Identifying and Removing Barometric Pressure Effects in Confined and Unconfined Aquifers

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Abstract

Failing to account for barometric pressure effects in water level measurements can introduce errors by misestimating the total head and by adding noise to water level measurements. For determining the total head in an aquifer, we assert that the air pressure head at the water surface in the well must be added to measured water levels (equivalent to using an absolute pressure transducer) even though the resulting values may have larger temporal and spatial variability than the original water level measurements. At the Savannah River Site in South Carolina, the average barometric pressure variation is 6 to 7 cm, with a range of over 30 cm. Failure to account for barometric pressure variability could result in misestimation of the direction and magnitude of the hydraulic gradient at the site. We also demonstrate procedures for removing barometric effects, such as to reduce noise during an aquifer pumping test, and to identify mechanisms by which barometric pressure affects water levels. Three mechanisms are summarized including: an instantaneous response for confined aquifers; a delayed response due to borehole storage in confined and unconfined aquifers; and a delayed response in unconfined aquifers due to the passage of barometric pressure changes through the unsaturated zone. Using data from the Savannah River Site, barometric efficiencies are estimated using linear regression and a modification of Clark's Method. Delayed responses are estimated using regression deconvolution. The type of barometric effect provides diagnostic information about whether the aquifer is confined or not, the presence of borehole storage or skin effects, and the air diffusivity coefficient within the unsaturated zone. We also show how removal of barometric pressure effects improves the ability to observe otherwise unnoticeable effects.

1. Introduction

Modern pressure transducers and dataloggers allow ground-water levels to be monitored at rapid rates and with excellent precision. While automated methods have the potential for reducing measurement errors, systematic errors may provide faulty estimates of the total head and hydraulic gradient (see, e.g., Spane and Mercer, 1985). Although it is commonly acknowledged that barometric pressure changes can substantially affect water level measurements, little guidance is available for adjusting water levels to incorporate barometric pressure changes. The objective of this paper is to provide a methodology for accounting for barometric pressure changes when measuring and interpreting water levels in confined and unconfined monitoring wells.

Examples to explain and demonstrate the methodology are taken from monitoring wells at the U.S. Department of Energy's Savannah River Site (SRS), which is currently managed by the Westinghouse Savannah River Corporation. An important function of ground-water monitoring wells at SRS is to determine the piezometric surfaces within target hydrogeologic units. Water levels are routinely used to determine the local or regional hydraulic gradient within the hydrogeologic unit or to determine the vertical hydraulic gradient between units. Hydraulic gradients are used to estimate the darcian flux and fluid velocities within or between units. The principal concern related to fluid flow at any waste site undergoing remediation, or any proposed waste disposal site, is the determination of the direction and magnitude of the darcian flux and the fluid velocity.

2. Barometric Pressure, Water Levels, and Total Head

Fluctuations in water levels in open wells due to barometric pressure changes were noted by Blaise Pascal in 1663, who was the first to propose that the earth's atmosphere exerted a surface pressure (Pascal, 1973; see also Gossard and Hooke, 1975). The relationship between water level and barometric pressure is an inverse one; increases in barometric pressure create declines in observed water levels and vice versa (see, e.g., Freeze and Cherry, 1979, p. 233). Barometric pressure measurements are used to

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establish the barometric efficiency, which is the ratio of change in hydraulic head to the change in barometric pressure:

$$\alpha = -\frac{\Delta W}{\Delta B} \tag{1}$$

where α is the barometric efficiency, ΔW is the change in the water surface elevation in the well during an arbitrary unit of time, and ΔB is the change in the barometric pressure head at the water surface during the same time interval.

The barometric efficiency is important because of the relationship between water levels and the total head (equivalently, fresh water, static, piezometric or potentiometric head). The total head, H, is the sum of the barometric pressure head, B, and the water surface elevation head, W:

$$H = B + W \tag{2}$$

where the water surface elevation head is measured with respect to an arbitrary vertical datum, usually mean sea level, and the barometric pressure head is measured relative to an arbitrary standard, usually the mean barometric pressure head at sea level. Failure to account for changes in the barometric pressure head can result in errors in the calculation of the magnitude and direction of the hydraulic gradient for areas where the water table is near-horizontal. Barometric pressure is not the only factor that may affect the total head. Also important are fluid density fluctuations due to temperature, salinity, or dissolved gasses, and even gravitational variability (see e.g., Oberlander, 1989; Spane and Mercer, 1985).

The barometric response of a well can be understood by considering the total head at two locations: within an open well, and within the aquifer at some arbitrary distance away from the well. While the total head within an open well is instantly affected by a barometric pressure change, the total head within the aquifer may or may not be affected by barometric pressure changes. For cases where the total head immediately equilibrates between the two locations (which holds in most small diameter boreholes within aquifers), a change in water level within the well depends upon the sensitivity of the total head within the aquifer to barometric pressure changes.

One can postulate two extreme cases. The first case occurs when the total head in the aquifer increases instantly and completely following a barometric pressure change, yielding $\alpha = 0$. An example is a shallow aquifer where the water table is close to the surface. In this case the air pressure travels quickly through the unsaturated zone and quickly increases the total head within the aquifer (i.e., $\Delta H/\Delta B = 1$), and the barometric efficiency is zero. A second case arises in an aquifer where the total head is insensitive to barometric pressure changes, such as within a deep, unconfined aquifer, yielding $\alpha = 100\%$. If the barometric pressure change does not immediately affect the total head in the aquifer, then the water level in the well must compensate to maintain the constant total head:

$$\frac{\Delta W}{\Delta B} = \frac{\Delta(H - B)}{\Delta B} = \frac{\Delta H}{\Delta B} - 1 = -1 \tag{3}$$

for $\Delta H/\Delta B = 0$. Thus, the barometric efficiency is 100 percent for a deep, unconfined aquifer in which the barometric pressure does not affect the total head within the aquifer. For this case, an analysis based only on water level measurements in an open well would lead us to the erroneous conclusion that the water level is changing in the aquifer due to barometric pressure changes. In fact, the water level in the well is responding to barometric pressure, while the total head in the aquifer is constant and independent of barometric pressure. Water levels within the open well fluctuate because the barometric pressure on the water surface is offset by a reduction in the height of the fluid column. This compensation maintains a constant total head in equilibrium with the surrounding aquifer. If the well is sealed so that atmospheric pressure changes do not affect the total head in the well, then the water level elevation in the well does not fluctuate in response to barometric pressure changes.

In cases where the well is not sealed, the total head is estimated by simultaneously measuring the barometric pressure and water levels. An equivalent technique is the use of absolute pressure transducers instead of gauge pressure transducers. Absolute pressure transducers respond to the total pressure, rather than the difference between total head and the atmospheric pressure. One practical advantage of using absolute pressure transducers lies in the ability to dispense with both the vent tube on the gauge pressure transducer and the barometric pressure measurement. While the resulting total head measurements may fluctuate more than gauge measurements, the total head is the basis for computing hydraulic gradients. The principal disadvantage of using an absolute pressure transducer is the poorer instrumental accuracy that results from the higher range needed to measure the sum of atmospheric and water pressures. In general, instrument accuracy decreases as the range increases.

3. Barometric Pressure Response Functions

While the time series of total heads at a well can be readily determined as the sum of the barometric pressure head plus the water level elevation, the relationship between barometric pressure head changes and water level changes is not so readily determined. 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 diffusivity of the unsaturated zone near the well.

In other situations, the effects of barometric pressure fluctuations must be removed to identify the hydraulic response to a natural perturbation (e.g., rainfall) or artificial perturbation (e.g., aquifer pump tests). The barometric pressure response often confounds the identification of much smaller responses, such as the aquifer response to pumping during the latter part of a pumping test. In these cases, the objective is to identify the hydraulic properties of the ground-water system. To do so we must first remove the barometric effects using barometric pressure response functions.

Three types of barometric pressure response functions are presented for quantifying the influence of barometric pressure on total head in aquifers: an instantaneous total head response in confined aquifers; a delayed response due to borehole storage or skin effects; and a delayed total head response in unconfined aquifers due to the transmission of the barometric pressure perturbation through the unsaturated zone. The time dependency of the barometric efficiency is provided for each of the mechanisms.

Rojstaczer (1988) examined the frequency response of water wells to barometric pressure changes as a function of steady periodic fluctuations for each of the above processes. He showed that the calculated barometric efficiency is related to the frequency of the barometric pressure perturbation. Convolution in the time domain (Furbish, 1991) provides an alternative method to the frequency domain analysis. Convolution is used here to examine the time-dependent relationship between barometric pressure and water levels:

$$H(t) = \sum_{\tau=0}^{n} u(\tau)\, \Delta B(t - \tau) \tag{4a}$$

or, equivalently:

$$H(t) = \sum_{\tau=0}^{n} \Delta u(\tau)\, B(t - \tau) \tag{4b}$$

where $H(t)$ is the time series of observed total heads, $B(t)$ is the observed time series of barometric pressure, $\Delta B(t)$ is the first difference of barometric pressure changes, $u(\tau)$ is the barometric response to a step change in barometric pressure, and $\Delta u(\tau)$ is the barometric response to a barometric pressure pulse. For clarity, we distinguish the time of observation, t, from the time delay, τ, between a barometric pressure change and the water level response. The step response, u, as a function of delay, τ, is related to the impulse response using:

$$u(\tau) = \sum_{i=0}^{\tau} \Delta u(i) \tag{5}$$

The barometric efficiency, α, is a function of the delay, τ, following the barometric pressure change, and can be related to the step response function by noting:

$$\alpha(\tau) = 1 - u(\tau) \tag{6}$$

Thus, the barometric efficiency can be considered to be a function of the lag time between the barometric change and the response in the borehole. For a constant, instantaneous water level response to a barometric pressure change, $u = 1 - \alpha$ for all τ.

Estimating the time-lag response between barometric pressure changes and water level responses in a well can be accomplished using regression deconvolution. A linear set of equations is established to estimate the unknown barometric response function. As a practical matter, the $(\Delta u, B)$ form of equation (4b) generally provides a more robust fit to the data than the $(u, \Delta B)$ form of equation (4a). The regression equation used is:

$$H(t) = \beta_0 + \beta_1 t + \Delta\mu_0 B(t) + \Delta\mu_1 B(t-1) + \ldots + \Delta\mu_n B(t-n) \tag{7}$$

where $H(t)$ is the total head at time step t, β_0 is the regression intercept, β_1 is a linear trend coefficient, Δu_i are the fitted barometric response coefficients, $B(t - i)$ are observed barometric pressures at lags between 0 and n, and n is the maximum lag. The maximum lag is set so that long-term responses are not ignored.

3.1 Confined Response

Jacob (1940) used a constant barometric efficiency to relate changes in barometric pressure to changes in the water level of a well. In Jacob's model for barometric effects on confined aquifers, the pressure change is transmitted instantaneously without attenuation through the confining bed to the aquifer. The model assumes that the pressure load within the aquifer is shared by the confined water and aquifer skeletal matrix and that the pressure load within the well is borne entirely by the water. A pressure imbalance is induced by a change in barometric pressure, which results in an instantaneous water level change in the well. In general, the elasticity of an aquifer decreases as the overburden pressure increases, thus increasing the barometric efficiency. The barometric efficiency should be 100 percent for a confined aquifer with an inelastic skeleton.

The barometric efficiency for confined aquifers is readily determined if the changes in water level are due only to changes in barometric pressure. One method for estimating the barometric efficiency is to form an ordinary least-squares regression equation between B and W:

$$W = -\alpha_L B \tag{8}$$

where both W and B have been detrended and the means have been subtracted to remove the intercept. Equation (8) fits the long-term fluctuations in barometric pressure; α_L reflects the change in water levels due to large, persistent changes in barometric pressure. An alternate approach is to form the first differences of water levels and barometric pressure head:

$$\Delta W = -\alpha_S \Delta B \tag{9}$$

where ΔW and ΔB are the changes in water level and barometric pressure between measurements, respectively, and both variables have been detrended and their means subtracted. Equation (9) tends to estimate the short-term response of water level changes induced by rapid changes in barometric pressure.

Water levels commonly respond to many other influences, such as earth and ocean tides, siesmically induced stresses, recharge, and evapotranspiration. These additional perturbations make estimation of the barometric efficiency difficult when the form of these other perturbations is unknown. Clark (1967) presented an alternative method for removing the influence of the other perturbations. Davis and Rasmussen (1993) show that Clark's Method is robust when the response to barometric pressure perturbations is instantaneous. This method provides estimates that are consistent with α_S, in part because Clark's Method is consistent with the difference form, equation (9).

3.2 Borehole Storage or Skin Effects

Water level responses to barometric pressure perturbations may not be instantaneous if a time delay is required for water to flow between the borehole and the aquifer. The flow is induced by the total head imbalance between the aquifer and the borehole caused by the barometric pressure change. As a result, an incorrect estimate of the barometric efficiency in the well may result. There is a need, therefore, to assess the factors which control the borehole storage delay caused by the time needed for aquifer-borehole equilibration. Borehole skin effects (i.e., a reduction in formation permeability near the borehole) may exacerbate the equilibration of total heads in the borehole and aquifer. Furbish (1991) suggests that a step increase in barometric pressure leads to conditions that are indistinguishable from the case where the level of the water is raised initially by injecting a slug of water, or where the water level is lowered by bailing water from the well. It follows that a continuously varying barometric pressure induces the equivalent of a continuous series of slug and bail tests. Thus, the barometric response function can be determined from solutions to the set of equations governing a slug or bail test. Furbish (1991) offers an analytical solution that was first described by Hvorslev (1951). The exponential response function that describes the aquifer response to a unit increase in barometric pressure is:

$$u(\tau) = e^{-\beta\tau} \tag{10}$$

where β incorporates the well shape and size and aquifer hydraulic properties, and τ is the lag between the barometric pressure change and the total head response.

3.3 Unconfined Response

Weeks (1979) described a phenomenon responsible for barometrically induced fluctuations in wells tapping unconfined aquifers. He concluded that water levels in such aquifers are affected by variations in barometric pressure through a mechanism substantially different from that causing such fluctuations in confined aquifers which cannot be explained by a constant, instantaneous barometric efficiency correction as applied to water levels in confined aquifers. Barometrically induced water level fluctuations result from the resistance to soil gas flow imposed by the materials composing the unsaturated zone and to the compressibility of the soil gas within the air-filled pores.

Figures 1a-d summarize the total head and water level response in a well and aquifer to a unit change in barometric pressure, the locations of which are shown in Figure 1a. Figure 1b displays the effect of pressure both in the well and in the aquifer in response to a step increase in barometric pressure. The pressure on the surface of the water inside the borehole equals the barometric pressure. There is a lag in the pressure in the aquifer, however, because of the time required for the barometric pressure wave to propagate down through the open pores in the unsaturated zone, t_d in Figures 1b-d. As shown in Figure 1c, the total head in the aquifer eventually responds to the barometric pressure change once the pressure change reaches the water table. In Figure 1d, the water level in the aquifer, which is the difference between the total head and the pressure at the water surface, remains constant. However, the water level in the well responds instantaneously to the step increase in barometric pressure by first falling and then gradually rising back to the initial water level.

The equation describing soil gas pressure, b, as a function of depth, z, and time, t, in the unsaturated zone is (see, e.g., Weeks, 1979; Shan, 1995; Rojstaczer and Tunks, 1995):

$$D_a \frac{\partial^2 b}{\partial z^2} = \frac{\partial b}{\partial t} \tag{11}$$

subject to no-flow boundary conditions at the water table (assumed fixed at a constant elevation) and a prescribed pressure head upper boundary, $b(z=0, t) = B(t)$. The air diffusivity, D_a, is treated as a lumped parameter that includes both the properties of the unsaturated materials and of the soil gas. Given a known or estimated D_a, the total head in the well, H(t), can be estimated for a known surface barometric pressure time-series, B(t), using the convolution summation where u(i) is given as (Carslaw and Jaeger, 1959, Equation 3.3.8):

$$u(\tau) = 1 - \frac{4}{\pi} \sum_{j=0}^{\infty} \frac{(-1)^j}{k} \exp(-v\pi^2 k^2) \tag{12}$$

where $k = 2j - 1$ and $v = \tau D_a / 4L^2$ is a dimensionless diffusivity coefficient that incorporates the air diffusivity, D_a, the lag between the impulse and response, τ, and the thickness of the unsaturated zone, L. A smaller barometric pressure effect results from larger values of dimensionless diffusivity, which correspond to high air diffusivities or shallow water tables. As the value of the dimensionless diffusivity decreases, the delay increases between the perturbation and the return to the unperturbed water level. For an impermeable cap over the aquifer, a step change in the perturbation causes a step change in the water level, as expected.

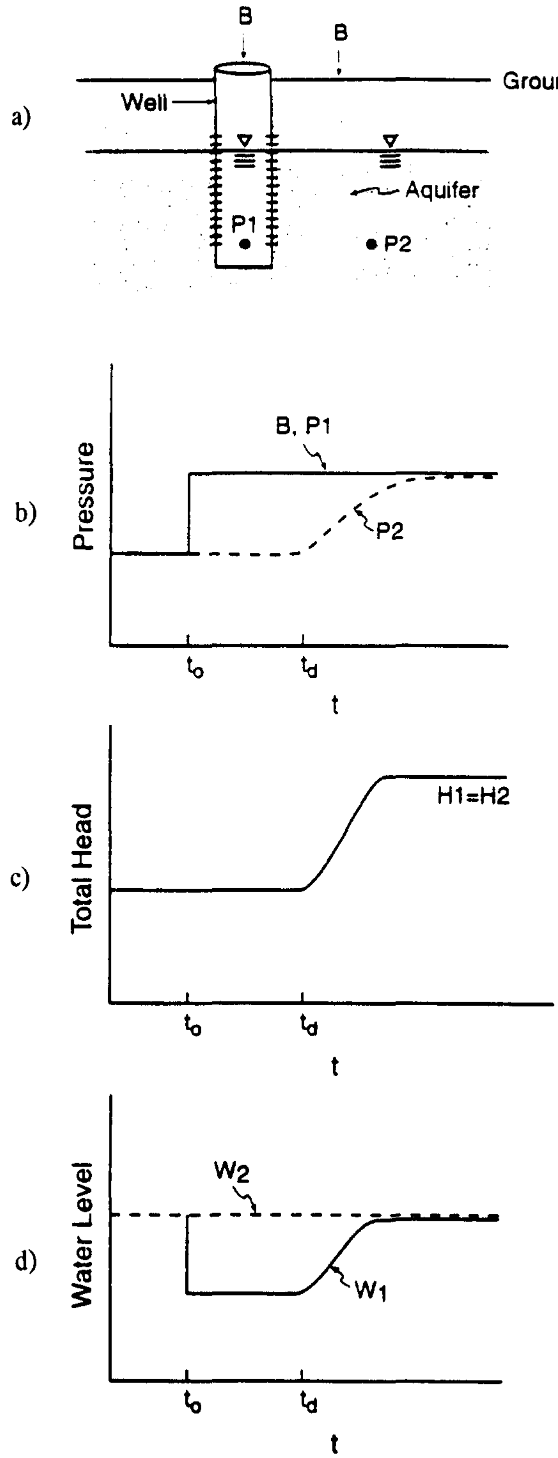

Fig. 1. Effects of a barometric pressure step increase in an unconfined aquifer. a) Diagram of locations of measurement Points 1 and 2 within the well and aquifer, respectively. Well and aquifer responses of b) pressure head, c) water total head, and d) water levels.

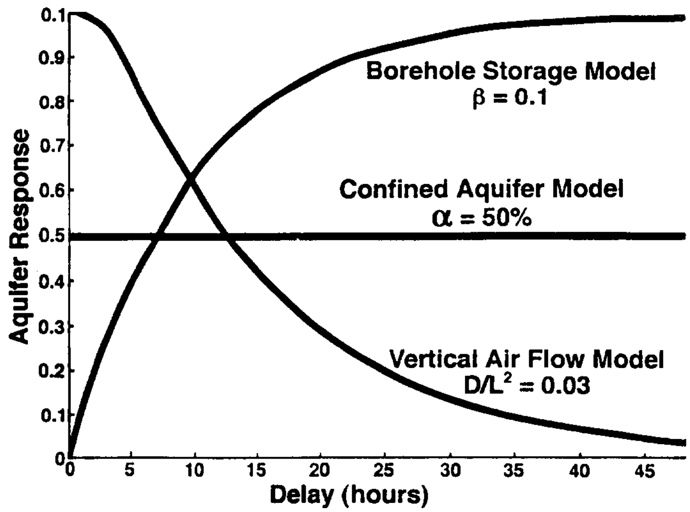

Fig. 2. Three types of barometric pressure response functions: confined aquifer, borehole storage or skin, and unconfined aquifer.

3.4 Summary of Response Functions

Figure 2 summarizes the lag-dependent nature of the barometric efficiency for the three models described above; a constant barometric efficiency for the confined aquifer model developed by Jacob (1940); a borehole storage or skin effect model developed by Hvorslev (1951); and an unconfined, vertical airflow model developed by Weeks (1979). Values of model parameters shown in Figure 2 are presented for comparison purposes only.

The step barometric response function for a confined aquifer is a constant, $u(\tau) = 1 - \alpha_0$, for all lags, τ, set equal to $\alpha = 0.5$ in the figure. In this example, the barometrically induced water level fluctuations are in phase with the barometric change and are a constant fraction of the barometric fluctuations. The borehole storage or skin model assumes a value of $\beta = 0.1$. The vertical airflow model assumes a value of $D_a / L^2 = 0.03$. As can be noted from the figure, each of the relationships have a substantially different shape, which should provide diagnostic information for identification of processes and parameters in aquifers.

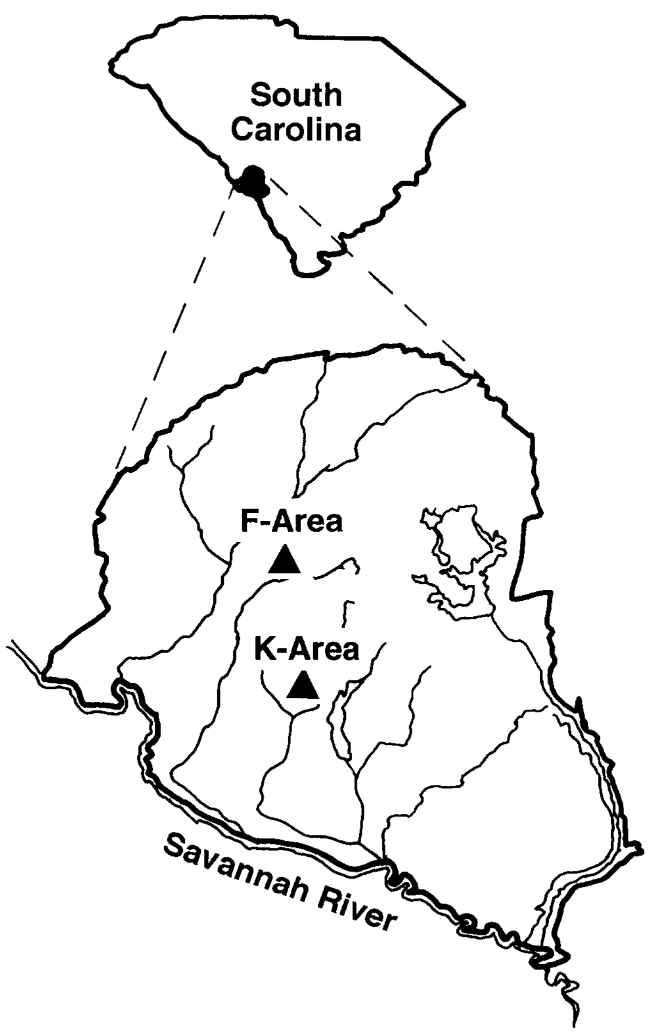

Fig. 3. Location of study areas at the Savannah River Site.

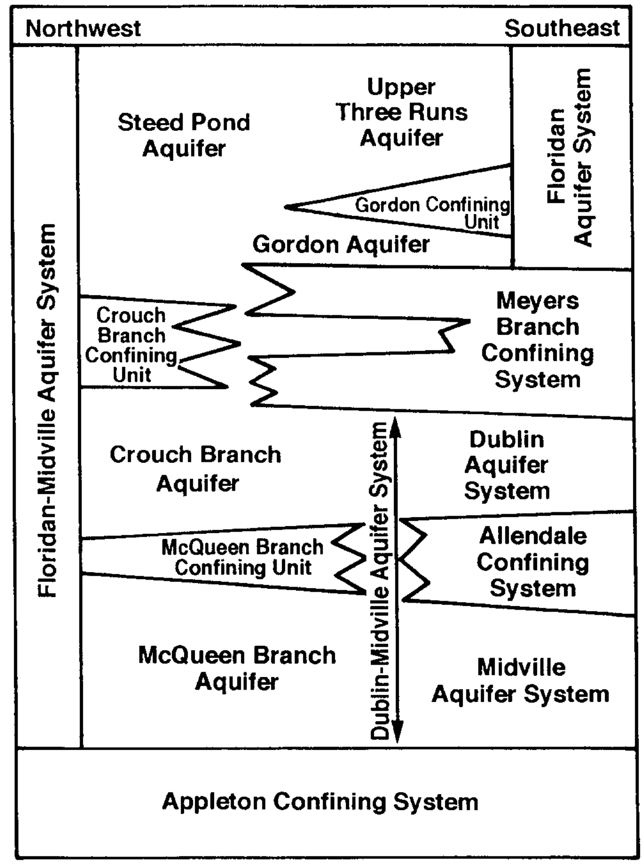

Fig. 4. Hydrostratigraphic units in the Southeastern Coastal Plain Hydrogeologic Province.

4. Application

Data for demonstrating methods to estimate the effects of barometric pressure changes on measured water levels were collected at the Savannah River Site (SRS). SRS is owned by the U.S. Department of Energy and has been managed by the Westinghouse Savannah River Corporation since 1989. The site is located in South Carolina (Figure 3) and occupies an area of approximately 770 km^2. SRS lies on the Atlantic Coastal Plain and is underlain by a seaward thickening wedge of unconsolidated and semiconsolidated strata that ranges from late Cretaceous to Holocene (Figure 4). The sequence thickens from approximately 200 m at the northern edge of SRS to 365 m at the southern boundary. The regional dip of the land surface is to the southeast, averaging 6 m km^{-1} (Aadland, 1993). Because the regional dip of the top of the pre-Cretaceous basement is 9 m km^{-1}, the sedimentary wedge is thickening at a rate of approximately 3 m km^{-1}.

4.1 Data Collection

Monitoring wells near the K-area Acid-Caustic Basin were selected for investigation because water levels in this area exhibit substantial seasonal and long-term fluctuations. The KAC wells surround the Acid-Caustic seepage basin which is located in the eastern part of K-Area. The basin, constructed in the early 1950s, is an unlined pit that received dilute sulfuric acid and sodium hydroxide solutions. The basin provided an area for the mixing and neutralization of dilute solutions before their discharge to nearby streams. The monitoring wells were installed to observe water levels in the unconfined, surficial aquifer. The wells are screened at the water table which occurs approximately 14 m below ground surface. A clay lens is generally present beneath the site at about the same depth as the water table; the water table lying within the clay lens at some wells, and lying above the clay lens in other wells. Water levels monitored on a quarterly basis have fluctuated more than a meter during the course of a year, and have fluctuated more than three meters during the 10-year period of record. Four wells (KAC-1 to KAC-4) were installed in the early 1980s while five (KAC-5 to KAC-9) were installed in the early 1990s.

A second study area was selected in the F-Area to investigate the effects of barometric pressure fluctuations on vertical hydraulic gradients and also to investigate the behavior of water levels in confined hydrogeologic units. This cluster was installed in the mid-1970s as part of a baseline hydrogeologic study. Wells FC-2E and FC-2F monitor the unconfined Upper Three Runs Aquifer and Well FC-2B monitors the locally confined Gordon aquifer. The average depth to the water table is approximately 20 meters. The P28 well cluster lies adjacent to the FC-2 well cluster, and monitors deeper hydrostratigraphic units. The deepest well, P28-TA, monitors the Midville aquifer system. Well P28-TE is completed in the overlying Dublin aquifer system. Well P28-TC is completed in the McQueen Branch confining unit which separates the Dublin and Midville systems.

Water level measurements were obtained using strain-gage type pressure transducers vented to the atmosphere. The transducers were lowered to a depth of between 0.3 to 3.0 m below the water surface in each well. The ranges of the pressure transducer varied from 3.5 to 7 m of water. The wells caps were removed so that the wells were open to the atmosphere. Manual water level measurements were taken before the transducers were placed in the wells. A barometric pressure sensor (80 to 106 kPa range, ± 0.03 kPa accuracy) collected barometric pressure readings. Water level and barometric pressure data were collected using a datalogger every two hours for 21 days at K-Area wells, and for 29 days at F-Area wells. A calibration program internal to the datalogger was used to convert pressure readings to equivalent water depths. A laptop computer was used to collect data from the datalogger. Daily precipitation data were obtained from the SRS weather department.

Barometric pressures and daily precipitation data collected during late 1993 at K-Area wells are presented as Figure 5, and selected water level measurements for the same period are presented as Figure 6. Similar data for data collected at F-Area wells during a sampling period in early 1994 are shown in Figures 7

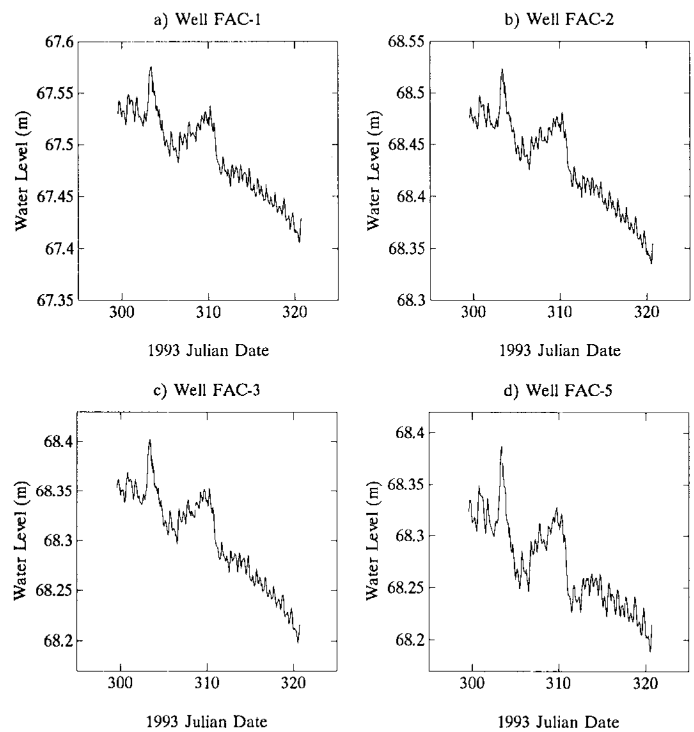

Fig. 6. Water level measurements at K-Area wells: a) KAC-1; b) KAC-2; c) KAC-3; and d) KAC-5. All wells are completed in an unconfined aquifer.

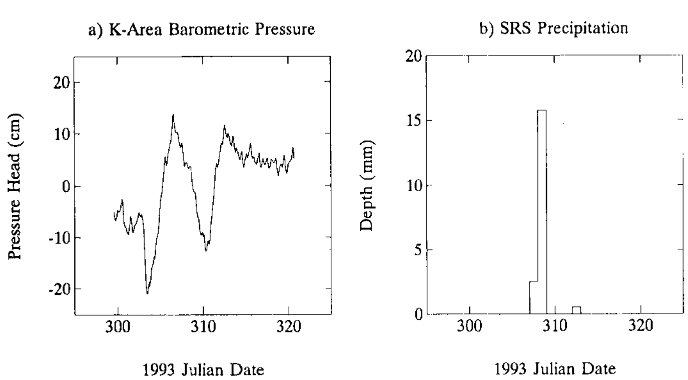

Fig. 5. K-Area a) barometric pressure and b) daily precipitation.

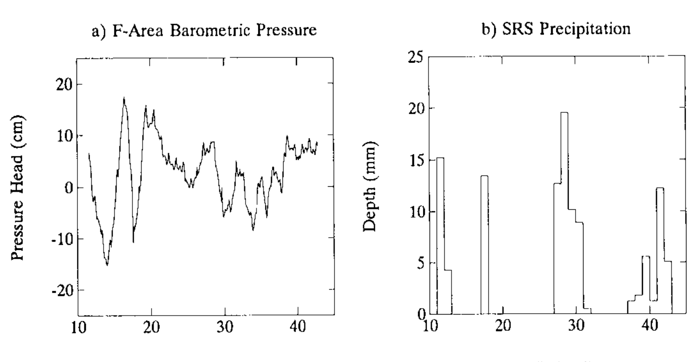

Fig. 7. F-Area a) barometric pressure and b) daily precipitation.

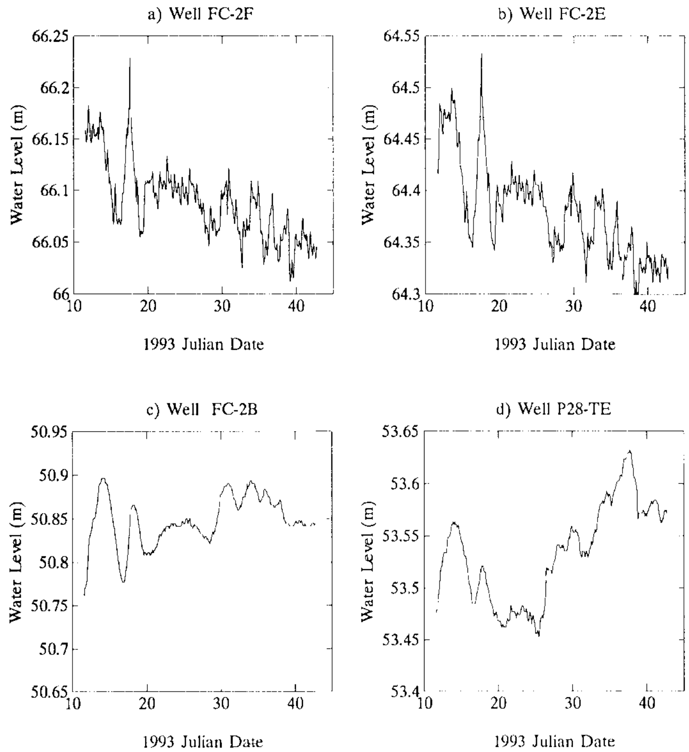

Fig. 8. Water level measurements at F-Area wells: 1) FC-2F; b) FC-2E; c) FC-2B; and d) P28-TE. FC-2F and FC-2E are completed in an unconfined aquifer.

and 8. Barometric pressure changes average approximately 7 cm for both periods, with a maximum range of over 30 cm. Water levels in the unconfined units (all K-Area wells and FC-2F and FC-2E) show a downward trend. Water levels in confined units (i.e., FC-2B and P28-TE) tend to be smoother than water levels in unconfined units.

4.2 Barometric Efficiencies

Linear regression estimates of aquifer barometric efficiencies are provided in Table 1. The regression procedure used both equations (8) and (9) to determine the long-term, α_L, and short-term, α_S, responses to barometric pressure, respectively. Also presented in Table 1 are barometric efficiencies estimated using Clark's Method as modified by Davis and Rasmussen. As can be noted in the table, the Modified Clark's Method provides estimates that are not significantly different from the short-term estimates. Substantial differences between the short- and long-term responses (α_S and α_L, respectively) are seen in the table, which can be explained by the time-delay needed for the aquifer and well to respond to barometric pressure changes. In confined aquifers with no borehole or storage or skin effects, there should be no difference between the two measures. For unconfined aquifers, the short-term response should be larger than the long-term response. For a delayed yield response in a confined aquifer, the short-term response should be smaller than the long-term response.

Using these diagnostic rules as a guide, it is clear that the unconfined aquifers include all KAC wells and Wells FC-2F and FC-2E. This inference is consistent with our a priori understanding of the site. If we were faced with a situation where the degree of confinement was unknown, then this simple diagnostic test would allow us to determine the degree of confinement. As expected, the diagnostic rules conclude that the remaining wells (FC-2B, P28-TC, and P28-TA) are confined. We can also see possible borehole storage or skin effects in the wells, especially in Well P28-TA. Because the well diameters are relatively small (<25 cm) and are completed in relatively productive aquifers, the possibility of borehole storage is slight. Yet, because the wells were constructed using mud drilling techniques, they may be subject to skin effects. Regardless, the diagnostic analysis indicates the possibility for decreased response in Well P28-TA.

4.3 Barometric Response Functions

Regression deconvolution is used to estimate the barometric response functions at K-Area and F-Area wells. The objective of this exercise is to demonstrate the utility of the response functions for identifying well response behavior. Figures 9a-d present the barometric response functions, along with their standard errors, for K-Area wells. The response functions for these wells, installed within the surficial, unconfined aquifer, are similar. A step change in barometric pressure causes a quick change of approximately 60 percent of the barometric change, and a slow recovery over several hours to the pre-step water level. The slow recovery is an indication that the air pressure wave is being transmitted through the unsaturated zone, and the pressure head on the water table is slowly equilibrating with the air pressure on the water surface in the well.

In the F-Area, the shallowest well, FC-2F (Figure 10a), shows a similar, initial response in water levels of approximately $\alpha = 0.5$, which means that a step decrease of 1 cm in barometric pressure results in a water level increase of 0.5 cm in the well. Over time the water level in the well returns to zero as the barometric pressure change reaches the water table and total pressures equilibrate. The slow recovery (decline) in water levels reaches a minimum at 20 hours, but increases to another maximum at 24 hours. The water level then declines to zero by 40 hours. The peak at 24 hours is puzzling, and may be attributed to daily oscillations in barometric pressure or to earth tides. This type of unusual behavior was not observed in other wells.

Table 1. Barometric Efficiencies (Expected Value ± One Standard Error)

Well	Aquifer type	Linear regression α_L	Linear regression α_S	Clark's method α_C
KAC-1	Unconfined	0.139 ± 0.013	0.474 ± 0.028	0.458 ± 0.184
KAC-1	Unconfined	0.141 ± 0.015	0.471 ± 0.030	0.442 ± 0.134
KAC-3	Unconfined	0.144 ± 0.016	0.497 ± 0.027	0.492 ± 0.136
KAC-5	Unconfined	0.211 ± 0.018	0.668 ± 0.029	0.645 ± 0.125
KAC-6	Unconfined	0.164 ± 0.017	0.614 ± 0.028	0.596 ± 0.142
FC-2F	Unconfined	0.231 ± 0.027	0.456 ± 0.039	0.389 ± 0.075
FC-2E	Unconfined	0.400 ± 0.030	0.753 ± 0.022	0.753 ± 0.064
FC-2B	Confined	0.313 ± 0.015	0.157 ± 0.013	0.150 ± 0.021
P28-TE	Confined	0.241 ± 0.035	0.157 ± 0.015	0.156 ± 0.034
P28-TC	Confined	-0.028 ± 0.064	0.007 ± 0.018	0.027 ± 0.026
P28-TA	Confined	1.077 ± 0.086	0.456 ± 0.097	0.478 ± 0.085

Notes:
α_L estimated using observed barometric pressures and water levels.
α_S estimated using first differences of barometric pressures and water levels.
α_C estimated using modified Clark's method (Davis and Rasmussen, 1993).

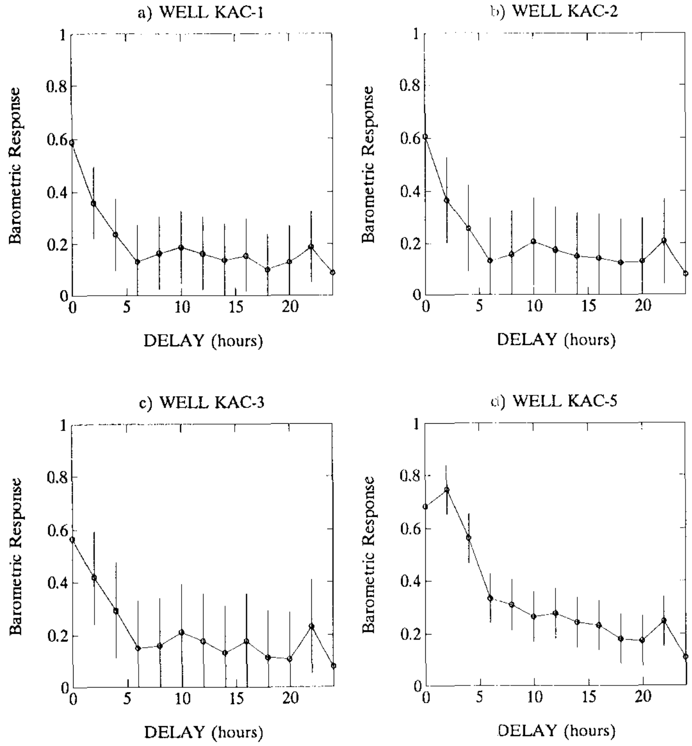

Fig. 9. Barometric response functions (± one standard error) for K-Area wells: a) KAC-1; b) KAC-2; c) KAC-3; and d) KAC-5.

For the next deeper well, FC-2E (Figure 10b), also in the unconfined aquifer, the response starts at a higher value, $\alpha_0 \approx 0.85$, and decreases slowly over time. Because the standard errors are small for the estimated values of the barometric response function, the function was used to fit the observed water level record, with residual errors less than 1 cm. To estimate the optimal value of the air diffusivity, a least-squares approach was used in this unconfined well. The minimum error is found at approximately $D_a = 21\ m^2/hr$. This value of vertical diffusivity compares favorably with measurements (D_a ranged from 6 to 25 m^2/hr) at a site in the same hydrogeologic province (Rojstaczer and Tunks, 1995). A residual error of approximately 3 cm remains after fitting this value of diffusivity to the data.

The next deeper well, FC-2B (Figure 10c), demonstrates a behavior which is consistent with a combination of a confined aquifer response along with a borehole storage or skin response. The confined barometric efficiency is approximately 0.4 based on the long-term response. Yet the borehole storage or skin component causes the initial response to be approximately 0.1. The slow change from 0.1 to 0.4 over the course of approximately 24 hours results from the equilibration in total head between the well and the aquifer. The deepest well, P28-TE (Figure 10d), also shows behavior similar to FC-2B, although the large errors about the estimated response values precludes any definitive statements. In general, the response function tends to change with time to a value of approximately 0.4.

Comparison of Table 1 with the Figures 10a-d demonstrates the influence of lag on the estimated barometric efficiency. Barometric efficiencies estimated using changes in water levels, α_S, or using Clark's Method, α_C, are generally consistent with the zero-delay barometric efficiency. Also, barometric efficiencies estimated using observed water levels and barometric pressures, α_L, are generally consistent with the value of the barometric efficiencies after a longer lag, approximately 10 hours. The high and low frequency components of barometric pressure fluctuations induce different responses in confined and water-table aquifers.

As a general rule, unconfined aquifers show a decrease in the barometric efficiency with lag due to the delay required for the barometric pressure change to travel through the unsaturated zone. Confined aquifers, on the other hand, show a constant barometric efficiency that is independent of lag. In both cases, the additional influence of borehole storage or skin complicates the analysis by reducing the calculated barometric efficiency for the early period. Thus, a confined aquifer that also exhibits a strong borehole storage or skin component would have a coupled response of small values of barometric efficiency at short lags that eventually stabilizes at a constant value of barometric efficiency at larger lag times.

4.4 Removing Barometric Effects

The previous section focused on understanding the effects of barometric pressure on water level fluctuations. If, instead, our objective is to examine some underlying process that is not otherwise apparent, then we need to remove these effects. A barometric-corrected head can be obtained by removing the barometric influence. Given an estimate of the barometric efficiency (i.e., α_L, α_S, or α_C), we obtain the corrected, or residual head, R, using:

$$R(t) = H(t) - (1 - \alpha)\, B(t) = W(t) + \alpha B(t) \qquad (13a)$$

and using the barometric response function:

$$R(t) = H(t) - [\Delta\mu_0\, B(t) + \Delta\mu_1\, B(t-1) + \ldots + \Delta\mu_n\, B(t-n)] \qquad (13b)$$

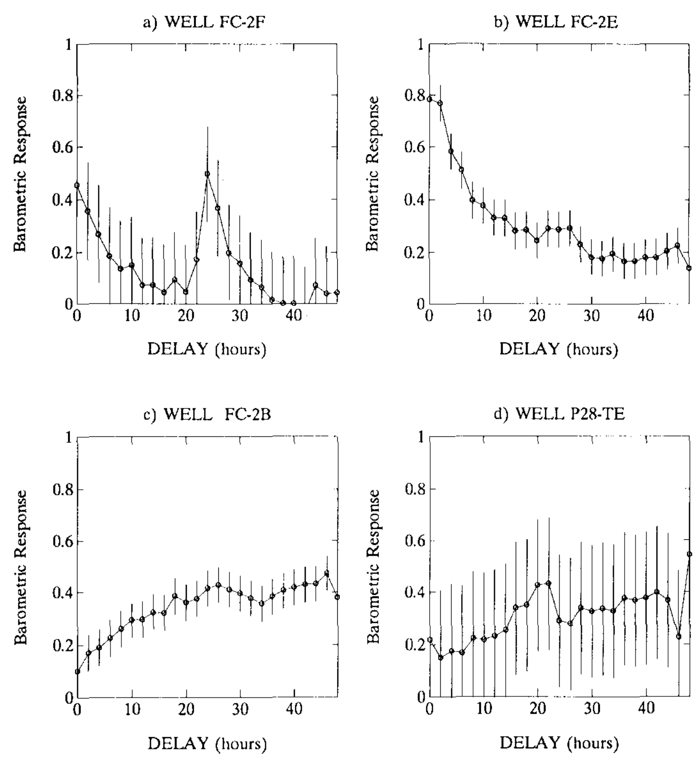

Fig. 10. Barometric response functions (± one standard error) for F-Area wells: a) FC-2F; b) FC-2E; c) FC-2B; and d) P28-TA.

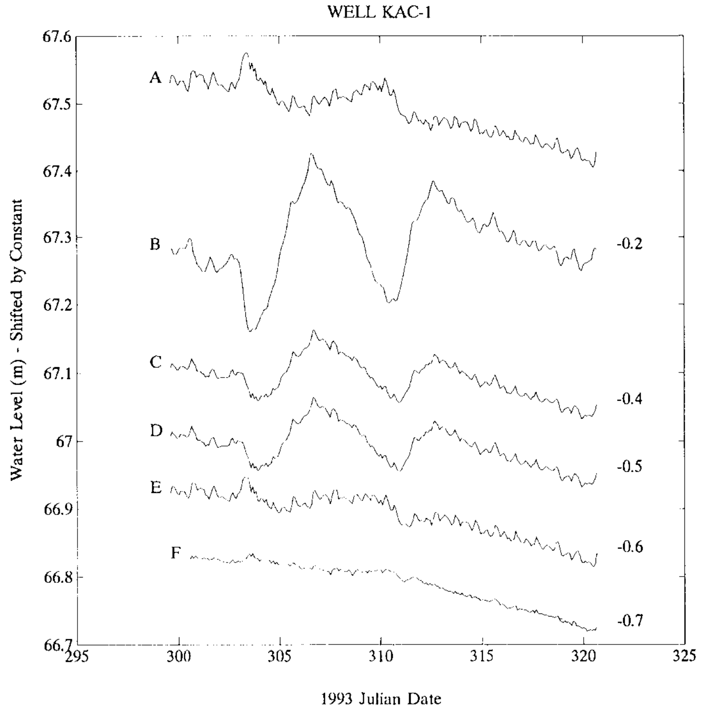

Fig. 11. Well KAC-1: A) water levels; B) total heads; and corrected heads using barometric efficiencies using C) modified Clark's method, α_C, D) short-term, α_S, E) long-term, α_L, and F) barometric response functions, $\mu(\tau)$. Plots B-F are shifted downward by indicated constant for clarity.

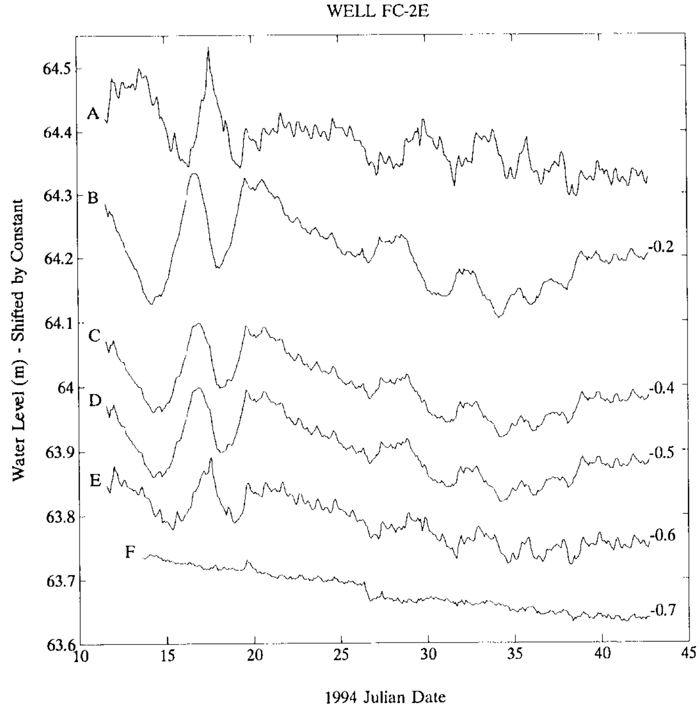

Fig. 12. Well FC-2E; A) water levels; B) total heads; and corrected heads using barometric efficiencies using C) modified Clark's method, α_C, D) short-term, α_S, E) long-term, α_L, and F) barometric response functions, $\mu(\tau)$. Plots B-F are shifted downward by indicated constant for clarity.

It should be stressed that the residual head should not be used to calculate hydraulic gradients, or for plotting a piezometric surface. Three wells (KAC-1, FC-2E, and P28-TE) were selected to demonstrate the use of this approach. Figures 11-13 show for each well, respectively, how the correction reduces the barometric effects. Each figure shows: (A) the original water levels, (B) total heads, and residual heads calculating using (C) the modified Clark's method, (D) the short-term (difference) barometric efficiency, (E) the long-term barometric efficiency, and (F) the barometric response correction. For clarity, the individual plots have been shifted downward by the constant value indicated on the plot to the right of the line.

From Figure 11 (Well KAC-1), it is clear that the residual head calculated using the barometric response function (Line F) is substantially smoother than the original. Residual heads calculated using constant barometric efficiencies do not fare as well, and show substantial remaining barometric effects. Figure 12 (Well FC-2E) shows a similar dramatic reduction in the noise of the original water level measurements. In fact, a small change around day 27 is clearly apparent in Line F, which was not visible in the original data (Line A). Figure 13 (Well P28-TE) is an example in which the residual head (Lines C-F) are as noisy as the original water levels. Yet the residual response could be a useful indicator of the response of the system to nonbarometric influences.

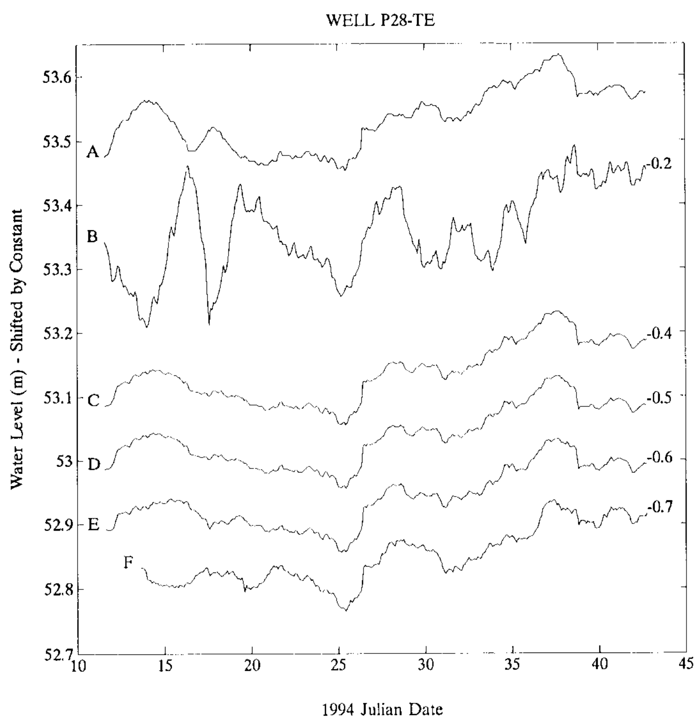

Fig. 13. Well P28-TE; A) water levels; B) total heads; and corrected heads using barometric efficiencies using C) modified Clark's method, α_C, D) short-term, α_S, E) long-term, α_L, and F) barometric response functions, $\mu(\tau)$. Plots B-F are shifted downward by indicated constant for clarity.

5. Summary and Conclusions

Water level measurements in wells are routinely used without correction at the Savannah River Site (SRS) to determine the magnitude and direction of hydraulic gradients, and to interpret aquifer pumping tests. In most cases the water levels are used as an estimate of the total head within the hydrostratigraphic unit. This paper demonstrates that fluctuations in barometric pressure at SRS cause water levels in wells to deviate from the total head within aquifers. Because the magnitude and direction of the ground-water gradient is based on spatial changes in total head, failure to incorporate barometric pressure measurements when obtaining water levels can cause systematic errors in the gradient calculation. This is because relatively large perturbations are induced by barometric pressure fluctuations, which average 7 cm of water head and can exceed 30 cm at SRS.

To minimize errors in the calculation of the hydraulic gradient, it is recommended that the total head (the sum of water level plus barometric pressure) be used to calculate both vertical and horizontal ground-water gradients. The adjustment is recommended especially in cases where wells are closely spaced, form acute triangles, and where the gradient is small. With the advent of modern pressure transducers, this means that absolute pressure transducers should be used instead of differential or gauge transducers.

This paper also shows that variations in barometric pressure can be used diagnostically to distinguish confined from unconfined aquifers, and to estimate the unsaturated zone air diffusivity near a well in an unconfined aquifer. Estimation of aquifer properties is made possible using a barometric response function, which relates a change in barometric pressure to the observed change in water level within the well. Three types of models (confined response, unconfined response, and borehole storage or skin) are examined and compared to observed barometric response functions.

Removal of barometric effects is useful when trying to identify the hydraulic response to rainfall or during aquifer pumping tests. In most cases examined in this study, residual water levels are shown to behave more smoothly when barometric effects are removed.

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