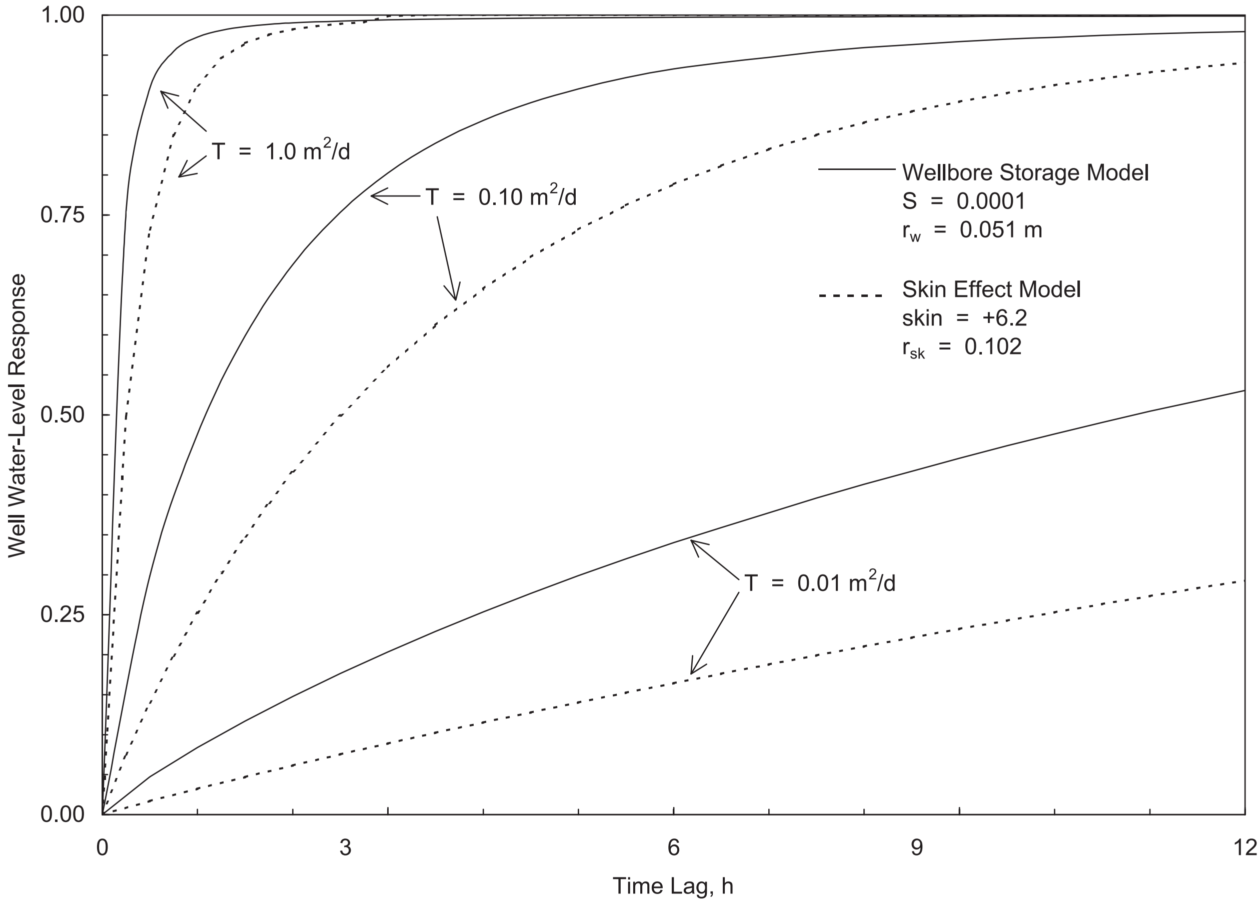

Figure 4. Diagnostic barometric response function for well bore storage and positive well skin model.

[24] In reality, a response pattern based only on well bore storage/skin behavior would not occur without also being associated with either a confined or unconfined aquifer well response. To illustrate a composite well response pattern, the combined well bore storage and confined and unconfined aquifer models are shown in Figures 5 and 6, respectively. The same well bore storage conditions (no skin) in Figure 4 were used in Figures 5 and 6 together with the indicated aquifer and well properties. For such composite models, the initial and early time lag responses follow the well bore storage pattern, transitioning in later time to the appropriate aquifer model.

4. Impact of Barometric Fluctuations in Low-Gradient Areas

[25] The previous discussions demonstrate the differences and the effect of temporal barometric pressure fluctuations on well water level elevation and total head conditions within an aquifer. These differences can have a significant impact on the characterization of groundwater flow within low-gradient areas having variable vadose zone or well/aquifer BE characteristics. For sites exhibiting these conditions, barometric effects may lead to erroneous indications of groundwater flow direction and hydraulic gradient within the aquifer, if corrections of these temporal barometric effects are not made to the well measurements. This is particularly the case for lateral, groundwater flow characterization based on well water level elevations not measured at the same moment in time (i.e., susceptible to temporal barometric effects).

[26] To demonstrate the impact of barometric pressure fluctuations on groundwater flow characterization within low-gradient areas, two unconfined aquifer example simulations are examined. The first examines the "miscalculation" of flow direction and gradient conditions based on well water level elevation measurements obtained at different times in the presence of temporal barometric pressure fluctuations, and the second illustrates temporal variations in actual groundwater flow (based on calculated aquifer head values) imposed by barometric fluctuations and variations in vadose zone characteristics.

[27] The first example is representative of waste management areas located within much larger monitoring facilities, such as the Hanford Site, which encompasses 24 Resource Conservation and Recovery Act of 1976 (RCRA) facilities. At such sites, routine well water level measurement surveys are completed over time and, in most cases, completed over a several-day period. To illustrate the effect of temporal barometric fluctuations on the "miscalculation" of groundwater flow direction and hydraulic gradient, a simple "three-point" problem was examined for hydrologic conditions believed representative of a low-hydraulic-gradient area ($\leq$0.1 m/km). For this example a constant hydraulic gradient of 0.05 m/km was assumed, and a due east groundwater flow direction was selected for ease of flow direction

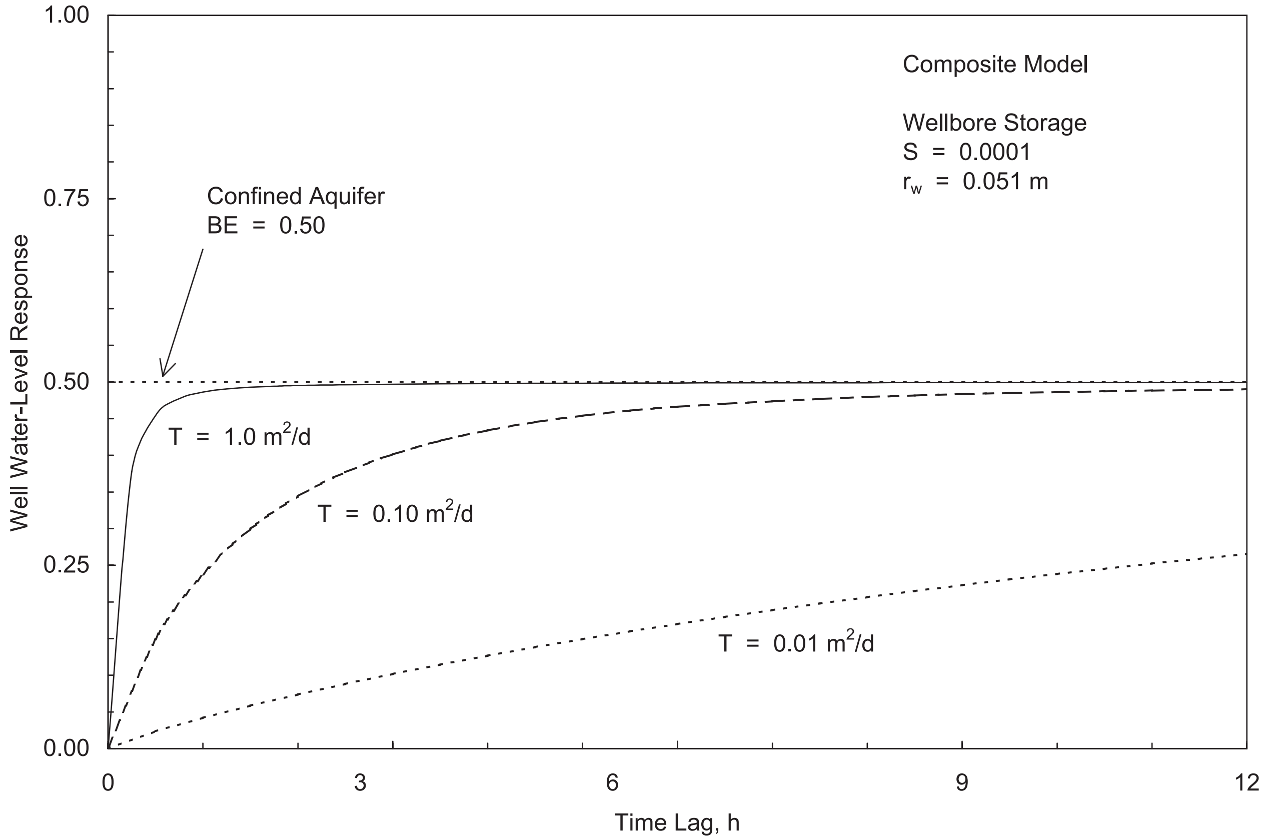

Figure 5. Composite diagnostic response function for well bore storage/confined aquifer model.

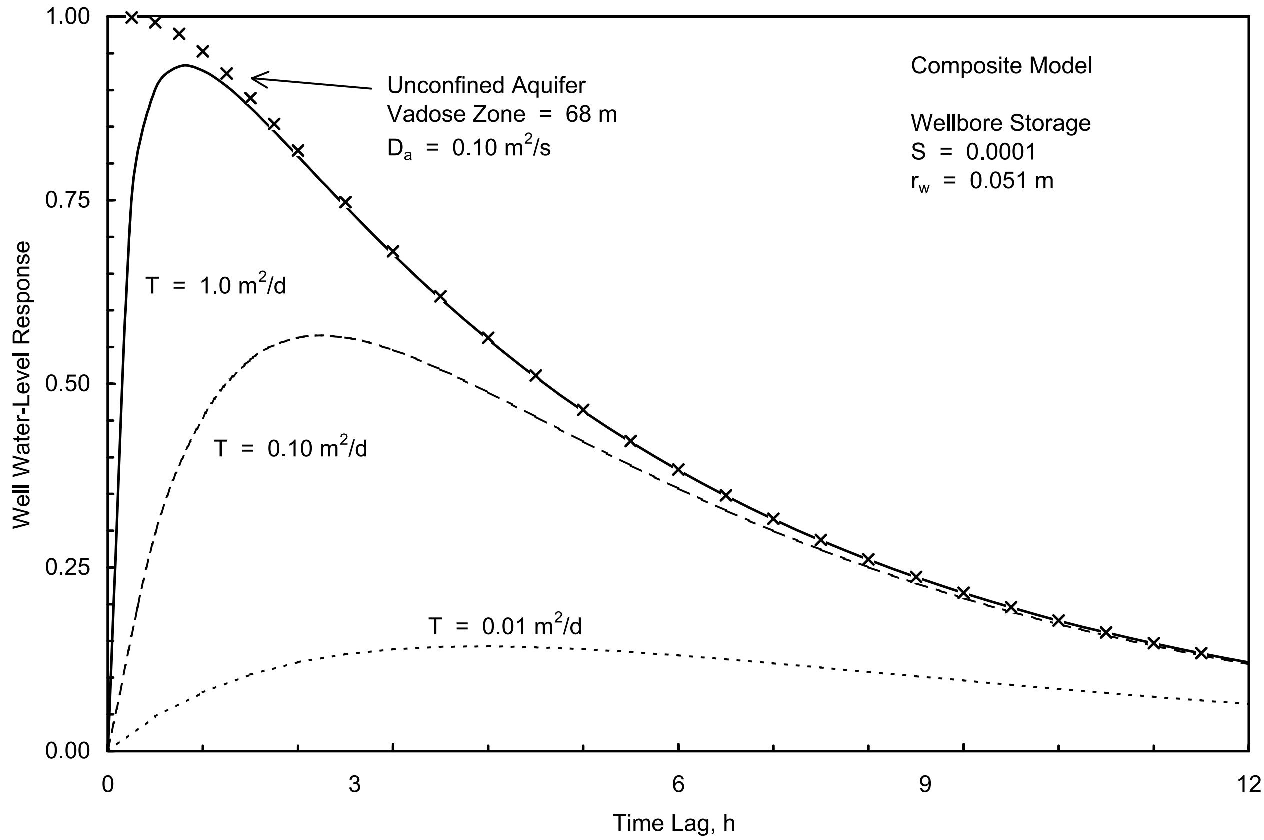

Figure 6. Composite diagnostic response function for well bore storage/unconfined aquifer model.

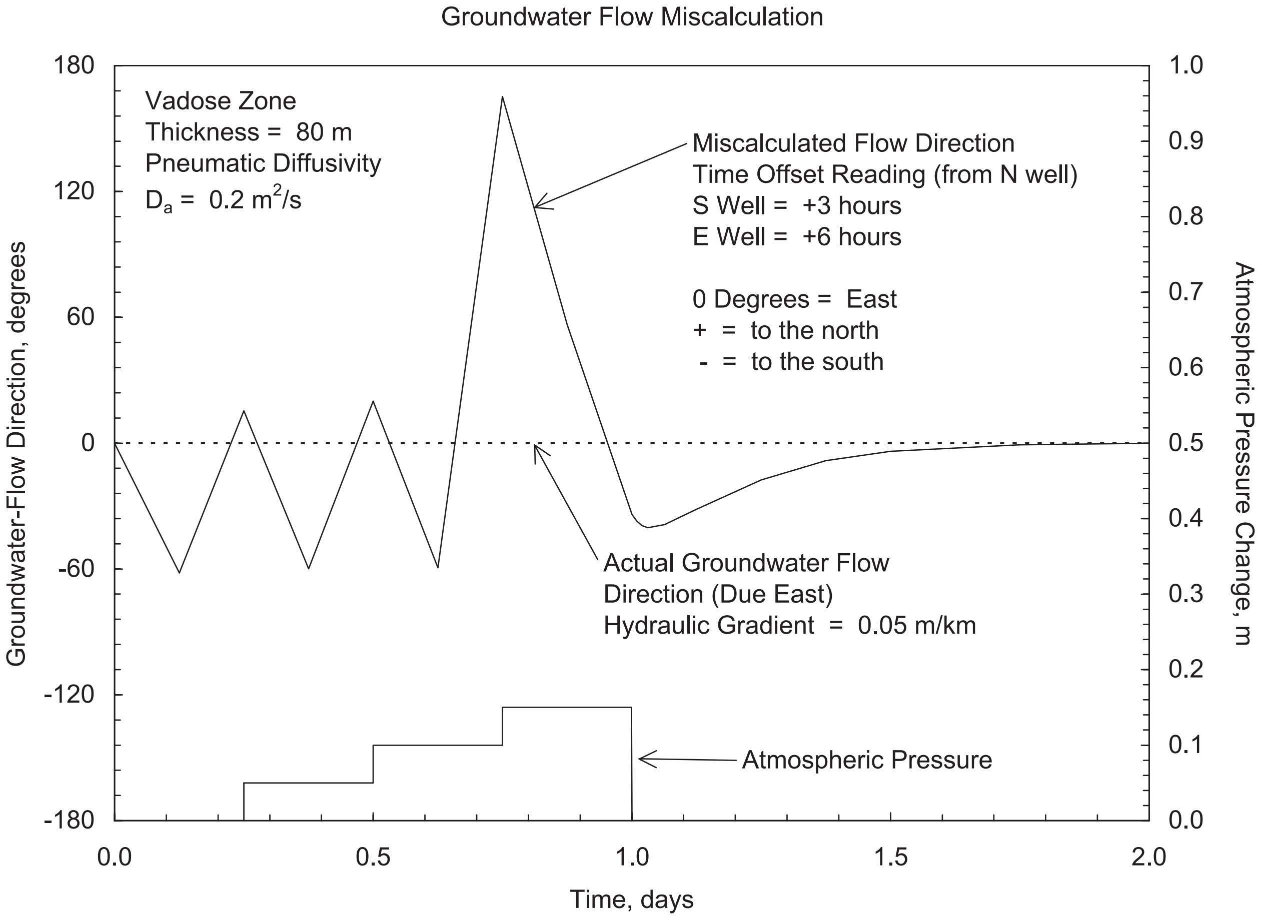

Figure 7. Miscalculation of groundwater flow direction in low-gradient areas using well measurements not collected at the same time.

comparison. The two perimeter wells assigned in the three-point analysis were located 1000 m due north and east, respectively, from the third-central (south) control well location. The well water level elevation response to barometric fluctuations was calculated using the WBAR analytical model described by *Weeks* [1979]. A uniform vadose zone thickness of 80 m and a pneumatic diffusivity of 0.20 m^2/s were assumed for the calculations. The pneumatic diffusivity value is within the upper range commonly reported for vadose zone conditions at the Hanford Site [*Spane*, 1999]. Three incremental atmospheric pressure step changes of +0.05 m were applied in the simulation for the given well/aquifer system, with individual step changes occurring at elapsed times of 0.25, 0.50, and 0.75 days. At an elapsed time of 1.0 day, an atmospheric pressure step of −0.15 m was applied, bringing the net applied barometric pressure back to zero for the given well/aquifer system.

[28] To examine the severity in miscalculating the groundwater flow characteristics, well water level elevations for the central (south) well and the east well were "taken" 3 and 6 hours after the north well, respectively. Figure 7 shows the miscalculated groundwater flow direction from the given due east (zero degrees) condition, while Figure 8 displays miscalculations in hydraulic gradient from the assigned value of 0.05 m/km. As shown for the example, areal well water level elevation measurements obtained at different times during periods of significant temporal barometric pressure fluctuations can produce considerable miscalculations for groundwater flow direction (up to 180 degrees) and hydraulic gradient (within a factor of 4) over actual site conditions. The step change in barometric pressure likely contributes to some of the variability exhibited in the plot figures; however, the relative magnitude of pressure change is well within the maximum daily range recorded at the Hanford Site (e.g., greatest daily barometric pressure of change equal to 0.35 m [*Hoitink et al.*, 1999]). Less variability would have been exhibited if total head measurements were used in this example instead of the observed well water level elevation (i.e., flow direction error ±45°; gradient within a factor of 2.5). However, the example demonstrates that even for low-gradient sites having relatively uniform vadose zone characteristics, considerable error in groundwater flow characterization would occur in well measurements not taken relatively close in time during periods of significant barometric pressure fluctuation.

[29] While the first example illustrates how groundwater flow characteristics can be miscalculated by using areal well water level elevations not measured at the same time, barometric fluctuations can also cause significant temporal variations in actual groundwater flow patterns when vadose zone conditions vary (e.g., thickness, pneumatic diffusivity)

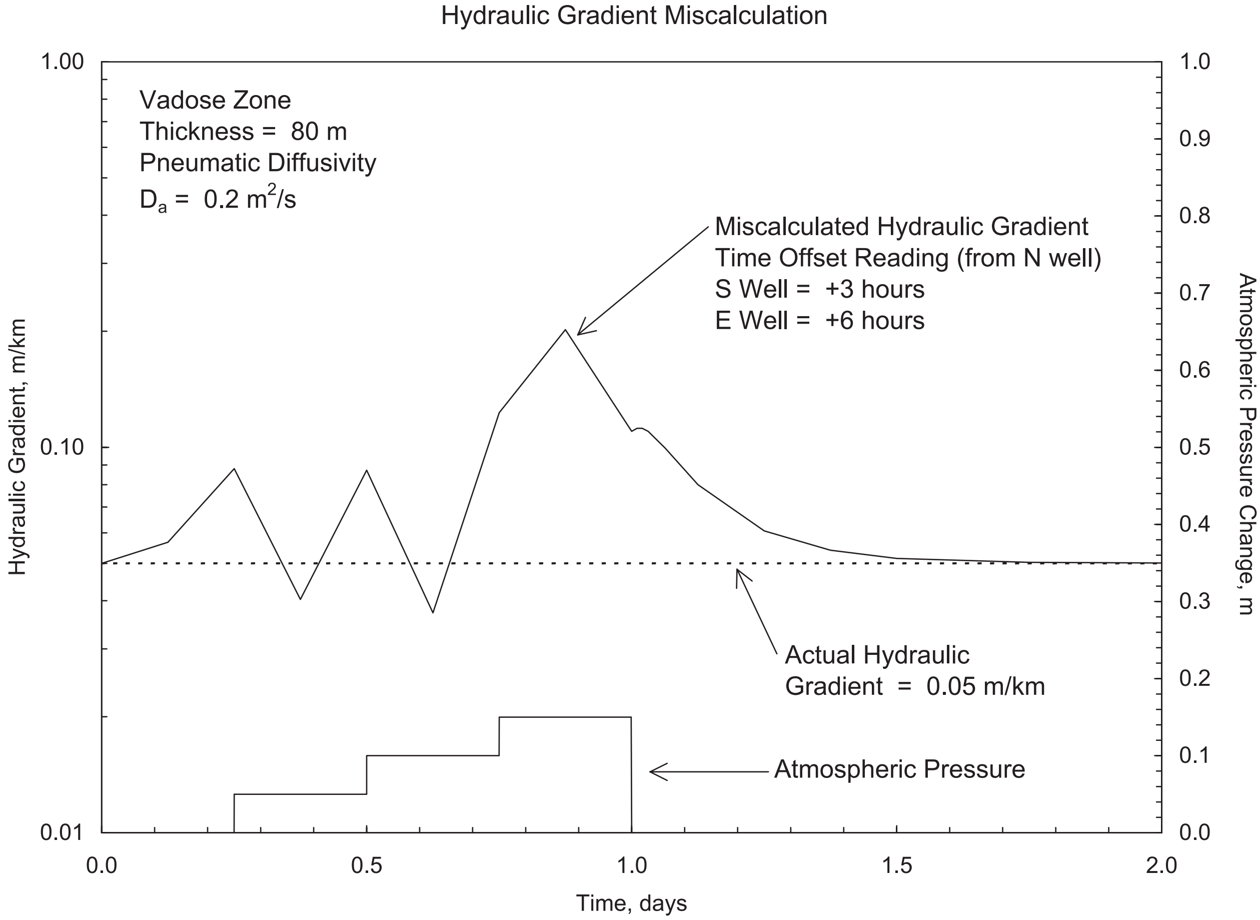

Figure 8. Miscalculation of hydraulic gradient in low-gradient areas using well measurements not collected at the same time.

or have been altered (e.g., landfill covers [*Hare and Morse*, 1997, 1999]) within the low-gradient area. To illustrate the magnitude of possible groundwater flow changes, the same simulated atmospheric pressure step changes were utilized. Vadose zone pneumatic diffusivities of 0.15 m^2/s (central/south well), 0.20 m^2/s (east well), and 0.25 m^2/s (north well) were assigned for the three wells used in the three-point flow characterization analysis. It is not known whether this amount of areal variability is common; however, a recent study by *Spane and Thorne* [2000] in a similar-size area on the Hanford Site indicated well/vadose zone barometric response characteristics ranging over a factor of 2. In addition, vadose zone thickness variations also contribute to barometric pressure variations occurring at the water table. Keeping the vadose zone thickness constant for the second example therefore decreases the effect of barometric fluctuations on actual groundwater flow changes.

[30] Figure 9 shows the actual changes in groundwater flow direction within the aquifer from the initial due east direction, due to barometric pressure fluctuations and variations in vadose zone characteristics (e.g., pneumatic diffusivity). It should be noted that the groundwater flow direction changes were based on aquifer head conditions measured for the same moment in time. As indicated, actual groundwater flow directions within the aquifer varied by over 60 degrees over the 2-day period, while the hydraulic gradient (not shown) varied by less than a factor of 2 from 0.04 to 0.07 m/km. Greater variation in flow direction (and hydraulic gradient) would have been realized by increasing the magnitude and period of barometric pressure change, which can occur during extended periods of high- or low-pressure activity. The results of this example simulation indicate that discrete well measurements (i.e., converted to discrete hydraulic head values) used for groundwater flow characterization within low-gradient areas may not be indicative of average, long-term groundwater flow conditions and are highly reflective of the temporal aquifer conditions that can be significantly influenced by transient barometric pressure fluctuations. Average, long-term groundwater flow conditions, however, can be determined by correcting temporal barometric effects from the well response. This requires determination of the barometric response characteristics for each well used in the groundwater flow characterization and correction of short-term barometric effects using one of the correction methods discussed below.

[31] The analysis results also suggest that groundwater flow characterization within low-gradient areas using other direct, in-well measurement techniques (e.g., flow meters, colloidal boroscopes) may also be susceptible to the effects of barometric fluctuations that can significantly influence temporal groundwater flow conditions. Determination of representative groundwater flow characteristics using these

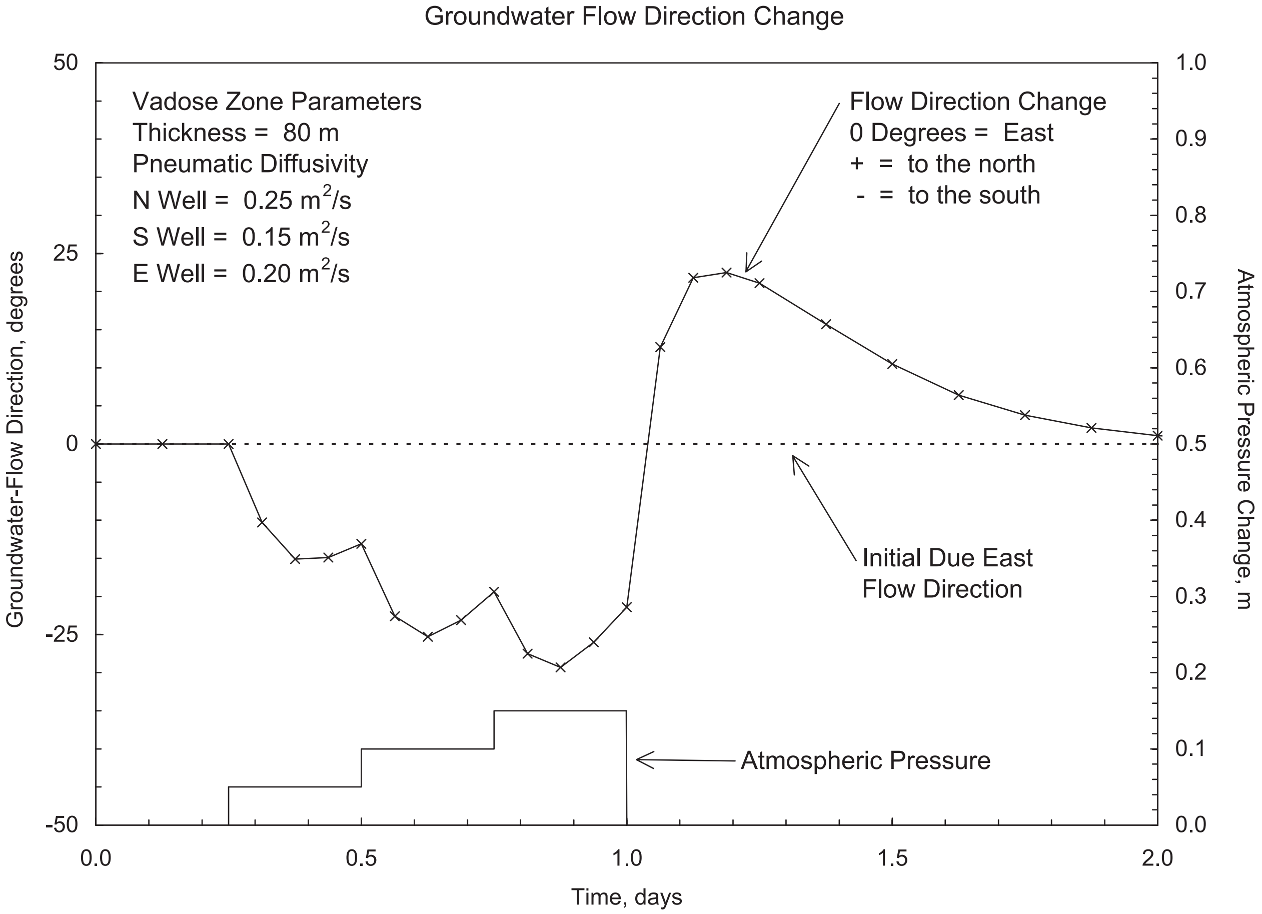

Figure 9. Temporal variations in groundwater flow direction induced by barometric pressure fluctuations in low-gradient areas.

in-well measurement techniques therefore would likely require extended periods of in-well measurement (e.g., weeks) for determination of average, long-term groundwater flow behavior.

5. Barometric Correction Methods

[32] For determination of average, long-term groundwater flow characteristics in areas adversely affected by temporal barometric pressure fluctuations, a number of correction techniques can be utilized. The correction method used is dependent on the barometric response model exhibited for monitor wells within the characterization site. Barometric correction methods examined include closed-well systems, the BE method, the multiple-regression deconvolution technique, an analytical vadose zone model, and a frequency-based method.

5.1. Closed-Well Systems

[33] Closed-well systems (i.e., closed below the water table) provide a direct means of eliminating the delayed response effects of well bore storage caused by direct atmospheric pressure fluctuations applied within an open well. As previously discussed, the presence of well bore storage adds an additional effect to the open-well response in the presence of barometric pressure fluctuations. Eliminating this component facilitates barometric correction using one of the methods discussed in the following sections. Closed-well system pressures measured with an absolute pressure gauge provide total head values within the aquifer and, for unconfined aquifers, represent the water table elevation and the component of atmospheric pressure that is transmitted through the vadose zone to the water table surface. For a static water table elevation condition within an unconfined aquifer, closed-well system measurements would vary only as a result of the time-lagged response to atmospheric pressure changes occurring at land surface.

[34] To evaluate the performance of closed-well systems over an extended period of barometric pressure fluctuations, data were collected at a Hanford Site well (well 699-43-42K) over a 4-week period (6 August through 3 September 1998) using a Westbay Instruments, Inc., closed-well monitoring system. This closed-well installation provided access to four separate depth intervals using a Westbay Instruments Multiport (MP™) system. A detailed description of the test facility is given by *Gilmore* [1989] and *Gilmore et al.* [1991]. The lower three ports were monitored during this period and provided nearly identical total head measurement patterns. The measurement point depths of the three zones were located approximately 0.5, 4.5, and 9 m below the water table, which at that time was ~53 m below ground surface. Each of the individual monitoring intervals was isolated with bentonite grout placed in the annular area outside the well. A Westbay Modular Subsurface Data

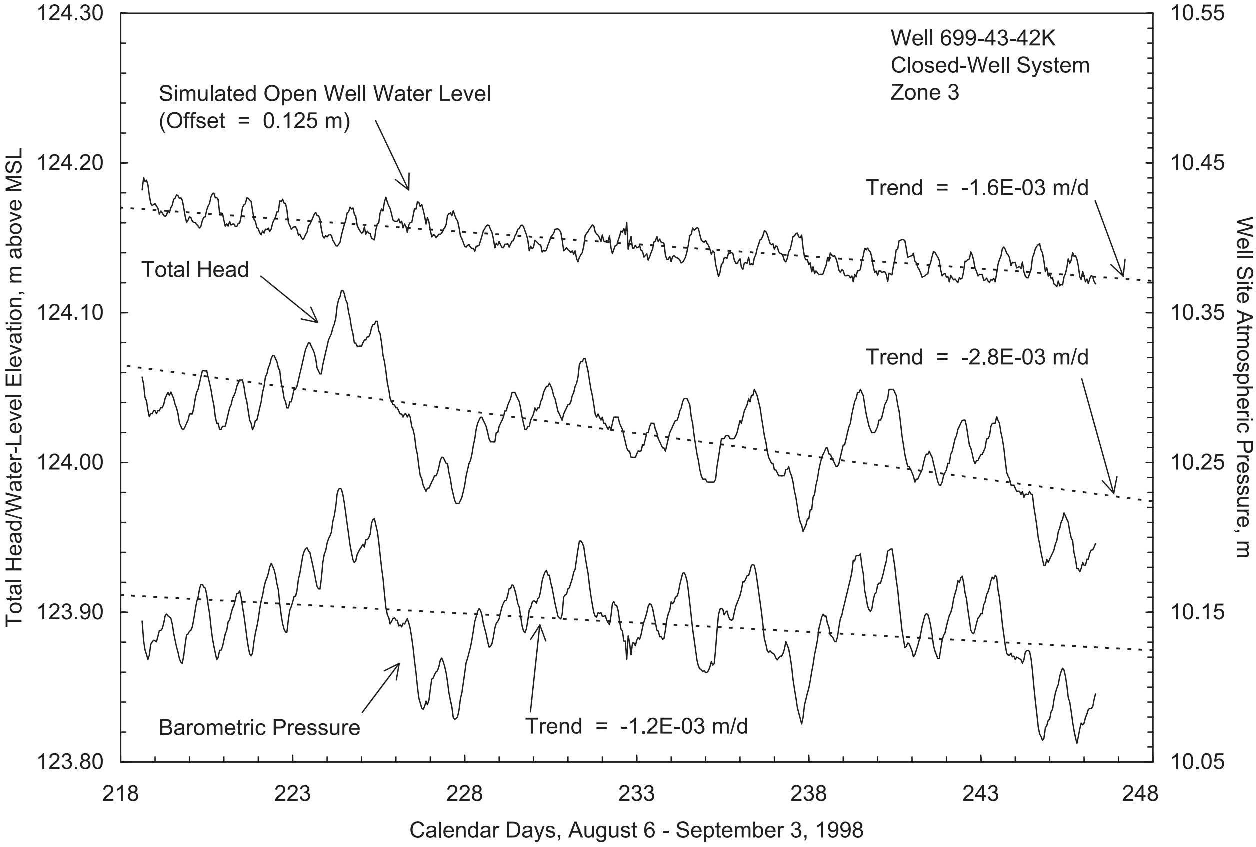

Figure 10. Total head and atmospheric pressure measurements for well 699-43-42K, zone 3 (closed-well system).

Acquisition System (MOSDAX™) was used to record monitoring zone pressures simultaneously, as well as to test site atmospheric pressure conditions. The test data were collected at 10-min intervals, with the objective of providing a data set of total head within the aquifer, which could be used to assess barometric correction techniques in support of groundwater flow characterization.

[35] The monitoring system employed provides a closed-well system at the point of pressure measurement, thereby eliminating the impact of well bore storage effects on total head measurements. If a monitoring well is closed or isolated above the water table (e.g., with a surface well head system), the compressibility of the closed air (gas) column above the water table will cause additional time delay and possibly dampen down-hole pressure measurements in comparison with actual aquifer conditions.

[36] Figure 10 shows the variability of total head at well 699-43-42K, as recorded for the middle closed-well monitoring interval (zone 3), located ~4.5 m below the water table. As shown, an apparent high visual correlation between total head and site atmospheric pressure conditions is evident, suggesting a relatively rapid transmission of the atmospheric pressure fluctuation signal through the 53-m vadose zone thickness. For comparison purposes, the theoretical open-well water level elevation response (i.e., if the well were not closed in) is also shown. The well water level response was calculated (assuming no well bore storage effects) by subtracting the atmospheric pressure change occurring at land surface and adding the reference atmospheric pressure for the site of 10.087 m directly from the total head measurement obtained for the monitoring interval, as indicated in equations (2) and (4). The well water level elevation response shown in Figure 10 exhibits considerably less variability and is a poor indicator of total head variability occurring within the aquifer. This lack of well water level response is attributed to the rapid vadose zone transmission of the atmospheric pressure, which lessens the impact of atmospheric pressure changes applied immediately to the open well. At other locations on the Hanford Site where the vadose zone is thicker and the pneumatic diffusivity is lower, well water level elevations exhibit more variability in comparison with the total head response within the aquifer.

[37] Linear regression analysis of the observed data indicates that the total head trend was approximately twice that indicated for the barometric pressure record (-2.8×10^{-3} versus -1.2×10^{-3} m/d). This suggests that a background water table trend was prevalent during the 4-week period of observation. The observed background negative trend in total head (-1.6×10^{-3} m/d) is consistent with decommissioning activities at a nearby recharge facility, and this declining head trend has been observed at other surrounding monitoring wells.

5.2. BE Method

[38] For well/aquifer systems exhibiting a confined aquifer barometric response, the temporal effects of barometric pressure can be corrected for by subtracting the component

BE $(\Delta P_a)/(\rho_o g)$ from the observed well water level elevation or (1-BE) (ΔP_a) from the down-hole absolute pressure measurement, P_f. The total head at the well site can then be calculated using either equations (3) or (4) for observed or freshwater conditions.

[39] The method described by *Clark* [1967] is particularly useful for calculating BE for confined aquifer wells that are influenced by other extraneous pressure trends (e.g., distant groundwater withdrawals). Briefly stated, the method determines the barometric efficiency from the slope of a summation plot of the incremental changes in down-hole formation pressure, $\Sigma\Delta P_f$, versus the incremental change in atmospheric pressure, $\Sigma\Delta P_a$. Incremental changes in down-hole formation pressure are added to the summation total when the incremental sign change is equal to that of the incremental atmospheric pressure, ΔP_a, sign change for the observed incremental period (e.g., when ΔP_f and ΔP_a are both positive or negative). Conversely, incremental changes in down-hole formation pressure are subtracted from the summation total when the incremental sign change is unequal to that of the incremental atmospheric pressure sign change for the observed period. In addition, no incremental change in down-hole formation pressure is added to the summation total when no change in atmospheric pressure is recorded. A slightly modified form of the Clark method was employed with good results by *Spane* [1990] and *Davis and Rasmussen* [1993] in determining barometric efficiencies of confined aquifers at the Hanford Site.

5.3. Multiple-Regression Technique

[40] Multiple-regression deconvolution techniques can be used to correct temporal barometric effects from open- or closed-well measurements that exhibit either aquifer or composite well bore storage/aquifer response characteristics. To demonstrate the correction procedure, the 4-week total head record for zone 3 of the multilevel monitoring system described in section 5.1 (shown in Figure 10) was analyzed using the multiple-regression technique described by *Rasmussen and Crawford* [1997]. Changes in observed total head, ΔH_t, versus associated time-lagged barometric pressure changes, ΔP_a, were used in the regression rather than observed H_t versus observed P_a. Figure 11 shows the barometric response pattern obtained from the multiple-regression analysis of the observed total head for all three monitoring zones. The total head analysis results are consistent with an unconfined aquifer barometric response model, as shown in Figure 2. The rapid transmission of barometric pressure through the vadose zone at this site is evident from the larger head response dependence for early time lag periods.

[41] A comparison of the monitoring zone response patterns indicates nearly identical characteristics for zones 3 and 4, the deepest monitoring zones. The reason for the slightly time lagged response for zone 2, which suggests additional well bore storage, is not completely understood. Previous hydrologic testing activities [see *Spane and Thorne*, 1995; *Spane et al.*, 1996] at the site have incorporated air/gas at the top of the unconfined aquifer as a result of the lowering and subsequent recovery of the water table surface. This could explain the "storage-"induced, time-lagged response observed at the top monitoring zone, which is within 0.5 m of the current water table surface.

[42] To demonstrate the "goodness of fit" of the regression analysis, the predicted total head response was calculated for zone 3, based on the multiple-regression coefficients determined for 0.5-hour time lags, for a maximum 9-hour period. Figure 12 shows the comparative match between observed and predicted total head using the multiple-regression method. As indicated, a very close match was obtained for zone 3 (r^2 = 0.99). Similar matches were also obtained for zones 2 and 4 (not shown). Given the high correspondence between predicted and observed total head, it would be expected that the temporal effects of barometric fluctuations could be removed to determine the average total head conditions within the aquifer at this well site location. To remove the temporal effects of the barometric fluctuations, a total head correction was calculated by summing the products of the previously determined regression coefficients multiplied by their respective time-lagged ΔP_a values. The summed head correction was then subtracted from the observed total head values. The comparison of observed and corrected total head values is shown in Figure 12; essentially all of the observed total head variability caused by temporal barometric fluctuations during the time period was eliminated. This suggests that the significant effects of barometric fluctuations on total head conditions within the aquifer at the site can be effectively corrected using a closed-well system and multiple-regression deconvolution techniques.

[43] The corrected total head response shown in Figure 12 was based on the observed total head and barometric pressure responses shown in Figure 10. As such, the corrected response removes the background water table trend (-1.6×10^{-3} m/d), which should be done if an average, long-term head condition is desired over the period of record. For the actual average head response, which exhibits the background trend in the water table (i.e., -1.6×10^{-3} m/d), the observed total head and barometric pressure responses should be detrended prior to multiple-regression analysis.

5.4. Vadose Zone Model

[44] Temporal barometric effects from open- or closed-well measurements that exhibit unconfined aquifer response characteristics can also be corrected using the vadose zone model (WBAR) presented by *Weeks* [1979]. The same examples that were examined using the multiple-regression technique were also used to analyze the observed closed- and open-well responses to evaluate its utility for removing barometric effects from total head and well water level elevation data. It should be noted that the original WBAR program only predicts open-well water level response. To facilitate closed-well response prediction, E. Weeks, in a personal communication with the author in 1999, provided a modification to the program. The program was also modified by the author to include the effects of background water table trends.

[45] Figure 13 shows the results of matching the observed total head record obtained with the closed-well system for zone 3 in well 699-43-42K. As shown, the vadose zone model provides a close match and was derived using a pneumatic diffusivity of 0.15 m^2/s and a water table trend of -1.6×10^{-3} m/d. The moderately high pneumatic diffusivity, obtained with vadose zone model analysis, is con-

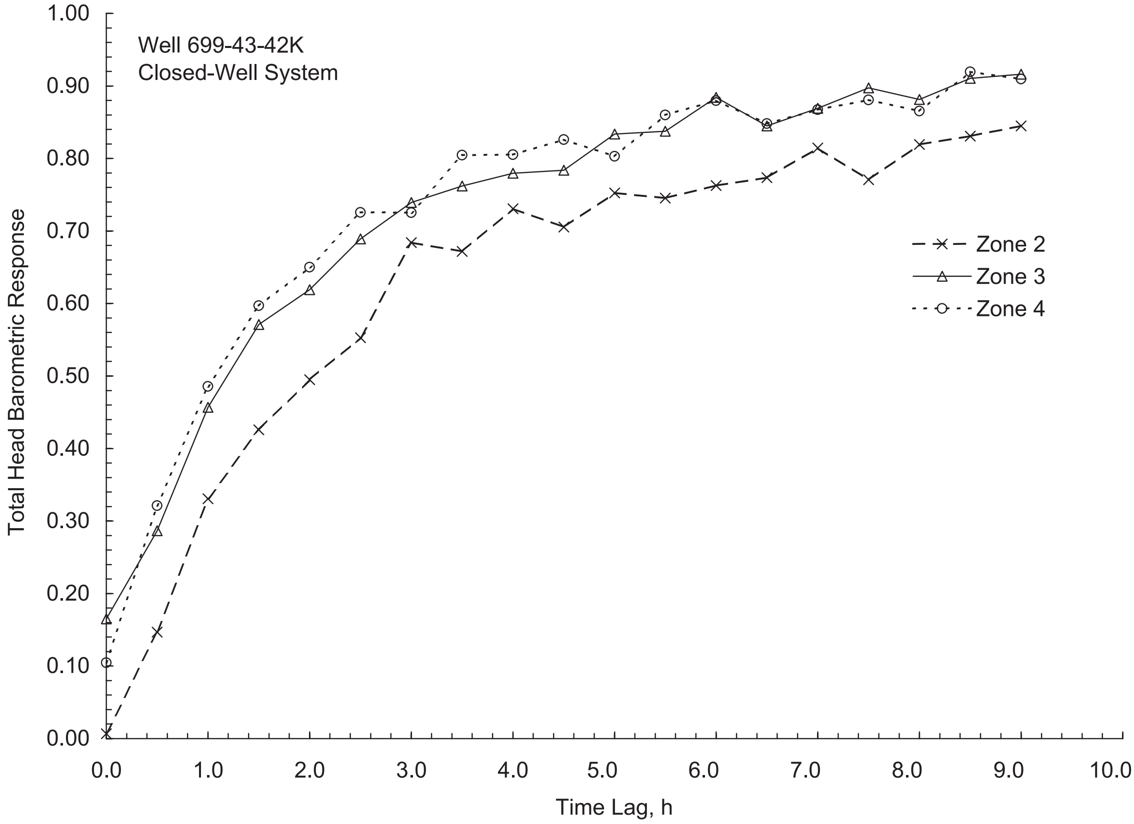

Figure 11. Total head barometric response patterns for well 699-43-42K, zones 2, 3, and 4.

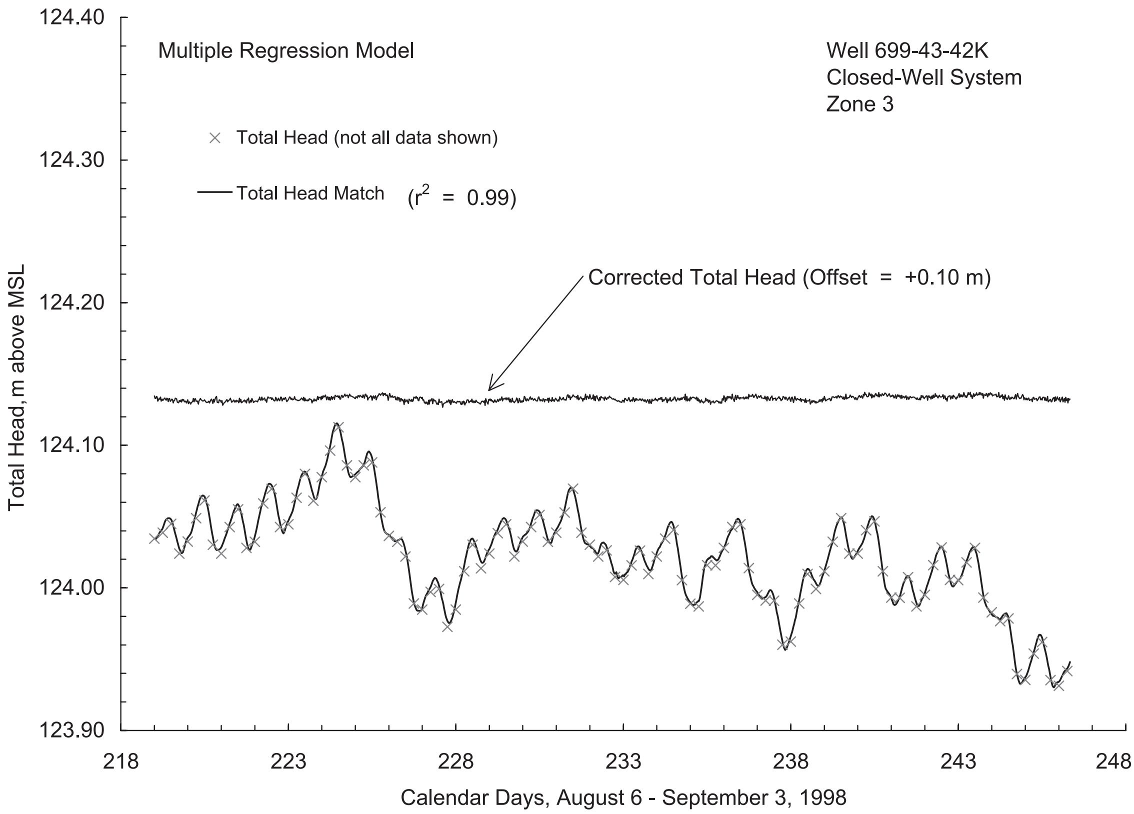

Figure 12. Multiple-regression match and barometric correction of closed-well total head response for well 699-43-42K, zone 3.

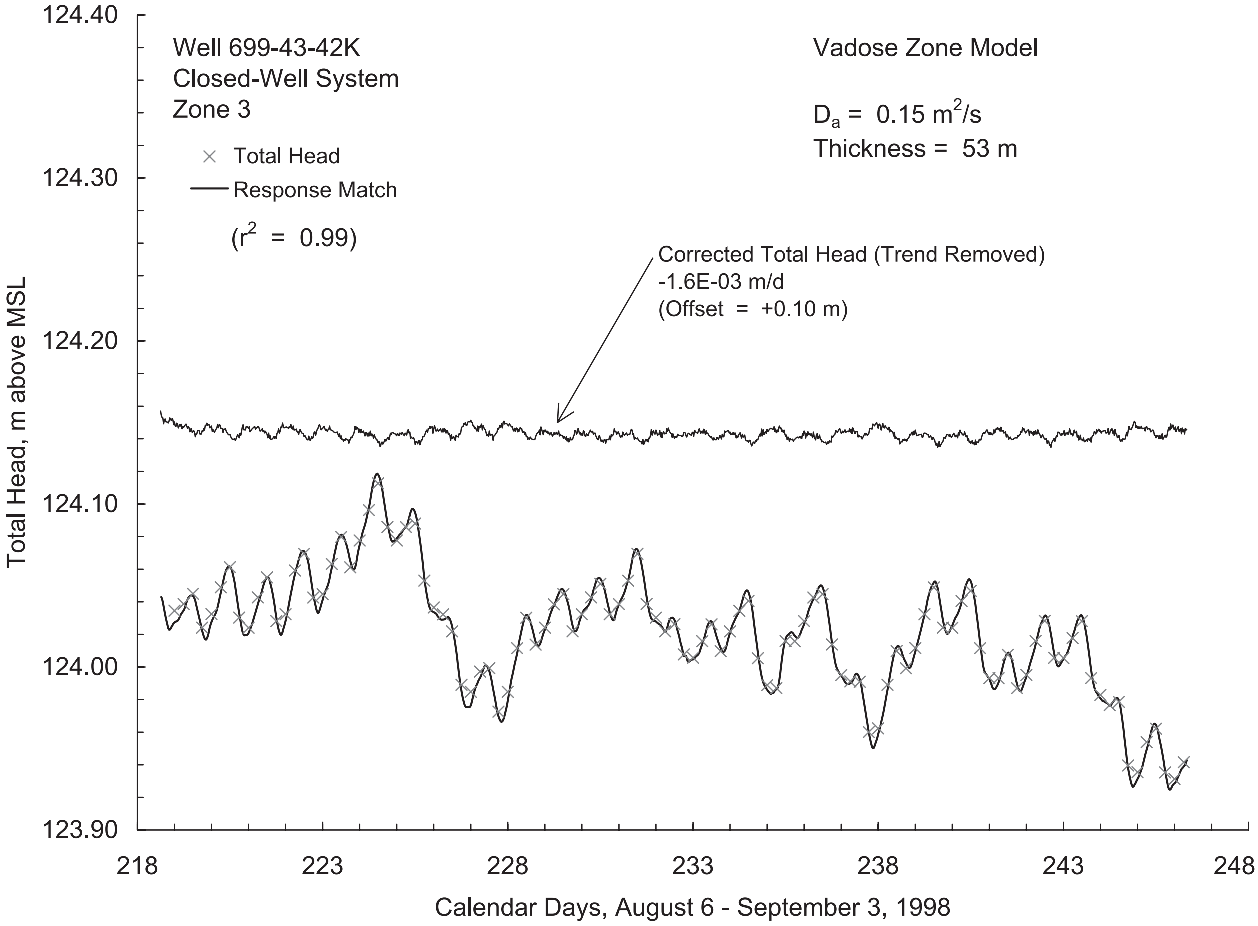

Figure 13. Vadose zone model match and barometric correction of closed-well total head response for well 699-43-42K, zone 3.

sistent with the previous regression analysis findings of relatively rapid transmission of the barometric signal to the water table (i.e., high dependence on early time lags).

[46] Figure 13 also shows the total head barometric correction plot developed using the vadose zone model. The vadose zone model results can be directly compared with the multiple-regression correction plot presented in Figure 12. A visual examination of the two methods indicates slightly more residual variability for the vadose zone model in comparison with the multiple-regression results.

5.5. Frequency-Based Method

[47] Because of the periodic nature exhibited by barometric pressure fluctuations, some correction techniques have focused on frequency-based methods. All frequency correction methods assume that the dynamics exhibited by barometric pressure response and expressed within the well water level record can be approximated by a combination of sines and cosines of different frequencies. To accomplish this, responses are converted from time into the frequency domain using fast Fourier transforms. Particular patterns that may be masked within the time record (e.g., diurnal, semidiurnal events) may become evident when expressed in the frequency domain. Frequency analysis of the transformed data provides a spectrum of the frequencies within the response record. Visual and statistical correlation is then made between the well and barometric spectral patterns to identify significant barometric frequencies expressed in the well response record. On the basis of the cross-correlation characteristics (amplitude ratios, phase shift information), significant barometric frequencies can be selectively removed or filtered from the well record. The resulting filtered well record represents the corrected response for the effects of barometric pressure fluctuations. Examples of barometric corrections of well water levels using frequency-based methods are presented by *Chien et al.* [1986], *Rojstaczer and Riley* [1990], and *Quilty and Roeloffs* [1991].

[48] To demonstrate this correction method, the same 4-week total head and barometric pressure data set shown in Figure 10 was analyzed using the frequency analysis procedure presented by *Hydrotechnique Associates* [1984] and summarized by *Chien et al.* [1986]. Figure 14 shows a comparison of the continuous frequency spectra of the total head and barometric pressure for the observed time period. Trends were removed from the head and barometric response records using linear regression prior to performing the frequency analysis. Removal of trend effects reduces the low-frequency amplitude response in the frequency spectral plots, enabling identification of long-term phenomena.

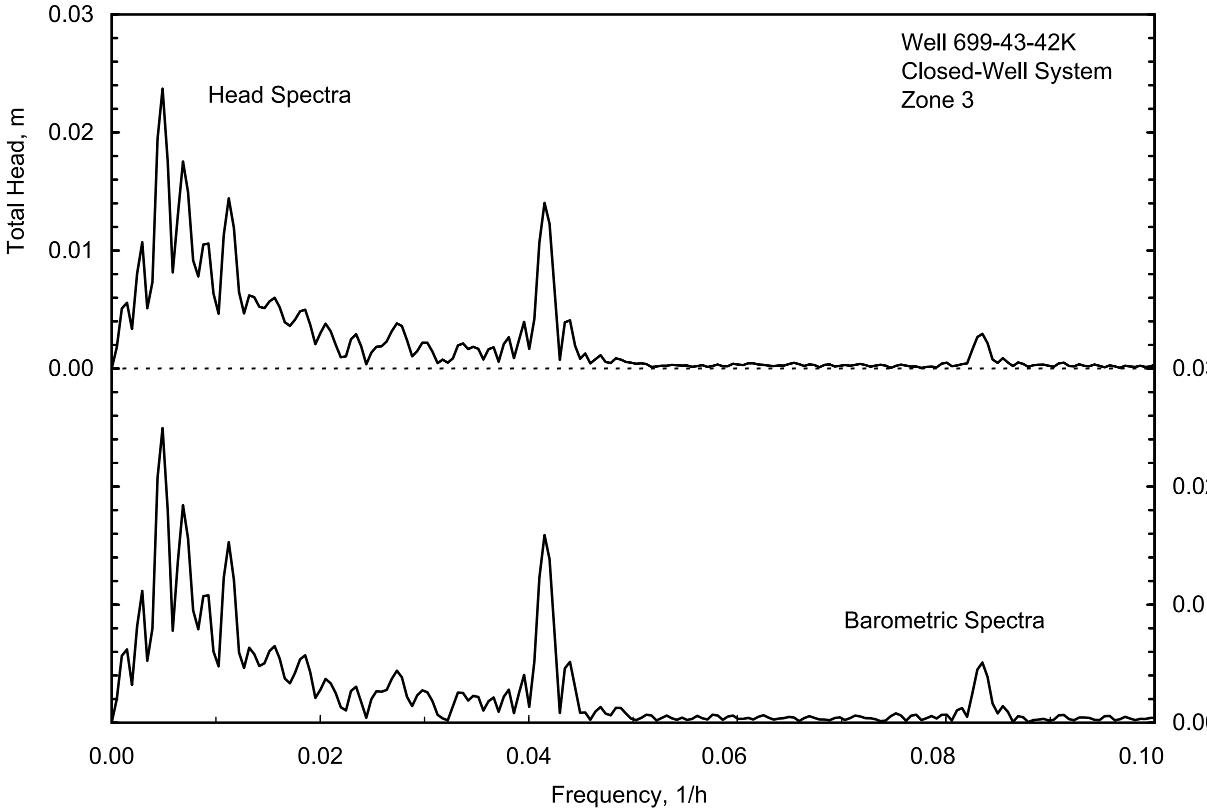

Figure 14. Continuous frequency spectrum of barometric pressure and closed-well total head response for well 699-43-42K, zone 3.

[49] Visual examination of the plots indicates a nearly identical spectral pattern, in both frequency and amplitude. This is expected given the relatively rapid transmission of barometric pressure from land surface to the water table at this location. The spectral patterns exhibit distinctive diurnal ($\sim$0.042 cycles/hr) and semidiurnal ($\sim$0.083 cycles/hr) frequency peaks that are commonly associated with atmospheric heating and cooling. Most of the spectral response, however, is expressed in the low-frequency range of $\leq$0.045 cycles/hr (i.e., periods $\geq$22 hours), which is characteristic of longer-period climatic patterns.

[50] To correct for the temporal impact of barometric fluctuations on the total head record, cross correlation of the detrended total head and barometric records was first performed to assess phase shift relationships. The cross-correlation analysis indicated a phase lag within the head records of $\sim$1.5 hours. Cross-correlation analysis of filtered segments of the response record (e.g., semidiurnal, diurnal), indicated an increase in phase lag with decreasing frequency and ranged between 0.9 and 2.5 hours over the data record. The lack of uniformity of phase over the frequency spectrum suggests effects from other stresses (e.g., earth tides at diurnal and semidiurnal frequencies) may be present.

[51] Barometric effects were removed by applying the phase lag and amplitude ratio relationships determined from the cross-correlation analysis of the dominant barometric spectral frequencies and subtracting these filtered frequency responses from the total head record. Figure 15 shows matched and corrected response using this frequency-based method. As shown, a good match between observed and predicted total head is exhibited. Additional smoothing of the corrected head response may have been realized if barometric corrections had been extended across the entire frequency range (i.e., primarily the higher-frequency range), and not just the dominant frequencies indicated in Figure 14.

5.6. Correction Method Comparison

[52] Although the comparison of barometric correction methods is not fully comprehensive, a number of observations can be stated about their characteristics and application. Closed-well systems provide a means of directly removing well bore storage effects and facilitate the correction of temporal barometric effects using one of the aquifer response model methods (e.g., vadose zone model).

[53] For open- or closed-well measurements exhibiting a simple confined-aquifer response model, the BE method can be used to correct for the temporal effects imposed by barometric pressure fluctuations. The Clark method is particularly useful in determination of BE under variable background trend conditions.

[54] The multiple-regression deconvolution technique has a wide application in correcting the temporal barometric effects from various aquifer and composite well/aquifer response systems. Because of this wider adaptability, higher-quality correction results are likely. Multiple-regression methods, however, require longer baseline data periods to be effective, and quantitative characterization of the physical system properties controlling the barometric

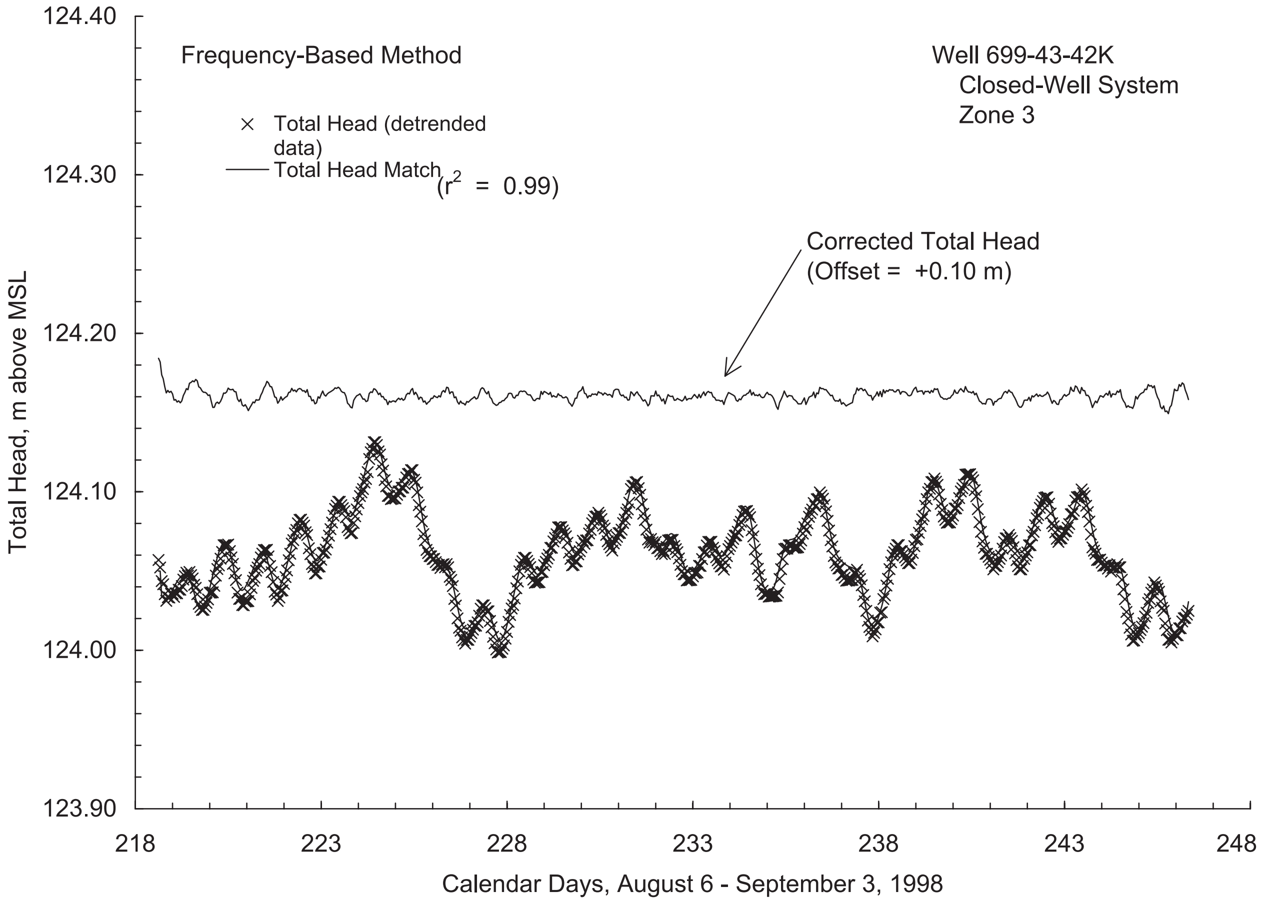

Figure 15. Frequency-based method match and barometric correction of closed-well total head response for well 699-43-42K, zone 3.

response (e.g., pneumatic diffusivity) cannot be directly determined by the matching analysis results.

[55] For open- or closed-well measurements exhibiting simple, unconfined aquifer response behavior, the analytical vadose zone model can be used to correct for the temporal effects imposed by barometric pressure fluctuations. The vadose zone model can be applied with minimal baseline data, and physical system properties (e.g., pneumatic diffusivity, vadose zone thickness, background water table trend) can be determined directly from the analysis. A weakness of the vadose zone model is its inability to account for well bore storage, well skin, and specific boundary situations where the water table occurs within the well screen section, allowing direct transmission of the atmospheric pressure signal to the water table through the well. Depending on the imposed severity of these local well and boundary conditions, removal of barometric effects from aquifer test data may be more limited using the vadose zone model.

[56] Frequency-based methods can be effectively used in removing barometric fluctuations and other external stress factors (e.g., earth tides) from confined and unconfined well/aquifer systems not exhibiting significant well bore storage/well skin effects. They require the application of a number of analysis procedures (e.g., frequency spectrum development, cross-correlation analysis, selective filtering of the dominant frequencies), however, which can be more time-intensive in comparison with other removal methods. In addition, since most of the energy in the barometric spectrum is in the low-frequency range (associated with longer-period storm events), it is likely that the low-frequency barometric and well measurement spectrum pattern would be somewhat different for different periods of the year (e.g., July versus November). The significance of this is that longer monitoring periods would be required to fully resolve the barometric spectra. The correction of discrete well water level measurements for barometric pressure fluctuations therefore would not be as straightforward as with the multiple-regression method, which (after an initial well/barometric response pattern has been established) can be applied to correct individual, discrete well measurements (i.e., if the preceding barometric readings prior to the well measurement are known).

6. Summary

[57] For lateral groundwater flow characterization, well water level elevation information should be converted to total head measurements for quantitative analysis of flow direction and hydraulic gradient conditions within the aquifer. Open wells, however, may exhibit a delayed response to variations in barometric pressure and provide erroneous indications of total head conditions within the surrounding aquifer. The manner in which a well/aquifer

system responds to changes in atmospheric pressure is related directly to the existing aquifer system and well bore storage/well skin conditions. Closed-well installations (i.e., systems closed below the water table) provide a means to eliminate barometric pressure-induced well bore storage effects and provide direct measurements for total head within the surrounding aquifer. Absolute pressure probe measurements can be utilized directly for calculating total head within the aquifer. For open-well measurements not exhibiting significant well bore storage/skin effects, total hydraulic head can be calculated by adding the incremental change in barometric pressure from a reference value (e.g., 10.333 m for mean sea level) to the observed well water level elevation. For low-gradient areas the precision and resolution of in-well measurements may be improved by using gauge sensors (differential pressure probes) having selectively low full-scale range characteristics.

[58] Diagnostic barometric response analysis can be used effectively to distinguish between confined and unconfined aquifer system behavior, identify the presence of well bore storage/well skin effects, and assess the uniformity in vadose zone characteristics for unconfined aquifer monitor wells used in detailed groundwater flow characterization. Barometric response analysis requires the collection of baseline barometric and corresponding well water level measurements for extended periods of time ($\sim$5–10 days). For unconfined aquifers the measurement frequency is a function of water table depth and vadose zone characteristics (i.e., for shallow depths and higher vadose zone pneumatic diffusivity values, more frequent measurements are required). For water table depths >50 m and for pneumatic diffusivity values $\leq$0.15 m^2/s, it is expected that a measurement frequency of every 30 min can be effectively employed.

[59] For low-gradient areas ($\leq$0.1 m/km) and exhibiting variable vadose zone or well/aquifer BE conditions, diagnostic barometric response analysis should be performed at each monitor well used in the detailed groundwater flow characterization. Temporal barometric fluctuations should then be removed from the total head response using an appropriate correction technique, to obtain the average total head value over the period of record. The corrected value can then be used in determining average groundwater flow conditions (e.g., using trend-surface methods). Once the barometric response characteristics have been established for a well, subsequent discrete water level monitoring measurements can be corrected for temporal barometric pressure effects by analyzing the existing barometric pressure record prior to the well measurement. While a well's barometric response characteristics are expected to remain uniform with time, they should be reevaluated periodically to verify the absence of significant change, due to well damage/skin effects or changes in vadose zone characteristics (e.g., soil moisture).

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