U.S. Geological Survey Karst Interest Group Proceedings, Shepherdstown, West Virginia, August 20-22, 2002

Eve L. Kuniansky, *editor*

U.S. Geological Survey

Water-Resources Investigations Report 02-4174

Atlanta, Georgia
2002

POSTER SESSION ABSTRACTS

Evaluating Travel Times and Transient Mixing in a Karst Aquifer Using Time-Series Analysis of Stable Isotope Data

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Abstract

Stable-isotope samples were collected at about 6-week intervals over a 6-year period at a streamflow-loss zone that recharges the karstic Madison aquifer and at a well located near or within a main ground-water flowpath. Time-series analysis of isotope data indicates that the well is in direct and rapid response to recharge from a sinking stream during climatically wet periods. The hydraulic connection between the loss zone and well primarily results from karst conduits. During dry periods when streamflow is small, isotopes in the well samples primarily are influenced by aquifer-matrix water that has been stored for many months or years. These data were analyzed by correlation and linear-systems analysis for a 34-month period of high recharge rates. The two data sets correlate most closely when the stream data are lagged 22 days, which may approximate the traveltime from the loss zone to the well. Linear-systems analysis estimates a traveltime to the well of about 15 days and a system memory of 2-3 years resulting from diffuse matrix flow. Based on these analyses, conduit-flow velocity is estimated at 380–800 ft/day (120–240 m/day). A log-normal distribution approximates the distribution of traveltimes of a plume for conduit flow.

INTRODUCTION

Stable isotopes of oxygen (^{18}O) and hydrogen (D, deuterium) can be used as naturally-occurring tracers for evaluating traveltimes and mixing conditions in ground water. Stable-isotope data for samples from a well and a sinking stream that recharges the Madison aquifer indicate that the well water exhibits a rapid response to recharge from the stream. Time-series analysis, including a linear-systems approach, is used to evaluate traveltimes, transient mixing, and the relation between conduit and matrix flow. Linear-systems analysis of tracer data also provides valuable information regarding the movement, traveltimes, and residence times of potential contaminants.

The study area is located on the eastern flank of the Black Hills uplift in western South Dakota (fig. 1). The Madison aquifer primarily is contained in the upper part of the Madison Limestone where numerous fractures and solution openings provide extensive secondary porosity (Greene, 1993). The Madison Limestone in this area ranges from about 300 to 450 feet thick and is part of a series of sedimentary units that generally dip away from the uplifted Black Hills. Because of the dipping sedimentary units, the Madison aquifer is confined in most of the study area with a narrow unconfined area near the outcrop.

In the study area, the Madison aquifer receives recharge primarily from streamflow loss to the Madison Limestone outcrop and secondarily from infiltration of precipitation on the outcrop. On the eastern flank of the Black Hills near Rapid City (fig. 1), streamflow loss is the dominant form of recharge (Naus and others, 2001). Greene (1997) concluded that part of the recharge from Spring Creek loss flows north toward Rapid City and makes up a large portion of the water that is discharged at Jackson-Cleghorn Springs, which is located about 5 miles north-northeast of the Spring Creek loss zone.

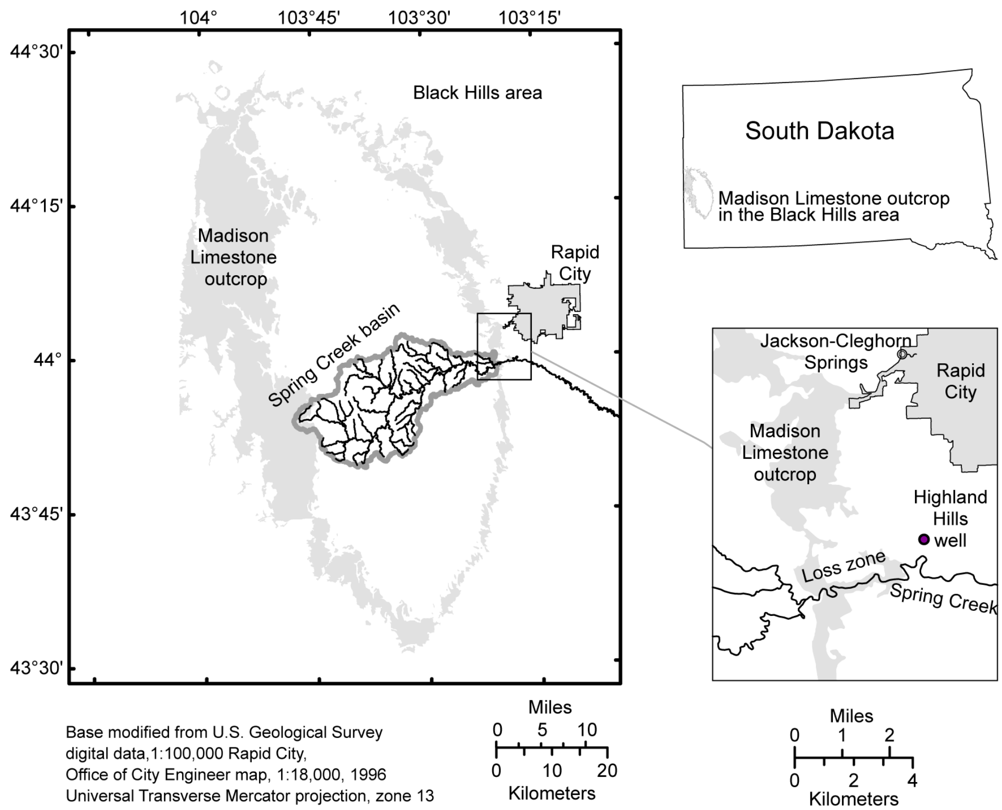

Figure 1. Location of the study area.

In western South Dakota the Madison aquifer has been extensively studied by collecting and analyzing stable isotope data. Anderson and others (1999) described the use of stable isotopes to characterize ground- and surface-water interactions in the Rapid City area. Greene (1993) used stable isotopes to evaluate the spatial distribution of recharge from sinking streams in the Madison aquifer in the Rapid City area. Naus and others (2001) described the regional distribution of stable isotopes for the Black Hills area and provided a general characterization of ground-water flow in the Madison aquifer. Naus and others (2001) also discussed the influence of orographic and climatic conditions on stable isotopes. Long and Derickson (1999) applied a linear-systems analysis to study the hydraulic-head response of the Madison aquifer to streamflow recharge from Spring Creek.

STABLE ISOTOPE DATA

Delta $(\delta)^{18}$O and δD are a measure of the concentrations of stable isotopes of oxygen and hydrogen, respectively, compared to a standard and are expressed in parts per thousand or per mil (Clark and Fritz, 1997). Isotope concentrations are referred to as isotopically heavier for higher concentrations and isotopically lighter for lower concentrations. Oxygen and hydrogen isotopes were sampled in Spring Creek above the loss zone from 1993 through 2001. Because a nearly linear relation exists between δ^{18}O and δD in the Black Hills (Naus and others, 2001), the following analysis uses only δ^{18}O for simplicity. This data set includes a period of above-average precipitation beginning in the spring of 1995 extending through the spring of 2000. The cumulative departure of precipitation from average during this extended wet period is

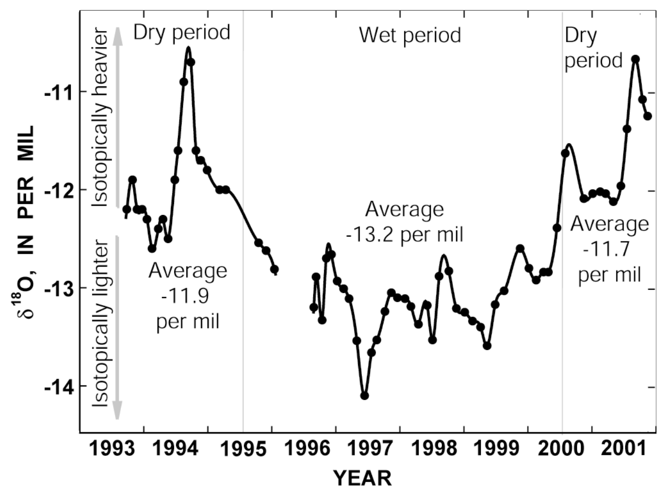

Figure 2. Measured $\delta^{18}O$ values for Spring Creek above streamflow-loss zone. Periods of generally dry or wet climatic conditions are noted. The curved line through the $\delta^{18}O$ data points was interpolated by a cubic spline.

about 25 inches (National Oceanic and Atmospheric Administration, 1993-2001). The resulting change in isotope fractionation during the wet period produced a lighter $\delta^{18}O$ in Spring Creek. The average $\delta^{18}O$ values in Spring Creek for the two dry periods are –11.9 and –11.7 per mil compared to –13.2 per mil during the wet period (fig. 2).

Stable isotopes were sampled in the Highland Hills (HH) well (fig. 1) beginning in the fall of 1996 to observe the response of the Madison aquifer to changes in Spring Creek isotope concentrations (fig. 3). The HH well is 780 feet deep and is open only to the upper 135 feet of the Madison Limestone. The well produces about 30 gallons per minute and serves a suburban development of about 10-15 homes. All analyses for this study include daily values for $\delta^{18}O$ interpolated by a cubic spline approximation, which is represented by the curved lines connecting sampled data points (fig. 3). The streamflow-recharge rate to the Madison aquifer (fig. 3), which varies with flow in Spring Creek up to a maximum estimated rate of 21 ft^3/s (Hortness and Driscoll, 1998), must be considered because of its influence on transient mixing. Response of $\delta^{18}O$ in the HH well also may be influenced by other aquifer dynamics caused by hydraulic head changes or well withdrawals.

EVALUATION OF TRAVEL TIMES AND TRANSIENT MIXING

The $\delta^{18}O$ values in samples from the HH well indicate a response to variable recharge rates and $\delta^{18}O$ values in Spring Creek (fig. 3). During extended periods when Spring Creek recharge is at or near the maximum loss rate, the $\delta^{18}O$ trend for the HH well is similar to that of Spring Creek (A sections, fig. 3), and ground water moves from the conduits into the matrix because conduits have reached capacity. During periods of low recharge (B sections, fig. 3), the influence of conduit flow diminishes, and ground water moves from matrix to conduits. Matrix water moves slowly compared to conduit water and, thus, probably has an isotope signature closer to the average recharge water from several years prior. The average $\delta^{18}O$ for Spring Creek during the dry period prior to the summer of 1995 was –11.9 per mil (fig. 2), and a single sample in 1986 was –11.2 per mil (Naus and others, 2001). Furthermore, $\delta^{18}O$ for samples from Madison aquifer

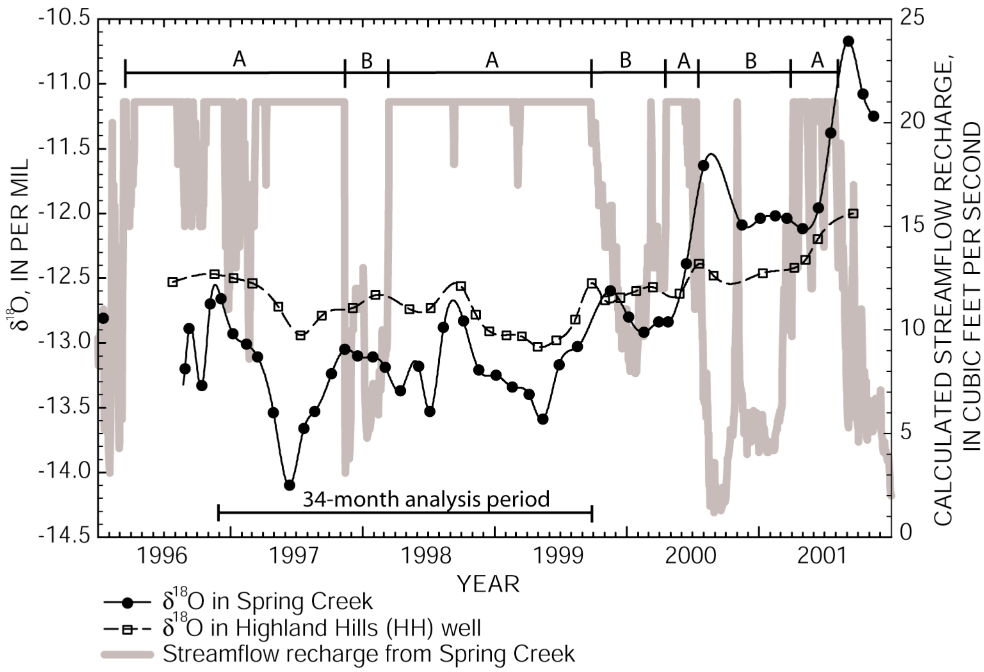

Figure 3. $\delta^{18}O$ data and streamflow recharge to the Madison aquifer from Spring Creek for 1996 through 2001. The curved line through the $\delta^{18}O$ data points was interpolated by a cubic spline. The A sections indicate periods of near-maximum recharge, whereas B sections indicate periods of lower recharge. The streamflow recharge has a maximum estimated rate of 21 ft^3/s (Hortness and Driscoll, 1998).

wells south of Rapid City in 1986-87 generally were about –12 per mil (Anderson and others, 1999). Based on these data, the average $\delta^{18}O$ for the period of 1986-95 probably was about –12 per mil or heavier, which also may approximate the aquifer-matrix value later than 1995. The movement of water from matrix to conduits is illustrated in figure 3, where $\delta^{18}O$ for the well in every B section increases toward the assumed matrix value of -12 per mil, even when $\delta^{18}O$ in Spring Creek decreases, which indicates a larger contribution from the matrix during periods of low recharge.

An analysis of correlation of the $\delta^{18}O$ daily time-series data for Spring Creek and the HH well is used to approximate the ground-water traveltime from the loss zone to the well. The analysis includes a 34-month time period from December 1996 through September 1999 (fig. 3) when the recharge rate from Spring Creek was relatively steady and generally was at or near the maximum loss rate of 21 ft^3/s. The Spring Creek data were consecutively lagged from 0 to 40 days in relation to the HH data with a correlation coefficient calculated for every lag time (fig. 4). Thus, for the period of analysis, traveltime is

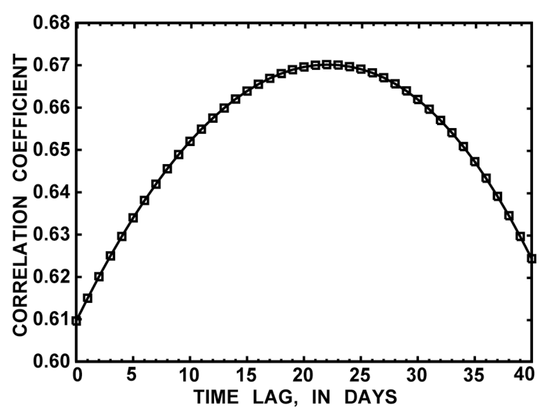

Figure 4. Correlogram of $\delta^{18}O$ time-series data for Spring Creek and Highland Hills (HH) well. The Spring Creek data were lagged from 0 to 40 days for correlation.

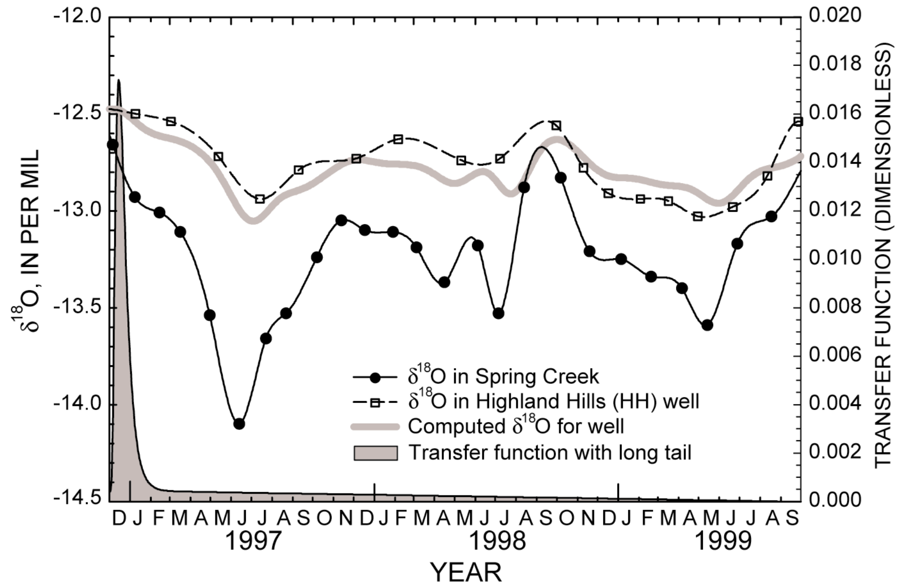

Figure 5. Results of linear-systems analysis including the computed $\delta^{18}O$ data for the sampled well and the transfer function used in the analysis. The curved line through the $\delta^{18}O$ data points was interpolated by a cubic spline.

estimated to be approximately equal to the lag time corresponding to the maximum correlation of about 0.67, which occurs at a lag of 22 days.

Linear-systems analysis was applied to the daily $\delta^{18}O$ data of Spring Creek and the response of $\delta^{18}O$ at the HH well for the 34-month analysis period (fig. 3). A time-invariant transfer function can be estimated as a translation of the forcing function (Spring Creek) and the observed response (HH well). The method assumes that the system is linear, time invariant, and stationary, meaning the character of the response does not change with magnitude of the forcing function or with time, and that the physical characteristics of the system do not change. In this case, the assumption is valid for periods of streamflow recharge that generally are near the maximum loss rate. A linear, time-invariant system is described by the convolution integral:

$$y(t) = \int_0^t h(t-\tau)x(\tau)d\tau$$

where $y(t)$ is the system response, $x(\tau)$ is the forcing function, $h(t-\tau)$ is the transfer function, and $(t-\tau)$ represents the delay time from forcing function to response (Dooge, 1973; Singh, 1988). Convolution for this analysis was calculated in the Fourier-transform domain.

The response in $\delta^{18}O$ at the HH well to $\delta^{18}O$ in Spring Creek was modeled by convolution with a time-invariant transfer function, which represents the statistical distribution of traveltimes. A log-normal distribution, which is used to model many kinds of environmental contaminant data (Gilbert, 1987), was used for this transfer function. However, the log-normal curve was only adequate to represent the short-term response and, therefore, a long tail was added in the form of a straight line with a declining slope to represent the long-term response. Convolution of the Spring Creek $\delta^{18}O$ data with this composite transfer function produced modeled output for the HH well that matched the observed data fairly well (fig. 5).

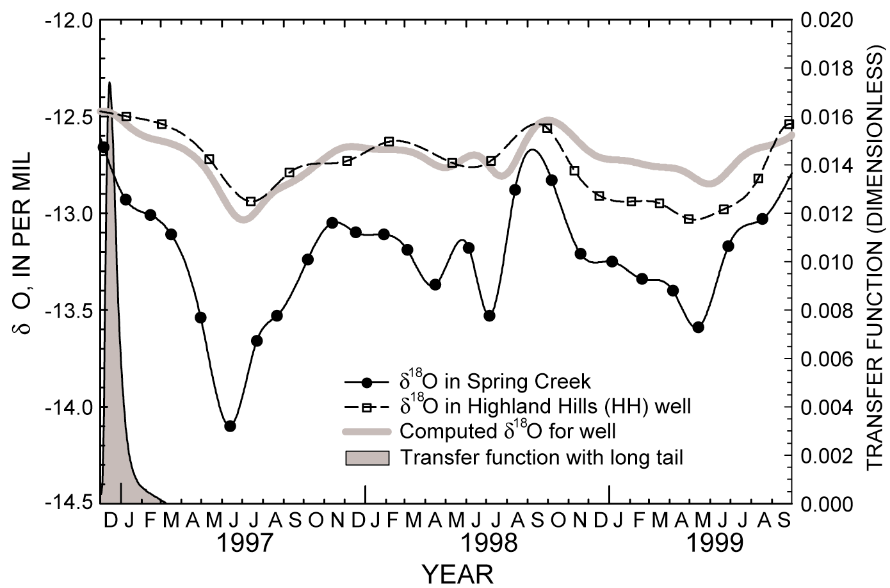

Figure 6. Results of linear-systems analysis using a shortened transfer-function tail, which produced a poorer fit to observed data than did the long-tail transfer function. The curved line through the $\delta^{18}O$ data points was interpolated by a cubic spline.

To illustrate the necessity of the extended tail, figure 6 shows the results of convolution using the same transfer-function except with a shortened tail, which produced a poorer fit to the observed data. Using the short tail, the computed data for the HH well have a more upward sloping trend (fig. 6) compared to that produced by the long tail (fig. 5). The observed $\delta^{18}O$ data (spline interpolated) for the well appear to have a general slope that is similar to the system response computed by the long-tail transfer function (fig. 5). The long tail of the transfer function (fig. 5) has a very small height compared to the log-normal part of the function, but extends for a great length. The character of this tail indicates a long system memory; however, the tail has minor effects compared to that of the log-normal part of the function.

The shape of the transfer function (fig. 5) characterizes the system and represents the form of response of any 1-day pulse from the input function. The peak response occurs about 15 days after a pulse and declines rapidly, whereas the system memory is 2-3 years, as indicated by the tail's length. The log-normal part of the transfer function describes conduit flow, whereas the linear tail describes diffuse matrix flow. The sharp contrast in the transfer function between peak response (log-normal) and long-term memory (linear tail) probably results from the dominant influence of conduit flow during periods of high recharge.

The transfer function also represents the statistical distribution of traveltimes for a contaminant plume. If a contaminant were to spill into the stream above the loss zone, the contaminant concentration in the well could be predicted by the transfer function (fig. 5). Peak concentration would occur about 15 days later, and the main body of the plume would be expected to leave the well area within about 100 days (fig. 5); however, minor contaminant concentrations could linger for 2-3 years or more depending on specific contaminant characteristics. In areas farther along the flowpath, the main plume body could become larger because of dispersion, with a greater fraction of the total contaminant contained within the matrix. This transfer function (fig. 5) applies to periods of prolonged high-recharge conditions similar to those present during the analysis period; aquifer response and traveltimes might be different during low-recharge conditions.

The lighter $\delta^{18}O$ values in Spring Creek during the wet period of the late 1990's (fig. 2) was gradually influencing matrix concentrations, which consequently affected $\delta^{18}O$ values in the HH well. However, $\delta^{18}O$ in the matrix probably was decreasing much more gradually than in water sampled from the well, which represented primarily conduit water during that period. Therefore, when the influence of the matrix is introduced by adding a long tail to the transfer function, the result is to lessen the otherwise upward trend because $\delta^{18}O$ in the matrix had been declining. The particular mixture of conduit and matrix water may have been influenced by pumping of the HH well; the transfer-function tail might have a different character had the well not been pumped.

Long and Derickson (1999) determined a transfer function for the response of hydraulic head in the Madison aquifer to streamflow recharge from Spring Creek. These authors concluded that a logarithmic curve best approximated the transfer function and determined that the system has a time to peak response of less than 1 month and a system memory of about 6 years. The results of this previous research are consistent with the results of time-series analysis of stable isotopes described in this article.

SUMMARY AND CONCLUSIONS

Stable-isotope data indicate that isotope concentrations in the Highland Hills well respond rapidly to stream loss that recharges the Madison aquifer during climatically wet periods; during dry periods when streamflow is low, aquifer-matrix water primarily influences concentrations in the well. The time-series data were analyzed by correlation and linear-systems analysis for a 34-month period of high recharge rates. The two data sets correlate most closely when the stream data are lagged by 22 days, which indicates the approximate traveltime from the loss zone to the well. Linear-systems analysis of the time-series data indicates that traveltime to the well is about 15 days and that the system has a memory of 2-3 years resulting from diffuse matrix flow. Based on these analyses, conduit-flow velocity is estimated at 380–800 ft/day (120–240 m/day). A log-normal distribution approximates the distribution of traveltimes of a plume for conduit flow. This time-series analysis is valid for periods of prolonged, high recharge rates and may produce different results for low-recharge periods. Characterizing flow by correlation and linear-systems analysis of natural-tracer data can provide useful information for interpretation of dye-tracer tests, monitoring long-term water-quality trends, and managing potential aquifer contamination.

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