EFFECTS OF BAROMETRIC PRESSURE ON WATER LEVELS AND GRADIENTS AT THE SAVANNAH RIVER SITE

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Abstract. It is shown that ignoring or removing barometric pressure fluctuations is incorrect if the objective is to calculate the direction and magnitude of the hydraulic gradient. This results from the need to consider the gradient in the total head, which is the sum of the water surface elevation and the barometric pressure at the water surface. The proper method for obtaining the total head is to add the barometric pressure to the water level. The effects of barometric pressure can be subtracted, however, if the objective is to identify responses to perturbations that are masked by the barometric response. The misspecification of the hydraulic head is shown to significantly affect the calculation of hydraulic gradient if the well triplet used to calculate the gradient lie close to each other or if they form a shallow angle. In general, neglecting the barometric pressure correction introduces only a small error at the Savannah River Site.

INTRODUCTION

An important function of groundwater monitoring wells is to determine the water table elevation or piezometric surface within a hydrogeologic unit. Water levels are used to determine the local or regional hydraulic gradient within the hydrogeologic unit or to determine the vertical hydraulic gradient between units. Knowledge of the hydraulic gradient is required to estimate the darcian flux and fluid velocities within or between units, which are the primary concern at proposed waste disposal sites, and waste sites undergoing remediation, because they control the direction and magnitude of waste migration.

This paper presents an analysis of the effects of barometric pressure on water levels in monitoring wells at the Savannah River Site (SRS). Water levels in SRS wells at two study areas at SRS were used to evaluate the influence of barometric pressure on horizontal and vertical hydraulic gradients. In contrast to current practices in which the barometric pressure effect is either ignored or removed from the observed water level, we found that the barometric pressure should be added to the water level measurement. No barometric correction is required if an absolute pressure transducer is employed. Barometric fluctuations are useful for estimating the barometric efficiency, which can be used to estimate aquifer properties. The barometric pressure should be removed from the record if the response to a natural perturbation (e.g., earth tides, recharge) or to an induced perturbation (e.g., pump tests) is desired. In these situations, the proper functional relationship between water levels and barometric pressure should be incorporated.

STUDY AREA

The Savannah River Site (SRS) occupies an area of approximately 770 km^2 on the Aiken Plateau in South Carolina. The site is owned by the United States Department of Energy (DOE) and has been managed by the Westinghouse of the site was to produce special nuclear materials for national defense. The current mission is to mitigate groundwater contamination caused by nuclear materials production and processing. SRS is situated on the Atlantic Coastal Plain which is underlain by a seaward thickening wedge of unconsolidated and semi-consolidated strata that ranges from Late Cretaceous to Holocene in age. The sequence thickens from approximately 198 m at the northern edge of SRS to 365 m at the southern boundary. SRS lies within the Southeastern Coastal Plain Hydrogeologic Province which constitutes a multi-layered hydraulic complex of interbedded fine- to coarse-grained sand with local gravel and limestone lenses deposited under relatively high energy conditions in fluvial to shallow marine environments (Miller and Renken, 1988). The aquifer units are separated by clay beds and marls that may or may not be continuous across the site. The lower permeability units occur where quieter depositional conditions prevailed (Aadland, 1993).

K-area Acid-Caustic Basin

Nine monitoring wells near the K-area Acid-Caustic Basin were selected for investigation because water table elevations in this area exhibit substantial seasonal and long-term fluctuations. Water levels monitored on a quarterly basis fluctuate over one meter during the course of a year, with a total range of over three meters for the period of record. Four wells (KAC1 to KAC4) were installed in the early 1980s while five (KAC5 to KAC9) were installed in the early 1990s. The wells are located in the eastern part of K-Area near a tributary of Pen Branch.

The K-area Acid Caustic Basin, constructed in the early 1950s, is an unlined earthen pit that received dilute sulfuric acid and sodium hydroxide solutions and other wastes from areas within SRS. The topography near the basin is moderately sloping to the east, with an outfall effluent stream near the site. Monitoring 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. The sediments of the surficial aquifer near the basin lie in the Barnwell Group.

F-area wells

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. The FC-2 well cluster is located outside the F-Area perimeter fence. This cluster was installed in the mid-1970s as part of a baseline hydrogeologic study, along with other clusters distributed across SRS. Wells FC-2E and FC-2F are unconfined wells in this cluster. Well FC-2E is 30-m deep with a screened interval from 28 to 30 m. Well FC-2F is 25-m deep with a screened interval from 22 to 24 m. Both wells use a 10-cm carbon steel casing. The P28 well cluster is a deep exploratory cluster situated immediately adjacent to the FC-2 well cluster that is used to monitor the piezometric heads in various units of the Floridan Aquifer.

DATA COLLECTION METHODS

Water level measurements were obtained using Instrumentation Northwest, Inc. PS-9000 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 Väisälä PAI-247 barometric pressure sensor (80 to 106 kPa range, ± 0.03 kPa accuracy) collected barometric pressure readings. Water level and barometric pressure data were collected every two ours using an Aquistar PL-4A eight-channel datalogger. A calibration program internal to the datalogger was used to convert pressure readings to equivalent water depths. A Zenith Masterport 386-SX lap-top computer was used to collect data from the datalogger. Daily rainfall depths were obtained from the SRS weather department. Additional rainfall measurements were collected manually in the F-Area.

BAROMETRIC PRESSURE AND WATER LEVELS

Barometric pressure fluctuates due to many causes, the most significant source of variation being weather disturbances such as frontal systems. An additional significant cause of barometric pressure variation results from daily and twice-daily responses due to the rotation of the earth. These periodic fluctuations result from changing gravitational forces, similar to ocean tides, and also due to atmospheric heating by the sun. Many other sources of barometric pressure variation are also present, including global disturbances from volcanic eruptions and local disturbances such as wind eddies (Gossard and Hooke, 1975).

The fluctuation in water levels in open wells due to barometric pressure changes was noted by Pascal in 1663, who originally formulated the concept of atmospheric pressure (Pascal, 1973). The relationship between water level and barometric pressure changes is an inverse one; increases in barometric pressure create declines in observed water levels (see, e.g., Freeze and Cherry, 1979, p. 233). Barometric pressure measurements are used to establish the barometric efficiency, which is the ratio of change in hydraulic head to the change in barometric pressure:

$$\alpha = -\frac{\Delta W}{\Delta B} \qquad (1)$$

where α is the barometric efficiency, ΔW is the water level change in the well, and ΔB is the barometric pressure head change. This relationship can be understood using the total head, H, which is the sum of the pressure head, B, and an elevation head, W:

$$H = B + W \qquad (2)$$

where the elevation head is usually measured with respect to mean sea level and the pressure head is relative to the mean barometric pressure at sea level. One can hypothesize two extreme well response cases. The first case occurs when the total head equilibrates instantly after a barometric pressure change. An example is a pond or shallow aquifer where the water table is very close to the surface. In this case the change in total head equals the change in the barometric pressure, (i.e., $dH/dB = 1$), and the barometric efficiency is zero. The barometric efficiency for well P28-TC was calculated using Ordinary Least Squares (OLS) regression to be 0.026 ± 0.040 (expected value ± one standard error), which is not statistically different from 0. This indicates that the total head in the well equilibrates instantly with changes in barometric pressure. In this case the response is likely due to the completion of the screened interval in a confining unit, which effectively isolates the water within the well from an aquifer response.

An alternate case is an aquifer in which the total head is insensitive to barometric pressure changes, such as within a deep, unconfined aquifer. If barometric pressure changes do not affect the total head in the aquifer (i.e., $dH/dB = 0$), then the water level in the well must compensate to maintain the constant total head:

$$\frac{dW}{dB} = \frac{d(H-B)}{dB} = -1 \tag{3}$$

Thus, the barometric efficiency should be 1 for an aquifer in which the barometric pressure does not affect the total head within the aquifer. The barometric efficiency for well P28-TA was calculated to be 1.077 ± 0.107, which is not statistically different from 1. It is apparent that the total head is unaffected by the barometric pressure in this unit. An analysis based upon the raw water level measurements would lead us to the erroneous conclusion that the potentiometric surface in well P28-TA is changing due to changes in barometric pressure. In fact, the changing water level is an artifact of the water level measurement technique; the open borehole allows rapid equilibration with barometric pressure at the water surface within the borehole.

Water levels within an open well fluctuate only because the barometric pressure force on the water surface must be offset by a reduction in the height of the fluid column to maintain a constant total head. Thus, the water level in an open well must compensate to the barometric pressure change to maintain a total head that is in equilibrium with the constant total head in the aquifer while the water level in a well isolated from the atmosphere does not.

Table 1 presents regression estimated barometric efficiencies for Wells FC-2 and P28 using regression of observations, α_L, and first differences of observations, α_s. Significant differences exist between the methods. These differences can be explained by noting that α_L is more sensitive to long-period fluctuations while α_S responds to short-period fluctuations. In other words, α_L is a better estimate of the low-frequency relationship between the two variables, while α_S is a better estimate of the high-frequency relationship.

HYDRAULIC GRADIENTS

An important additional objective was to evaluate the influence of barometric pressure variation on measured hydraulic gradients. Of special interest was whether barometric pressure perturbations cause inaccurate estimates of groundwater flow gradients. This interest arises from the need to constrain potential contaminant transport rates and pathways using water level data and the concern that substantial uncertainties in calculated transport rates and directions may result if barometric pressure fluctuations are ignored.

Figure 1 presents errors in total head or water level measurements due to fluctuating barometric pressures. Note that the average and maximum errors increase as the delay between water measurements increases, up to a delay of approximately two days. After two days, the measurement error tends to stabilize at a value of approximately 10 cm for the average error and 20 to 30 cm for the maximum error. For example, in a well with $\alpha = 0$ (i.e., an aquifer with instantaneous equilibration with barometric pressure changes), the water level will not respond to barometric pressure fluctuations and two measurements separated by any interval of time will be constant (assuming no other trend components). Yet the total head will be in error by the amount of the barometric pressure change. On the other hand, a well with $\alpha = 1$ (i.e., the total head is constant over time) responds dramatically to barometric pressure changes, and two measurements separated by any interval of time will demonstrate large changes in water level.

TABLE 1. Barometric Efficiencies (expected value ± one standard error) in FC2 and P28 Wells.

Well	Hydrogeologic Unit	Screen Elevation (m)	Total Head (m)	Linear Regression		Clark's Method
				α_L	α_S	α_C
FC-2F	Upper Three Runs Aquifer	63.2 to 64.7	66.1 ± 0.1	0.231 ± 0.035	0.456 ± 0.061	0.389 ± 0.075
FC-2E	Upper Three Runs Aquifer	57.9 to 59.1	64.4 ± 0.1	0.400 ± 0.051	0.753 ± 0.081	0.753 ± 0.064
FC-2B	Gordon Aquifer	24.0 to 25.5	50.9 ± 0.1	0.313 ± 0.036	0.157 ± 0.021	0.150 ± 0.021
P28-TE	Crouch Branch Aquifer	-40.8 to -37.5	53.4 ± 0.1	0.297 ± 0.045	0.149 ± 0.023	0.149 ± 0.034
P28-TC	McQueen Branch Confining Unit	-86.0 to -82.7	52.9 ± 0.1	0.124 ± 0.077	0.024 ± 0.040	0.047 ± 0.025
P28-TA	McQueen Branch Aquifer	-150.6 to -140.7	53.2 ± 0.1	1.077 ± 0.141	0.456 ± 0.107	0.478 ± 0.085

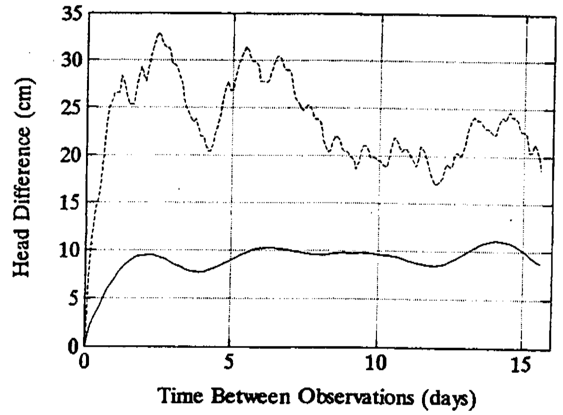

Figure 1: Influence of time delay between water level measurements on water level error assuming average (lower line) and maximum (upper line) conditions.

To demonstrate the effects of barometric pressure perturbations on the interpreted gradient, we examine two types of gradients; vertical gradients estimated from the FC-2 and P28 well clusters, and horizontal gradients estimated from KAC wells. The vertical gradient, G_v, can be calculated using two wells screened at different depths within the same or in different hydrogeologic units. The vertical gradient is calculated using the total head drop, ΔH, between the screened intervals:

$$G_v = \frac{\Delta H}{\Delta z} \tag{4}$$

where Δz is the elevation difference between the screened zones. The ratio between the error in the vertical gradient, $\sigma(G_v)$, and the introduced by an error in the total head difference, $\sigma(\Delta H)$, is:

$$E(G_v) = \frac{\sigma\,(G_v)}{\sigma\,(\Delta H)} = \frac{1}{\Delta z} \tag{5}$$

Table 2 presents an analysis of errors introduced by failing to incorporate changes in barometric pressure between measurements. The last column of the table is calculated assuming a 10-cm error in total head estimation. As can be observed from the table, the barometric error is minor in comparison to the mean gradient. In no case will the error induced by a misspecification of the total head cause a substantial changes in the direction of the hydraulic gradient. In most cases, the error due to excluding the barometric pressure is comparable to the gradient error.

The horizontal groundwater gradient can be estimated by assuming a planar surface represents the potentiometric surface within the hydrogeologic unit. A minimum of three wells are required in the same unit to represent this planar surface. The direction of the hydraulic gradient is parallel to the maximum dip of this surface, and the slope in this direction is the magnitude of the hydraulic gradient. To find the direction of flow, one must assume homogeneity of material properties or have some knowledge of the hydraulic conductivity tensor. Also, one must generally assume a constant aquifer thickness and neglect recharge and discharge from the hydrostratigraphic unit. Ideally, groundwater level observations from a number of locations within a single unit should be used to determine the direction and magnitude of the groundwater gradient. The piezometric surface can be estimated by using information from many sites, and the gradient vectors can be mapped.

The three-point method uses total head measurements at three wells, H_o, H_1 and H_2, to calculate the horizontal direction and magnitude of the groundwater gradient. The method uses the distance, L_1, between one of the wells (called the pivot well which is usually the well with the highest total head, H_o) and the well where H_1 is measured. Similarly there exists a distance, L_2, between the pivot well and the third well. The interior angle, λ, between the three wells is known if the distances between the wells are known:

$$\cos(\lambda) = \frac{L_1^2 + L_2^2 - L_0^2}{2\,L_1\,L_2} \tag{6}$$

TABLE 2. Vertical Gradients in FC-2 and P28 Wells.

Well Pair	Elevation Difference (m)	Vertical Gradient (m/km)	
		Mean ± Std. Dev.	Barometric Error
FC-2F to FC-2E	5.6	304.5 ± 4.3	± 17.8
FC-2E to FC-2B	33.6	403.1 ± 1.6	± 3.0
FC-2B to P28-TE	64.0	-41.6 ± 0.6	± 1.6
P28-TE to P28-TC	45.2	13.5 ± 2.4	± 2.2
P28-TC to P28-TA	61.4	-5.0 ± 2.5	± 1.6

where L_o is the distance between the two non-pivot wells. It is easily shown that the magnitude of the horizontal gradient, G_h, is:

$$G_h = \frac{G_1}{\cos(\beta)} = \frac{G_2}{\cos(\lambda-\beta)} \tag{7}$$

where $G_i = (H_i - H_o)/L_i$ and ß is the direction of the horizontal groundwater gradient, determined from:

$$\tan(\beta) = \frac{G_2}{G_1}\csc(\lambda) - \cot(\lambda) \tag{8}$$

Of interest to us is determining the error in the magnitude and direction of the gradient which is introduced by an error in the total head; the total head error resulting from failing to include the changing barometric pressure. It is shown in the Appendix that the ratio of the error in the magnitude of the horizontal gradient, $\sigma(G_H)$, to the error in total head, $\sigma(H_1)$, at one of the wells is:

$$E(G_h) = \frac{\sigma(G_h)}{\sigma(H_2)} = G_h \tan(\beta)\, E(\beta) \tag{9a}$$

$$E(\beta) = \frac{G_1 \sin(\lambda)}{L_2\left(G_1^2 - 2G_1G_2\cos(\lambda) + G_2^2\right)} \tag{9b}$$

Water level observations at K-area wells are used in conjunction with Equations (9a) and (9b) to evaluate the effects of neglecting barometric pressure changes. A barometric error of $\sigma(H_1) = 0.1$ m is again used.

Table 3 presents the interpreted magnitudes and directions of the hydraulic gradient for the well pairs. The first three well triplets in the table (KAC-3, KAC-5 and KAC-6) are very near each other and form a shallow angle, λ = 16.8°. The second well triplet (KAC-2, KAC-5, and KAC-1) forms a nearly equilateral triangle, with longer average distances between wells. As can be noted in the table, the magnitude of the gradient differs between the wells, with the second triplet having a smaller standard deviation. Also, the error introduced by neglecting variations in barometric pressure have a larger influence on the magnitude of the first well triplet.

The direction of the gradient is similarly affected, with wells more equidistant and spaced further apart being less sensitive to the error associated with neglecting barometric pressure. It appears that the barometric pressure error has a more significant effect on the gradient when wells are very closely spaced or form an acute triangle.

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TABLE 3. Horizontal Gradients in KAC Wells.

Well Triplet	Distance Between Wells (m)			Angle Between Wells, λ	Gradient Magnitude (m/km)		Gradient Direction (degrees)	
	L_o	L_1	L_2		Mean ± Std. Dev.	Barometric Error	Mean ± Std. Dev.	Barometric Error
KAC-3, KAC-5, KAC-6	9.1	12.4	20.3	16.8°	10.8 ± 0.6	± 25.3	194.3 ± 11.7	± 157.8
KAC-2, KAC-5, KAC-1	30.9	31.7	33.3	56.8°	102.0 ± 0.2	± 3.8	203.0 ± 0.2	± 0.3