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Groundwater-stream connectivity from minutes to months across United States basins as revealed by spectral analysis

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Abstract

Stream corridors are dynamic places where streams and aquifers are connected and interact to various degrees, depending on geology, climate, stream morphology, and water use. Water table fluctuations propagate through the unconfined aquifer and are linked with changes in solute export to streams and biogeochemical transformations in floodplain soils. Through publicly available USGS data, this study aims to better understand the behaviour of stream-groundwater connectivity and water table fluctuations by analysing continuous time series of water levels from 17 pairs of stream gauges and nearby (<100 m) groundwater monitoring wells. Sites are located within 8 of 18 major hydrologic units (HUC-2) across the contiguous United States and span a variety of stream sizes, climates, and land use practises. More than 50% of sites have a water table that remains within 3 m of the land surface year-round. Energy spectral densities and cross-wavelet transformations generally reveal strong coherence between the water table and stream stage over daily to monthly periods. The transfer function, which describes relative variations between the water table and stream stage, shows that 10 of 17 sites are more stream-dominated at daily and monthly frequencies, meaning that water level fluctuations are greater in the stream and propagate into the aquifer. Only 1 of 17 sites is more groundwater-dominated at daily and monthly frequencies, meaning that water level fluctuations are greater in the aquifer. This study shows the utility of frequency-domain analysis for revealing specific timescales of stream-aquifer interaction.

KEYWORDS
hyporheic, riparian, signal processing, spectral analysis, surface water-groundwater interactions, water table

1 | INTRODUCTION

Along stream corridors (or riparian zones), stream water and groundwater closely interact. Water moves from the aquifer to the stream and vice versa in response to the interactions of currents with bedforms and meanders (Boano et al., 2014), changes in alluvial cover (Tonina & Buffington, 2009), groundwater pumping (Condon & Maxwell, 2019), and a variety of other mechanisms. Streams that receive a net influx of groundwater are termed gaining, and those that supply a net outflow of water to the surrounding aquifer are termed losing (Winter et al., 1998). In addition to this net exchange flux, water also enters the subsurface and returns to the stream as hyporheic flows, which count towards the gross exchange flux (Payn et al., 2009). Both net and gross exchanges influence stream and groundwater quality (Mojarrad et al., 2019; Ward et al., 2019).

The height of the water table along stream corridors is critical for controlling surface water-groundwater exchange (Winter et al., 1998) and many related biogeochemical processes, including the production of greenhouse gases (Evans et al., 2021) and flow of nutrients and contaminants to streams (Bernhardt et al., 2017; McClain et al., 2003).

Water table height especially controls the export of redox-sensitive solutes like nitrogen (Cirmo & Mcdonnell, 1997; Willems et al., 1997), arsenic (Berube et al., 2018), manganese (Harvey & Fuller, 1998; Jones et al., 2018), and organic carbon (Jardine et al., 1989). In the case of nitrate, water table fluctuations can cause a change in flow direction between streams and aquifers and increase water residence times, providing more opportunity for denitrification (Gu et al., 2008; Willems et al., 1997). As the water table rises, floodplain soils also act as a source of dissolved organic carbon (Battin et al., 2008; D'Elia et al., 2017; Mann & Wetzel, 1995), the electron donor for denitrification. Meanwhile, a rising water table can also trap oxygen in pore spaces and promote oxic conditions that limit denitrification (Haberer et al., 2012; Williams & Oostrom, 2000). Changes in soil saturation and pore water chemistry also influence microbial community composition (Danczak et al., 2016; Stegen et al., 2016) and activity (Schlesinger & Andrews, 2000), illustrating the multiple connections between the water table and riparian biogeochemical processes.

Stream and water table fluctuations can be caused by a number of processes, including snowmelt or rain, tides, and dam releases. In some cases, fluctuations have characteristic timescales or rhythms. Stegen et al. (2016) examined daily fluctuations related to upstream dam operations on the Columbia River and showed that they caused changes in both microbial community dynamics and water chemistry within the hyporheic zone, or the area where groundwater and stream water mix. Boyer et al. (1997) showed that seasonal and daily alpine snowmelt in the Deer Creek watershed (Summit County, Colorado) flushed dissolved organic carbon from adjacent soils and increased stream concentrations. This flushing happened quickly at upstream locations, but it took all season (~84 days) for dissolved organic carbon levels to return to baseline at downstream locations. The connection between the water table and stream over hours, days, and years has important implications for the rate that catchments release water and solutes (McGuire et al., 2005; Vidon, 2012; Winter et al., 1998).

Continuous, long-term datasets are valuable for understanding stream-groundwater interactions and transport processes. For example, Wu et al. (2020) used continuous USGS stream temperature and discharge data to estimate thermal exchange rates across the streambed throughout the Mississippi Basin. Scott et al. (2019) used USGS stream gauge data to understand stream-floodplain connectivity by calculating the fraction of stream flow that spills onto floodplains. Riml et al. (2019) examined continuous stream and groundwater carbon dioxide concentration data along with water table elevation data and found that stream carbon dioxide levels were closely connected to water table elevations at the daily timescale.

By examining continuous, long-term datasets in the frequency domain, new insights often emerge that are not apparent in the time domain, especially in short-term or synoptic datasets. For example, frequency-domain analysis reveals fractal behaviour in stream chemistry and concentration—discharge relationships (Godsey et al., 2009; Kirchner et al., 2000). Schuite et al. (2019) used frequency-domain analysis of hydrological signals, such as stream discharge and precipitation, to constrain catchment properties. Other studies have developed approaches in the frequency domain for estimating river resistance and hydraulic diffusivity in confined aquifers (Shih, 1999; Wang & Wörman, 2019). In headwaters of the Mississippi River, Wu et al. (2020) used frequency-domain analysis to show that hyporheic exchange moderates stream temperature fluctuations, particularly at higher frequencies, but river regulation reduces the moderating effect. Wallace et al. (2019) used the cross-wavelet transform to reveal tidal fluctuations in redox potential within an aquifer near a coastal stream. The fluctuations increased in strength during the summer months. Schuler et al. (2021) examined coherence between precipitation and spring discharge data from Ireland to understand surface water infiltration and exchange dynamics within a low-lying karst aquifer. Here, we use water level records from paired stream and groundwater monitoring sites to better understand stream-groundwater connectivity over a range of timescales from minutes to seasons. While similar in many respects to previous analyses of water levels in confined aquifers (Shih et al., 1999, 2008), our study focuses on unconfined aquifers that are subject to both vertical infiltration and lateral propagation of hydraulic head signals. We begin by examining general regional trends of water table position and head gradient between streams and aquifers using annual average statistics. We then examine frequency-dependent variability in surface water-groundwater interactions using energy spectral densities and wavelet coherence. We use these analyses to classify the degree of hydraulic connectivity between streams and aquifers and direction of connectivity (whether fluctuations are more dominant in the stream or aquifer).

2 | METHODS

2.1 | Site selection

Paired stream and groundwater monitoring sites were selected from the USGS database of stream gauge and well monitoring sites across the entire United States based on three criteria. First, we chose pairs where the groundwater well was no more than 100 horizontal metres from the stream gauge station. This somewhat arbitrary threshold was intended to ensure that water level differences between the stream and groundwater monitoring locations would reflect local surface water-groundwater interactions. Second, we removed any pairs where the groundwater well was not completed in an unconfined aquifer, based on USGS National Water Information System site description data. We assume that flow within these unconfined aquifers is mostly horizontal and that groundwater levels approximate the water table position. Third, we sought pairs where there was at least one full year of continuous data (spanning a water year from October 1 to September 30 of the following year) for both the stream and groundwater well.

Only 17 pairs met these three criteria (Table S1). All are located in the contiguous United States and span 8 of the 18 USGS two-digit hydrologic units (Figure 1). It is important to note that these sites were selected entirely on the basis of available data, so stream-groundwater interaction at these sites is unlikely to be statistically representative of the spectrum of stream-groundwater interactions

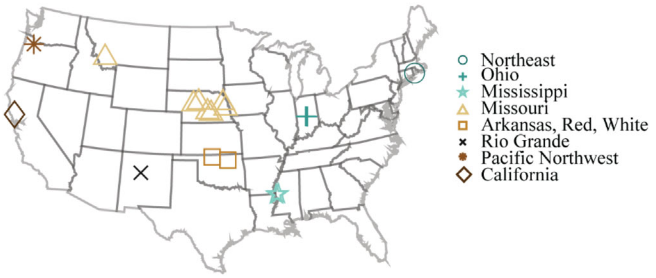

FIGURE 1 Paired site locations, coloured by their HUC-2 watershed

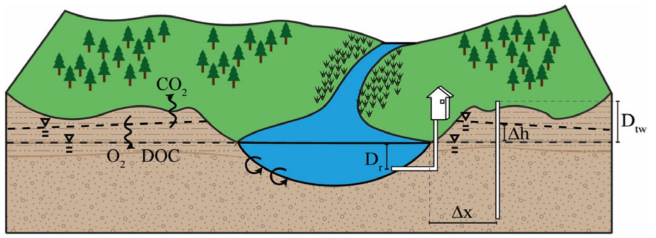

FIGURE 2 River corridor processes related to a fluctuating water table and variables used to characterise generalised (frequency-independent) stream-groundwater interactions

throughout all watersheds. Sampling intervals were at either 15- or 30-minute intervals, depending on the site, so all data were down-sampled to 30 min to maintain the same resolution in the frequency-domain analysis. Continuous data for both stream and groundwater levels were available over a range of 2 to 13 years, depending on the site. There was no single water year for which all sites contained continuous data. Therefore, a water year was chosen for detailed analysis between 2009 to 2018, depending on the region and availability of data (Table S1). We analysed only one water year for each site to maintain the same number of data points for the frequency-domain analysis and thus analyse all sites over the same range of frequencies.

Even with a flexible selection of water years, two of the 17 pairs had small data gaps of 1.7 and 1.8 days. For the two sites with small gaps, we used linear interpolation to fill the gaps. Sensitivity testing on an intact dataset (Missouri-6788350 EWP) showed that applying a linear interpolation across a gap of less than 2 days has a negligible influence on spectral analysis (Table S2).

2.2 | Generalised characteristics of stream-groundwater interactions

To understand broad behaviours in stream-groundwater interaction and water table fluctuations, we estimated the following characteristics that are independent of time scale. The median depth to the water table (median D_{tw}) was calculated as an indication of the typical depth to the water table (Figure 2 and Table 1). We also sought to understand how often shallow, organic soils and sediments remain saturated. In floodplains, organic-rich layers tend to lie within the first 3 m of the land surface (D'Elia et al., 2017). We therefore calculated the percentage of the water year that the water table remained within 3 m of the land surface (P_{3m}) (Table 1). We expected that dry regions would have deeper water tables and therefore greater median D_{tw} and smaller P_{3m}. Variance in depth to water table, Var(D_{tw}), was calculated as an indication of typical variability in the water table position (Figure 2 and Table 1). Var(D_{tw}) has implications for nutrient cycling and related geochemical processes such as metals redox, microbial respiration, and soil carbon dioxide efflux (Battin et al., 2008; Borch et al., 2010; Dwivedi et al., 2018). We expected that Var(D_{tw}) might be greatest in moderately-sized streams that have sufficient contributing area to generate large floods but have less extreme flow regulation than the largest rivers.

To indicate whether a stream tended to be gaining or losing, we determined the median difference in stream and groundwater levels (Δh) and head gradient between the stream and well (both $\Delta h/\Delta x$ and $\Delta h/\Delta L$, where Δx is horizontal distance and ΔL is total distance from stream edge to well screen) (Figure 2). The direction of Δh has implications for the direction of water and solute exchange between streams and aquifers, while the magnitude of $\Delta h/\Delta x$ or $\Delta h/\Delta L$ has implications for potential rates of exchange. Greater magnitudes of $\Delta h/\Delta x$ or $\Delta h/\Delta L$ indicate a greater potential for flow and transport, given a constant aquifer hydraulic conductivity, but hydraulic conductivity varies widely, and hydraulic head gradients can be large where aquifer materials are less conductive and seepage rates are small (Yeh et al., 1985). To determine a typical value of Δx and therefore also ΔL, we used Google Earth Engine to measure the distance from the well location to the visual edge of the stream in monthly images over the year of interest and averaged those distances. We expected that losing streams (with negative Δh) would be more prevalent in arid areas (Table 1). It is important to note, however, that inflows to streams can be very local, even if a reach is overall losing, and local measures of Δh do not necessarily reflect the direction of exchange over larger areas.

We also determined how often the local stream changed from gaining to losing or vice versa by examining changes in the direction of Δh. Only changes in sign that exceeded the combined error of instrument sensitivity (12 mm) were counted (Sauer et al., 2010). Frequent reversals in the flow direction imply strong bi-directional exchange of solutes between the stream and aquifer (Table 1).

We sought to understand these generalised hydrologic characteristics in the context of potential controls such as location within the river network (stream order), the degree of river regulation, land and water use, and climate. Stream order was taken from The National Hydrography Dataset (Mitchell et al., 2004). To reflect how wet or dry the local climate is, we calculated annual available water (P/ET), the ratio of annual precipitation (P) to actual evapotranspiration (ET). Local monthly precipitation and actual evapotranspiration were taken from the National Land Data Assimilation System-Variable Infiltration Capacity Macroscale Model (Mitchell et al., 2004) and summed over the water year of interest. To reflect potential effects of stream regulation, we counted the number of upstream dams in the Existing Hydropower Plant Dataset database, from Oak Ridge National

TABLE 1 Study objectives and their relation to biogeochemical processes

Analysis or metric	Examples of related processes	Prediction	Supported by observations?
Median D_{tw}, P_{3m}	Soil respiration rates (Danczak et al., 2016), carbon cycling (Battin et al., 2008; Mann & Wetzel, 1995), dissolved organic carbon supply in groundwater (Jardine et al., 1989)	Sites in more arid areas have deeper water tables that spend less time in the upper 3 m of soil. Higher floodplain elevations also have deeper water tables	Partially (floodplain elevation relationship)
Var (D_{tw})	Nutrient cycling (Barnes et al., 2019), soil respiration rates (Schlesinger & Andrews, 2000)	Sites in moderately-sized streams have greater variance	Yes
Δh, $\Delta h/\Delta x$, $\Delta h/\Delta L$	Water, solute, and heat exchange (Galloway et al., 2019; Winter et al., 1998; Wu et al.)	Sites in more arid regions will have more losing streams	No
# Flow reversals	Bi-directional solute exchange (Sawyer et al., 2014), microbial community structure (Stegen et al., 2016)	More neutral sites (small Δh) in moderately-sized streams have more flow reversals	Yes
TF-based classification (stream-dominated, groundwater-dominated)	Solute and heat exchange (Vidon, 2012), sources of groundwater recharge (Lerner, 1997), soil respiration (Battin et al., 2009); Riml et al., 2019)	Connectivity is greatest (TF near 1) for medium-sized streams	No
Wavelet coherence	Seasonality in solute and heat exchange (Song et al., 2018; Willems et al., 1997)	Coherence is weaker in summer at sites where plant and/or human water use may increase	Yes

Note: D_{tw} is depth to water, P_{3m} is the percentage of time that the water table is within 3 m of the land surface, and TF is transfer function (Equation 1).

Laboratory, accessed through the HydroSource Web Application (https://hydrosourcec-data.ornl.gov/#externalaccess). All upstream dams within the same HUC-12 watershed were included in this analysis, regardless of distance from the stream gauge. This calculation assumes that any hydropower plant has the potential to disrupt natural flows downstream on the scale of HUC-12 watersheds, which is likely a conservative estimate, as the distances of upstream hydropower plants to each site ranged from 5 to 200 km along the flow path. To consider the effects of groundwater extraction, we focused on water use for irrigation, as it contributes to 42% of all groundwater use in the United States (Dieter et al., 2018). For each site's county, we obtained the number of irrigated acres from the USDA (https://www.nass.usda.gov/Quick_Stats/CDQT/chapter/2/table/1/state/AL/year/2017) and examined both the total irrigated acres and the irrigated acreage density (the percentage of land in the county that is irrigated). It is worth noting that municipal and industrial groundwater extraction can also influence stream-groundwater connectivity. For example, this municipal pumping effect has been recorded near Denver (Flores et al., 2020) and other cities, but we lacked a way to estimate these non-agricultural groundwater uses for all sites.

2.3 | Frequency-domain analysis

To understand frequency-specific variations in water table fluctuations and surface water-groundwater interactions, we computed energy spectral densities for stream levels (ESD_{sw}) and groundwater levels (ESD_{gw}) using the fast Fourier transform (FFT) in MatLab. To compare the relative strength of the fluctuations at different frequencies, we computed the transfer function (TF), after Schuite et al. (2019) and Wu et al. (2020):

$$\mathrm{TF} = \frac{\mathrm{ESD_{gw}}}{\mathrm{ESD_{sw}}}. \tag{1}$$

Values of TF > 1 indicate that the water table varies more than the stream stage at that frequency (in other words, the amplitude of water table fluctuations is greater than the amplitude of stream stage fluctuations). Values of TF < 1 indicate that the stream stage varies more at that frequency (the amplitude of water table fluctuations is less than the amplitude of stream stage fluctuations).

It is important to note that TF in open aquifers is influenced by a number of interacting factors, including disturbances from nearby stream stage fluctuations, changes in local recharge, and groundwater extraction, to name a few. In the simple case of a one-dimensional, linear aquifer without vertical recharge, TF ranges from 0 to 1, and the amplitude of the water table fluctuation relative to the stream stage fluctuation depends on distance to the stream-aquifer interface, hydraulic diffusivity, and frequency (Shih, 1999; Singh, 2004; Wang & Wörman, 2019). Specifically, TF approaches 1 for short separation distances between the well and stream, long signal periods, and large aquifer diffusivities. In the paired sites within this study, the aquifers are unconfined, and an unknown set of external forces such as groundwater pumping and local recharge may influence TF at various frequencies. TF may exceed 1, due to both nonlinear aquifer behaviour and local effects on the water table (pumping, plant-water use, recharge) that propagate towards the stream. We suggest that TF values near 1 still indicate good hydraulic connectivity between the stream and aquifer, while TF values approaching 0 or infinity indicate a disconnection, but using TF to estimate aquifer properties or constrain other information would require greater site characterisation.

The energy spectra and transfer function hold no information about variations in frequency content over time, nor do they indicate the relative timing between stream stage and water table fluctuations. To explore this, we analysed wavelet coherence, which measures the linearity of the relationship between stream and groundwater signals over various frequencies and time intervals (in essence, it is a localised correlation coefficient in the frequency-time domain) (Grinsted et al., 2004; Schuler et al., 2021). Given two signals *X* (groundwater level) and *Y* (stream level) with wavelet transforms $W^X n$ (s) and $W^Y n$ (s), a cross-wavelet power spectrum $W^{XY} n$ (s) can be calculated using $W^{XY} n\ (s) = W^X n\ (s)\ W^{Y^*} n\ (s)$ where $W^{Y^*} n$ (s) is the complex conjugate of $W^Y n$ (s). The coherence of stream and groundwater levels $R^2 n$ (s) is then given by,

$$R_n^2(s) = \frac{\left|S\left(s^{-1} W_n^{XY}(s)\right)\right|^2}{S\left(s^{-1}\left|W_n^X(s)\right|^2\right) \cdot S\left(s^{-1}\left|W_n^Y(s)\right|^2\right)}, \tag{2}$$

which ranges between 0 and 1 (Grinsted et al., 2004; Schuler et al., 2021). Greater values indicate a higher correlation coefficient (in other words, fluctuations of similarly large magnitude and consistent phase relationship), whereas lower values indicate a lower correlation coefficient. For frequencies and time intervals with strong coherence, we also determined mean phase angle, which indicates relative timing between stream stage and water table fluctuations.

3 | RESULTS

3.1 | Generalised behaviour across paired sites

The 17 paired sites span from small 1st order streams to large 8th order rivers (Table S1). Climate ranges from arid to humid, with annual precipitation ranging from 238 to 1743 mm. The distance from the monitoring well to the stream (Δx) ranges from 1 to 106 m.

For most of these sites, the water table tends to remain near the land surface. At 11 of 17 sites, the water table remains within 3 m of the land surface for at least half of the year (Figure 3). P_{3m} ranges from 0% (the water table is always deeper than 3 m) to 100% (the water table is always shallower than 3 m) (Figure 3) and shows no obvious relationships with climate, distance from the stream (Δx or ΔL), irrigated acres, or upstream dams (Table S1). Similarly, the median depth to water ranges from 0 to 15 m (Figure 3) and shows no obvious relationship with climate, distance from the stream, irrigated acres, or upstream dams (Table S1). As anticipated, there is a weak relationship between median depth to water and height of the floodplain (at the well location) above median stream stage ($R^2 = 0.19$, $p = 0.08$). Many of the sites with shallow water tables are located in the Missouri Basin, while some of the sites with deeper water tables are located in the, Arkansas, Red, White, Pacific Northwest, and California basins (Figure 3).

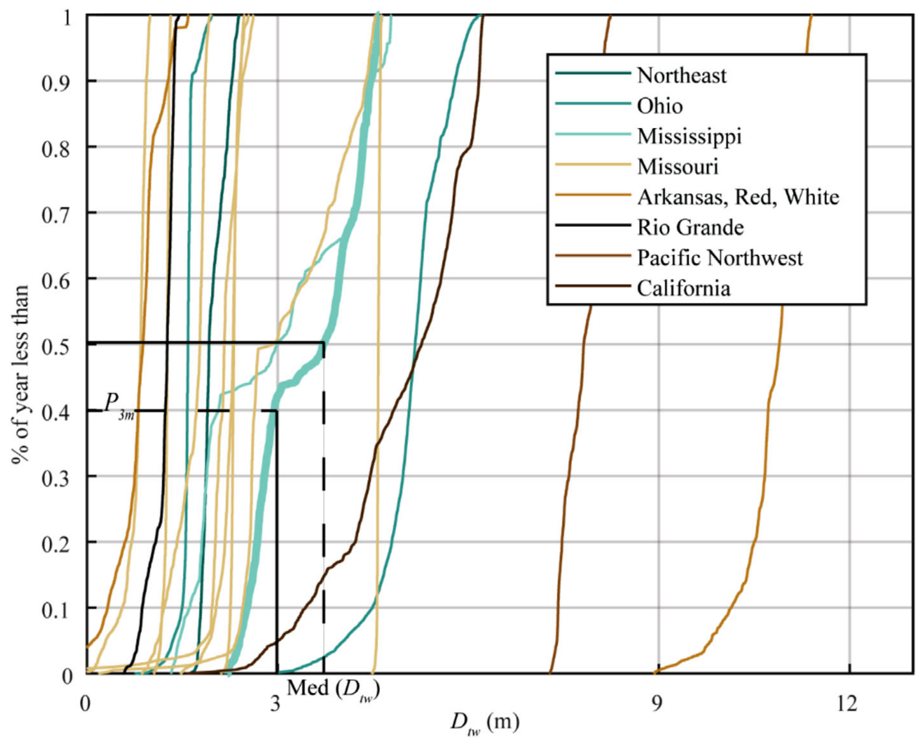

FIGURE 3 Cumulative distribution of D_{tw} for all 17 sites. 14 sites have their water table within 3 m of the land surface for at least half of the year

Water tables adjacent to moderately-sized streams (4th–6th order) have the greatest variability in depth to water table (Figure 4a). Not surprisingly, those same size streams also tend to have a large number of reversals in groundwater flow direction (to or from the stream) in the analysed water year (Figure 4b). The number of available site pairings in this study limits our ability to identify trends with confidence across continental scales. However, the small variance in depth to water (Figure 4a) and small number of flow reversals (Figure 4b) in small streams appears to be consistent across wet and dry climates, suggesting that stream order plays a dominant role in the variability of water levels and flow directions within stream corridors. We expected that the variance in depth to water and number of flow reversals might also depend on river regulation. No clear relationships were evident between the number of upstream dams and either the variance in depth to water or number of flow reversals (Table S1), but the number of upstream dams is not an ideal parameter, as different dams regulate river levels to varying degrees. Other parameters to explore in future studies include the turnover time of all upstream reservoirs, number of hydroelectric dams, and distributions along the stream network.

Land use practises and climate appear to influence Δh and related stream losses or gains in complex ways. Somewhat surprisingly, there were no clear trends between Δh and climate (Figure 5a) or irrigation (Figure 5b). Of the 4 sites with typically losing conditions, one site falls in an arid region (Rio Grande) (Figure 5a), and one site is found in a county where a substantial portion of land is irrigated (Figure 5b). At that site, groundwater extraction for irrigation may draw down the water table, a process that is known to impact streams in locations such as the Missouri Basin (Barlow & Leake, 2012; Condon & Maxwell, 2019; Kendy & Bredehoeft, 2006). Note, however, that irrigation can have complex effects on water table elevation, as the site with most positive Δh is also in an area with substantial irrigated land (site Mississippi-7288847 SBGA). Overall relationships between available water and irrigation versus or $\Delta h/\Delta x$ were similarly scattered (Table S1). We also carried out the same analyses against $\Delta h/\Delta L$ and found no clear trends (Table S1). We also analysed the total number of irrigated acres within the county rather than the percentage of irrigated land and found no clear trends.

3.2 | Frequency-domain analysis

In the time domain, stream, and groundwater hydrographs exhibit short disturbances from storms, water management, and other processes that are superimposed on longer-term changes associated with seasons, as shown for a representative site, Missouri-6025500 BHD (Figure 6a). In the frequency domain (Figure 6b), energy spectra for both stream and groundwater levels decay with increasing frequency (Figure 6b). In other words, water levels vary more over longer periods. The transfer function, TF (Equation 1), highlights differences in energy between the stream and groundwater level at a given frequency. For the example of Missouri-6025500 BHD (Figure 6c), the water level in the stream is slightly more variable than in the aquifer over timescales of roughly 12 h to 1 day, indicating that hydraulic head signals at the stream bank propagate laterally into the surrounding aquifer. In other words, stream stage fluctuations from upstream runoff or dam releases drive much of the local variation in water table height at this shorter timescale. Over longer timescales of months, however, the water level in the aquifer is slightly more variable than the stream, indicating greater influence from multiple interacting disturbances, which may include local recharge and groundwater extraction (Figure 6c). This interpretation assumes a linear aquifer response to hydraulic head fluctuations, as expected in confined aquifers or thick, unconfined aquifers.

The general magnitudes of the transfer function vary widely across sites (Figures 7 and 8). Missouri-6025500 BHD is an example of a site where stream and groundwater levels have fairly similar energy (TF near 1) across frequencies (Figure 7), indicating a moderate degree of stream-groundwater connectivity over both short and long timescales. In contrast, the transfer function for a Mississippi Basin site Mississippi-7288847 SBGA (Figure 7), is noticeably less than 1 at the daily to monthly time scales, indicating that water table fluctuations are damped relative to the stream at those intermediate frequencies. Meanwhile, the transfer function is noticeably greater than 1 at the annual timescale, indicating that stream fluctuations are damped relative to the aquifer. We interpret an overall weaker stream-aquifer connection at this site compared to Missouri-6025500 BHD (Figure 7), and the direction of signal propagation (stream to aquifer vs. aquifer to stream) depends on the timescale. Sites like

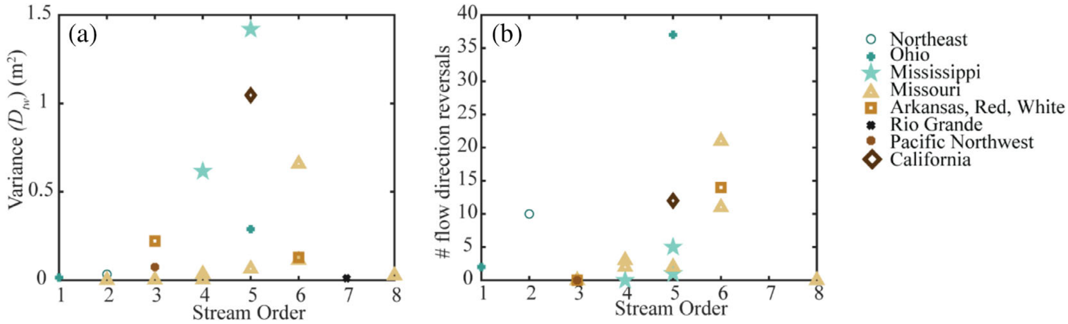

FIGURE 4 (a) The variance in depth to water (D_{tw}) over the year tends to be greatest near moderately-sized streams. (b) Number of flow direction reversals per year is greatest in moderately-sized streams. Symbols indicate HUC-2 watershed (Figure 1)

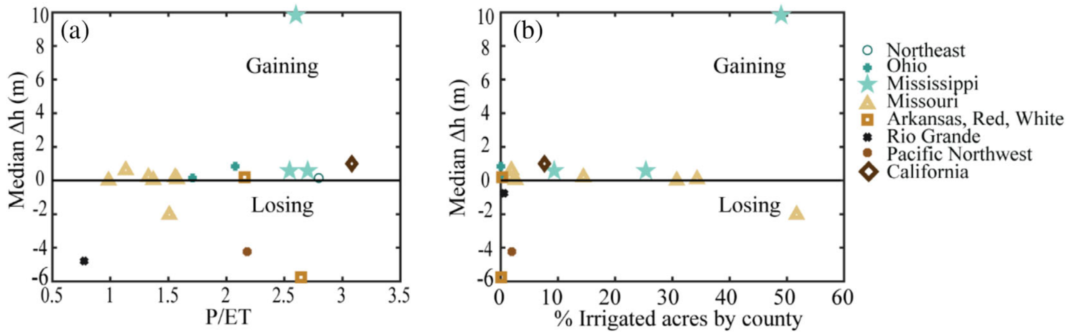

FIGURE 5 (a) Precipitation/evapotranspiration versus median Δ*h* shows no clear climatic influence on whether streams are gaining or losing. (b) There is also no clear relationship with the fraction of irrigated land and whether streams are gaining or losing

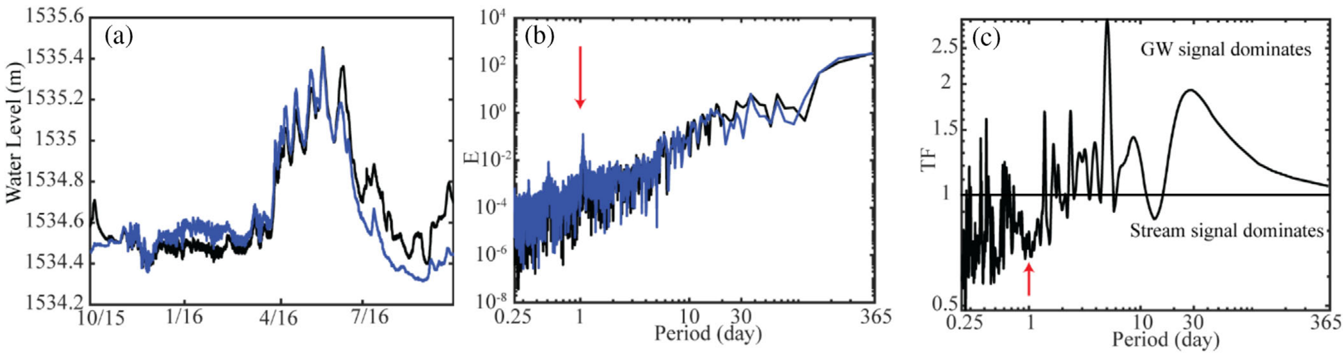

FIGURE 6 (a) Time-series of water levels in both the stream (blue) and well (black); (b) energy spectral density of both the stream and well; and (c) the transfer function, TF (Equation 1), for Missouri-6025500 BHD. The stream stage varies more than the water table height (TF < 1) at the 1-day period (red arrows)

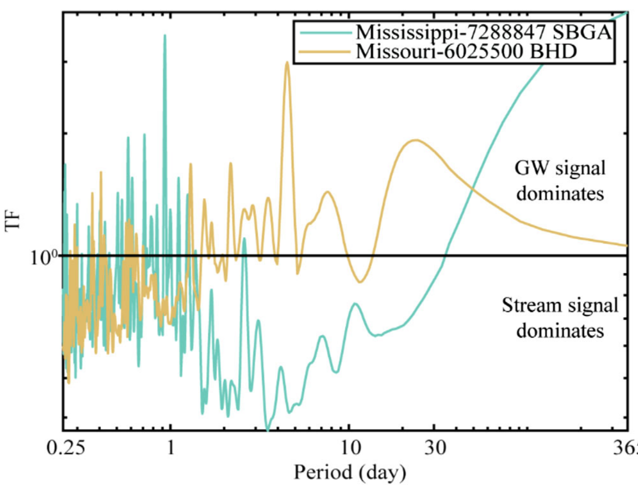

FIGURE 7 Transfer function, TF (Equation 1), for a representative Mississippi Basin site (blue) and Missouri Basin site (yellow). TF values <1 indicate the stream stage varies more; TF values >1 indicate the water table varies more

Missouri-6788350 EWP in the Missouri Basin have a consistently stronger stream signal (TF < < 1) that propagates into the aquifer across frequencies (Figure 8). No sites have a consistently stronger groundwater signal (TF > > 1) that propagates to the stream across all frequencies (Figure 8).

Transfer functions are information-rich, but some periods are more important for interpreting hydrologic processes than others. For example, the 1-day period is relevant to diel cycles of plant-water uptake and snowmelt, and the 30-day period reflects longer time-scales of groundwater recharge and discharge or plant growth. The transfer function for both these timescales is near 1, indicating good connectivity, for 2 of 17 sites (Figure 9 and Table S1). An additional 9 sites have a transfer function much less than 1 at both frequencies, indicating that the stream signal dominates at both daily and monthly periods. Sites do not tend to cluster strongly by region (Figure 9). In the Missouri Basin, the transfer function is near 1 at the 30-day period for almost all sites, but shows a wide range of behaviours at the 1-day period. Some sites are stream-dominated at both the high and low period, some sites are groundwater-dominated at the daily period, and only one site is groundwater-dominated at both the 1-day and 30-day period. There are also no clear trends with stream order. For example, both 1st order and 8th order sites are stream-dominated (Figure 9).

Wavelet coherence between stream and groundwater levels is a way to examine frequency-dependent relationships between streams and aquifers that may change over time, particularly over seasons

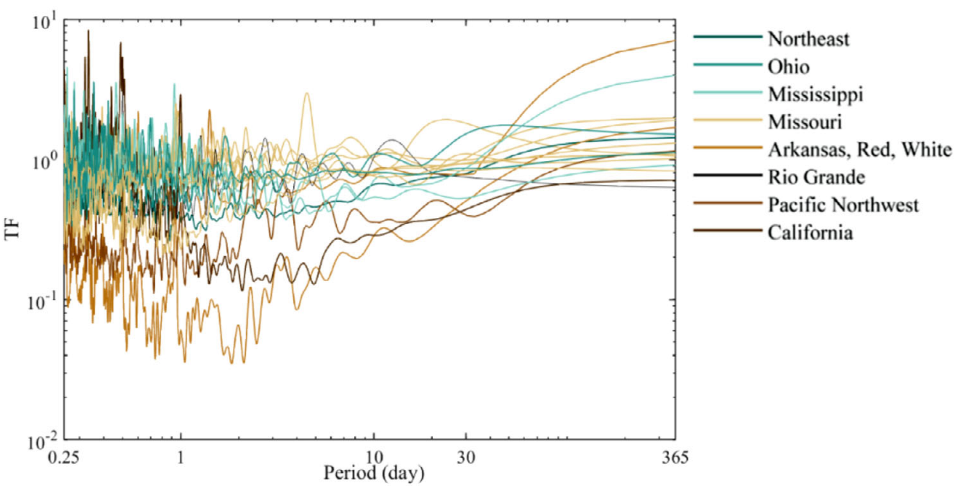

FIGURE 8 Transfer function (TF), for all sites

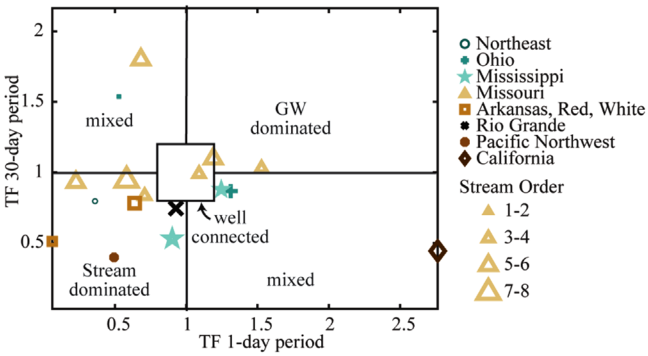

FIGURE 9 Transfer function (TF), for all sites at 1 and 30 days with marker size scaled to increasing stream order. Most sites tend to be stream-dominated at both periods or have TF near 1 at both periods (well-connected)

(Figure 10). For the representative site in the Missouri Basin with relatively strong stream-aquifer connectivity across timescales (Figures 6 and 7, Missouri-6025500 BHD), coherence is near 1 over most of the year for most longer periods, and the stream and groundwater fluctuations are mainly in-phase (Figure 10a). In comparison, Missouri-6025500 NLT has strong coherence across frequencies in fall and winter, but coherence decreases in spring and summer at timescales of days to weeks (Figure 10b). The decline in coherence may be related to chaotic fluctuations associated with springtime rain and snowmelt. Changes in plant-water uptake or groundwater extraction in spring and summer may also contribute to reduced coherence between the stream stage and water table height. Phase differences between stream and groundwater signals are variable in these seasons (Figure 10b), but they may yield some insight into underlying processes. For example, arrows pointing to the right and slightly downward near a period of 1 day in July (Figure 10b) indicate that daily water table fluctuations slightly lead stream stage fluctuations, due perhaps to a strong effect of transpiration on the local water table. Signals of plant-water use in the adjacent stream may lag behind and be weaker because the stream hydrograph integrates the effect of transpiration processes throughout the catchment. Other sites also show a similar decrease in coherence in summer, including the two in the Ohio basin (Figures S14 and S15).

By region, most sites in the Missouri, Northeast, and Ohio basins exhibit moderate coherence between stream and groundwater levels for daily and longer periods over most of the year, regardless of stream order (Figures S6–S15). The Missouri Basin sites also reflect a wide range of land use practises, with irrigated acres per county ranging from 4000 to 130 000. In contrast, neither of the two sites in the Mississippi Basin (Figures S4–S5) shows consistently high coherence for daily and longer periods, despite sharing many of the same characteristics of the Missouri Basin. Since sites in both basins share similar climates, this difference may be related to regional water use or river regulation in the Mississippi Basin.

4 | DISCUSSION

4.1 | Advantages of frequency-domain analysis

Through spectral analysis, we have classified stream-aquifer connectivity at 17 paired monitoring sites in the United States over short and long timescales (Figure 9). Our analysis shows that the majority of sites (10 of 17) have prominent stream stage fluctuations that propagate into the aquifer at both daily and longer (30-day) frequencies. Two of the sites are very strongly connected at both frequencies. This observation has diverse implications for biogeochemical processes in river corridors and stream water quality (Table 1). As an example, it is known that more soil respiration tends to happen when the water table rises (Battin et al., 2009; Butman & Raymond, 2011; Cole et al., 2007; Riml et al., 2019; Schlesinger & Andrews, 2000). In sites like Missouri-6788350 EWP where the water table is strongly coupled to the stream over timescales of hours to months, greenhouse gas production may fluctuate strongly over timescales of hours to months. In contrast, at sites like Arkansas, Red, White-7176950 HC, where the transfer function is much smaller over timescales of days to months, greenhouse gas production may be more stable and perhaps smaller in magnitude overall.

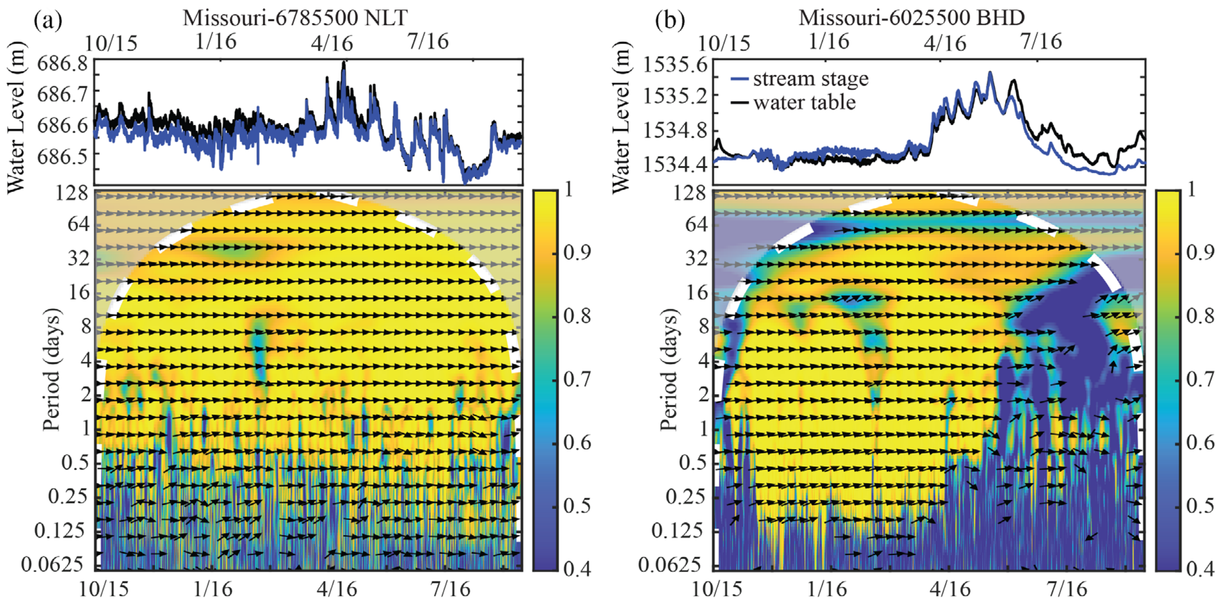

FIGURE 10 Time series (above) and wavelet coherence (below) for two representative sites from the Missouri Basin, Missouri-6025500 BHD (a) and Missouri-6785500 NLT (b). Right-facing arrows on wavelet coherence plots indicate that stream stage and water table are in-phase, and upward-facing arrows indicate that the water table fluctuation lags the stream stage fluctuation. In (a), stream and groundwater levels are strongly correlated down to the sub-daily period throughout the water year. In (b), stream and groundwater levels show strong correlation in winter but weaker correlation over hours to weeks during the spring and summer

In theory, the transfer function should be useful not just for considering biogeochemical processes but also for determining the hydraulic properties of aquifers, particularly hydraulic diffusivity (Singh, 2004). Pedretti et al. (2016) showed the significance of the transfer function in a study of hydraulic parameters within a fractured aquifer. Using transfer functions, they were able to obtain storativity and transmissivity values that were consistent with estimates from traditional well tests. As pressure waves propagate through porous medium, the Earth naturally acts as a low-pass filter, attenuating the amplitudes of higher-frequency signals more than lower-frequency signals, which should manifest as a monotonic decline in transfer function with frequency (Cartwright et al., 2003). This behaviour is not consistently evident in our transfer functions, but the aquifers considered here are unconfined and are likely subject to multiple interacting disturbances from the stream, land surface, and nearby pumping wells. Recharge may occur in various locations (riverbanks, floodplains, and hillslopes) over a variety of timescales, and disturbances may also exist due to evapotranspiration or local groundwater extraction. Thus hydraulic head signals likely propagate in three dimensions from a variety of sources. This complicates efforts to extract hydraulic diffusivity information from the shape of the transfer function.

Through wavelet analysis, we have also revealed differences in the seasonality of stream-aquifer connectivity, which has implications for rates of solute exchange and contaminant transport across seasons. For instance, at sites like Missouri-6025500 BHD with strong stream-aquifer connections in fall and winter (Figure 10), water and solute exchange may increase then. Meanwhile, at sites with high connectivity year-round like Missouri-6025500 NLT (Figure 10), water and solute exchange between the stream and aquifer may be more consistent over the year. Frequency-invariant metrics like the number of times per year a stream changes from gaining to losing also have implications for chemical transport (Boyer et al., 1997; Brunner et al., 2009; Malzone et al., 2016). Flow reversals appear to occur more often in intermediate-scale streams, regardless of climate (Figure 4). Flow reversals, coupled with drying-rewetting from water table fluctuations and rainfall events, could mobilise harmful contaminants such as arsenic or manganese (Berube et al., 2018; Jones et al., 2018).

4.2 | Data limitations

Finding paired sties with continuous data proved to be challenging, even in a nation with a relatively extensive network of stream and groundwater monitoring sites. Not only are there limited numbers of co-located stream and groundwater monitoring sites, but there are also frequent gaps in data for either the stream or the groundwater well. Gaps in stream data often occur during winter (due to ice cover) or after a large flood. Gaps in groundwater data can occur from flooding of the well station or other loss of power issues. These gaps introduce errors in frequency-domain analysis. We were forced to parse these large multi-year datasets down to just one water year in an effort to avoid larger data gaps. With continuous, long-term time series, we may be able discern long-term stream-aquifer connectivity patterns in the transfer function and their changes through time in wavelet coherence, due to changes in groundwater use, climate, river regulation, and other factors.

Another important factor in this analysis is bias in site selection. The 17 sites analysed in this study were established with the goal of long-term stream gauge monitoring and selected based on characteristics that would yield the most accurate rating curves, or relationships between stage and streamflow. Such sites often have relatively straight, simple channel planforms that may be associated with less hyporheic exchange or surface water-groundwater interactions. Sites may be selected for gauging because they are perceived to be more stable and less prone to erosion, which may exclude geomorphically diverse settings with braided channels, vernal pools and wetlands, or other features associated with varying degrees of stream-groundwater interaction. All of these factors illuminate the potential bias in the types of stream-groundwater connectivity that we are able to detect through our analysis. This may also explain why we observed so few sites with losing conditions (Figure 5). A recent study of millions of drilling records from wells near streams suggests that losing stream conditions may be surprisingly prevalent, particularly across dry climates (Jasechko et al., 2021). It is possible that our 17 sites are biased towards neutral to gaining conditions due to a range of factors such as the geology or the degree of valley confinement. As a valley widens, streams often recharge the surrounding valley fill aquifer, and there is also more space available for hyporheic mixing (Kasahara & Wondzell, 2003). Farther downstream where the valley constricts, groundwater may discharge to the stream, and there is less space available for hyporheic mixing. It is possible that the selection of USGS stream gauge sites leads to systematic biases in these geologic factors. With more paired sites from diverse settings, we might observe more diverse patterns in surface water-groundwater connectivity.

5 | CONCLUSION

Based on our study of 17 paired monitoring sites, moderately-sized streams appear to have the most variable stream-groundwater interactions, with the highest number of flow reversals and the largest variability in depth to water table. Most sites (10 of 17) tended to have larger fluctuations in stream stage that propagated into the surrounding aquifer over timescales of days to months. Only two sites exhibited a high level of connectivity between the stream and the shallow aquifer at timescales of both 1 day and 30 days. This classification effort may prove useful for understanding solute fluxes and related biogeochemical process such as greenhouse gas production in river corridors.

This study showcases the capacity for spectral analysis to reveal stream-groundwater interactions over a wide range of timescales. However, opportunities abound to extend spectral analysis to water quality data. With the implementation of a standardised geochemical sensor network for stream and groundwater monitoring sites, even using simple sensors like electrical conductivity, at the same locations where high-resolution water level data exists, we could begin to better understand solute fluxes at a greater watershed scale.

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DATA AVAILABILITY STATEMENT

All data are publicly available through the US Geological Survey.

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SUPPORTING INFORMATION

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