



An Examination of Earth and Atmospheric Tides to Estimate Aquifer Properties of the Barton Springs Segment of the Edwards Aquifer

RR-22-04; May 2022

Abel Porras, P.E., Kori Navarro, & Michael Markowski, P.G.

City of Austin

Watershed Protection Department

Floodplain Office and Modeling Division

ABSTRACT

Scientists have widely observed daily and sub-daily fluctuations of groundwater levels in wells for decades, including at multiple monitoring wells in the Barton Springs Segment of the Edwards Aquifer. We can use these small fluctuations (along with corresponding barometric pressure and synthetic Earth tide data) to estimate the hydrogeologic properties of the Barton Springs Segment by implementing a new computational method. This report describes the process by which these properties can be estimated using this new passive technique. We then compared the estimates to the more active field tests of aquifer storage, which show commensurate results. Long-term, continuous monitoring in groundwater systems like the Barton Springs Segment may provide an underutilized source of information and potential insight into groundwater systems when combined with new analytical techniques.

INTRODUCTION

It is well known that both the Sun and the Moon exert a gravitational influence on the Earth's oceans, as evidenced by the daily oceanic tides on Earth. What is less known is that these gravitational influences can cause displacements on the Earth's land surface, as well. These displacements, called Earth tides, allow for the movement of water within the soil matrix, which changes the pore water pressure within an aquifer. Furthermore, atmospheric tides also respond to forces (either thermal, gravitational, or both) stemming from the Sun and the Moon, which can also influence the movement of groundwater due to these periodic changes in atmospheric pressure.

For decades, scientists have recognized fluctuations of the hydraulic head in groundwater wells and their connection to Earth and atmospheric tides. Young (1913) described daily groundwater pressure head fluctuations observed in an artesian well in South Africa, which were attributed to fluctuations in Earth tide and atmospheric tide effects. Recent advancements in more precise instrumentation, along with data collection equipment capable of long-term continuous recording, allows researchers to conduct new analyses of the influence of Earth and atmospheric tides on groundwater systems and to reassess aquifer properties previously discovered through more expensive, non-passive means, like pumping tests.

Within the Edwards Aquifer, observers have noted fluctuations in groundwater wells mostly incidentally. These are primarily attributed to barometric, tidal, and pumping effects. Asquith and Gary (2005) observed that flow velocities from Barton Springs pool fluctuated daily for three consecutive days under low spring flow conditions and speculated the causes to be natural or anthropogenic. Hunt et al. (2012) noted these velocity fluctuations at Barton Springs could be related to water level fluctuations observed in Lovelady Well (YD-58-50-301). He also noted that barometric, tidal, and pumping effects could also be possible causes. More recently, a Watershed Protection Department scientist noted consistent sub-daily fluctuations in conductivity at Barton Springs leading to applied research on this topic and the development of this report.

Multiple studies in the Edwards Aquifer use observed water level fluctuations to estimate aquifer properties traditionally obtained by pumping tests. Hovorka et al. (1993) used continuous water level data from nine wells, plus barometric pressure data, to calculate barometric efficiency and storativity values for confined sections of the San Antonio Segment of the Edwards Aquifer. Mitchell and Dutton (2006) used well level fluctuation data generated by seismic events to calculate seismic efficiency and specific storage values for unconfined and confined sections of the San Antonio Segment.

Recent work has made the incorporation of various synthetic Earth and atmospheric tide effects readily available. Scientists can now study their effects on groundwater systems and use them to estimate aquifer properties. Briciu et al. (2018) were able to characterize fluctuations in specific conductance and temperature data in freshwater streams and attribute them to Earth's tide-driven fluctuations in water level elevation fed by a deep karstic aquifer. Our staff are currently analyzing similar observations of daily fluctuations in water quality parameters sometimes present at Barton Springs. Acworth et al. (2016) developed a technique to incorporate time series of hydraulic head, atmospheric pressure, and Earth tides into an estimate of storativity of the underlying aquifer at three sites in Australia. This technique was made more accessible through newly developed software, which is able to predict the Earth tides anywhere on the Earth's surface for any duration (Rau, 2021).

Using this computational method, elucidated herein, we estimated the storativity for the northern portion of the Barton Springs Segment of the Edwards Aquifer. This report aims to:

1. describe the technique used to passively estimate storativity in aquifers;
2. apply this technique to the Barton Springs Segment of the Edwards Aquifer as an exploratory exercise; and
3. compare the results with more traditional techniques used to infer the storativity in the aquifers.

THEORY

The theory behind this paper comes from using the Barometric Efficiency, or BE, as a method of inferring aquifer storage properties by observing the response of the groundwater head in an aquifer from changes in barometric pressure (see McMillian et al, 2019, for an overview and history of this phenomena). BE is a measurement that captures changes in hydraulic head in the groundwater as it responds proportionally to changes in the atmospheric pressure. Specifically, BE can be mathematically represented by the equation (Gonthier, 2007):

$$BE = \frac{\Delta P_{atm} - \Delta P_{aq}}{\Delta P_{atm}} \quad (1)$$

In this equation, ΔP_{atm} is the change in atmospheric pressure, and ΔP_{aq} is the resulting change in hydraulic head pressure. For idealized unconfined aquifers, BE is equal to zero since the water table is at atmospheric pressure (by definition). That is, any change in atmospheric pressure instantaneously results in a change in groundwater hydraulic head (i.e. $\Delta P_{atm} = \Delta P_{aq}$). In idealized confined aquifers, the formation will adjust to changes in atmospheric pressure rather than transmit that energy to the water. In that scenario, $\Delta P_{atm} > \Delta P_{aq}$. Thus, the barometric efficiency will approach unity as the formation adjusts more to the change in atmospheric pressure. Any increase in barometric pressure causes a decrease in hydraulic head pressure with a time lag.

Typically, BE was calculated directly from discrete measurements of atmospheric pressure and (sometimes lagged measurements of) hydraulic head. Recently, though, Acworth and Brain (2008) suggested that BE can be estimated by taking “the ratio of the separate amplitudes of the wave forms.” The wave forms (or time series) in question are those of the atmospheric pressure and hydraulic head. This new formulation allows for a BE quantification that is more suitable for time series observations currently measured at Barton Springs, and it is this formulation which we will utilize.

However, an additional step is needed. The hydraulic head time series in the numerator needs to be corrected to incorporate the influences of the Earth tides. Fortunately, using synthetic (or simulated) time series of Earth tides makes it easy to disentangle its influence on hydraulic head (Rau et al, 2020). As discussed in the next section, analysis of this synthetic Earth tide data will inform the degree to which the hydraulic head is adjusting to changes from the Earth tides. This additional Earth tide information improves upon prior methods of BE calculation by providing a corrected ratio of the amplitude of the hydraulic head time series.

Time Series Analysis

Since any time series is comprised of the superposition of many frequencies, isolating Earth and atmospheric tides is accomplished by inspecting the frequency domain of the atmospheric and hydraulic head time series, along with the Earth tide time series. We convert the time series to the frequency domain through a Fast Fourier Transform (FFT) and provide estimates of the strength (or amplitude) of each frequency on the underlying time series.

Both Earth and atmospheric tides exhibit a consistent pattern of exactly 1 and 2 cycles per day (cpd) frequencies. However, Earth tides are comprised of at least five specific components, which contribute to approximately 95% of the Earth tides cycles (Cutillo and Bredehoeft, 2011). These cycles are displayed in Table 1.

Table 1: Earth Tide Components

Earth Tide Component Symbol	Earth Tide Component Name	Earth Tide Component Frequency (cpd)
O₁	Principal Lunar Diurnal	0.9295
K₁	Lunisolar Diurnal	1.0029
M₂	Principal Lunar Semidiurnal	1.9324
S₂	Principal Solar Semidiurnal	2.0000
N₂	Lunar elliptic Semidiurnal	1.8996

To separate the Earth tide cycles from the atmospheric tide cycles, we used two Earth tide frequencies to estimate the barometric efficiency. Specifically, we used the Principal Lunar component at 1.9324 cycles per day (typically denoted M_2) and the Principal Solar component, which occurs at 2.0000 cycles per day (denoted S_2).

Using the amplitudes at the S_2 and M_2 frequencies, Acworth et al (2016) showed that the hydraulic head time series can be corrected for Earth tides by:

$$S_2^{GW-corrected} = S_2^{ET} \cdot \cos(\Delta\phi) \cdot \left(\frac{M_2^{GW}}{M_2^{ET}} \right) \quad (2)$$

In Equation (2), the terms S_2^{ET} represents the amplitude of the Earth tides at the S_2 frequency; and M_2^{GW} and M_2^{ET} represents the amplitudes of the hydraulic head observations and atmospheric pressure observations at the M_2 frequency, respectively. In the absence of atmospheric tides at the M_2 frequency, Equation (2) shows that the Earth tide's influence can be adjusted proportionally to the ratio of the groundwater to Earth tide's strength. Then, by the Harmonic Addition Theorem, this correction in amplitude can then be added directly to the amplitude of the hydraulic head observations S_2^{GW} , at the S_2 frequency.

Putting it all together, the barometric efficiency (BE) can now be calculated using the equation:

$$BE = \frac{S_2^{GW} + S_2^{ET} \cdot \cos(\Delta\phi) \cdot \left(\frac{M_2^{GW}}{M_2^{ET}} \right)}{S_2^{AT}} \quad (3)$$

In Equation (3), the terms S_2^{GW} , S_2^{AT} , and S_2^{ET} represent the amplitudes of the hydraulic head observations, the atmospheric pressure observations, and the Earth tides at the S_2 frequency, respectively. The term $\Delta\phi$ is the phase difference between the Earth tide and atmospheric tide at the S_2 frequency. Prior methods of calculating BE relied solely on fluctuations of barometric and hydraulic head measurements to evaluate changes in hydraulic head. By incorporating analyses of time series observations in the frequency domain and examining the fluctuations of Earth tides at the M_2 component essentially "corrects" any change in hydraulic head to account for influence of the Earth tides when atmospheric tides are absent.

Once BE is calculated, the loading efficiency of the formation, γ , can be determined through:

$$\gamma = 1 - BE \quad (4)$$

From this, the formation compressibility, α , can be estimated through:

$$\alpha = \frac{\gamma\theta\beta}{1-\gamma} \quad (5)$$

In Equation (5), θ is the aquifer porosity and β is the fluid compressibility, which for water is $4.59 \times 10^{-10} \text{ Pa}^{-1}$ at 20° C.

And from this, the specific storage, S_s , for the confined formation can be calculated by:

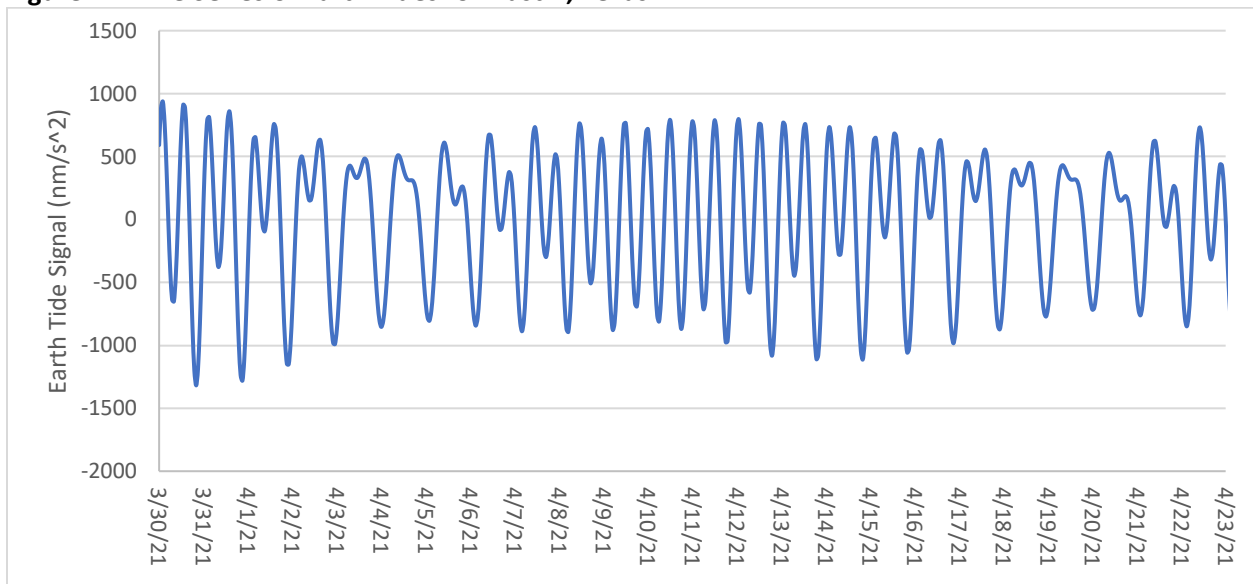
$$S_s = \rho g(\alpha + \theta\beta) \quad (6)$$

In Equation (6), ρ is the density of water, which is approximately 1.0 kg/L, and g is the gravitational constant of 9.8 m/s².

MODEL INPUTS

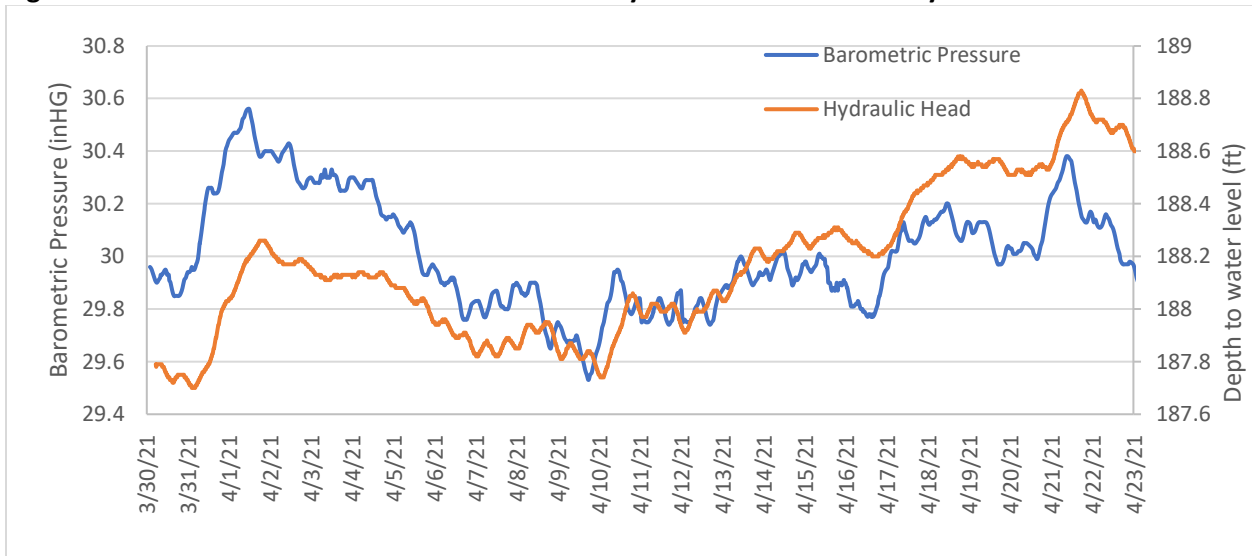
To calculate aquifer storativity, a time series of hydraulic head and barometric pressure measurements are needed along with a synthetic time series of Earth tides. The Earth tides can be computed for a date range anywhere on Earth. For this report, Austin, Texas during the March 30, 2021 to April 23, 2021 time period was input into the PyGTide package in Python (Rau et al, 2021). The result was a time series of Earth tides, shown in Figure 1 below.

Figure 1: Time Series of Earth Tides for Austin, Texas



Similarly, field observations of barometric pressure and hydraulic head at Lovelady Well (close to Barton Springs) for that same time period in Austin, Texas are depicted in Figure 2 below.

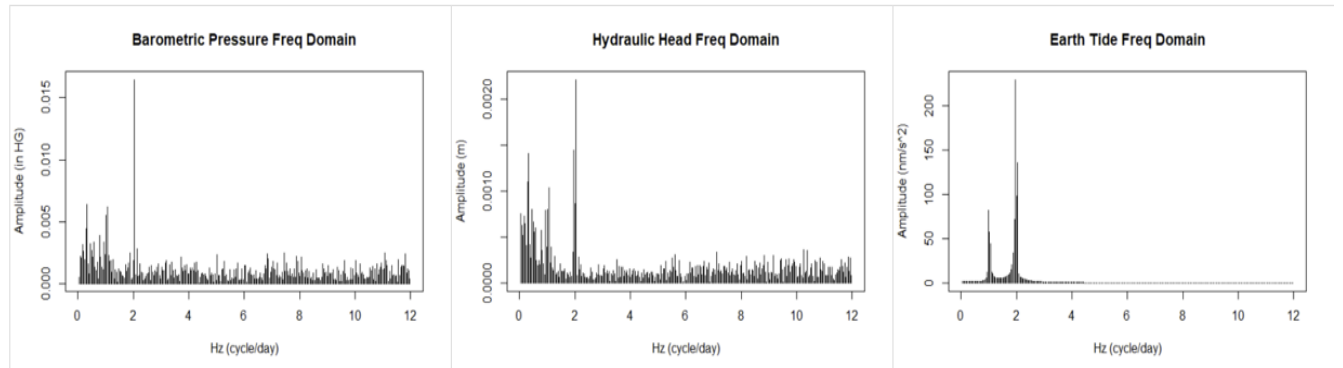
Figure 2: Time Series of Barometric Pressure and Hydraulic Head at Lovelady Well



RESULTS

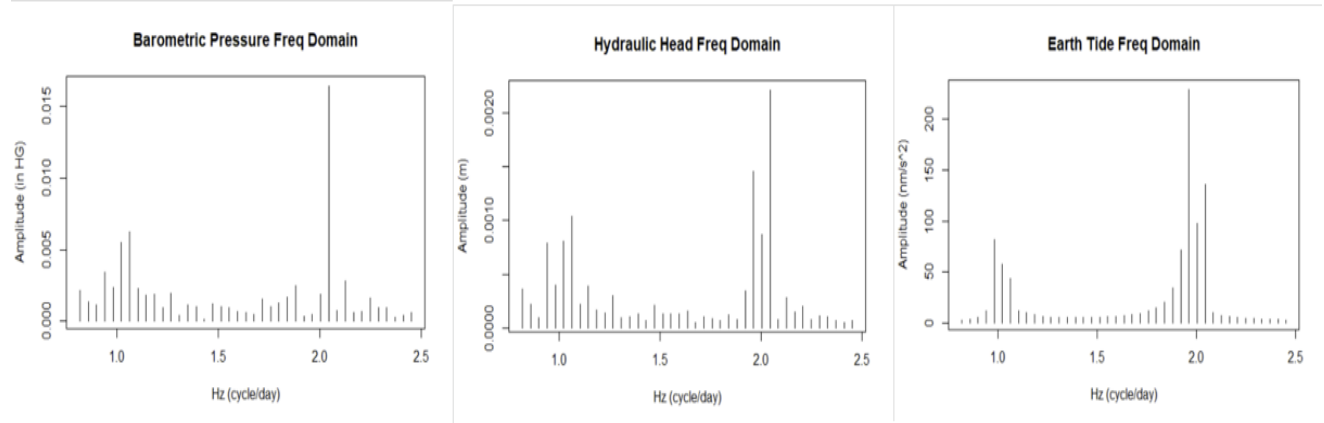
We converted the three time series to data in the frequency domain using a Fast Fourier Transform (FFT). The results from the FFT, displayed in Figure 3, show that all three time series were comprised of daily (i.e. a large amplitude at 1 cycle per day) and sub-daily (i.e. a large amplitude at 2 cycles per day) frequencies. For the purposes of this report, interest lies around the 2 cycle per day window, which is shown in Figure 4.

Figure 3: Frequency Plots of Barometric Pressure, Hydraulic Head, and Earth Tides



Specifically, we used the frequencies occurring during the M_2 (1.9324 cpd) and S_2 (2 cpd) components to conduct the calculations. We calculated and converted to similar units the amplitudes at these frequencies for the synthetic Earth tides, the barometric pressure, and the hydraulic head. These estimates can be seen in Table 2. However, the amplitudes around the 2 cpd frequency can vary significantly for each of the time series. We anticipate that analysis of a longer time series will ameliorate these differences.

Figure 4: Frequency Plots of Barometric Pressure, Hydraulic Head, and Earth Tides at a narrower window



The phase difference is also given for each frequency and was also calculated for Earth tides and atmospheric tides at S_2 frequency

Table 2: Amplitudes of the M_2 and S_2 Components

Component	Description	Parameter	Unit	Amplitude
M_2	Earth tide (synthesis)	M^{ET}	$nm\ s^{-2}$	71.87
	Hydraulic Head	M^{GW}	mm H_2O	0.3435
S_2	Earth tide (synthesis)	S^{ET}	$nm\ s^{-2}$	98.135
	Hydraulic head	S^{GW}	mm H_2O	0.871
	Atmospheric Pressure	S^{AT}	mm H_2O	5.008

Table 3: Barometric Efficiency Results

Description	Parameter	Unit	Value
Phase difference	$\Delta\theta$	radians	-0.711
Porosity	θ	Dimensionless	0.4
Barometric Efficiency	BE		0.245
Formation Compressibility	α	$m\text{-sec}^2/kg$	5.43E-10
Specific Storage	S_s	1/m	7.04E-06
		1/ft	2.15E-06

Table 3 shows the output of Equation (6) after inputting the amplitudes, phase difference, and estimated porosity. The result show that the aquifer has a specific storage of $2.15 \times 10^{-6}\ ft^{-1}$. This value appears to fall within the representative values of fissured rock, which tend to fall close to the $1.0 \times 10^{-6}\ ft^{-1}$ range. However, we can compare the estimates using passive techniques to site-specific estimates of specific storage through the more traditional testing that has been conducted in the Edwards formation.

Comparison with Traditional Active Testing

The Barton Springs / Edwards Aquifer Conservation District (BSEACD) is the governing body managing the groundwater resources in central Texas. As part of their duties in characterizing the hydraulic properties of the aquifer, the BSEACD has compiled reports of pumping tests throughout the area and summarized them (Hunt, et.al, 2012). We will use this summary to first calculate the specific storage of the aquifer from the pumping tests and then compare that to the specific storage calculated passively using Earth tides. First, it is important to describe the relation and importance of the aquifer properties.

Flow through a confined aquifer follows the equation (in one-dimension):

$$S_s \frac{\partial h}{\partial t} = K \frac{\partial^2 h}{\partial x^2} \quad (7)$$

In this equation, S_s is the specific storage (ft^{-1}); K is the saturated hydraulic conductivity (ft/day); h is the hydraulic head (ft); and x and t are the spatial and temporal coordinates.

The relationship between specific storage, S_s (ft^{-1}), and storativity, S , is given by:

$$S = S_s \cdot b \quad (8)$$

And, the relationship between transmissivity, T (gpd/day), and hydraulic conductivity, K (ft/day), is given by:

$$T = K \cdot b \quad (9)$$

In both Equations, b is the saturated thickness (ft).

Equations (8) and (9) are significant because storativity, S ; hydraulic conductivity, K ; and transmissivity, T are all measured through in-situ pumping tests. From Equation (8), we can estimate the saturated thickness, b . We can then input this estimate of saturated thickness into Equation (9), along with the measured storativity to determine the specific storage. Table 4 provides a summary of the results compiled by BSEACD. We can compare this specific storage calculated through in-situ testing to the specific storage calculated through passive testing provided herein. Table 4 also shows the calculated saturated thickness, which is then used in Table 5 to calculate the specific storage from measured storativity.

Table 4: Summary of Pump Test Results from BSEACD

Statistic	Hydraulic Conductivity, K (ft/day)	Transmissivity, T (gpd/ft)	Saturated Thickness, b (calc in ft)
Average	28.15	71,849	341.2
Median	5.71	15,000	351.2
Q1	1.97	4,443	301.5
Q3	23.05	70,250	407.4

Table 5: Incorporating Storativity and Saturated Thickness Results from BSEACD to calculate Specific Storage

Statistic	Storativity, S (dimensionless)	Saturated Thickness, b (calc in ft)	Specific Storage, S_s (calc from data in ft⁻¹)
Average	6.10E-03	341.2	1.79E-05
Median	7.00E-04	351.2	1.99E-06
Q1	3.54E-04	301.5	1.17E-06
Q3	1.60E-03	407.4	3.93E-06

The range of values for specific storage estimated from the pump tests between the first and third quartile range from 1.2×10^{-6} to $3.9 \times 10^{-6} \text{ ft}^{-1}$. The value of specific storage predicted by the barometric efficiency (from this report) was $2.15 \times 10^{-6} \text{ ft}^{-1}$, which is within the range calculated from the pump tests. However, it is important to note that the traditional hydrogeological investigations, such as those performed from the pump tests, assume that the aquifer matrix is rigid, which may be an oversimplification. Regardless, the proximity of the values indicate that estimates from both methods appear to be valid values of storativity.

CONCLUSION

We considered a new, passive method of measuring aquifer properties in this report. Using time series data of barometric pressure, hydraulic head at Lovelady Well, and synthetic Earth tides for Austin, Texas, we estimated the barometric efficiency of the underlying aquifer. The time series data was first converted to the frequency domain using Fast Fourier Transforms. Using the method developed by Acworth et al (2016), we input the amplitudes of the frequencies at 1.93 and 2.00 cpd into Equations 2 through 4. The result is an estimate of the specific storage of the Barton Springs Segment of the Edwards Aquifer. Comparisons with field pump tests of specific storage showed commensurate results, which can be utilized in current efforts at groundwater modeling. Other applications could include identifying useful monitoring wells for dye trace study design or aiding in the interpretation of tracer results.

To further understand the implications of this technique, further investigation is needed. For example, calculating the barometric efficiency for different wells could inform whether that well is mostly screened in karst or matrix sections of the aquifer. Similarly, barometric efficiencies at different locations or for longer time periods could apprise the variation in specific storage throughout the aquifer. Finally, cross-correlation with specific conductivity measurements could lead to more information, especially regarding the springs.

REFERENCES

1. Acworth, R. I., & Brain, T. (2008). Calculation of barometric efficiency in shallow piezometers using water levels, atmospheric and earth tide data. *Hydrogeology Journal*, 16(8), 1469-1481.
2. Acworth, R. I., Halloran, L. J., Rau, G. C., Cuthbert, M. O., & Bernardi, T. L. (2016). An objective frequency domain method for quantifying confined aquifer compressible storage using Earth and atmospheric tides. *Geophysical Research Letters*, 43(22), 11-671.
3. Briciu, A. E., Mihăilă, D., Oprea, D. I., Bistricean, P. I., & Lazurca, L. G. (2018). Orthotidal signal in the electrical conductivity of an inland river. *Environmental monitoring and assessment*, 190(5), 1-15.
4. Cutillo, P. A., & Bredehoeft, J. D. (2011). Estimating aquifer properties from the water level response to earth tides. *Groundwater*, 49(4), 600-610.
5. Gonthier, G.J. (2007). A Graphical Method for Estimation of Barometric Efficiency from Continuous Data—Concepts and Application to a Site in the Piedmont, Air Force Plant 6, Marietta, Georgia: U.S. Geological Survey Scientific Investigations Report 2007-5111, 29 p., Web-only publication available at <http://pubs.usgs.gov/sir/2007/5111/>.
6. Hunt, B., Smith, B., & Kromann, J. (2010). Compilation of pumping tests in Travis and Hays Counties, Central Texas. BSEACD Data Series Report 2010-0701.
7. McMillan, T. C., Rau, G. C., Timms, W. A., & Andersen, M. S. (2019). Utilizing the impact of Earth and atmospheric tides on groundwater systems: A review reveals the future potential. *Reviews of Geophysics*, 57(2), 281-315.
8. Rau, Gabriel C., et al. "Disentangling the groundwater response to Earth and atmospheric tides to improve subsurface characterisation." *Hydrology and earth system sciences* 24.12 (2020): 6033-6046.
9. Rau, G., Schweizer, D., Turnadge, C., Blum, P., & Rasmussen, T. (2021, April). A new Python package to estimate hydraulic and poroelastic groundwater properties using standard pressure records. In EGU General Assembly Conference Abstracts (pp. EGU21-4679).