ground water

Removal of River-Stage Fluctuations from Well Response Using Multiple Regression

by Frank A. Spane[1] and Rob D. Mackley[2]

Abstract

Many contaminated unconfined aquifers are located in proximity to river systems. In groundwater studies, the physical presence of a river is commonly represented as a transient-head boundary that imposes hydrologic responses within the intersected unconfined aquifer. The periodic fluctuation of river-stage height at the boundary produces associated responses within the adjacent aquifer system, the magnitude of which is a function of the existing well, aquifer, boundary conditions, and characteristics of river-stage fluctuations. The presence of well responses induced by the river stage can significantly limit characterization and monitoring of remedial activities within the stress-impacted area. This article demonstrates the use of a time-domain, multiple-regression, convolution (superposition) method to develop well/aquifer river response function (RRF) relationships. Following RRF development, a multiple-regression deconvolution correction approach can be applied to remove river-stage effects from well water-level responses. Corrected well responses can then be analyzed to improve local aquifer characterization activities in support of optimizing remedial actions, assessing the area-of-influence of remediation activities, and determining mean groundwater flow and contaminant flux to the river system.

Introduction

Groundwater characterization investigations are important for accurately predicting and monitoring the migration of groundwater contaminants within hazardous waste locations. Many of these contaminated unconfined aquifer sites are located in proximity to river systems, which impose a dynamic response within the adjacent intersected aquifer. The periodic fluctuation of river-stage height at the intersected aquifer boundary produces associated responses within the adjacent aquifer, the magnitude of which is a function of a number of physical factors, including well conditions (wellbore storage and well-skin effects), aquifer characteristics (hydraulic diffusivity), boundary conditions (well/river distance, aquifer penetration, river-bed resistance), and characteristics of river-stage fluctuations (magnitude and period/frequency of the fluctuation).

The presence of well responses induced by the river stage can significantly limit characterization activities within the impacted area. Field hydrologic tests conducted to determine aquifer hydraulic and transport properties (e.g., pumping tests, multiwell tracer tests) and well water-level measurements used to determine groundwater flow characteristics (i.e., flow direction, velocity) may be adversely impacted by river-induced aquifer hydraulic head responses.

This article demonstrates the use of a time-domain, multiple-regression convolution (superposition) method to develop river response function (RRF) relationships and a correction approach (multiple-regression deconvolution) to remove river-stage effects from well water-level responses. Corrected well responses can then be analyzed to improve aquifer characterization activities in support of optimizing remedial actions, assessing the

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area-of-influence of remediation activities, and determining the mean groundwater flow and contaminant flux to the river system. In addition, the multiple-regression coefficients used in developing an individual well RRF relationship can also be used to predict groundwater responses due to river-stage fluctuations. This relationship may be particularly relevant when using forecast river discharge behavior (e.g., National Oceanic and Atmospheric Administration) for predicting future changes in groundwater elevations caused by streamflow-runoff events.

Background

Groundwater literature has an extensive history of studies pertaining to aquifer responses associated with periodic fluctuations imposed by river-stage or ocean tides. Because associated aquifer responses exhibit amplitude attenuation and phase-shift characteristics to applied periodic boundary stress conditions, most of these previous investigations used frequency-domain-based methods for various applications. The earliest studies documented the use of river or tidal fluctuations as a basis for analyzing associated groundwater well responses to determine average aquifer hydraulic properties from the point of observation to the point of stress application (i.e., river or ocean boundary). Published analytical methods for analyzing river/ocean-induced hydrologic responses within well hydrograph records can generally be grouped within three broad categories: those based on regular sinusoidal or systematic fluctuations (e.g., ocean tides), those based on singular, large-scale events (e.g., high river-stage events), and those that examine composite river-aquifer interaction behavior. Examples of previously published reports of note for each general category include the following: for sinusoidal-based, fixed-frequency methods—Ferris (1952, 1963), Gregg (1966), Carr and van der Kamp (1969), and Erskine (1991); for those based on high river-stage events—Rowe (1960), Cooper and Rorabaugh (1963), Pinder et al. (1969), and Reynolds (1987); and composite river/aquifer interaction—Barlow and Moench (1998), Zlotnik and Huang (1999), Barlow et al. (2000), Moench and Barlow (2000), and Singh (2004). The reader is directed to Barlow and Moench (1998) for a more thorough discussion of the contributions of previous investigators for these and other areas of river/aquifer response study.

Recently, Smith (2008) noted the commonality in using frequency-domain techniques to examine periodic fluctuation studies within aquifers induced at boundaries as well as spatially applied periodic fluctuations associated with seismic events, groundwater recharge, barometric pressure, and earth tides. An important generalization stated in Smith (2008) related that if an aquifer is subjected to an arbitrary number of linear forcing terms (and the groundwater flow system is governed by linear flow conditions), then the principal-of-superposition can be applied to describe the total groundwater system behavior by summing the individual response relationship for each individual stress. Applying the principal-of-superposition means that each individual stress-response that is added in describing the composite total system behavior is possible due to the independence of each contributing stress-response relationship (Reilly et al. 1987).

Applying the principal-of-superposition also requires that the areal-temporal characteristics of the aquifer system (e.g., transmissivity, hydraulic gradient) do not significantly change over the area of investigation. For a coupled, unconfined, aquifer-river system, however, changes in saturated aquifer thickness could conceivably produce nonlinear system behavior. These conditions would likely occur when an unconfined aquifer is relatively thin (i.e., with respect to periodic, saturated thickness changes), and/or where relatively high hydraulic-gradient conditions may be present (e.g., for aquifers exhibiting lower permeability characteristics). Smith (2008) examined a number of scenarios to assess nonlinear system behavior and concluded that linear approximations of periodic flow conditions were adequate in many situations as long as the variation in aquifer-saturated thickness changes were relatively small. This is similar to the general finding of Reilly et al. (1987) for applying the principal-of-superposition to “mildly” nonlinear unconfined aquifer systems. As a rule-of-thumb, Reilly et al. (1987) conjectured that the principal-of-superposition would apply if an unconfined aquifer-saturated thickness at a location varied temporally by 10% or less.

River-Stage/Groundwater Response Factors

Periodic river-stage fluctuations represent temporal variations of hydraulic head at the boundary with the intersected aquifer system. The manner in which a well/aquifer system responds to changes in river-stage head variations is variable and directly related to a number of factors, including well effects, aquifer characteristics (hydraulic diffusivity, T/S), boundary conditions, and characteristics of river-stage fluctuations (magnitude and period/frequency of the fluctuation).

Well effects pertain to wellbore storage, well skin, and well completion aspects, and boundary-condition relationships include well-river boundary distance, river/aquifer contact characteristics, and streambed resistance/impedance. Wellbore storage, well skin, and well completion (e.g., aquifer partial penetration) effects represent artificial conditions that can delay the observed well response from reflecting the actual behavior of surrounding aquifer-head responses. The imposed delayed response from these factors is analogous to the hydrologic impact exhibited within observation wells during controlled hydrologic tests, for example, pumping tests. Neuman (1974), Fenske (1977), and Moench (1997) previously examined the delayed hydrologic impact of observation well storage, skin, and partial penetration during hydrologic testing. Although the nature of inducing a hydrologic stress within an aquifer is different for hydrologic tests conducted in wells (vertical line source) and for imposed stresses produced by river-stage fluctuations (boundary source), the general hydrologic impacts are similar. Examples of previous studies that examined the potential impacts of river/aquifer boundary conditions on river/aquifer response interactions include Hantush (1965), Zlotnik and Huang (1999), and Singh (2004).

From a historical perspective, Jacob (1950) was one of the first to examine periodic fluctuation characteristics imposed by river-stage and ocean tides on associated aquifer response as it relates to aquifer hydraulic diffusivity conditions. Based on similar derivations of classical heat-flow equations, Ferris (1952, 1963) expanded on the earlier work of Jacob (1950) and derived the following relationship for groundwater response for a uniform river-stage fluctuation imposed at a distant, communicative aquifer/river boundary:

$$s_{\mathrm{w}} = s_{\mathrm{r}} \mathrm{e}^{-x(\pi S/t_{\mathrm{o}}T)^{1/2}} \sin[(2\pi t/t_{\mathrm{o}}) - x(\pi S/t_{\mathrm{o}}T)]^{1/2} \quad (1)$$

where s_{w} is the associated well water-level response [L], s_{r} the river-stage water-level response [L], t_{o} the period of river-stage sinusoidal fluctuation [T], t the observation time after stress occurrence [T], x the well distance to aquifer/river boundary [L], T the aquifer transmissivity [L^2/T], S the aquifer storativity [dimensionless].

The first exponential term of Equation (1) quantifies the decrease in the amplitude of the associated well water-level response to a river-stage fluctuation with increasing distance from the aquifer/river boundary while the second term of the relationship pertains to the time-lag of the induced aquifer signal observed at a distance, x, from the aquifer/river boundary. This led Ferris (1952, 1963) and others (Erskine 1991) to separate Equation (1) into two separate relationships for the observed aquifer/river-stage amplitude ratio, AR, and time lag, t_{L}:

where
$$A_{\mathrm{R}} = s_{\mathrm{w}}/s_{\mathrm{r}} = \mathrm{e}^{-x(\pi S/t_{\mathrm{o}}T)^{1/2}} \quad (2)$$

$$t_{\mathrm{L}} = x(t_{\mathrm{o}}S/4\pi T)^{1/2} \quad (3)$$

From Equations (1) through (3), the following generalizations pertaining to associated aquifer response with distance from the aquifer/river boundary can be deduced: (1) the associated response for a given river-stage fluctuation attenuates (decreases) with aquifer/river boundary distance, (2) stress periods of longer duration (i.e., period) propagate further into the aquifer, and (3) the propagating aquifer signal becomes more delayed (lagged) with distance to the boundary.

As noted in Ferris (1952), for shallow confined aquifers where the river-stage fluctuation stress is transmitted to the aquifer through loading and not by a direct, communicative aquifer/river boundary contact, then the amplitude ratio, AR, in Equation (2) should be modified by reducing the river-stage fluctuation stress, s_{r}, by the standard loading relationships for confined aquifer systems originally presented in Jacob (1950).

The time-lag relationship expressed in Equation (3) suggests that the time-domain-based, multiple-regression method previously used successfully in removing the periodic stress impacts of barometric fluctuations from well/aquifer response may have similar applications in correcting periodic responses imposed by river-stage fluctuations. Because frequency- and time-domain-based methods for examining periodic flow conditions require linear-system behavior, it is assumed that the time-domain-based, multiple-regression methods would be appropriate for all situations where frequency-domain techniques are applicable. The remainder of this article examines the applicability of the multiple-regression deconvolution procedure as originally presented in Rasmussen and Crawford (1997) and expanded upon in Spane (2002) for removing the effects of river-stage fluctuations from well water-level response records.

It should be recognized that the multiple-regression deconvolution approach presented in this article may be considered a simplified form of more complex, multivariate auto-regressive, integrated moving-average (ARIMA) time-series models. These models are commonly used in economic and scientific forecast applications. Unlike the well-established controlling factors of river-stage fluctuations on well responses, more involved ARIMA model applications may be more appropriate for cases when the underlying processes controlling a dependent time-series response are not well known. A number of papers have been published in the literature that compare forecast capabilities of various ARIMA models (Mohammadi et al. 2005; Weisang and Awazu 2008). The reader is directed to these references and statistical textbooks (Pankratz 1983, 1991) for detailed discussions on the capabilities and application of ARIMA models.

Multiple-Regression Removal Method

Rasmussen and Crawford (1997) and Spane (1999, 2002) demonstrated the multiple linear-regression method and its application for correcting well water-level responses for barometric pressure fluctuations. An important result of the multiple-regression procedure was the development of barometric response plots (BRPs) from the analyzed well water levels as they relate to the observed barometric response record. An individual well BRP can be used diagnostically to provide information concerning the well/aquifer system (e.g., aquifer type, presence of wellbore/storage/well-skin, and vadose zone characteristics). A BRP shows the time-lag dependence of the change in well water-level response with a unit change in barometric pressure. The plots are developed by performing multiple linear-regression convolution analysis of the water-level response to the barometric pressure change over the time-lag period with a constant observation period, for example, 1-h frequency.

This same analysis approach was applied for comparing time-lag dependence of well water-level response to river-stage fluctuations. Because observations are recorded at a constant measurement frequency, the multiple linear-regression model relationship developed between well water level and river-stage change can be represented as follows:

$$\Delta h_{\mathrm{w}} = \alpha_0 + \beta_0 \Delta h_{\mathrm{Ri}} + \beta_1 \Delta h_{\mathrm{Ri}-1} + \beta_2 \Delta h_{\mathrm{Ri}-2} + \cdots + \beta_n \Delta h_{\mathrm{Ri}-n} + \varepsilon \quad (4)$$

where Δh_{w} is the water-level change over the last time interval, Δh_{Ri}, river-stage change over the last time interval, $\Delta h_{\mathrm{Ri}-1}$ the river-stage change for the previous time interval, $\Delta h_{\mathrm{Ri}-n}$ the river-stage change from n time interval to $(n-1)$ previous time interval, α_0 the regression intercept for the entire time interval, $\beta_0 \ldots \beta_n$ the regression coefficients corresponding to time lags of 0 to n, ε the residual error term, n the number of time intervals that lagged river-stage effects are statistically significant.

After calculating the regression coefficients $\beta_0 \ldots \beta_n$, a predicted change in aquifer well response can be calculated for each observed change in river-stage level using Equation (4). It should be noted that the regression intercept (α_{o}) in the multiple-regression relationship of water-level and river-stage change, shown in Equation (4), represents and accounts for the background linear trend over the specific model fitting period. As such, α_{o} would be expected to change for different data time periods while the established β regression coefficients would remain relatively constant as long as the aquifer-river system maintains linear-system behavior. The residual error term, ε, represents the difference between the observed vs. the predicted well water-level change, Δh_{w}, using the established time-lag relationship. Strictly speaking, the standard multiple linear-regression assumes that regression residuals (ε) are normally distributed with a mean = 0, whose variance, σ^2, is constant, and are not strongly autocorrelated (Pankratz 1991). Because river-stage fluctuations are not completely independent, there may be a level of correspondence (multicolinearity) exhibited between the observed time-lag, river-stage changes, $\Delta h_{\mathrm{Ri}} \ldots \Delta h_{\mathrm{Ri}-n}$, which may be reflected in nonrandom ε characteristics. This does not invalidate the use of multiple linear-regression applications for predicting Δh_{w}, but does influence the statistical assessment of the importance of individual time-lag, regression coefficients, $\beta_0 \ldots \beta_n$. As a general guideline, the multiple linear-regression relationship should be extended to include river-stage time lags that produce the "best" corrected well water-level response. For river-stage fluctuations exhibiting a high-level of independence, a consistent pattern for common statistical correlation, "goodness-of-fit" parameters, for example, high adjusted coefficient of determination (R^2), low sum-of-squares (error [SSE], total [SST], regression [SSR]), and residual mean square statistics, can be used as a guide for time-lag significance.

As in the development of a BRP, an RRF plot can also be constructed by summing the calculated, time-lag, regression coefficients (β_i) up to n number of the associated time lag; for example, for a time lag of 0, the RRF time-lag value = β_0, and for a time lag of 3, the RRF time-lag value = $\beta_0 + \beta_1 + \beta_2 + \beta_3$, as indicated in Equation (5):

$$\mathrm{RRF}_n = \sum_{i=0}^{n} \beta_i \quad (5)$$

It should be noted that the only difference between BRP and RRF development is that in generating a well BRP, the calculated time-lag, regression coefficients have to be first normalized (i.e., multiplied by -1) before summation to account for the opposite stress effect that barometric pressure has on well water levels (i.e., positive barometric pressure changes cause negative well water-level responses). This would not be the case in RRF development because positive changes in river stage produce positive changes in well water levels. Detailed examples of how a well response BRP is developed are provided in Spane (1999) and Toll and Rasmussen (2007).

Figure 1 presents generalized depictions of RRF plots produced with the multiple-regression convolution process described in the preceding paragraphs and establishes the dependence of the observed well response to antecedent (time-lagged) river-stage changes. The time-lag dependence exhibited by individual well RRFs can be used diagnostically to assess general aquifer hydraulic characteristics. As shown in the figure, wells exhibiting relatively high/early time lag correspondence are indicative of wells located in proximity to the river/aquifer contact boundary and/or for aquifers possessing high T/S conditions. Theoretically, RRFs can be normalized for their relative well-to-river boundary distance differences and compared to assess the spatial variability of hydraulic diffusivity for different inter-well/river areas within an investigation area. As indicated in the figure, other factors contribute to the shape and response characteristics of individual well RRFs. The significance of these other factors should be addressed before making quantitative interpretations of aquifer hydraulic characteristics.

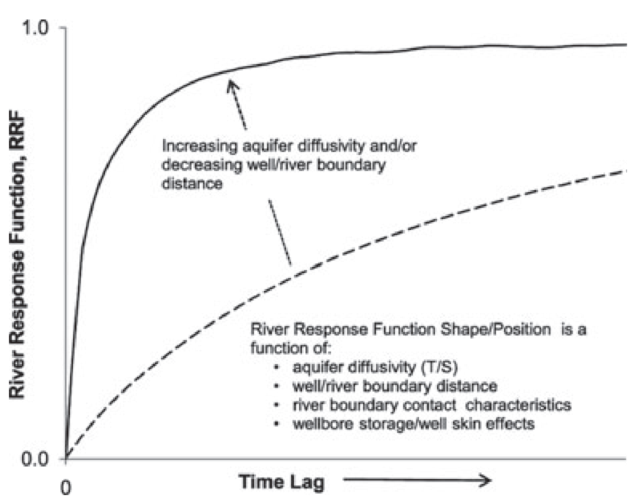

Figure 1. General river response function plots and influencing relational parameters.

Results of multiple-regression time-lag analyses presented in this article were calculated with Minitab 15 Statistical Software (Minitab, Inc. 2007). A *Ground Water* review of the statistical capabilities of an earlier version of Minitab 12 is provided by Diodata (1998). After calculating the time-lag-dependent regression coefficients using ordinary least-squares linear multiple regression, the well water-level-corrected response, $\mathrm{WL_{cor}}$, can be calculated by subtracting the summation of the calculated change in well water-level, $\sum \Delta h_{\mathrm{w}}$ (Δh_{w} determined using Equation (4)), from the observed well response, $\mathrm{WL_{obs}}$, with commercially available mathematical spreadsheet software (e.g., EXCEL), as indicated in the following relationship:

$$\mathrm{WL_{cor}} = \mathrm{WL_{obs}} - \sum \Delta h_{\mathrm{w}} \tag{6}$$

where

$$\sum \Delta h_{\mathrm{w}} = \Delta h_{\mathrm{wi}} + \Delta h_{\mathrm{wi}-1} + \Delta h_{\mathrm{wi}-2} + \cdots + \Delta h_{\mathrm{wi}-n} \tag{7}$$

A predicted well water-level response, $\mathrm{WL_{pred}}$, can be calculated similarly by adding the summation of the calculated change in water level, $\sum \Delta h_{\mathrm{w}}$, to the observed well water level at the beginning of the data set ($\mathrm{WL_{obs_0}}$) as follows:

$$\mathrm{WL_{pred}} = \mathrm{WL_{obs_0}} + \sum \Delta h_{\mathrm{w}} \tag{8}$$

As a cautionary note, one could theoretically use the multiple-regression convolution and deconvolution capabilities of the barometric removal software program BETCO (Toll and Rasmussen 2007) to remove river-stage fluctuations from well water-level responses. However, there are several restrictions and design elements in BETCO that limit its use in river-stage correction applications. For example, BETCO restricts the maximum lag response interval to less than 100 time-lag intervals, which may not be extensive enough to capture all the well/river-stage response time-lag dependence. Additionally, BETCO does not fully support the graphing of RRFs because of sign conventions designed in the barometric-focused software program.

Test Case Example

The test case example is located within the 300 Area of the Hanford Site, a U.S. Department of Energy site located in south-central Washington State (Figure 2). Historical nuclear reactor fuel fabrication and research activities have resulted in uranium contamination to the vadose zone and unconfined aquifer as well as migration to the Columbia River on the eastern boundary of the 300 Area. Consequently, many groundwater wells have been drilled and constructed throughout the 300 Area in support of repeated site characterization and groundwater modeling studies. Several of the test case wells used in this study were recently installed, unconfined aquifer wells that support ongoing field-scale hydraulic and geochemistry experiments associated with the Integrated Field Research Challenge (IFRC) project (Bjornstad et al. 2009). Two of the four wells used in this river-stage study (wells 399-2-5 and 399-2-13) are located in this IFRC project site area (note: the Hanford Site 399 well designation is removed for brevity for paper discussion purposes).

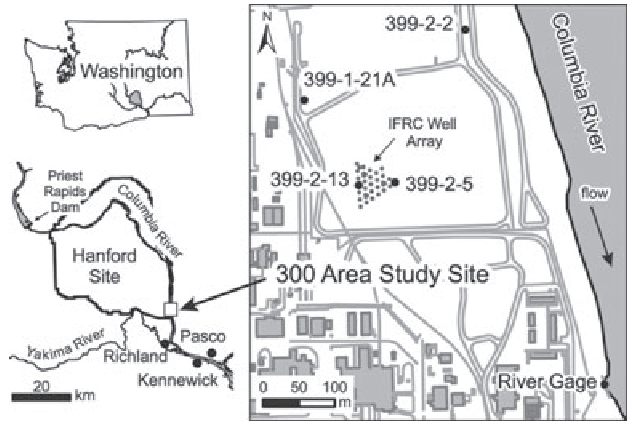

Figure 2. Location map showing monitoring well and river-stage gauge locations.

The unconfined aquifer beneath the general 300 Area consists of a heterogeneous layering of fluvial and lacustrine sediments of the Ringold Formation and overlying glaciofluvial gravels and sands of the informally recognized Hanford formation. The unconsolidated gravels and sands of the Hanford formation are highly permeable and form the dominant zone of groundwater flow and contaminant transport within the unconfined aquifer. Reported hydraulic conductivity (K) estimates for the Hanford formation in the 300 Area are extremely high and range between 100 and >1000 m/d (Williams et al. 2008; Vermeul et al. 2009). In contrast, reported K estimates for the more underlying, highly compacted, fine-grained sediments of the Ringold Formation are significantly lower and range between 0.4 and 40 m/d (Williams et al. 2007).

The average water-table elevation in the 300 Area is approximately 105.5 m above mean sea level (msl; NAVD88), but varies and responds dynamically (e.g., ~1.5 to 2.5 m annually) to periodic fluctuations in the Columbia River stage. The composite saturated thickness of the unconfined aquifer is approximately 25 m within the investigated area surrounding the four well site locations. However, because of the low-K nature of the Ringold Formation compared to the highly permeable Hanford formation, the effective aquifer thickness is more reflective of the Hanford formation saturated thickness, which is approximately 8 m in this inter-well area.

The four 300 Area wells examined in this river-stage study are completed and fully penetrate the highly permeable Hanford formation sediments. The relative locations of the three far-wells (1-21A, 2-5, 2-13) with respect to near-river well 2-2 and the river-stage gaging station are shown in Figure 2. The measured distances to the Columbia River for far-wells 1-21A, 2-5, and 2-13 and near-well 2-2 are 323, 235, 285, and 80 m (±2 m), respectively.

Hourly well water levels and river-stage elevation data were collected continuously during the study period of parts of 2008 and 2009. Water levels in the study site wells were collected with a combination of analog pressure transducers (Druck model 1830, 10 PSIG, 0.1% full-scale accuracy [±0.007 m]) connected to automated dataloggers (Campbell Scientific, Inc. model CR10X, 0.05% full-scale accuracy [±0.003 m]) and digital pressure sensors with internal data recording functionality (Instrumentation Northwest, Inc. model PT2X, 15 PSIG, 0.06% full-scale accuracy [±0.006 m]). The downhole water-level data for the site wells were periodically verified (i.e., every few weeks) with manual water-level measurements using a nonelastic, metal-taped, water-level meter, traceable to the National Institute of Standards and Technology. The water-level measurement tapes are marked in 0.003-m (0.01 feet) gradations. Elevation data for the Columbia River stage were obtained from the Hanford Virtual Library, a web-based data-acquisition tool that allows the Hanford Site end users direct access to data stored in the Hanford Environmental Information System (HEIS). All water levels are referenced to an engineering-surveyed elevation datum.

Temporal Response Characteristics

Hourly water-level data for individual wells examined in this study were available for different starting periods in calendar year 2008 and extended continuously to September 27, 2009. Because data were available for all four well locations during calendar year 2009, this calendar year served as the basis for the primary multiple-regression assessment. Figure 3 shows the hourly temporal response characteristics of well water levels over the time period January 1 to September 27, 2009 (2009 calendar days: 1 to 270) for the three far-wells examined in this study. As indicated, a high visual correspondence was exhibited for the three far-well locations, which all fluctuated over a range of approximately 1.5 m during the period. Also evident in the figure was the inadvertent, temporary lowering of the water table within well 1-21A below the in-well pressure transducer depth-setting, shown starting on calendar day 245 (September 2, 2009). As a result of this loss of continuous well response data, all comparative multiple-regression well analyses were limited to well response data collected during the first 240 days of calendar year 2009.

Figure 4 shows the hourly well water-level responses for far-well 1-21A, near-well 2-2, and the Columbia River stage-height elevation as measured at the gauge station location shown in Figure 2. As indicated, the Columbia River-stage elevation exhibits considerably more hourly variability than displayed at either the near-well or far-well locations. A comparison of water-level elevations indicates that the Columbia River is primarily on average a "gaining stream" (i.e., groundwater flows from the aquifer into the river system) over most of the year within the study-area reach. During high seasonal river peak-flow periods (generally between calendar days 140 to 180 on long-term average), however, "losing" stream conditions occur, and river water flows into the adjacent aquifer as temporary bank-storage.

Spectral Frequency Analysis

Spectral frequency analysis is important for identifying underlying frequency patterns (i.e., well response vs. river stage) that may be masked when only examined as a time-domain, time-series plot. To examine the association of the temporal responses exhibited by the wells to river-stage fluctuations, spectral analysis was performed on the hourly response data over the selected 180-d period

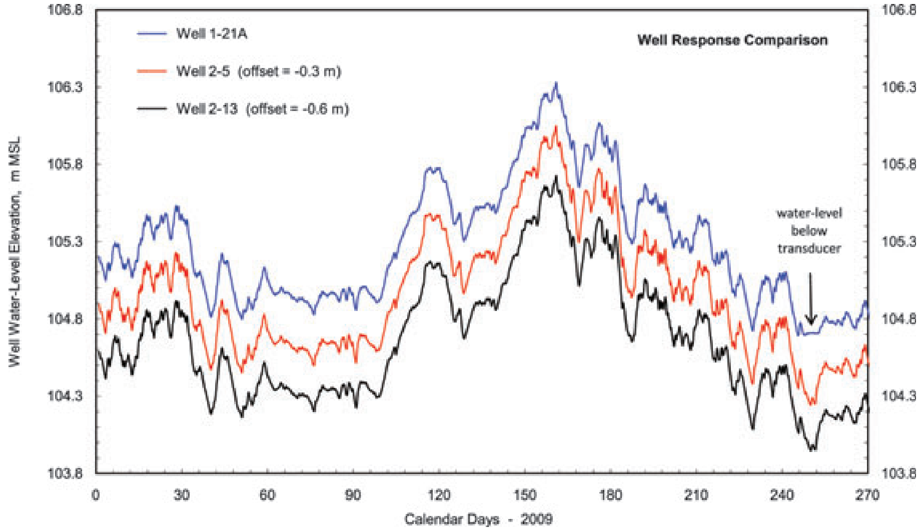

Figure 3. Temporal far-well water-level response characteristics.

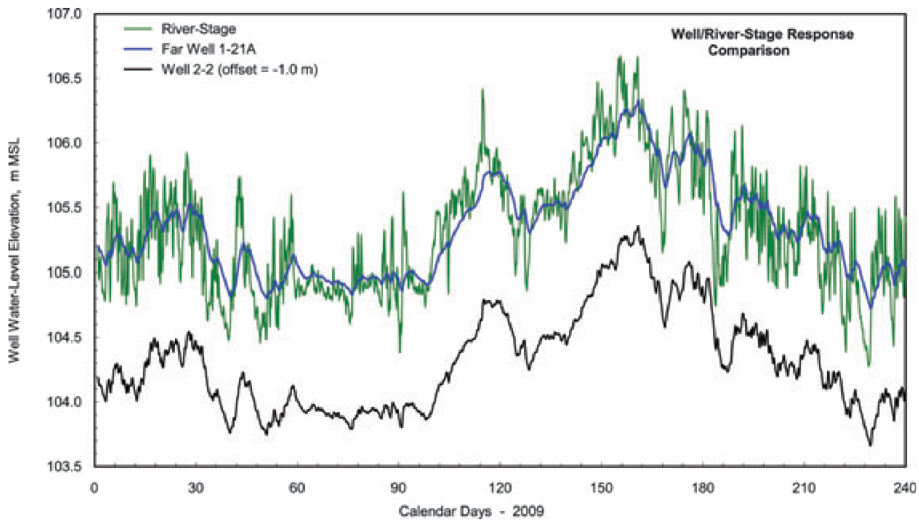

Figure 4. Comparison of far-well 1-21A, near-well 2-2, and river-stage elevation response characteristics.

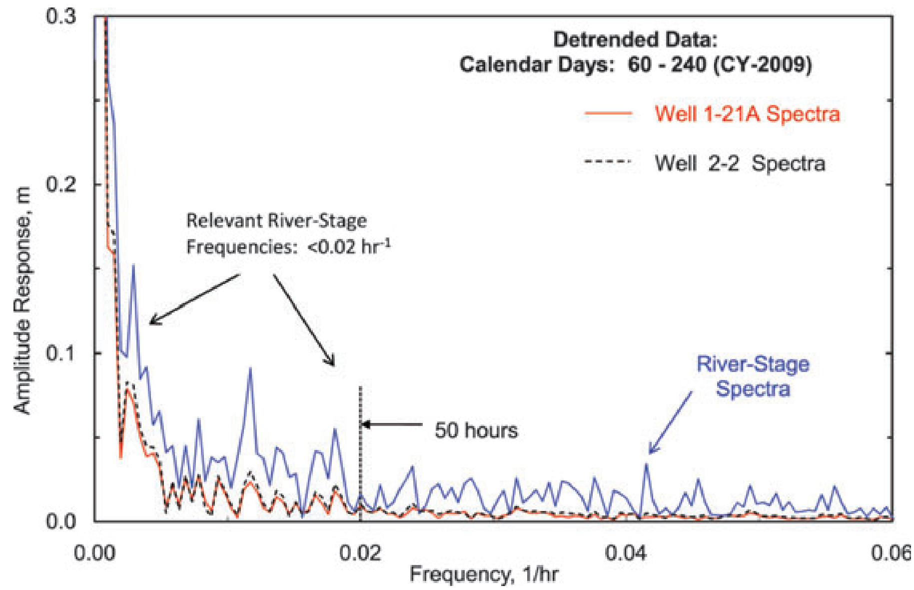

Figure 5. Spectral analysis comparison: far-well 1-21A, near-well 2-2, and river-stage elevation response.

between March 1 and September 18, 2009 (2009 calendar days: 60 to 240). The analysis period encompasses the seasonal, high river-stage event, which during 2009 and most years occurs between calendar days 140 to 180. To perform the spectral analysis, the procedure outlined in Spane (2002) was used. The hourly well and river-stage responses were first detrended using a linear-regression fit to the entire data set. The mean value was then subtracted from the detrended data, which were then converted to the frequency domain using the Fast Fourier transform program ETFFT (Hydrotechnique Associates 1984), that is based on Fourier analysis theory as presented in standard text books such as Bendat and Piersol (1971). Frequency analysis of the transformed data provides an amplitude spectrum of the frequencies within the response record. Visual and statistical correlations (cross-spectral analysis) can then be made between the well and river spectral patterns to identify significant river frequencies expressed in the well response record.

Figure 5 shows a comparison of the spectral density functions for far-well 1-21A, near-well 2-2, and the river-stage response over the designated time period. The spectral frequency analysis procedure as presented in Hydrotechnique Associates (1984) and summarized in Chien et al. (1986) was used in developing the spectral relationships shown in the figure. The spectral density function plots can also be generated using various commercially available mathematical software programs (MATLAB™ 2010). As previously noted, the data were detrended before performing the frequency analysis. As reported in Spane (2002), detrending the data set removes long-term trend effects, which reduces the low-frequency amplitude response in the frequency spectral plots, enabling proper identification of the hydrologic impact of shorter period phenomena (e.g., a seasonal high river-stage event).

A visual examination of the plots shown in Figure 5 indicates a nearly identical spectral pattern, both in frequency and amplitude, for both far-well 1-21A and near-well 2-2. The high correspondence between wells is reflective of the high, inter-well aquifer hydraulic diffusivity, which is well known for this Hanford Site area (Williams et al. 2007, 2008; Bjornstad et al. 2009). A comparison of the spectral plots in Figure 5 indicates that a significant association with river-stage fluctuations only occurs for frequencies with periods $\geq$50 h. Based on frequency-based relationships presented originally in Ferris (1952, 1963), higher river-stage frequencies should have propagated and had associated well-response expressions at distances extending beyond near-well 2-2. The fact that these higher frequency river signals are not observed suggests that the aquifer/river boundary contact is more complex than assumed in the simple, frequency-based Ferris model. This assumed boundary complexity may include the lack of a fully penetrating or well-defined aquifer/river contact zone at the river-shore boundary and streambed resistance effects (i.e., the presence of a low-permeability "river skin") at the aquifer/river boundary. These boundary complexities tend to filter and dampen the hydrologic impact of short-duration (i.e., high-frequency), and relatively low-magnitude, river-stage fluctuations at adjacent well/aquifer locations. Identified significant river-stage frequencies can be selectively removed or filtered from the well record based on the cross-spectral correlation characteristics (amplitude ratios, phase-shift information). Previous investigators have applied frequency-based, correction methods for similar, periodic stresses imposed by barometric fluctuations with varying degrees of success (Chien et al. 1986; Rojstaczer and Riley 1990; Quilty and Roeloffs 1991; Spane 2002). As noted in Spane (2002), this removal procedure can be quite lengthy because a high-level of correction requires that all relevant frequencies (exhibiting different amplitude attenuations and phase-shift effects) have to be accounted for in the total correction process. Because of this and the lack of a consistent well/river correlation correspondence in the frequency-domain as indicated in the spectral plots in Figure 5, emphasis was placed on examining the applicability of the time-domain-based, multiple-regression, deconvolution method. This method has been used with a high-degree of success in removing the blanket-load stress effects of barometric pressure from well responses in support of detailed aquifer test characterization investigations (Spane and Thorne 2000; Spane 2002, 2008; Spane and Newcomer 2009). Identifying river-stage frequencies that are expressed in the well water-level spectral response provides a basis for assessing the multiple-regression time-lag range that may be required for removing river-stage effects from the well record. The identified frequency range can then be used in Equation (3) to evaluate a relevant time-lag range that may be required in the multiple-regression correction procedure. As indicated in Equation (3), for a given well location/distance, x, the associated time lag, t_L, of the propagating river-stage fluctuation is directly related to the period (1/frequency) of the fluctuation, t_o, and inversely to the aquifer diffusivity, T/S, between the well and river boundary distance. For example, for the well 1-21A located at a distance, x, of 323 m, an expected range of multiple-regression time-lag dependence of between approximately 0.4 and 250 h is indicated. This time-lag dependence range was calculated with the following appropriate minimum and maximum input range values in Equation (3): $t_o = 50$ to >1000 h (Figure 5; relevant river-stage frequency range 0.02 h^{-1} and <0.001 h^{-1}), $T = 800$ to >8000 m^2/d (from previously cited site conditions), and $S = 0.0001$ to 0.25 (assumed unconfined aquifer elastic storativity and specific yield values).

River–Stage Response Function

Because of previously discussed river/aquifer boundary complexities, Ferris (1952, 1963) stated that well-response analysis of river-stage fluctuations would achieve better results if the river stress-response record used in the analysis were provided from a fully penetrating well located in proximity to the river (i.e., instead of the observed river-stage measurements). To evaluate this potential stress input difference, RRFs for the three far-well locations were developed using both the near-river well 2-2 and the observed river-stage response as aquifer response input signals. Figure 6 shows the results of the multiple-regression convolution analysis using the two different sources for periodic input signals. As noted previously, the RRFs were developed by sequentially summing the time-lag dependence of the calculated regression coefficients for the respective far-wells over the 240-d period of record shown in Figure 4. The RRFs shown were smoothed slightly using a 5-spot central moving-average scheme to reduce some of the observed plot variability.

As might be expected, RRFs developed using the near-river well 2-2 as the input stress exhibited a high cumulative river response (i.e., >0.9) for time lags up to approximately 48 h. In comparison, extended time lags of 480 h and greater were required to reach similar RRF levels for the far-wells using the actual observed river stage as the direct aquifer input stress. Each set of RRF plots exhibits a consistent shape pattern, which suggests relatively uniform aquifer hydraulic diffusivity conditions over the well-to-aquifer boundary distance. The RRF plotting locations are also consistent with well-river distance relationships, with wells located closer to the river shifted to the left in the figure. The proximity of the near-well 2-2 RRF to far-well plots developed using the river stage as the input stress is also consistent with the observations of a high-aquifer-diffusivity condition and high hydrologic resistance/impedance for the aquifer/river boundary contact area.

It should also be noted that RRF plots were generated (not shown) for three sequential 60-d periods within the 180-d period, and nearly identical RRF plots were

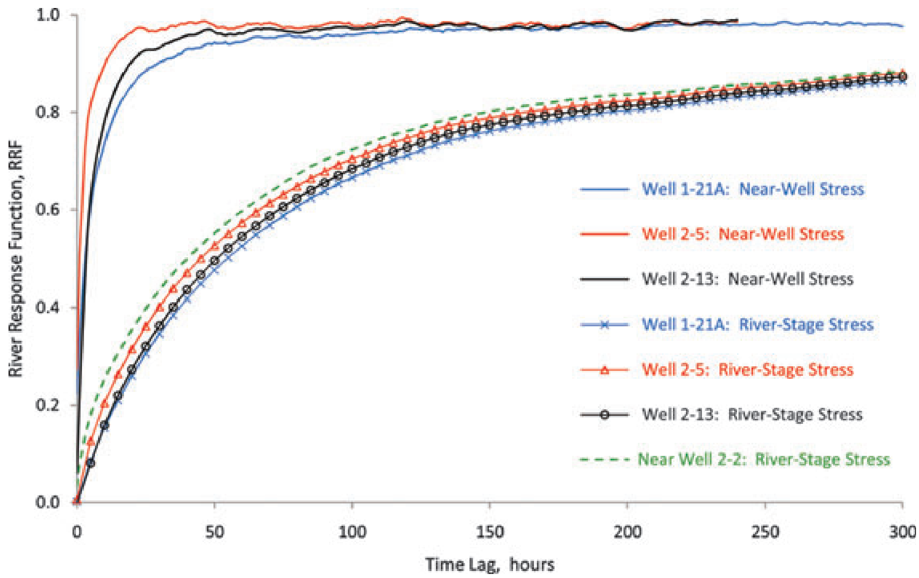

Figure 6. River response function plot for far-wells using near-well 2-2 and river-stage elevation response as stress input.

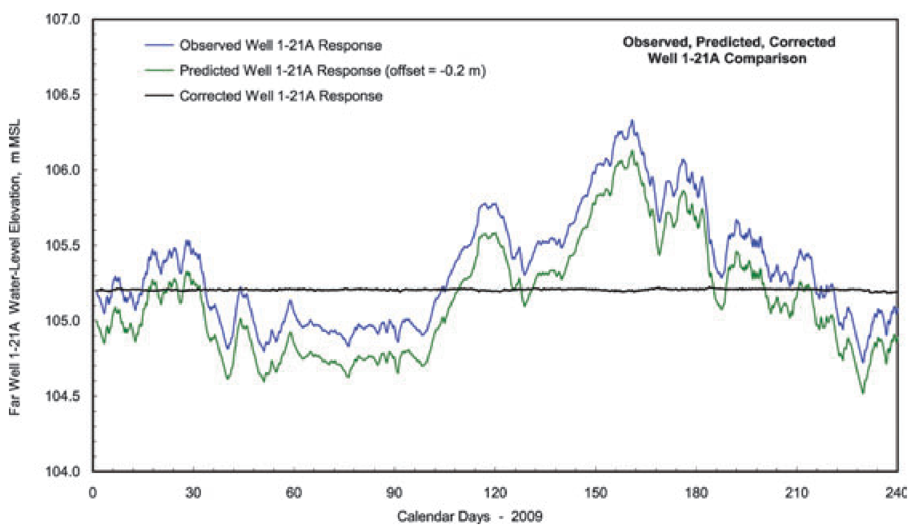

Figure 7. Observed, predicted, and corrected far-well 1-21A response comparison, using near-well 2-2 as stress input (time lag = 240 h).

realized for each well location. This suggests that RRF development and multiple-regression correction for river-stage effects within the well response are consistent throughout the year and valid for both "gaining" and "losing" streamflow conditions.

Near-Well Correction

To assess the removal of river-stage effects using the multiple-regression method, the CY-2009 far-well records were deconvolved with the calculated time-lag-dependent, regression coefficients for each of the wells using near-well 2-2 as the aquifer/river-stress input signal. Individually, the three far-wells exhibited the best corrected well water-level responses for time lags ranging between 182 and 248 h. Comparatively, however, differences in corrected well responses were insignificant using various regression time lags within this range. Figure 7 shows a comparison of the observed, predicted, and corrected response for far-well 1-21A, based on multiple-regression-coefficient relationships developed using near-well 2-2 as the river-stage input stress to the aquifer system (time lag = 240 h). As shown, the predicted response closely simulates the observed well record, which is reflected by the nearly uniform corrected response (i.e., observed minus predicted).

Figure 8 shows the results of the multiple-regression deconvolution correction at each of the far-well locations using an expanded vertical scale (1 m) to support visual comparison. For a consistent well comparison, a uniform, 240-h, time-lag period was used at each of the far-well locations. As indicated, the approximately 1.5 m of periodic response induced by the river stage exhibited for far-wells in Figures 3 and 4 over the 240-d period of

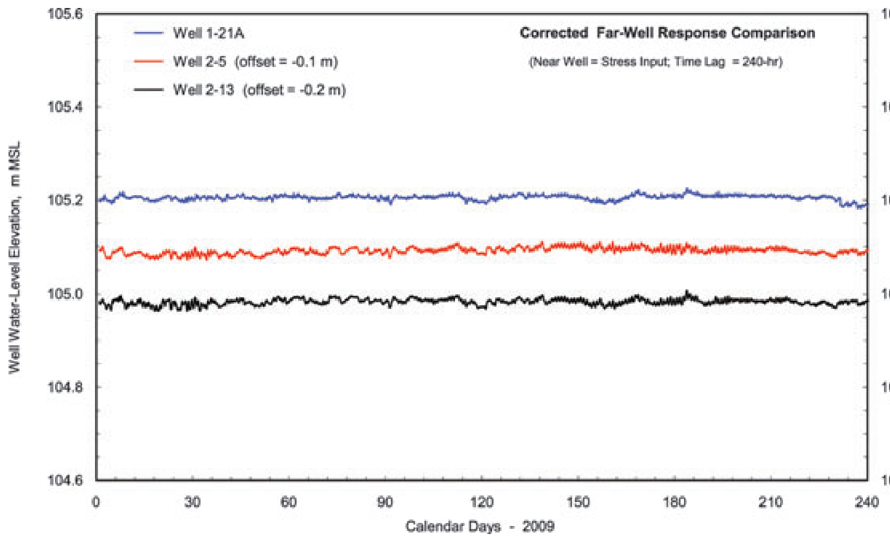

Figure 8. Corrected far-well response comparison, using near-well 2-2 as stress input.

record was effectively removed at each of the three far-well locations. The highest level of visual correction was exhibited for far-well 1-21A, which exhibits a corrected well-response variation of less than 0.02 m over the entire 240-d period.

For comparison purposes, well 1-21A was similarly corrected with the multiple-regression deconvolution method using the observed river-stage record as the aquifer stress input. Because of the greater time-lag dependence exhibited for far-well RRFs in Figure 6, corrections started with an initial 240-h time dependence and were sequentially increased until corrected results exhibited no statistical improvement. No added improvement in corrected responses was realized above a 480-h, time-lag dependence (i.e., using river stage as the stress input). As shown in Figure 9, corrected responses for using river-stage stress provided reasonable, but less robust, results for well 1-21A. Similar results (not shown) were obtained for correction comparisons for the other two far-well locations.

To assess a more universal application of the multiple-regression method for other time periods not encompassed by the multiple-regression convolution period (i.e., used for developing the well RRF), well 1-21A responses during the previous calendar year 2008 were similarly corrected using the regression coefficients determined during 2009 (using near-well 2-2 as the river-stress input). Figure 10 shows a comparison of the observed far-well 1-21A response to the observed river-stage record in calendar year 2008. As during 2009, far-well 1-21A exhibits a general visual correspondence to lower frequency river-stage events. The 2008 period record reflects a more typical Columbia River response pattern, with the occurrence of a dominant, single, high

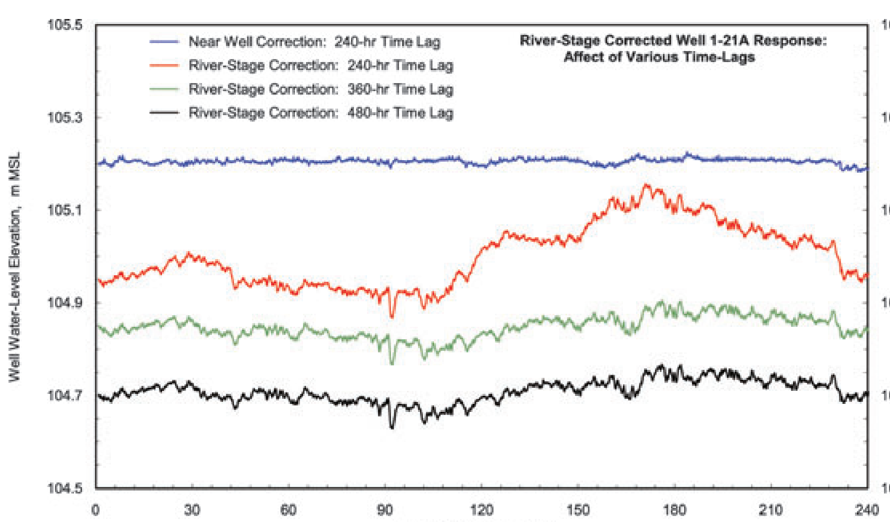

Figure 9. Comparison of river-stage corrected well 1-21A response, using various time lags (responses offset for comparison purposes).

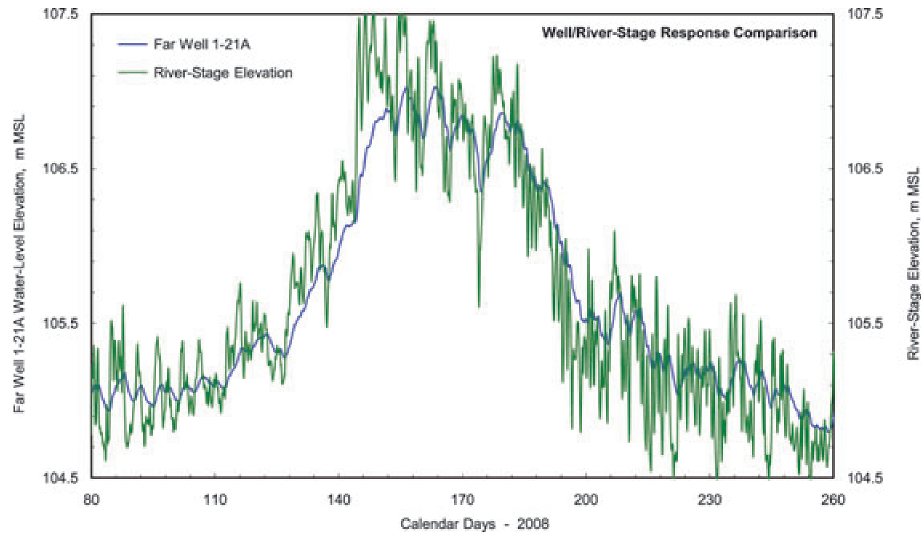

Figure 10. Comparison of far-well 1-21A and river-stage elevation response characteristics—2008.

river-stage event during the period of record. Of note is that the seasonal high river-stage event was of higher magnitude and as a result produced higher associated well water levels. A comparative examination of the water-table elevation at all well locations indicates that the aquifer exhibited a uniform, peak, saturated-thickness increase of approximately 0.7 m during 2008 with an expected commensurate higher aquifer transmissivity during this elevated water-level time period (i.e., in comparison to the conditions that occurred during the 2009 period of the time-lag regression development). This represents an increase of saturated thickness percentage of approximately 9% over the similar high water-table period occurring during 2009.

Figure 11 shows observed and corrected responses for far-well 1-21A during 2008 using the multiple-regression coefficients developed in 2009. As shown, a reasonable corrected response was obtained, although slightly more variability was exhibited during the 90-d period that occurred during and immediately following the elevated water-table condition (i.e., between calendar days 130 and 220). This increase in variability (i.e., ~0.06 m vs. 0.02 m) may be attributed to possible nonlinear system behavior associated with areal-temporal changes to the unconfined aquifer during this particular time period.

Conclusions

Multiple-regression deconvolution methods have been shown to be effective in removing blanket-load external stresses (e.g., barometric pressure fluctuations, earth tides) from well water-level measurements (Rasmussen and Crawford 1997; Spane 1999, 2002; Toll and Rasmussen 2007). Removing external stresses greatly enhances the

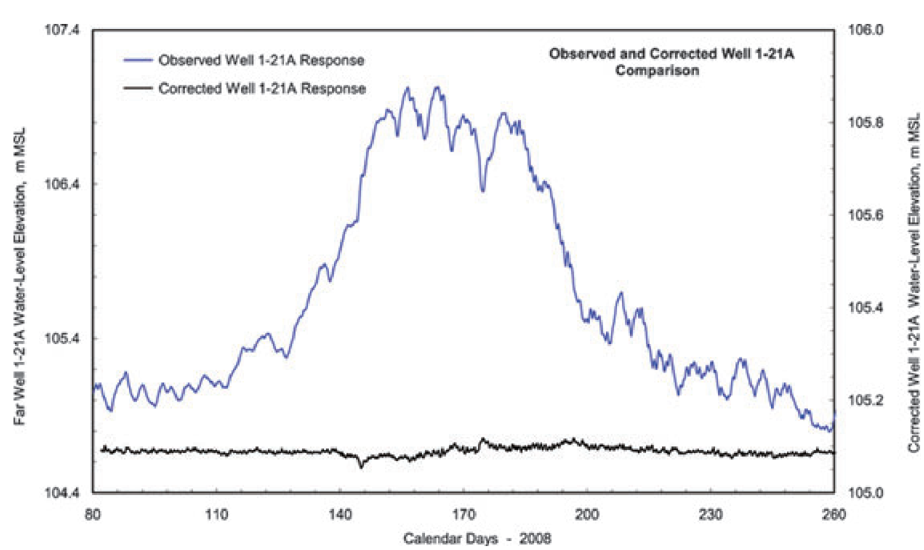

Figure 11. Observed and corrected well 1-21A 2008 response comparison, using 2009-derived, near-well 2-2 regression coefficients.

ability to determine underlying, mean groundwater-flow characteristics (flow direction, hydraulic gradient) and facilitates the analysis of controlled local hydrologic tests (e.g., pumping tests) conducted for detailed aquifer characterization (Spane and Thorne 2000; Spane 2008; Spane and Newcomer 2009). This article demonstrates that the multiple-regression technique can also be effectively used to remove periodic stresses imposed by river-stage fluctuations from well water-level response for similar groundwater hydrology applications.

Developing RRF plots with a multiple-regression convolution procedure illustrates the time-lag dependence of changes in well water-level responses to changes in river-stage stress. RRF plots are produced by simple summation of the calculated regression coefficients for individual time lags over a designated, baseline, analysis time period. Visual comparison of normalized RRF plots provides a qualitative means for evaluating general areal aquifer T/S conditions over the respective well/river distance lengths and can be used to assess the nature of the aquifer/river boundary condition (i.e., general hydraulic connection). River-stage fluctuation effects can be removed from the observed well water-level response using multiple-regression deconvolution procedures. The correction method relies on using the regression coefficients determined in developing a well's RRF plot for the various antecedent time-lag periods. The observed well response is corrected for changes in river stage by subtracting the summation of the products of the associated time-lag regression coefficient and the change in river stage for each associated antecedent, time-lag period. The removal of river-stage fluctuation effects may be significantly improved by using the associated river-stage response as monitored at a near-river well as the stress source in the multiple-regression process. The near-river well response provides a record of the river stress actually imposed on the hydraulically connected aquifer system and removes the uncertainty associated with aquifer/river contact boundary conditions (i.e., irregular and non-fully penetrating aquifer boundary, presence of streambed resistance/impedance).

When no near-river wells are available, the observed river-stage response can be used in the multiple-regression convolution/deconvolution process. Individual well RRF plots developed using the observed river-stage record commonly exhibit extended time-lag dependence to achieve similar statistical levels of regression significance (e.g., coefficient of determination, mean residuals) in the multiple-regression convolution analysis. Multiple-regression deconvolution using time-lag dependence coefficients based on actual river-stage response generally provide an adequate, but slightly less robust, level of correction in comparison to those using near-river well responses as a source of stress input. Generally, well RRF plots that exhibit values of ≥ 0.9 are required to provide a high-level of removal of river-stage effects from a respective well water-level response record, regardless of the source of the river-stress fluctuation used.

The authors have applied the multiple-regression method for the removal of river-stage fluctuations from well responses at a number of locations with similar levels of success (Vermeul et al. 2009). Based on this previous experience and results documented in this article, the following guidelines are provided to facilitate optimum removal of river-stage effects:

1. The analysis period for establishing a well's RRF should encompass well water-levels that bracket levels reflective of the period that will be corrected and be free from other nonriver stresses (e.g., hydraulic testing).
2. The number of time lags required for successful correction is dependant upon location, inclusion of near-river well input, and well/aquifer properties. The number of lags used in RRF should be increased incrementally within a reasonable range of values until there is no significant improvement in the common statistical correlation, "goodness-of-fit" parameters, for example, high adjusted coefficient of determination (R^2), low sum-of-square (SSE, SST, SSR), and residual mean square statistics.
3. An initial estimate of the time-lag range that may be relevant for the multiple-regression application for a given well location can be determined using Equation (3), and the appropriate ranges for the river-stage frequency expressed in the well response (spectral analysis) and aquifer diffusivity (T/S) conditions.
4. Established well RRF relationships can be used successfully for a respective well for previous and future years as long as aquifer-saturated thickness conditions are not significantly different (i.e., less than $\pm 10\%$). For extended use/application, the period for RRF development should continuously extend over well/river hydrograph periods capturing high and low water levels.
5. Data-recording frequencies from every 15 to 60 min generally provided adequate coverage for removing river-stage effects for unconfined aquifers exhibiting aquifer hydraulic diffusivities between 10^2 to 10^5 m/d and well/river distances of 30 to 400 m.
6. For sites exhibiting water-table depths greater than approximately 20 m and/or exhibiting low vadose zone vertical pneumatic diffusivity conditions, the effects of barometric pressure may also be relevant and require removal. In this situation, the principal stress exhibiting the greater level of influence (i.e., time-series or spectral frequency analysis of river stage as well as barometric and well response) is removed first through multiple-regression deconvolution and then followed by removing the secondary stress factor. This two-tiered removal procedure is analogous to the approach used in Spane and Thorne (2000) for removing barometric and then earth-tide stresses from a confined aquifer system using multiple-regression deconvolution procedures.

The previous discussions pertain to the association of well/aquifer water-level responses to periodic fluctuations imposed by river-stage fluctuations at a river/aquifer contact boundary. Similar results may be realized for well/aquifer water-level responses where the periodic boundary stress fluctuations are caused by ocean-tide fluctuations. This extension of the multiple-regression methods to ocean-tide impacted settings, however, is likely valid only for wells that are not closely located within the region of groundwater/ocean water exchange where varying and disparate fluid-density conditions within the aquifer may produce time-varying, time-lag, dependence relationships.

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