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BAROMETRIC AND EARTH-TIDE INDUCED WATER-LEVEL CHANGES IN THE INGLEFIELD SANDSTONE IN SOUTHWESTERN INDIANA

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ABSTRACT. Water-levels from a deep-shallow piezometer nest in the Inglefield sandstone depict a dynamic groundwater system. Water-levels at both the 33.5 m and 18.3 m depths fluctuate up to 0.15 m in a matter of hours. Most of this fluctuation is driven by responses to atmospheric pressure change. A strong inverse correlation exists between groundwater-levels and barometric pressure. Calculated barometric efficiency for this aquifer is 0.95, indicating a rigid aquifer skeleton. Following successful quantification and removal of the barometric effects on water-level data, the residual hydrographs suggested an additional, smaller amplitude periodicity was still present in the water-level records. These fluctuations were hypothesized to result from Earth-tide induced crustal deformation stresses. Evaluation of barometric-corrected head data by a Fast Fourier Transform method identified periodicities of water-level changes at 12.01 and 12.4 hours. These periodicities correlate well with solar and lunar tide stressors, respectively. Whereas barometric fluctuations of water-levels are driven through the well-water column and do not result from potential changes within the aquifer, Earth-tide induced fluctuations are the result of changes in aquifer potential. Further, these stress-induced changes are suggestive of a confined system, yet simple stratigraphy suggests the aquifer is unconfined. Lithologic variability within the sandstone, specifically a finer-grained and mica-rich shallow zone, likely generates confined behavior.

Keywords: Barometric efficiency, Earth-tides, groundwater, aquifer, Indiana

Water-level fluctuations in bedrock aquifers are essentially strain responses to stress. In large part, stress is typically a direct recharge or discharge that results in a raising or lowering of water-levels (groundwater potential), respectively. Other stresses also affect changes in potential. Measurable changes in groundwater potential on short time scales can result from seismic stresses, atmospheric pressure changes, and Earth and oceanic tides, whereas tectonic loading, basin-filling, and unroofing can change total stress on much longer scales (Furbish 1997).

Barometric pressure can change water-levels in piezometers within confined and deep unconfined aquifers. Barometric pressure directly affects water-levels in open piezometers, but loses energy in the form of heat as it exerts a force through a thick unsaturated zone, confining layers, and the aquifer (Seo 1999). The induced gradient across the well screen causes well-water fluctuations. The magnitude and rapidity of water-level change due to barometric pressure change is a function of the rigidity of the aquifer. A more rigid aquifer will react more efficiently to barometric pressure changes. Without the presence of the well, there would be no difference in potential.

Earth tidal stresses can change groundwater potential in an aquifer. As the Sun and Moon pass over a point on the Earth, gravitational forces generate a dilation of the bedrock, increasing pore space, and decreasing the potential of the groundwater in the aquifer. After the Sun and Moon pass, the gravitational force decreases, the aquifer (pore space) contracts, thus increasing the pore water potential. The more easily the aquifer deforms to gravitational stresses (less rigid), the greater the magnitude of potential change (Hsieh et al. 1987).

The objectives of our work, based upon observations of significant and short-term bedrock groundwater fluctuations, are to identify

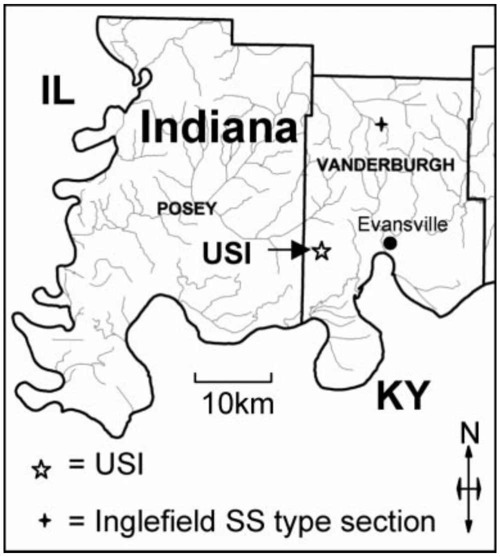

Figure 1.—A map of Posey County and Vanderburgh County in southern Indiana with the study site and type section of the Inglefield sandstone located. IL = Illinois, KY = Kentucky, and USI is the University of Southern Indiana.

the stresses, and consequent water-level changes, at work on the Pennsylvanian sandstone aquifer in southwestern Indiana. Perhaps the most important justification for this analysis is the recognition that the observed (measured) water-level fluctuations do not necessarily depict actual potential changes in the bedrock-aquifer system. Changes in the potential, or energy, of a groundwater system is generally observed by measuring water-levels in groundwater wells. However, some stresses, particularly barometric pressure changes, can generate well-water levels that do not represent actual groundwater potential. Without knowledge and quantification of these phenomena, significant error in water-level measurements may go unnoticed. Once these water-level changes are quantified, we can better evaluate and measure the true physical properties of, and potential changes in, the aquifer.

HYDROGEOLOGIC SETTING

The type section of the Inglefield Sandstone Member of the Pennsylvanian Patoka Formation and the focus of this study are located in Vanderburgh County in Southwestern Indiana (Fig. 1). The Inglefield sandstone is dominantly a fine to medium-grained quartz sandstone that reaches maximum thickness (up to 24 m) in Vanderburgh County and Posey County (Shaver et al. 1986). Bedrock cores recovered from the University of Southern Indiana campus contain partial sequences of the Inglefield sandstone from 16–19 and 31.5–34.5 meter depths. The micritic West Franklin limestone member of the Shelburn Formation underlies the sandstone to a depth of 35.7 m, and acts as a lower confining unit. In the deep core collected at the USI campus, a short (< 0.6 m) interval of a coarse conglomeratic unit containing limestone clasts separates the limestone from the sandstone.

Although we have not been able to identify with certainty an upper confining unit locally for the Inglefield sandstone, the unit does display a pronounced fining upward character with platy muscovite grains common. Slug test results suggest a horizontal hydraulic conductivity (Kh) in the shallow aquifer (15–18.3 m depth) of $4.65 \times 10\text{-}5$ cm/sec (Clark et al. 2002). A laboratory permeameter analysis of a core segment from the deep aquifer (32.6 m) indicates a vertical hydraulic conductivity (Kv) of $5.3 \times 10\text{-}4$ cm/sec. Assuming an anisotropy (Kh/Kv) ratio of 100, an estimated Kh of the deep Inglefield ($5.3 \times 10\text{-}2$ cm/sec) is likely three orders of magnitude greater than that of the shallow Inglefield sand, effectively generating a confined-aquifer system.

The Inglefield sandstone does serve as an aquifer locally, primarily for domestic users. Domestic and stock wells tap the Inglefield interval in the western part of Vanderburgh County where public water supply is not available. Based on the number of homes in the area that do not yet have access to the local public water supply, the total number of active domestic supply wells is approximately 100 within 5 km of the USI monitoring wells. Domestic well users discharge on the order of 1000 liters of water per day.

METHODS

Observations and data for this research were generated in the Ground-Water Monitoring Laboratory at the University of Southern Indiana. This lab comprises a deep (WMW, 33.5 m)–shallow (EMW, 18.3 m) piezometer nest installed in the Inglefield sandstone and housed in a ground-floor laboratory of the university Science Center. Each piezometer is of 5 cm PVC construction with a 3 m screened

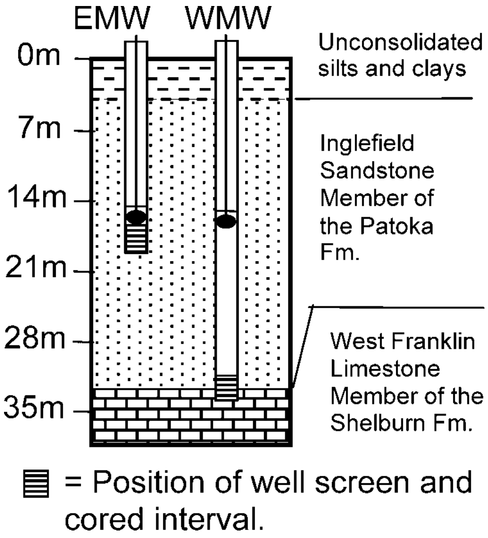

Figure 2.—Schematic diagram of the geologic setting and well installation for this study. EMW is the shallow monitoring well, and WMW is the deep monitoring well.

interval (Fig. 2). Water-levels were measured at hourly intervals using pressure transducers and data loggers. Hydrographs were plotted to show changes in groundwater levels over time. Barometric pressure was recorded on-site using a barometric pressure sensor and logger.

Removing barometric influence.—The ratio between change in water-level and change in barometric pressure describes the barometric efficiency of the well. This relationship is expressed as:

$$\omega = -(\Delta WL/\Delta BP) \qquad (1)$$

where ω = barometric efficiency, ΔWL = change in water-level (m), and ΔBP = change in barometric pressure (m).
Given a calculated barometric efficiency and the well-defined linear relationship between water-level change and atmospheric pressure change in these wells, then:

$$R(t) = W(t) + \omega[B(t) - J] \qquad (2)$$

where R(t) = residual (corrected) head (m), W(t) = well water-level (m), ω = barometric efficiency, B(t) = recorded barometric pressure (m), and J = A constant (bp at sea level, 10.3 m H_2O). This equation for residual (corrected) head removes barometric influence on measured groundwater-levels (Crawford & Rasmussen 1997).

Fourier Transform evaluation.—Corrected head hydrographs were evaluated to determine the presence of any periodicities in groundwater levels over time. Two overlapping series of 4096 hourly water-levels (170.7 days) from the deep piezometer (WMW) that had been corrected for barometric influence were evaluated using a Fast Fourier Transform. The two data sets overlap approximately three months.

The Fourier Transform reveals any oscillation frequencies that are present in a time series. The Fourier Transform is an integral transform,

$$F(\nu) = 1/\sqrt{(2\pi)} \int e^{-i\nu t} R(t)\, dt \qquad (3)$$

where ν = frequency, i = imaginary unit, R(t) = corrected head, and t = time.

In general, the Fourier Transform of real data is a complex valued function, with real and imaginary parts, so the transform of 4096 data points results in 2048 transformed points. Since the spacing of the data is one hour, the spacing in the transform is 1/4096 h^{-1}, and the domain of the transform is from 0–0.5 h^{-1}, that is, periods ranging from infinitely long down to two hours. Normally one is not interested in the real and imaginary parts separately, but rather the amplitude (Amp), or magnitude, of the transform, computed as:

$$Amp = \sqrt{\{Re^2[F(\nu)] + Im^2[F(\nu)]\}} \qquad (4)$$

where Re(F(ν)) and Im(F(ν)) are the real and imaginary parts of the Fourier Transform. Prominent frequencies have large amplitudes in the Fourier Transform spectrum. Well-defined peaks of large amplitude, and the presence of their harmonics, represent significant periodicities.

RESULTS AND DISCUSSION

Groundwater hydrographs from both the deep and shallow piezometers suggest a dynamic groundwater system. Both deep (WMW) and shallow (EMW) water-levels fluctuate up to 0.15 m in the matter of hours. Our observations began with the initial recognition of barometric influence on measured groundwater levels (Fig. 3). Water-level hydrographs display a strong inverse correlation

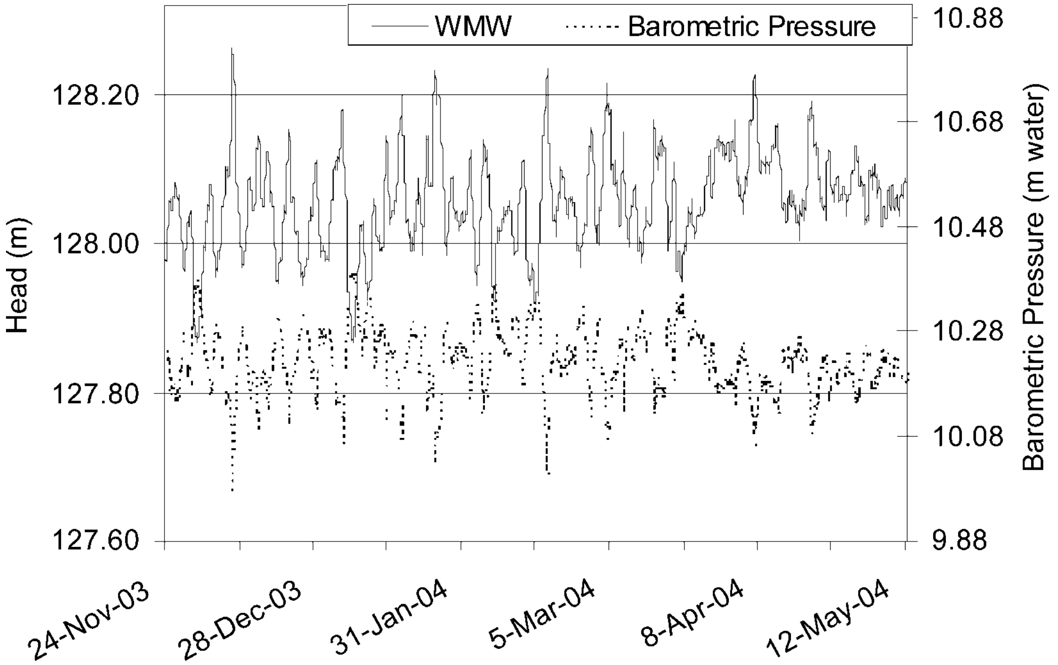

Figure 3.—Hydrograph of water levels from the deep (WMW) piezometer in the University of Southern Indiana Ground-water Monitoring Lab. Also shown is barometric pressure recorded on site. Measured water levels display a close inverse relation to barometric pressure changes.

to barometric pressure. Although both deep and shallow piezometer records clearly show this relationship, only the deep hydrograph data are used for our discussion. The inverse correlation of barometric pressure and groundwater levels is quantified by barometric efficiency (Fig. 4). The plot of head as a function of barometric pressure shows a high barometric efficiency of 0.95, indicating that during this monitoring interval, barometric pressure is a primary control of groundwater level changes.

Barometric efficiencies of confined aquifers typically range from 0.20–0.75 (Freeze & Cherry 1979). A range of ω may exist for a single aquifer because barometric pressure is not the only independent variable applying stress to the groundwater system during any monitoring interval. Because of the consistently, and atypically, high barometric efficiency observed in this study, we infer a particularly rigid skeleton for the Inglefield sandstone aquifer.

Hydrographs of corrected head are significantly different from originally recorded well-water elevation (Fig. 5). The application of Equation 2 to observed water-levels generated barometric corrections to hourly water-level data that were both positive and negative. In some cases measured water-levels were higher than actual aquifer potential, and at other times, measured water-levels were lower than the actual aquifer potential. Moreover, some of the corrections to measured levels were as large as −0.3 m and +0.1 m. Most corrections for this study were negative indicating that observed water-levels were generally higher than actual groundwater potential. This is, at least in part, due to our measured BP on site being generally lower than our selected constant value for J (sea level BP) in Equation 2.

The residual head hydrograph displays a periodicity that is not related to barometric changes (Fig. 5). The amplitude of the observed periodicity in the corrected head hydrograph is approximately an order of magnitude smaller than original water fluctuations. The large-scale influence of barometric pressure had masked these actual, small-scale fluctuations in aquifer potential. Corrected head does not have an inverse relationship with barometric pressure indicating that barometric

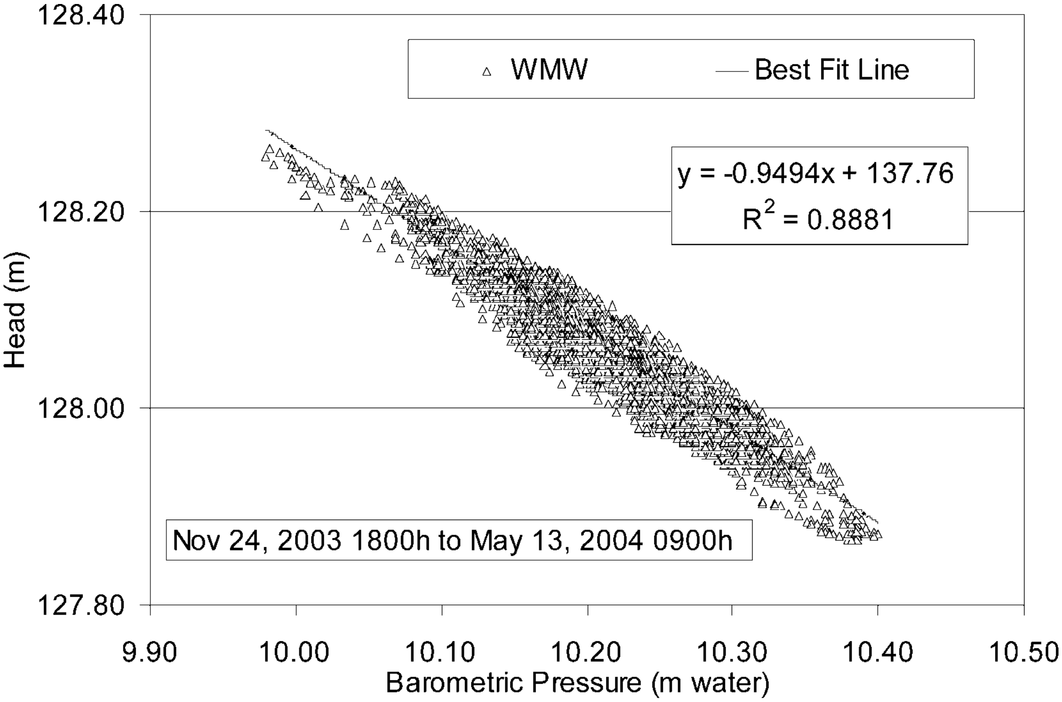

Figure 4.—Plot of ground-water levels from WMW as a function of barometric pressure for the interval shown in Fig. 3. The slope of this relationship, as characterized by the regression, represents the Barometric Efficiency (ω) of the aquifer. During this monitoring interval, ω equals 0.95.

influence was successfully removed from originally measured water-levels.

Fourier transforms of the two overlapping WMW data sets show similar results. For clarity, only the transforms of the November 2003 through May 2004 corrected head data are shown here (Fig. 6). Any purely sinusoidal influence in the data will appear in the transform as a single peak with a frequency the same as that of the influence. A periodic influence that is not sinusoidal will still appear in the transform, but also with additional peaks located at multiples of the fundamental frequency; these are the (higher) harmonics of the fundamental. Our data display four distinct peaks labeled A, B, C, and D. Peak A represents a period of 24.8 h, peak B corresponds to a period of 24.0 h, peak C corresponds to a period of 12.4 hours, and D to 12.01 hours. In these data, peak D is the 2nd harmonic of peak B, which is the fundamental (1st harmonic), and peak C is the 2nd harmonic of peak A.

Peaks B and D represent a fundamental 24 h periodicity in groundwater level fluctuations and its harmonic (12 h). This influence is presumably the combined effects of solar induced Earth-tides and any anthropogenic influences that operate with a 24 h period. Anthropogenic influences might include pumping from the aquifer, recharge to the aquifer, and daily loading of the land surface above the aquifer (leading to periodic elastic compaction and dilation).

Peaks A and C are similarly related. Peak A is indicative of a fundamental 24.8 h periodicity of water-level changes, and peak C is its harmonic. Given the close match of this periodicity to the fundamental period for lunar tides, and in the absence of other known influences with this period, we infer an unequivocal signature of the lunar gravitational effect on the aquifer.

The unlabeled large amplitude, low frequency peaks near the origin of the ‘‘native’’ output may be related to seasonal (periodic) and other long-term changes in groundwater levels (Fig. 6). It is also difficult to discern

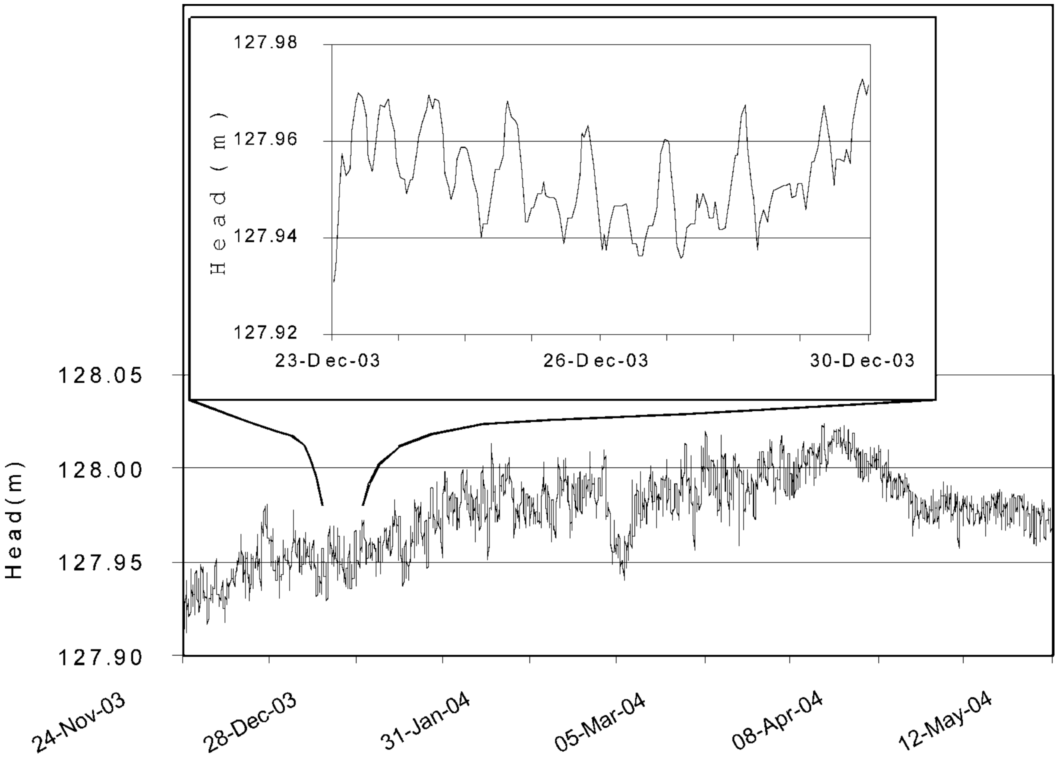

Figure 5.—Corrected head hydrograph for WMW for the period 25 November 2003 to 23 February 2004. Note the significantly smaller water level changes when compared to the observed water levels shown in Fig. 3. This hydrograph indicates that a periodicity in water-level change exists following barometric pressure correction. The inset graph is a magnification of the periodicity over a seven-day period, centered on a full moon that occurred on 27 December 2003.

real frequencies of long periodicities in these ‘‘short’’ data sets.

The output from the Fourier Transform of corrected head indicates that groundwater levels display periodic fluctuations over a range of frequencies. The moderately high relative amplitude (~10) of the solar and lunar tidal peaks, and the presence of harmonics, indicate that these variables have a demonstrable and measurable effect on periodic fluctuations of groundwater potential in the aquifer.

Water-levels recorded in the Inglefield bedrock piezometers display groundwater level fluctuations that result from external stresses. Specifically, the aquifer acts as a ‘‘high efficiency barometer,’’ displaying a strong inverse correlation between water-levels and atmospheric pressure variations. Small-amplitude fluctuations were observed in the corrected head that represent tidal stresses on the bedrock aquifer. A Fast Fourier Transform identified periodicities of 12.01 and 12.4 h, corresponding well to solar and lunar tidal stresses, respectively.

Given the pronounced response of this aquifer to external stresses, we hope to use these responses as passive tests of aquifer characteristics, specifically storativity. Further, we hope to modify our monitoring to much shorter intervals in an attempt to evaluate any responses of this aquifer to seismic stress. A broadband seismograph is located on the University of Southern Indiana campus, and we have access to real-time seismic monitoring data. We regularly record New Madrid and Wabash Valley seismicity as well as larger global events at our campus instrument. Recent work by Chia et al. (2002) has suggested that some groundwater responses to seismicity vary by stress field (extension versus compression). In addition, some rapid, coseismic groundwater level changes have been inter-

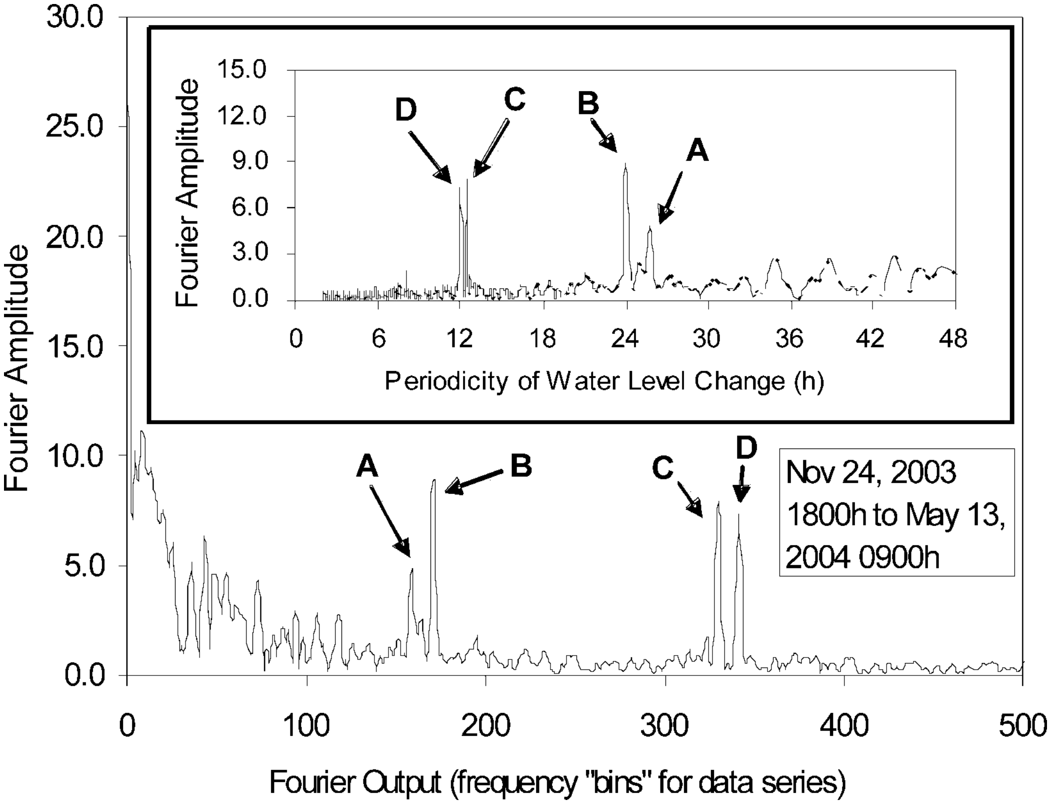

Figure 6.—Fourier Transform output for corrected head data displayed in Fig. 5. Large graph shows native output from the transform; Fourier output is defined in "Bins." For this series, (Bins/4096) = frequency of stress influence = period^{-1}. Inset graph shows the same data with x-axis modified to display units of periodicity in hours. Labeled peaks are discussed in the text and represent the periods of groundwater level fluctuations generated by solar (B, D) and lunar (A, C) tide stresses.

preted to alter fracture blockages at significant distances from the seismic focus (Brodsky et al. 2003).

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