Response of well-water elevations and spring discharge to changes in barometric pressure, Eastern Snake River Plain Aquifer, Hagerman, Idaho

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Abstract

The effect of barometric pressure change on well-water levels was identified in four wells penetrating the Eastern Snake River Plain [ESRP] aquifer between Milner Dam and King Hill, Idaho. Removal of barometric effects on well-water elevations allows measurement of external stresses [such as changes in drawdown during aquifer tests] that could be obscured by well-water fluctuations caused by barometric pressure changes. Multiple-regression deconvolution reveals that the wells penetrate confined aquifers and that well-water levels in one well are affected by wellbore storage or skin effects.

Application of a simple linear regression model between barometric pressure and spring discharge at National Fish Hatchery #15, Blind Canyon Springs, and Sand Springs suggests that changes in spring discharge may be independent of barometric pressure. Alternatively, changes in spring discharge are less than the precision of the instruments measuring discharge.

Because the hydraulic gradient in parts of the ESRP aquifer is as low as 1 ft per mile [0.0002 ft/ft], the addition of atmospheric head to elevation head should be further evaluated. The use of total head [elevation head plus the atmospheric head component] may increase the accuracy of the hydraulic gradient and change the inferred direction of groundwater flow in parts of the ESRP aquifer.

Introduction

Hydrogeologists create potentiometric maps by contouring points of equal hydraulic head. External stresses [e.g., pumping, river-stage fluctuations, changes in barometric pressure, etc.] may affect field measurements used to develop the potentiometric maps. These external stresses should be identified and removed from measured well-water elevations prior to the preparation of potentiometric maps.

There are several reasons to remove the effect of change in barometric pressure on water levels. First, changes in drawdown in an observation well may be very small at the end of long-term aquifer tests, and changing barometric pressure may obscure variations in late-time drawdown. Second, in aquifers where there is a very low hydraulic gradient, more accurate potentiometric maps will be created when the atmospheric head component is added to measured well-water elevation. Finally, the water elevation in wells completed in confined and unconfined aquifers respond differently to changes in barometric pressure. Diagnostic plots of the effects of barometric pressure changes on the well-water elevation will differentiate between confined and unconfined aquifers and identify well bore storage or well skin effects.

The changes in well-water elevations in four [4] wells penetrating the ESRP aquifer near Hagerman, Idaho, were correlated with changes in atmospheric pressure. This correlation was performed as part of the planning prior to an aquifer test in the ESRP basalts near Hagerman and to develop additional insights into aquifer characteristics. The effect of barometric pressure on spring discharge was also investigated.

Theory of Barometric Pressure Changes on Head

Hubbert [1940, as presented in Spane, 1999; Domenico and Schwartz, 1990] derived groundwater flow from the physics of fluid movement. He defined fluid potential, ϕ, as the sum of three terms.

$$\phi = g * z_i + \frac{(P_i - P_a)}{\rho} + \frac{V^2}{2} \qquad \text{Eq. 1}$$

Where

g = the acceleration due to gravity, [L/T^2]

z_i = the elevation of the pressure measurement point P_i above reference datum, [L]

P_i = the absolute fluid-pressure measurement at point i, [F/L^2]

P_a= the atmospheric pressure at fluid surface, [F/L^2]

ρ= the fluid density, [M/L^3]

V = the fluid velocity, [L/T]

Because groundwater flow is very slow, it has a low kinetic energy potential, and the third term, velocity, is usually omitted. Equation 1 reduces to two terms, i.e., elevation and fluid pressure:

$$\phi = g * z_i + \frac{(P_i - P_a)}{\rho} \qquad \text{Eq. 2}$$

Assuming that the groundwater has a homogeneous chemical composition and that its density is not a function of pressure, ϕ, can be expressed as fluid-column height.

$$\phi = g * z_i + \frac{[(\rho * g * h + P_a) - P_a]}{\rho} \qquad \text{Eq. 3}$$

When height h is combined with elevation z_i, Equation 3 reduces to the height of water.

$$\phi = g * h \qquad \text{Eq. 4}$$

Fluid potential is the product of the height of a fluid column of known density, measured against a known datum and the acceleration due to gravity. Typically, when hydrogeologists measure head [*h*], they ignore the effects of changes in fluid density and atmospheric pressure on total head.

Hydrogeologists regularly measure the depth to top of the water table using an electrical tape [the term D_w below]. Alternatively, they may use a pressure transducer and an electronic data logger to record the height of the fluid column, h_{fc} , above an arbitrary datum [typically mean sea level]. Regardless of technique, hydrogeologists refer to that elevation as the "observed" hydraulic head. This measurement can be expressed as

$$h_o = W_e = E - D_w \qquad \text{Eq. 5}$$

where

h_o = the observed hydraulic head.

W_e = the water level above some reference datum, [L].

E = the elevation from which the field measurement is made, [L].

D_w = the depth from surface datum to the fluid-column surface within the well, [L].

Equation 5 above is the basic equation for observed head h_o. However, the observed head, h_o, must be corrected to fresh-water head, H_{fw} in aquifers where the density of water is not uniform, e.g., the aquifer in the Culebra Dolomite at the Waste Isolation Pilot Plant [WIPP] in New Mexico [Rocky Mountain Environmental, 2000).

Freshwater head, H_{fw}, is a modification of the basic equation for observed head [Equation 5 above] (Spane, 1999).

$$H_{fw} = \frac{(P_f - P_a)}{\rho_{fw} * g} + z_i \qquad \text{Eq. 6}$$

$$h_{fc} = \frac{(P_f - P_a)}{\rho_0 * g} + z_i \qquad \text{Eq. 7}$$

$$(P_f - P_a) = [(\rho_0 * g) * (h_{fc} - z_i)] \qquad \text{Eq. 8}$$

where

P_f = the formation pressure (absolute) at measuring point, i, within aquifer/well fluid column, $[F/L^2]$.

z_i = the elevation of the pressure measurement point at P_f and above reference datum, [L].

h_{fc} = the height of well fluid column above measurement point P_f , [L].

ρ_{fw} = the density of freshwater at STP (0.999014 g/cm^3), [M/L^3].

ρ_o= the average fluid density filling well bore above measuring point, [M/L^3].

Regardless of whether freshwater head [Equation 6] or observed head [Equation 7] is used, the determination of aquifer head or potential assumes that atmospheric pressure is uniform over the area of investigation and the effects of atmospheric pressure variations are insignificant, compared to areal hydraulic gradients. In fact, changes in barometric pressure can cause water level changes of more that one foot in wells penetrating confined aquifers. Increases in barometric pressure drives water from the open well (exposed to changes in barometric pressure) into the confined aquifer that is partially isolated from changes in barometric pressure. This results in a lower observed water level in the well.

To define groundwater flow, the atmospheric pressure that exists at the upper aquifer boundary must be applied to the freshwater or observed head described above. Total head, H_t, is either:

$H_t = H_{fw} + H_a$ or Eq. 9

$H_t = h_{fc} + H_a$, where H_a is the atmospheric head component, [L]. Eq. 10

The atmospheric head component for fresh-water head is $P_a/(\rho_{fw}Hg]$, and the atmospheric head component for total head is $P_a/(\rho_o g]$ [Spane, 1999]. The atmospheric head component is calculated as an incremental value referenced to an arbitrary standard, P_{std}. For open well water level measurements [depth from surface datum] or water levels determined from downhole measurements using a differential pressure transducer, the incremental change in barometric pressure should be added to the well-water level to obtain total hydraulic head [Spane, 1999].

Whereas the adjustment to head [Equations 9 or 10] may be insignificant in aquifers with steep gradients, the addition of barometric head to well-water elevations may change the estimated direction of groundwater flow in aquifers with low hydraulic gradients. Spane (1999) recommends that well-water elevations should be corrected for changes in barometric pressure from the site reference value before potentiometric maps are created.

Eastern Snake River Plain Aquifer

The Eastern Snake River Plain [ESRP] is a flat depression that cuts an arcuate swath across southern Idaho. Ranging from 20 to 50 mi wide, it extends from Payette, Idaho, near the Oregon border, 120 mi southeast to Twin Falls and thence 150 mi northeast to Ashton, Idaho (located about 60 mi south of West Yellowstone). The Snake River Plain is bounded on the southeast by mountains of the Basin and Range province. These mountains consist of upper Precambrian through lower Mesozoic sedimentary rocks uplifted along normal faults during Neogene and Quaternary tectonism. Southwest of the Snake River Plain are mid-Miocene rhyolitic and basaltic rocks of the Owyhee Plateau. On the northeast end of the Snake River Plain are Quaternary rhyolitic and basaltic rocks of the Yellowstone Plateau (Kuntz, *et. al.*, 1992).

Between Milner Dam and King Hill, the ESRP is an area of low topographic relief, dotted by scattered volcanic cones that rise above the plain. The plain is covered by Middle to Late Cenozoic basalt interbedded with lacustrine and fluvial sediments. During extrusion, basalt filled and dammed the ancestral Snake River, forming temporary lakes. Basalt deposited downstream of these dams are dense subaerial lavas. Basalt flowing into the lakes formed pillow lavas and basaltic sands, filling the lake with subaqueous deposits. Then, subsequent lava again diverted the river, and the process of filling the ancestral canyons and of subaerial and subaqueous deposition was repeated.

The pillow basalts and basaltic sands are unsorted, coarse grained, and poorly indurated. They have very high porosity and hydraulic conductivity. The dam-and-fill process produced intercalated dense basalt, pillow lavas, sand, and sediments, and it created an aquifer with very high storativity and zones of very high transmissivity (Covington and Weaver, 1990).

Hydrologic parameters vary across the ESRP, and typical values are summarized in Table 1.

Table 1

ESRP Aquifer Properties

Aquifer Transmissivity	87,000 - 1,300,000 ft^2 /day
Aquifer Thickness	200 ft
Effective Porosity	0.045
Aquifer Storativity	0.045
Hydraulic Gradient near springs	0.01 ft/ft

(Whitehead, 1992, as summarized by Janczak, 2001)

The ESRP aquifer contains between 200 and 300 million acre-feet [MAF] of water. It discharges 10 MAF per year through spring flow, underflow, groundwater pumping, and evapotranspiration. Groundwater discharges from the ESRP aquifer in the Thousand Springs region, located from Milner Dam to King Hill in southern Idaho. Spring discharge provides most of the annual flow of the Snake River downstream of King Hill.

Whereas the ESRP aquifer contains between 200 and 300 MAF of groundwater, discharge from the springs located between Milner Dam to King Hill has been declining. Because of these declines, there is renewed interest from senior appropriators and water management officials in the factors that affect spring discharge. Because a relationship between aquifer well water elevations and spring discharges has been proposed (Janczak, 2001), the objectives of this study include identifying and correcting well-water elevations for barometric effects, identifying the degree of aquifer confinement, and determining correlations between spring discharge and barometric pressure changes.

Data Collection

Changes in barometric pressure were correlated with changes in well-water elevations in four wells and with discharge from three springs in the Milner Dam to King Hill reach of the Snake River.

Barometric pressure, measured hourly at the Twin Falls airport, was obtained from the

National Oceanic and Atmospheric Administration [NOAA] and converted from in. Hg to ft of water and from Universal Coordinated Time to Mountain Standard Time. Table 2 summarizes the barometric pressure measurements:

Table 2

Barometric Pressure Descriptive Statistics (ft of water)

Domain	0100 November 7, 2001 to December 31, 2001 2400 hours
Mean (ft of water)	34.056
Standard Error	0.008
Median	34.059
Mode	34.035
Standard Deviation	0.273
Variance	0.075
Range	1.416
Minimum	33.270
Maximum	34.686
Observations (n)	1314

Well-water elevation [i.e., open-well water elevation] in four wells [Sand Springs, Moore, Ehlers #2, and Janns] were extracted from the Idaho Water Resources Research Institute's [IWRRI] groundwater database. Figure 1 illustrates the barometric pressure and water elevations in the four wells from November 7 to December 31, 2001. This period of time was selected for analysis, because there are frequent changes in barometric pressure during the winter months and irrigation pumping and recharge from irrigation canals have ceased.

The four wells are located north of the Snake River Canyon above springs discharging from the ESRP aquifer. Each well was selected because of its proximity to springs at which discharge has been measured hourly during 2001 and early 2002. Each well is owned by residents who would allow hydraulic testing of the wells.

The Ehlers well is located about 1 mi east of the Devil's Washbowl Spring, east of Twin Falls, Idaho. The spring is at the head of a small canyon, and about 20.5 cfs discharges into Vineyard Lake. Devil's Washbowl Spring emerges from cooling joints and flow breaks in basalt member 7 of the Idaho Group. Basalt member 7 is a vesicular to dense, massive, very thick pahoehoe. No pillow basalts are mapped at Devil's Washbowl (Covington and Weaver, 1990). No Driller's Report for a well in the reported location of the Ehlers well was

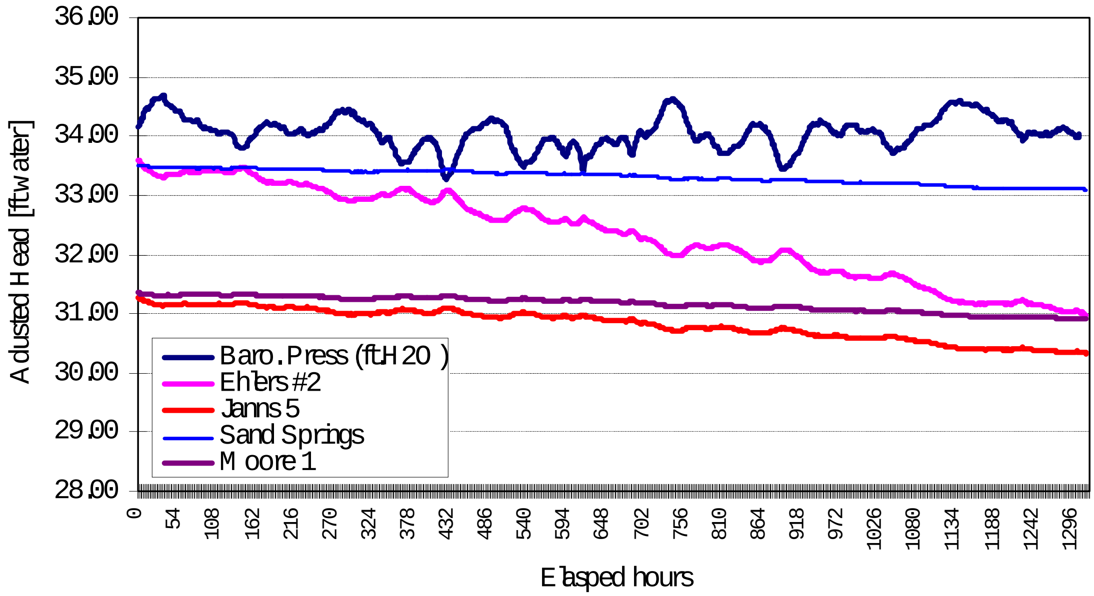

Figure 1. Barometric pressure and well water levels from Nov. 7 to Dec. 31, 2001. A constant has be added to well water elevations for plotting convenience.

found in the files at Idaho Department of Water Resources [IDWR], Twin Falls[1]. However, examination[2] of Driller's Reports for other wells in Section 34, T. 9 S., R 18 E. B. M., suggests there is a layer of clay stratigraphically above the basalt from which water is extracted.

The Janns well is unused, i.e., it does not provide irrigation or culinary water. It is located in Section 32, T. 7 S., R 14 E.B.M. about 1 ½ mi east of Rangen Spring. Rangen Spring discharges about 35.5 cfs, including flow from Curren Tunnel [Covington and Weaver, 1990; Bendixsen, 1995]. The spring emerges from a pillow basalt facies of the Malad Basalt at about 3,140 ft above msl (Johnson *et. al.*, 2001).

The Sand Springs well is located in Section 16, T. 8 S., R 14 E. B. M. about ½ to 1 ½ miles from the canyon rim where groundwater discharges from Sand Springs and Thousand

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[1]Submission of Well Driller's Reports was not required by IDWR regulations prior to 1977.

[2]There is a large variation in accuracy in the hydrogeologic information submitted to IDWR by Idaho Well Drillers. Wells are only located to the nearest 80 acres and are often mis-located, often by 80 or 160 acres. The lithologic descriptions of cuttings may be inaccurate.

Springs basalts (Johnson et. al., 2001; Covington and Weaver, 1990). About ½ mile south of the Sand Springs well, 79.8 cfs discharges at Sand Springs. No Driller's Report was found in the IDWR files for a well in the NW/4, SW/4 Sec 16, T8S, R14E. However, a 1973 well drilled in SW/4, NE/4 Section 16 penetrated 90 ft of brown, gray, black loose lava and black cinders. No lithologies that might act as confining layers were reported.

The Moore well is located above Blind Canyon Springs in NE/4, NW/4 Section 3, T. 9 S., R. 14 E. About 112 cfs discharges at Blind Canyon Springs through talus covering the Sand Springs Basalt. No Driller's Report was found in the IDWR files for this well.

Discharge measurements from three springs were also obtained from the IWRRI database [Johnson *et. al.*, 2001]. The National Fish Hatchery [NFH 15] spring discharges from beneath talus from the Thousand Springs basalt. Discharge is measured by a pressure transducer behind a v-notch weir. Crystal Springs discharge is measured by a pressure transducer in a stilling well on the northwest corner of the hatchery. Blind Canyon Spring discharges from the Sand Springs Basalt, and flow is measured by a pressure transducer installed behind a sharp-crested weir. Discharge from the Blind Canyon Spring is measured downstream of a hatchery, and hatchery operations periodically affect discharge. Discharge from the three springs and barometric pressure are summarized in Figure 2.

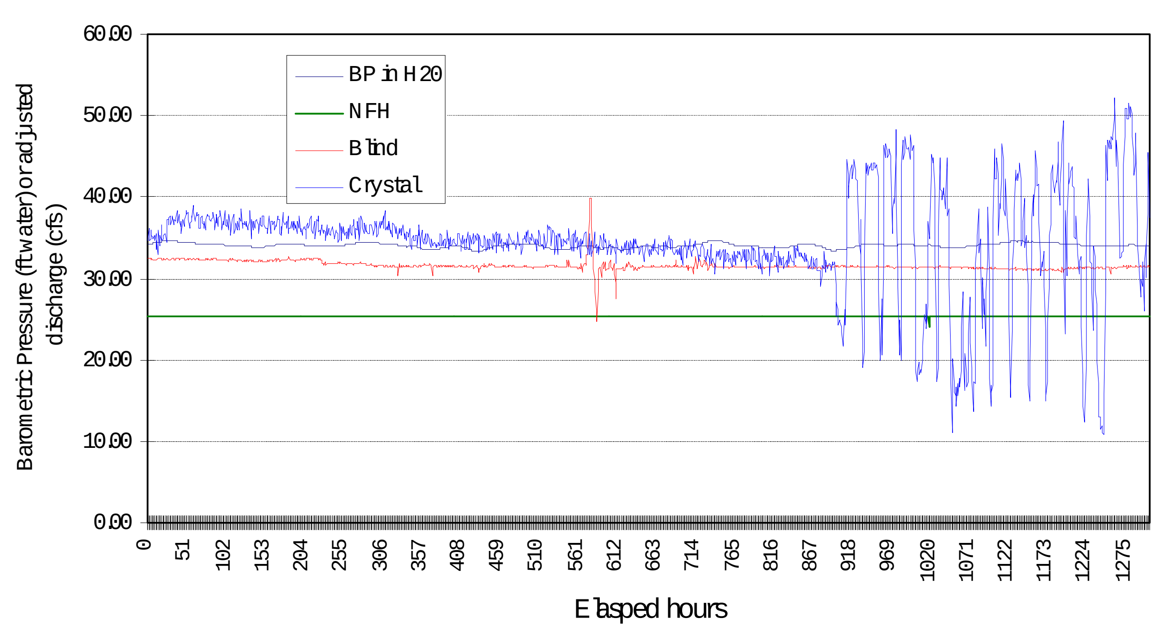

Figure 2. Spring discharge and barometric pressure. A constant has been added to spring dicharge for presentation.

Recognition and Removal of Barometric Effects on Head

Figure 1 illustrates the barometric pressure and corresponding well-water levels [open-well] in the four wells. There is a visual correlation between barometric pressure and water level in at least one well. Identification of barometric effects on well-water elevation followed the procedures outlined by Rasmussen and Crawford (1997) and Spane (1999). Specifically,

1. Hourly atmospheric pressure measurements from November 7 to December 31, 2001, were obtained from the National Weather Service [NWS], part of the National Oceanic and Atmospheric Administration [NOAA], Twin Falls, ID. Measurements were converted from Universal Coordinated Time [UCT] to Mountain Standard Time and from in. of Hg to ft of water.

2. The long-term (α_L) and short-term (α_S) barometric efficiencies were calculated using the linear regression algorithms outlined by Rasmussen and Crawford (1997).

   The linear regression equation used to estimate long-term barometric efficiency (α_L) is:

   $$W = (- \alpha_L \times B) \qquad \text{Eq, 11}$$

   The residual values of water level (W) and barometric pressure (B) were used in Equation 11 after temporal trends were removed. There is a negative sign in front of α_L and α_S, because an increase in pressure, B, causes a decrease in the well-water level, W.

   The linear regression equation to estimate short-term barometric efficiency (α_S) is:

   $$\Delta W = (- \alpha_S \times \Delta B) \qquad \text{Eq, 12}$$

   where both ΔW and ΔB are the incremental changes between successive, residual measurements of well-water level and barometric pressure.

Rasmussen and Crawford (1997) demonstrated that the comparison between α_L and α_S is a diagnostic tool to differentiate between confined and unconfined aquifers. In wells penetrating confined aquifers, without borehole storage or skin effects, there should be no difference between α_L and α_S. In wells penetrating unconfined aquifers, the magnitude of short-term efficiency (α_S) should be greater than the magnitude of long-term (α_L) barometric efficiency. For a delayed yield response in a confined aquifer, α_S should be less than α_L.

3. The Clark (1967) method was used to estimate barometric efficiency. Clark's barometric efficiency (BE) is:

$$BE = \Sigma\ \Delta W / \ \Sigma\Delta B \qquad \text{Eq, 13}$$

Clark (1967) outlined rules for calculating BE:

a When ΔB is zero, ignore ΔW to obtain $\Sigma\Delta W$.

b. When ΔW and ΔB have like signs, add ΔW to obtain $\Sigma\Delta W$.

c. If ΔW and ΔB have unlike signs, subtract ΔW to obtain $\Sigma\Delta W$.

Davis and Rasmussen [1993] demonstrated that Clark's method is robust when the barometric pressure change is instantaneous. Clark's ratio is consistent with α_S, because both methods are based on the first differences between barometric pressure and well-water level.

Barometric pressure changes continuously, and well-water levels respond to the succession of pressure changes. Thus, at any time, well-water elevation is the sum of the previous pressure changes applied to the well and aquifer. However, the changes in well-water elevation caused in pressure changes may not be instantaneously reflected in water level. The time lag between pressure change and water level change may be caused by skin effects [i.e., a reduction in hydraulic conductivity between the borehole and undisturbed aquifer], borehole storage, and the time for the pressure waves to be transmitted through the vadose zone. Because of the time lag between change in barometric pressure and change in water level, a multiple linear regression equation is used to estimate a barometric response function. The independent terms in the multiple regression equation are successive time lags.

4. The multiple-regression deconvolution formula (Rasmussen and Crawford, 1997) identifies the well-water elevation response to a succession of pressure changes. The formula is:

$$H(t) = \beta_0 + \beta_1 t + \Delta u_0 B(t) + \Delta u_1 B(t-1) + ... + \Delta u_n B(t-n) \qquad \text{Eq, 14}$$

where,

$H(t)$ is the residual head differential at time step t.

β_0 is the regression intercept.

β_1 is the linear trend coefficient for the independent variable, t.

Δu_i are the fitted barometric response coefficients for each time, i.

$B(t - i)$ are the residual barometric pressure differentials at time lags (t - i).

The domain of the linear regression model applied to well-water level and barometric pressure extended from November 7 to December 31, about 1314 hours. However, examination of Figure 2 indicates that factors other than barometric pressure affect spring discharge. Therefore, the domain of the linear regression model applied to spring discharge and barometric pressure extended to only 540 hours elapsed time.

Results of Data Analysis

Table 4 below summarizes long-term (α_L) and short-term (α_S) barometric efficiencies and the barometric efficiency calculated using the Clark Method for each well and for Blind Canyon Springs, Sand Springs, and the NFH. For α_L and α_S, the estimated value, the standard error of the estimate, and the coefficient of determination, R^2 , are shown.

Table 4 Barometric Efficiencies
(Expected value +/– one standard error)

	Inferred Aquifer Type	Linear Regression Coefficients, Φ and R^2 α_L	α_S	BE by Clark Method
Wells				
Ehlers #2	confined	-0.38± 0.002 R^2 =0.95	-0.26±0.005 R^2 =0.62	-0.32
Janns	confined	-0.17± 0.003 R^2 =0.76	-0.12± 0.003 R^2 =0.47	-0.14
Sand Springs	confined	-0.06±0.0014 R^2 =0.58	-0.022±0.003 R^2 =0.04	-0.03
Moore	confined	-0.089±0.0018 R^2 =0.66	-0.049±0.002 R^2 =0.28	-0.0590
Springs				
Blind Canyon Springs		-0.11±0.125 R^2 =0.0015	-1.15±0.66 R^2 =0.0055	-1.96
Sand Springs		+0.287±0.062 R^2 =0.016	-0.26±0.553 R^2 =0.002	+0.13
NFH 15		-0.0004±0.0003 R^2 = 0.0054	-8.8E-05±0.0027 R^2 =1.87E-06	-0.0086

Examination of Table 4 leads to the following inferences:

1. The long-term (α_L) barometric efficiency of all wells is greater than the short-term efficiency (α_S) of all wells, suggesting well water elevations may be affected by a delayed yield response.
2. The coefficients of determination [R^2] for the linear regression model between

barometric pressure and spring discharge are very small.

3. Estimated long-term (α_L) and short-term (α_S) barometric efficiencies for spring discharge probably have no hydrologic or physical significance.

Table 5 summarizes the results of multiple-regression deconvolution for the four wells. For each well, the regression coefficient [Δu_i] at each time lag is shown, and the column labeled "sum" is the sum of the absolute value of the regression coefficients at zero lag time minus the regression coefficient at subsequent lag times. The coefficient of determination, R^2, for the multiple regression model is also shown.

Table 5

Barometric Response Functions for Wells

Lag [Hr]	Moore		Ehlers		Janns		Sand Springs	
	R^2 =0.31		R^2 =0.75		R^2 =0.48		R^2 =0.06	
	Coefficient	Sum	Coefficient	Sum	Coefficient	Sum	Coefficient	Sum
0	-0.020	0.020	-0.178	0.178	-0.109	0.109	-0.020	0.020
1	0.004	0.016	-0.070	0.248	0.001	0.108	0.004	0.016
2	-0.003	0.019	-0.040	0.288	-0.013	0.121	-0.003	0.019
3	-0.004	0.023	-0.008	0.295	0.004	0.117	-0.004	0.023
4	0.000	0.023	-0.019	0.315	-0.007	0.125	0.000	0.023
5	0.003	0.020	-0.019	0.334	0.007	0.118	0.003	0.020
6	-0.012	0.033	-0.004	0.338	-0.009	0.127	-0.012	0.033
7	0.000	0.033	-0.009	0.347	-0.001	0.128	0.000	0.033
8	-0.003	0.035	0.000	0.347	-0.001	0.129	-0.003	0.035
10	0.000	0.035	-0.007	0.354	-0.001	0.130	0.000	0.035
12	0.000	0.035	-0.001	0.355	-0.004	0.135	0.000	0.035
14	-0.002	0.037	-0.008	0.363	0.005	0.130	-0.002	0.037
16	-0.001	0.039	-0.004	0.368	-0.005	0.135	-0.001	0.039
18	0.003	0.036	0.005	0.363	0.005	0.130	0.003	0.036
20	-0.005	0.041	0.001	0.362	0.004	0.126	-0.005	0.041
25	-0.002	0.044	-0.001	0.364	-0.002	0.127	-0.002	0.044
30	0.000	0.043	0.007	0.357	0.001	0.126	0.000	0.043
35	-0.009	0.053	-0.004	0.361	-0.005	0.131	-0.009	0.053
40	0.002	0.051	-0.001	0.362	0.004	0.128	0.002	0.051
45	0.002	0.050	0.004	0.358	-0.002	0.130	0.002	0.050
50	0.000	0.049	0.006	0.352	0.004	0.126	0.000	0.049
55	-0.006	0.055	0.003	0.349	0.000	0.126	-0.006	0.055

Interpretation and Discussion

Well-water Elevation and Barometric Pressure

For all four wells, the long-term (α_L) barometric efficiency is greater than the short-term barometric efficiency (α_S). Both α_L and α_S for the Ehlers well are greater than other wells. The larger barometric efficiency of Ehlers well is consistent with the response shown in Figure 1, where the amplitude of well-water response to changes in barometric pressure is greater in the Ehlers well than other wells.

In confined aquifers penetrated by wells without borehole storage or skin effects, α_L should be approximately equal to α_S. In unconfined aquifers, α_S should be greater than α_L (Rasmussen and Crawford, 1997). Spane (1999) use the shape of the sum of regression coefficients to infer aquifer characteristics (Figure 3). The well-water level responses to changes in barometric pressure for all four wells are shown in Figure 4. Comparison of Figure 4 with Figure 3 suggests that the well-water level responses in the Ehlers well are affected by wellbore-storage or well-skin effect. The well-water level responses for the Janns, Sand Springs, and Moore wells also suggest confined aquifers, but the degree of confinement is very small. Wellbore storage or skin effects in these three wells are less pronounced than in the Ehlers well. Well-bore storage or well-skin effects inferred from the well water response to changes in barometric pressure is difficult to conceptualize.

There are several reasons that wellbore storage is unexpected in wells penetrating the basalts of the ESRP. No measurable time lag would be expected in 6 in. or 8 in. wells penetrating the pillow basalt or basaltic sands, because the transmissivity of these aquifers is greater than about 100 ft^2/d [about 10 m^2/d]. At transmissivities greater than 100 ft^2/d, 95% of the wellbore effect dissipates within 5 minutes (Spane, 1999). Additionally, many wells are completed as "open holes," i.e., without casing below about 18 to 20 ft.

A well-skin effect inferred from the well water response in the Ehler's well to changes in barometric pressure [Figure 4] is also difficult to explain. In the ESRP aquifer, small-diameter [6 in. or 8 in.] wells are typically installed using air rotary, and it has always been assumed that there is no reduction in hydraulic conductivity around the borehole. Compressed air and a foaming agent are used, but drilling muds are almost never used. However, the cuttings generated by air rotary can be plastered along the borehole, filling crevices and vesicles and reducing hydraulic conductivity. Many wells are drilled "blind," i.e., without return of cuttings to the surface. Additionally, drillers in Idaho seldom develop wells by surging or overpumping. These procedures mean that cuttings may remain along the inside of the borehole, creating skins of reduced hydraulic conductivity around the wellbore.

The effects of changing barometric pressure on well-water levels were removed using the following equation:

$$R(t) = H(t) - [\, \beta_1 t + \Delta u_0 B(t) + \Delta u_1 B(t-1) + \ldots + \Delta u_n B(t-n) \,] \quad \text{Eq. 15}$$

Figure 5 illustrates the effectiveness of using the multiple-regression deconvolution technique to remove barometric effects on well-water elevations in the Ehlers well. Because the coefficient of determination for the multiple-regression deconvolution is high [R^2 =0.75], almost all the effects of barometric pressure fluctuations are removed. After these barometric effects on well-water levels have been removed, it will be possible to recognize external stresses [such as changes in drawdown during a long-term aquifer test] that would have been obscured by well-water fluctuations caused by changes in barometric pressure.

Well-water Elevation, Spring Discharge, Barometric Pressure

Janczak (2001) correlated the volume of spring discharge and aquifer water elevations in the ESRP aquifer. The common model is that the relationship between aquifer water level and spring discharge is linear, and spring discharge ceases when water levels decline to an elevation equal to spring elevation. The linear relationship may reflect a layered, confined aquifer. However, a non-linear relationship between aquifer water level and spring discharge may be the result of a combination of unconfined conditions, changing cross-sectional area in the spring, turbulent flow, and unrepresentative well and fracture system (Janczak, 2001).

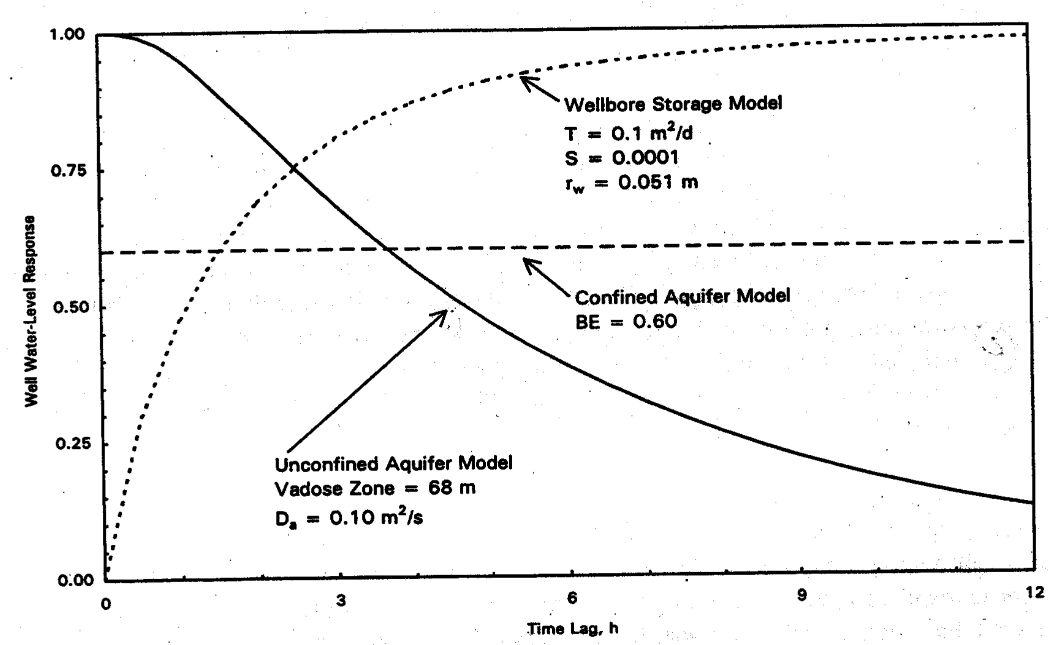

Figure 3. Water-level response for confined and unconfined aquifers. Wellbore storage can be superimposed on either response (from Spane, 1999)

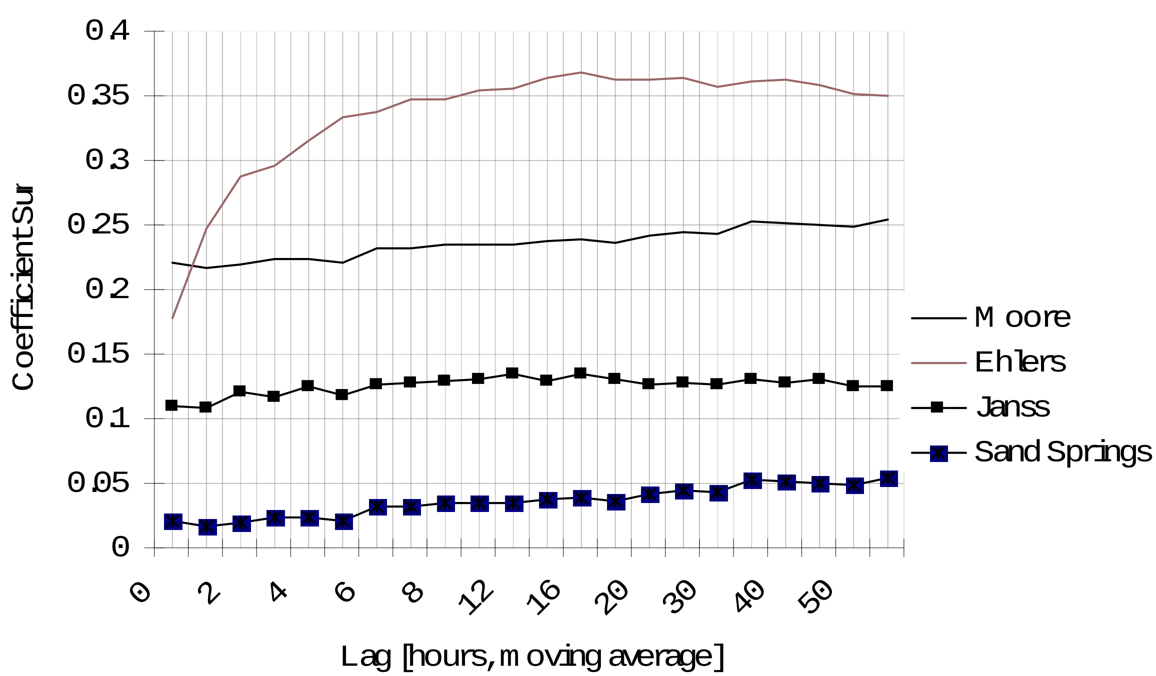

Figure 4. Graph showing sum of coefficients from different lags. The presented values for the Moore well has been offset by 0.2 ft for presentation.

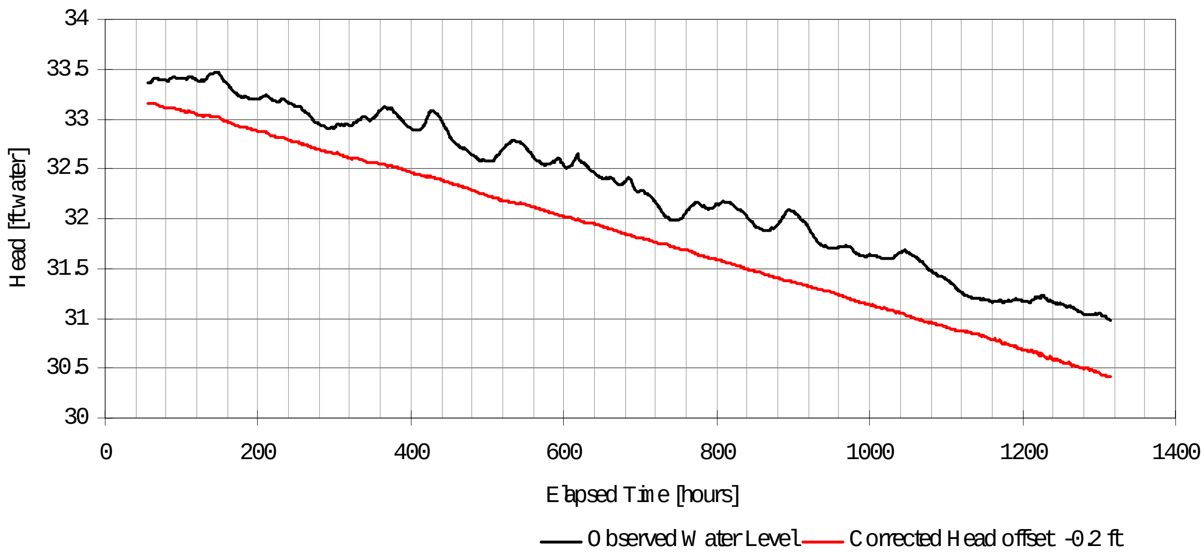

Figure 5. Water Levels in Ehlers' well corrected for barometric pressure.

The coefficient of determination [R^2] for a linear regression model [Table 4] between barometric pressure [independent variable] and spring discharge [dependent variable] is almost zero. R^2 is the proportional reduction of the total variation in the dependent variable with the introduction of the independent variable(s). A larger R^2 means that more of the total variation of the dependent variable Y [i.e., well-water elevation or spring discharge] is reduced by the introduction of the independent variable X [i.e., B or the incremental pressure change, ΔB]. When $R^2 = 1$, there is a perfect correlation, i.e. no difference between the predicted and actual y-values. As the value of R^2 approaches 0, the independent variable [barometric pressure] does not predict the dependent variable, spring discharge (Netter and Wasserman, 1974).

In the regression model between barometric pressure and spring discharge, R^2 is very small, and within the domain of the regression model, spring discharge appears to be independent of barometric pressure. The linear model may be in error because of the temporal delay between change in barometric pressure and change in discharge measured at the transducer. Spring discharge may change instantaneously with changes in barometric pressure, but there may be a temporal error, because discharge is measured at some distance downstream from the point of discharge. Changes in spring discharge may be less than the precision of the measurement instrumentation.

Examination of Figure 2 suggests there are other variables which affect spring discharge [or instrument errors], variables not included in the regression model. For example, recorded discharge at Blind Canyon Springs fluctuates at about 600 hours elapsed time. After about 875 hours, records from Crystal Springs change dramatically.

Conclusions

Procedures to recognize and remove the effects of changes in barometric pressure on well-water levels were applied to four wells penetrating the Eastern Snake River Plain aquifer. Well water-level measurements were extracted from the Idaho Water Resources Research Institute's groundwater database. Hourly barometric pressure measurements from the Twin Falls airport were obtained from the National Oceanic and Atmospheric Administration.

Multiple-regression deconvolution reveals that the wells probably penetrate confined aquifers and that well-water levels in at least one well may be affected by wellbore storage or skin effects. The reasons for the apparent wellbore storage or skin effects are unknown. The multiple-regression deconvolution technique removes barometric effects on well-water elevations and allows recognition of external stresses [such as drawdown during aquifer tests] that would be obscured by well-water fluctuations caused by changes in barometric pressure.

Prior to aquifer tests in the ESRP aquifer, well-water levels in proposed observation wells and barometric pressure should be measured hourly for five to seven days. These data should be used to determine the degree of aquifer confinement and to develop the multiple-regression deconvolution coefficients to remove the fluctuations in well-water elevations caused by changing barometric pressure.

The relationship between barometric pressure and spring discharge at three springs [National Fish Hatchery #15, Blind Canyon Springs, and Sand Springs] was investigated using a linear regression model. However, the coefficient of determination [R^2] for this simple model is almost zero, suggesting that changes in spring discharge are independent of changes in barometric pressure. Alternatively, changes in spring discharge resulting from changes in barometric pressure are too small to be measured with the existing devices.

Because the hydraulic gradient in parts of the ESRP aquifer is as low as 1 ft per mile [0.0002 ft/ft], the estimated direction of groundwater flow may change when the atmospheric head component is included in total head. Total hydraulic head includes two components: an elevation head *h* and an atmospheric head component. For open-well water level measurements [typically the depth to water from a surface datum], the addition of the incremental change in barometric pressure from a reference standard [P_{std}] to elevation head results in total head [Spane, 1999]. Because the range of barometric pressure in the Twin Falls area may be as much as 1.4 ft of water, this height of variation is possible in aquifer water levels. Because groundwater flows from areas of high total head to areas of low total head, the addition of atmospheric head component may significantly change the hydraulic gradient in parts of the ESRP aquifer.

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