ground water

Computer Note/

Removal of Barometric Pressure Effects and Earth Tides from Observed Water Levels

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Abstract

The effects of barometric pressure and earth tide changes are often observed in ground water level measurements. These disturbances can make aquifer test interpretation difficult by masking the small changes induced by aquifer testing at late times and great distances. A computer utility is now available that automatically removes the effects of barometric pressure and earth tides from water level observations using regression deconvolution. This procedure has been shown to remove more noise then traditional constant barometric efficiency techniques in both confined and unconfined aquifers. Instead of a single, instantaneous barometric efficiency, the procedure more correctly accounts for the lagged responses caused by barometric pressure and earth tide changes. Simultaneous measurements of water levels (or total heads) and nearby barometric pressures are required. As an additional option, the effects of earth tides can also be removed using theoretical earth tides. The program is demonstrated for two data sets collected at the Waste Isolation Pilot Plant, Carlsbad, New Mexico. The program is available free by request at http://www.hydrology.uga.edu/tools.html.

Introduction

Downhole pressure transducers—coupled with electronic dataloggers—are commonly used during ground water investigations to measure and record water levels in wells for long periods at relatively short intervals. Changes in barometric pressure often induce fluctuations in water level observations (Pascal 1973). Barometric pressure applies a load to the land surface as well as to the water surface in open wells (Jacob 1940). Barometric pressure changes cause water level changes because the total head in an aquifer is the sum of the water level in the well plus the barometric pressure. Water level fluctuations are dependent on aquifer properties, properties of overlying materials, and the characteristics of the observation well. The lag between the water level fluctuation and the barometric stress complicates removal of barometric-induced noise.

Earth tides may also cause variation in water levels (Bredehoeft 1967; Hsieh 1987). These variations, which are clearly periodic, result from the elastic behavior of the aquifer skeleton. The physical deformation caused by gravitational and centripetal forces can affect the pore fluid pressure, resulting in water level changes in wells. The density and orientation of fractures are important determinants how these forces affect pore fluid pressure (Bower 1983).

Water level fluctuations due to barometric and earth tide variation—while small in magnitude—can mask pressure changes induced by aquifer testing or by natural phenomena such as rainfall or seismic events. These fluctuations may complicate the analysis of water level data, especially when using the derivative pressure-time method, or when trying to estimate the magnitude and direction of the ground water gradient when the gradient is small.

A computer program, BETCO (barometric and earth tide correction), is presented that removes fluctuations in water level measurements caused by barometric pressure changes and earth tide responses. BETCO removes barometric effects alone or barometric and earth tide effects

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simultaneously. This paper describes the utility and how it can be used to correct observed water level data.

Theory

Rasmussen and Crawford (1997) describe how barometric response changes cause a range of ground water responses. Regression deconvolution was used to estimate the barometric response function using paired water level–barometric pressure observations. The residual—or corrected—head can be calculated once the response function is known. Regression deconvolution is a useful technique in estimating how a parameter in a system responds to a stimulus when the response is not instantaneous and the magnitude of the response changes with time.

Spane (2002) evaluated this approach and demonstrated how it improves smoothed aquifer water levels. The method removes more barometric noise from the data than a constant barometric efficiency because it incorporates the transient nature of the barometric efficiency of a well.

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 (Box and Jenkins 1976):

$$\begin{aligned}\Delta W(t) = {} & \alpha(0)\Delta B(t) + \alpha(1)\Delta B(t-1) \\ & + \alpha(2)\Delta B(t-2) + \cdots + \alpha(m)\Delta B(t-m)\end{aligned} \quad (1)$$

or

$$\Delta W(t) = \sum_{i=0}^{m} \alpha(i)\Delta B(t-i) \quad (2)$$

where $\Delta W(t)$ and $\Delta B(t)$ are the changes in water level and barometric pressure at time t, respectively, $\Delta B(t-i)$ is the change in barometric pressure i time steps before t, $\alpha(i)$ is the unit response function at lag i, and m is the maximum time lag.

For an instantaneous response, only the first term, $\alpha(0)$, is used and all the other terms are zero. In general, the barometric response function has more than one lag term due to borehole storage effects, well skin effects, aquifer overburden, and other delays between the change in barometric pressure and the observed water level response. The maximum lag should be set to a large enough number so that all long-term responses are included.

The response function is found using ordinary least squares linear regression. Once the values of $\alpha(i)$ are found, then the step barometric response function $A(j)$ is calculated by summing the impulse responses:

$$A(i) = \sum_{j=1}^{i} \alpha(j) \quad (3)$$

The step barometric response function is useful for diagnosing the aquifer type (confined vs. unconfined), borehole storage effects, well skin effects, and even estimating aquifer hydraulic properties. Rasmussen and Crawford (1997) and Spane (2002) document the regression deconvolution method and its use as a diagnostic tool.

Using the response function, a correction variable for each observation is calculated using:

$$\begin{bmatrix} W_m^* \\ W_{m+1}^* \\ W_{m+2}^* \\ \vdots \\ W_n^* \end{bmatrix} = \begin{bmatrix} \Delta B_1 & \Delta B_2 & \Delta B_3 & \cdots & \Delta B_m \\ \Delta B_2 & \Delta B_3 & \Delta B_4 & \cdots & \Delta B_{m+1} \\ \Delta B_3 & \Delta B_4 & \Delta B_5 & \cdots & \Delta B_{m+2} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \Delta B_{n-m+1} & \Delta B_{n-m+2} & \Delta B_{n-m+3} & \cdots & \Delta B_n \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \vdots \\ \alpha_m \end{bmatrix} \quad (4)$$

where W_t^* is the correction variable for each observation within t from m to n, m is the maximum lag selected by the user, and n is the total number of observations in the data set.

Using an extension of the regression deconvolution method, the fluctuations in the water level data caused by both earth tides and barometric pressure effects can be removed by simultaneously using both observed barometric pressures and earth tide (gravity) potential data. Earth tide potentials can be predicted for any location on earth for any time using programs available on the Internet or measured directly at the site using sensors. TSOFT is a freely available code to generate synthetic earth tide data (Van Camp and Vauterin 2005). Equation 1 within is modified as follows:

$$\begin{aligned}\Delta W(t) = {} & \alpha(0)\Delta B(t) + \alpha(1)\Delta B(t-1) \\ & + \alpha(2)\Delta B(t-2) + \ldots + \alpha(m)\Delta B(t-m) \\ & + \beta(0)\Delta ET(t) + \beta(1)\Delta ET(t-1) \\ & + \beta(2)\Delta ET(t-2) \\ & + \ldots + \beta(m)\Delta ET(t-m)\end{aligned} \quad (5)$$

The $\alpha(i)$ variables are the multiple regression coefficients for the barometric response, while the $\beta(i)$ variables are the coefficients for the earth tide response. Two vectors are calculated as in Equation 4, one for the barometric correction variables and one for the earth tide correction variables. These two vectors are then summed for the total correction to each water level observation.

The regression deconvolution method was implemented in C++ to create a program portable to any Windows XP or 2000 computer and is available by request on the Internet at http://www.hydrology.uga.edu/tools.html.

Program Use

A graphical user interface in BETCO is used to navigate its functions (Figure 1). BETCO uses either an Excel spreadsheet or an ASCII CSV file as input. The input file contains a table with time, water level or pressure head, barometric pressure, and, optionally, earth tide potentials. The measurements must be at equal time intervals. Water level and barometric pressure should be in consistent units. The unit of time is a floating point value, which is consistent with the decimal time format used by Excel.

BETCO uses the input file and a maximum lag time of $m = 12$ to estimate the initial response function. The user can adjust the maximum lag time to produce an

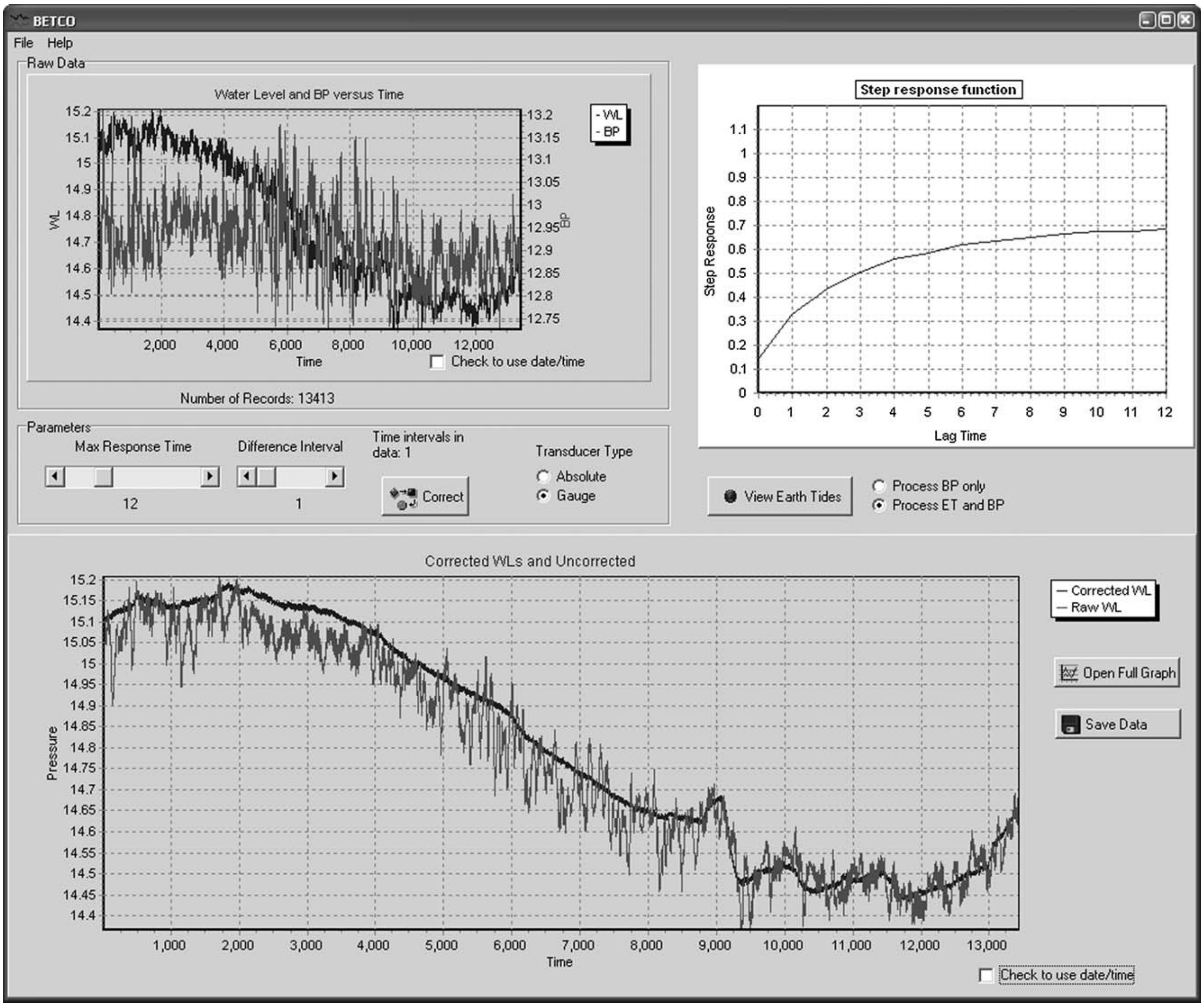

Figure 1. Primary graphical user interface for the Barometric and BETCO utility. Data shown from monitoring well WIPP-30 for the period from April 3, 2003, to October 13, 2004. Original barometric pressure and water level data shown in upper left-hand corner. Step response function is shown in the upper right-hand corner. Original and corrected water levels shown in lower panel.

optimum step response function. A sample optimum response function is shown in the upper right-hand corner of the graphical user interface (Figure 1). BETCO automatically estimates and displays a new response function whenever a new maximum lag or time interval is selected.

When removing barometric and earth tide effects simultaneously, a period of 12 to 24 h captures the majority of barometric and earth tides effects in most confined aquifer wells. However, some unconfined and deep confined systems have exhibited considerably longer maximum lags. The optimum step response function depends on the type of aquifer and the well/aquifer properties. As shown in Figure 2, there are two general types of step response functions that may be observed. For a confined aquifer with wellbore storage, the step response function starts low and increases to a local maximum response. The response at times later than the local maximum may fluctuate, but the response will generally form a plateau following the local maximum. The time at which the local maximum occurs is the ideal value for the maximum lag.

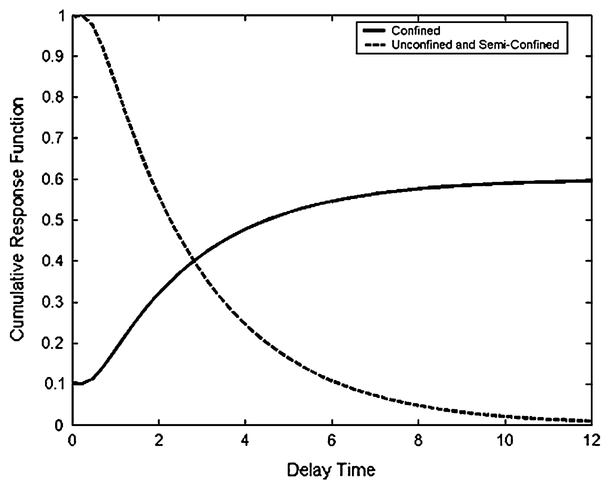

Figure 2. Example step barometric response functions for confined and unconfined aquifers demonstrating the different response function shapes.

For an unconfined aquifer with a substantial depth to water, the step response function should be an inverse (upside down) version of the confined aquifer step response function. In this case, the user should select a maximum lag at the local minimum. A more detailed summary of response functions is presented elsewhere (Rasmussen and Crawford 1997; Spane 2002). The step response functions shown are representative of the response of water levels or gauge pressure transducer measurements. If hydraulic head was used, i.e., via hydraulic head measurements from an absolute pressure transducer, the response is a function of $1 - BE$. In practice, the user is insulated from this because BETCO subtracts the barometric pressure from the total hydraulic head if the user specifies an absolute type transducer.

Application

To demonstrate the ability of BETCO to smooth water levels, the program is applied to water level observations for two different data sets collected at the Waste Isolation Pilot Plant (WIPP), located near Carlsbad, New Mexico. The first data set is a multiyear record of water level observations at well WIPP-30 collected during passive monitoring. The second data set is a water level record in well SNL-13 prior to, during, and after a 20-d aquifer test. Both wells are completed in the Culebra dolomite, a variably fractured, confined aquifer. Water levels are smoothed using BETCO and compared with the conventional smoothing method that assumes an instantaneous, constant barometric efficiency.

The data time step was set at 1 h for all observations. A maximum time lag of 7 h is used for WIPP-30 when only a barometric correction is performed, while a lag of 12 h is used when both barometric and earth tide effects were removed. A maximum lag of 18 h is used for SNL-13 for all cases.

One figure for each data set is presented showing (A) the raw water level data, (B) corrections applied using a constant barometric efficiency, (C) a regression deconvolution method for barometric effects only, and (D) a simultaneous regression deconvolution method for barometric and earth tide effects. The data sets are offset by a constant shown in the figures for clarity. The results from each correction method are offset for clarity.

Figure 3 presents the original and corrected data for WIPP-30 data. Note the substantial improvement in noise reduction after application of BETCO correction. Figure 4 presents equivalent analysis for SNL-13 data. Note that the response to aquifer testing in late August 2005 was not apparent prior to BETCO correction. Figure 5 presents a portion of the SNL-13 data set and illustrates the magnitude of the residual noise compared to the original fluctuations. The residual from the barometric pressure and earth tide removal is random noise within the sensitivity band of the pressure transducer.

Limitations

BETCO requires at least 2 weeks of hourly data collected at a constant time interval. However, some sites

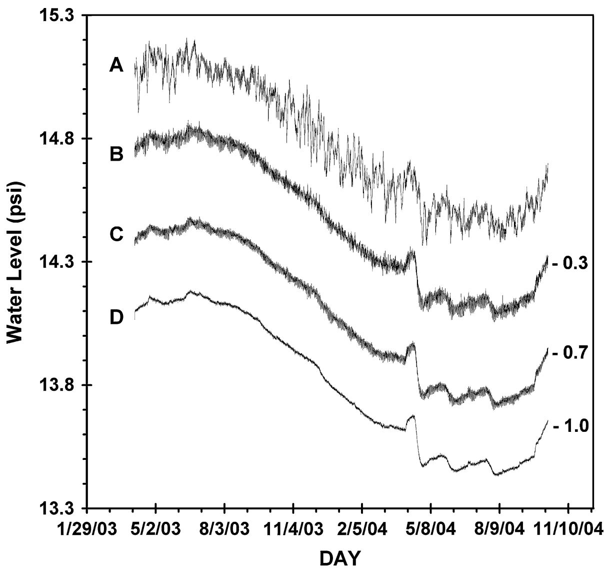

Figure 3. (A) Observed multiyear water levels for well WIPP-30, (B) water levels corrected using a constant barometric efficiency, (C) water levels corrected using barometric response function only, and (D) water levels once the barometric pressure and earth tides have been removed using regression deconvolution. Time series are vertically offset by indicated constant for clarity. Response between early March and late April 2004 is not distinguishable in the uncorrected data but becomes apparent once corrected.

may require monitoring periods up to 4 weeks. The ideal time difference is approximately 1 h because shorter time increments show little barometric pressure change and longer differences fail to capture important barometric pressure variation. The program can use observations

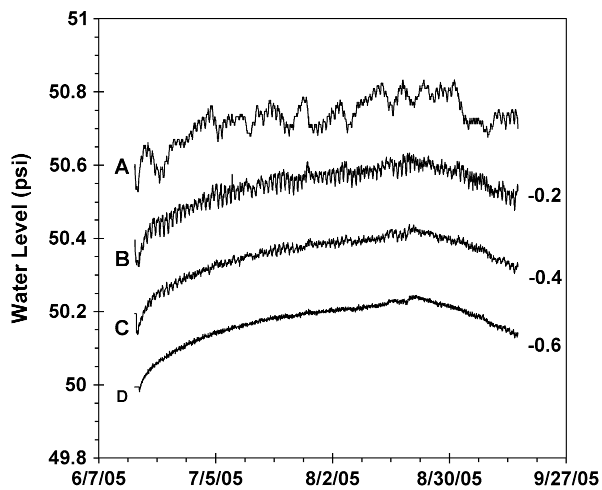

Figure 4. (A) Observed water levels during the SNL-13 aquifer test, (B) water levels corrected using a constant barometric efficiency, (C) water levels corrected in BETCO using barometric response function only, and (D) water levels once the barometric pressure and earth tides have been removed using BETCO. Time series are vertically offset by indicated constant for clarity. SNL-13 was completed in the Spring 2004 and developed shortly after, showing recovery from early June to late August. A response to the 20-d constant discharge test in late August is not distinguishable in the uncorrected data but becomes apparent once corrected.

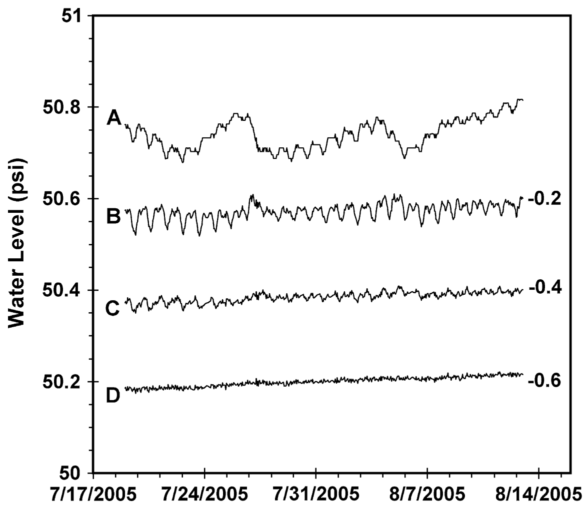

Figure 5. (A) Detailed section of observed water levels during the SNL-13 aquifer test, (B) water levels corrected using a constant barometric efficiency, (C) water levels corrected in BETCO using barometric response function only, and (D) water levels once the barometric pressure and earth tides have been removed using BETCO. Time series are vertically offset by indicated constant for clarity. Graph D illustrates the low magnitude of residual noise left in the water levels after removing the barometric and earth tide effects. The magnitude of the residual noise is less then the full-scale error of the monitoring equipment, suggesting that the residual is sensor noise.

collected at shorter time intervals, however, because these can be converted to hourly observations using data processing. While the effects of earth tides are effectively removed using BETCO, the physical basis of earth tide influences on aquifer water levels are not as clearly defined as for barometric influences due to the effects of fracture density and orientation on the hydraulic head.

Discussion

BETCO is a convenient tool for removing noise caused by barometric pressure and earth tide effects. Residual noise left in the water levels is within the range of accuracy of the pressure transducers typically used. While this function is useful on its own, the estimated response function can also be used to estimate aquifer properties, such as the aquifer storativity and porosity. Efforts to estimate these properties from the response function of wells are currently being developed and implemented. The software clearly removes noise caused by the earth tides; however, the theoretical nature of the earth tide response is not understood as clearly as the barometric response. Further work is being conducted to determine the mechanics of the earth tide response and to use this response to estimate aquifer properties such as fracture density and orientation. Finally, interpolation methods will ultimately be employed to allow data collected at varying time intervals to be processed.

Availability

BETCO is available as freeware for Windows XP and Windows 2000 operating systems. A manual with a tutorial to run test data sets is also provided. The software can be requested via a short form at http://www.hydrology.uga.edu/tools.html.

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