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Groundwater's Fingerprint in Stream Network Branching Angles

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Abstract Branching river networks are prominent features of the Earth's surface, but the mechanisms that create branching river networks patterns remain elusive. Recent studies have suggested that climate, tectonics, and lithology may control both longitudinal profiles of channel incision and the planform geometry of stream networks. Here we show, by analyzing almost 1 million river junctions and over 4.2 million groundwater wells across the contiguous United States, that stream network branching angles vary systematically with the degree to which streams lose water to, or gain water from, nearby groundwater aquifers. Streams whose surfaces lie above nearby groundwater levels, and thus are likely to be losing flow to underlying aquifers, tend to have narrower branching angles than streams that lie below nearby groundwater levels, and thus are likely to gain flow from groundwater. This systematic relationship persists across several stream orders, and across a wide range in channel gradients.

Plain Language Summary River networks are a striking reflection of the processes that shape Earth's surface, but it is still unclear what mechanisms created these distinctive geometric signatures. Branching angles of river networks tend to be narrower in regions with dry climate and wider in regions with humid climates, but the mechanisms behind this relationship remain unclear. By combining new continental data sets of groundwater well levels, river water levels, and river junction angle across the United States, we reveal the first continental-scale observational evidence on the potential contribution of groundwater to shaping river network branching angles, and thus to the development of large-scale drainage patterns.

1. Introduction

The processes that give rise to Earth's highly ramified branching stream networks remain poorly understood. Classical theories propose that channel incision by overland flow is the dominant mechanism by which streams dissect landscapes (Horton, 1932, 1945). This is the basis of many landscape evolution models (Dietrich et al., 2003; Tucker & Bras, 1998; Whipple & Tucker, 1999), but overland flow is relatively rare except in arid landscapes with soils that have limited infiltration capacities (Dunne, 1969; Kirkby & Chorley, 1967). By contrast, about two thirds of the water flowing into rivers is estimated to be derived from subsurface flows globally (Dirmeyer et al., 2006; Oki & Kanae, 2006). Dunne proposed that overland flow shapes network growth in dry climates, but that in wet climates, other runoff processes such as groundwater seepage and shallow subsurface flow predominantly control network growth (Dunne, 1969, 1980). Devauchelle et al. (2012) showed that the theoretically expected angle for network growth by groundwater-driven erosion is $2\pi/5$ (72°). They demonstrated that the tributaries that branch near 72° should concentrate more groundwater seepage at their tips, and thus advance headward faster, than tributaries that branch at other angles. Their findings closely corresponded to branching angles formed in a groundwater-dominated catchment in Florida. However, observational data that reveal controls on the planform geometry of river networks are scarce (Zanardo et al., 2014). In particular, observations of groundwater's contribution to streams and its relation to stream network branching angles at large scales are sparse.

Recent research has found systematic correlations between stream branching angles and climatic aridity across the United States (Seybold et al., 2017) and globally (Seybold et al., 2018). However, a mechanistic explanation for these correlations has remained speculative, because it relied on the assumption that groundwater would be a less important control on channel formation in arid climates. Newly available data (Jasechko et al., 2021) can shed light on this question, by quantifying groundwater levels relative to nearby streams. Groundwater contributions to

streamflow reflect the combined influences of topography, climate, land use, and lithology, potentially integrating many drivers of the erosional processes that generate stream network planform patterns. Here we compare millions of groundwater well levels to the elevations of nearby streams and derive a dimensionless index that measures the fraction of nearby groundwater wells with water levels that lie below the stream water level (the losing fraction). This "losing fraction" indicates whether a stream segment is potentially losing flow to groundwater (losing fraction >0.5) or gaining flow from groundwater (losing fraction ≤0.5). Here we demonstrate for the first time that this relationship between streams and their surrounding aquifers may substantially influence stream network planform geometry, as manifested by valley branching angles across the contiguous United States. The primary objective of this work is to evaluate the importance of groundwater's influence on stream network branching angles, relative to other proposed controls on stream network geometry, namely climatic aridity and channel gradients.

2. Materials and Methods

2.1. Junction Angles and Climate Data

An analysis of 1 million stream junctions across the contiguous United States has shown that stream network branching angles are wider, on average, in humid regions than in arid ones (Seybold et al., 2017). Our analysis uses these previously calculated stream branching angles (Seybold et al., 2017), which are based on the NHDPlus Version 2 stream network data set (McKay et al., 2014). NHDPlus, the best publicly available channel network data set that covers the entire contiguous United States, provides the centerline locations and connectivity of river segments at a resolution of approximately 30 m. Stream segments are defined as the streams connecting pairs of junctions or connecting channel heads to the first junction downstream. The average orientation of each stream segment is calculated by orthogonal regression and is independent of the segment's length. The angle between the fitted lines for each pair of upstream tributaries defines their branching angle. This approach measures the angle between the mean directions of the two tributary valleys, rather than the local angle at which the two channels join (which is a less durable feature of the landscape and more affected by fluctuations like meandering, which strongly depend on in-channel flow processes). We also used NHDPlus to calculate channel gradients. NHDPlus includes nearly 1 million stream junctions; we excluded junctions in distributary networks (e.g., deltas), rejoining braided streams, artificial side channels, and canals, leaving 934,207 branching angles across contiguous United States. We averaged all the branching angles in each Hydrologic Unit Code-6 (hereafter referred to as HUC-6) drainage basin. These basins average 17,000 km^2 in size and usually contain several thousand junctions. Although the standard deviation of the branching angle distribution in each basin is around 25°, the standard error of the mean branching angle is usually smaller than 2°.

The UN FAO aridity index (AI) (defined as AI = P/PET, the ratio of precipitation to potential evapotranspiration; thus higher values correspond to more humid climates) was computed at 4 km resolution using precipitation and temperature data from PRISM (PRISM Climate Group, Oregon State University, 2014) averaged over the period 1900–2012.

2.2. Losing Fractions of Streams

A continental-scale analysis, comparing over 4.2 million groundwater wells with nearby stream water levels across the contiguous United States (Jasechko et al., 2021), has revealed spatial patterns in the prevalence of losing and gaining streams (where "nearby" is defined as within 1 km from the bank of the nearest stream). In Jasechko et al.'s analysis, when more than 50% of nearby well water levels lie below the nearest stream's surface, the stream is considered to be potentially "losing," meaning that it could be losing flow to the underlying aquifer. Conversely, when most of the nearby well water levels lie above the stream's surface, the stream is considered to be "gaining," meaning that it is likely to be gaining flow from nearby groundwater. How much flow a stream actually gains from (or loses to) nearby groundwaters will depend on the permeability of its subsurface, which cannot be inferred from the available data.

We can generalize this binary classification by characterizing each stream by its "losing fraction," namely the fraction of nearby wells with water levels below the stream surface (Figure 1). Thus, a losing fraction of 1 indicates that all the nearby wells have water levels that are below the stream's water level (and thus the stream is likely to be losing), and a losing fraction of 0 indicates that all the nearby wells have water levels that are above
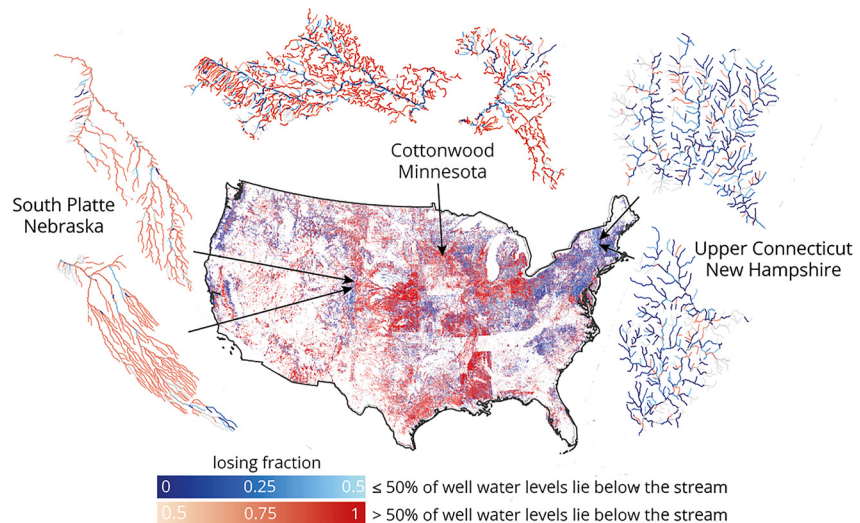
Figure 1. 580,000 gaining and losing streams across the contiguous United States (data of Jasechko et al. (2021)). Where nearby groundwater levels lie below stream surfaces, those streams can lose flow to the underlying aquifer (red stream segments on the map). Conversely, where nearby groundwater levels lie above stream surfaces, those streams are likely to be gaining flow from groundwater (blue stream segments on the map). Selected basins with contrasting losing/gaining conditions are shown to illustrate their respective stream network geometry. In these examples, losing streams tend to exhibit narrower branching angles (e.g., South Platte, Nebraska) while gaining streams tend to show wider branching angles (e.g., Upper Connecticut, New Hampshire). Cottonwood, Minnesota is shown as an example in which lower-order headwater streams are mainly losing and higher-order streams are mainly gaining.

the stream surface (and hence the stream is likely to be gaining). From Jasechko et al. (2021) 's water level data, we calculate each junction's "losing fraction" as the fraction of well levels that correspond to "losing" conditions in its two tributary segments and the downstream segment into which they flow.

2.3. Groundwater Pumping Corrections

Groundwater pumping (GWP) has substantially influenced the water levels reported by Jasechko et al. (2021), so present-day losing fractions reflect anthropogenic groundwater use. Drainage network patterns, however, have typically developed over thousands or millions of years. Therefore the losing fractions, derived from groundwater levels relative to stream water levels, must be corrected for the effects of GWP before they can be compared with drainage network patterns. Here we use USGS GWP data, available at the county level, to calibrate a gradient boosted machine learning model (Ke et al., 2017) that estimates the effects of pumping on losing fractions. We assume that the average losing fraction for each county (LF) is a function of AI, slope (S) and GWP, namely LF = f(AI, S, GWP), with the objective to predict the losing fraction for the case of zero pumping, namely LF = f(AI, S, GWP = 0). This function was estimated by machine learning; for details, see Text S1 in Supporting Information S1. The pumping-corrected averages at the county level were then used to calculate the HUC-6 basin averages of losing fractions using ARC GIS zonal statistics.

3. Results

3.1. Groundwater Levels and Stream Network Planform Geometry

Example basins spanning different climate conditions (subplots in Figure 1), suggest a potential link between the losing/gaining status of streams and their average branching angles. Gaining streams (such as those found in the Upper Connecticut River basin) tend to have wide branching angles, whereas losing streams (such as those found in the South Platte drainage) tend to have narrower branching angles, with streams flowing nearly parallel to one another. Using losing fractions and branching angles, calculated as described in Methods, we analyzed the relationship between surface water-groundwater interactions and stream network planform geometry across the United States.

The large-scale spatial patterns of branching angles and losing fractions can be visualized by averaging over larger basins, as shown in Figure 2. The large-scale patterns of average losing fractions (Figure 2a) broadly
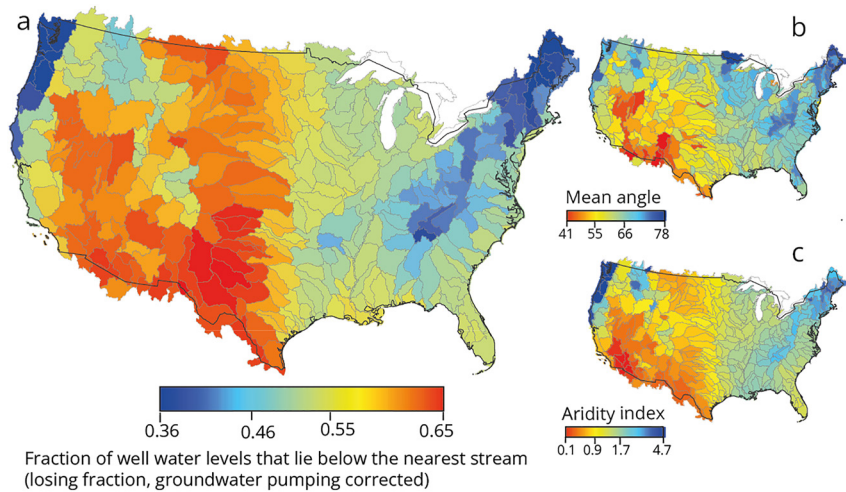
Figure 2. Fraction of losing streams corrected for groundwater pumping (a), compared to mean branching angles (b), and aridity index AI, the ratio of precipitation to potential evapotranspiration (c) in the contiguous United Sates, spatially averaged over Hydrological Unit Code-6 basins of the National Hydrological data set (McKay et al., 2014). The spatial distribution of losing streams broadly corresponds to spatial distributions of mean branching angles and aridity. Where the AI is smaller (more arid climates), the fraction of losing streams is larger and mean branching angles are narrower.

correspond to those of mean branching angles (Figure 2b), when both are averaged over HUC-6 basins of the National Hydrographic data set (Methods). Basins characterized by wide branching angles are more prevalent where climates tend to be humid and losing streams are rare; conversely, narrow branching angles are more prevalent where climates tend to be arid and losing streams are common.

Figure 3. (a) Mean branching angles versus the fraction of nearby wells with water levels lying below the stream surface (losing fractions, corrected for groundwater pumping). Gray points show averages for HUC-6 basins; larger red symbols show binned averages, each representing 5% of the data. The Spearman (ρ) and Pearson (r) correlation coefficients are calculated using the gray points, not the binned averages. Panels (b), (c) Gaining streams (losing fraction ≤0.5, shown in blue) tend to have wider branching angles (average 67.6°) than losing streams do (losing fraction >0.5, shown in red; average angle 59.5°). Mean branching angles become systematically wider as streams become more strongly gaining throughout the contiguous US.

A plot of branching angles versus losing fractions, spatially averaged over HUC-6 basins, shows that branching angles become systematically wider as losing fractions become smaller (streams become more gaining) across the United States (Figure 3). The spatial association of network branching angles and losing fractions shown in Figure 2 and the strong correlation between basin-averaged branching angles and basin-averaged losing fractions shown in Figure 3 (Spearman rank correlation coefficient of $\rho = 0.775$, $p < 0.0001$) and Figure S1 in Supporting Information S1 jointly suggest a substantial influence of groundwater-surface water interaction on planform geometry of stream networks. Basin-averaged gaining and losing streams have significantly different average branching angles (67.6° and 59.5°, respectively; $p < 0.0001$ by two-sample t-test). Losing fractions with and without correction for GWP yield broadly similar results in the analysis that follows (Figures 2–4 in Supporting Information S1). Losing fractions and branching angles are also strongly correlated ($\rho = 0.432$, $p < 0.0001$) when aggregated over the 2965 counties rather than the 328 HUC-6 basins in the contiguous US (Figure S5 in Supporting Information S1).

3.2. Other Factors Influencing Stream Network Planform Geometry

Climatic aridity and channel slope are two factors that have been proposed as drivers of stream network geometry (Howard, 1994; Seybold et al., 2017, 2018; Sun et al., 1994; Sólyom & Tucker, 2007). As shown in Figure 4, mean branching angles averaged over HUC-6 basins are strongly correlated with average losing fractions ($\rho = 0.775$) and mean climatic aridity ($\rho = 0.756$). Multiple regression of branching angles on both climatic aridity and losing fractions (all variables rank-transformed, making the analysis both nondimensional and robust) shows that there is a strong relationship between branching angles and losing fractions ($R^2 = 0.63$, $p < 0.001$) even after the
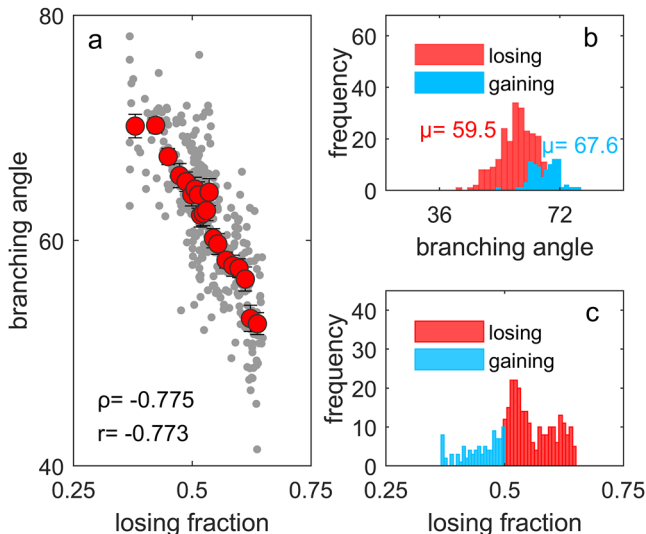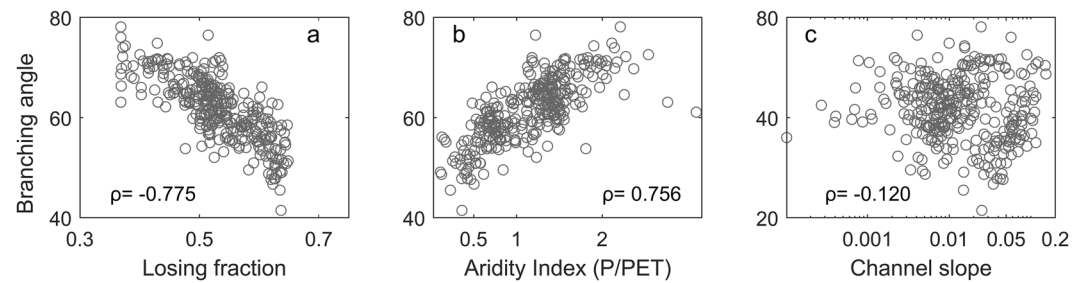
Figure 4. Mean branching angle averaged over HUC-6 basins as functions of panel (a) losing fraction (corrected for groundwater pumping), (b) aridity index, and (c) channel slope. Mean branching angle is more strongly correlated with losing fraction than with channel slope.

inter-relationship between losing fractions and aridity is taken into account. Thus the relationship between losing fractions and branching angles does not spuriously arise from the correlation of both variables with aridity. Instead, the dependence of branching angles on losing fractions (and thus on the likely predominance of groundwater inflows to streams) strengthens the case for groundwater seepage as a plausible mechanism underlying the empirical correlation between stream network branching angles and climatic aridity.

The branching angle is more tightly correlated with average losing fractions ($\rho = 0.775$) than with mean channel slopes ($\rho = 0.12$). We further tested whether the relationship between losing fractions and branching angles persists in different ranges of channel slopes, stream orders, and geological setting. The linear relationship between mean branching angles and losing fractions persists for shallow ($s \leq 0.003$), intermediate ($0.003 < s < 0.03$), and steep ($s \geq 0.03$) channel gradients (Figure 5a), implying that it does not arise artifactually from correlations between slope and both branching angles (Seybold et al., 2017) and losing fractions (Jasechko et al., 2021). In all three ranges of channel gradients, mean branching angles widen as losing fractions decrease (streams become more gaining).

Steeper channels, generally located in the headwaters of a stream network, tend to have narrower branching angles than lower-gradient streams farther downstream in the network (Seybold et al., 2017, Figure S6 in Supporting Information S1), as shown by the vertical offsets between the three channel gradient classes in Figure 5a. The slope of the regression lines among all three categories are significantly different ($p < 0.0001$). Stream branching angles increase systematically with Horton-Strahler stream order, in part because higher-order streams tend to have shallower channel gradients (Leopold, 1953). Low-order headwater channels make up the great majority of any branching network (e.g., first-order channel segments typically outnumber all other channel segments by roughly a 2:1 ratio); thus junctions between low-order channels will inevitably dominate any data set such as ours. To test for possible effects of stream order, we analyzed junctions between first-order, second-order, and third-and-higher-order channels separately. All of these stream order classes exhibit the same general tendency for narrower branching angles to be associated with
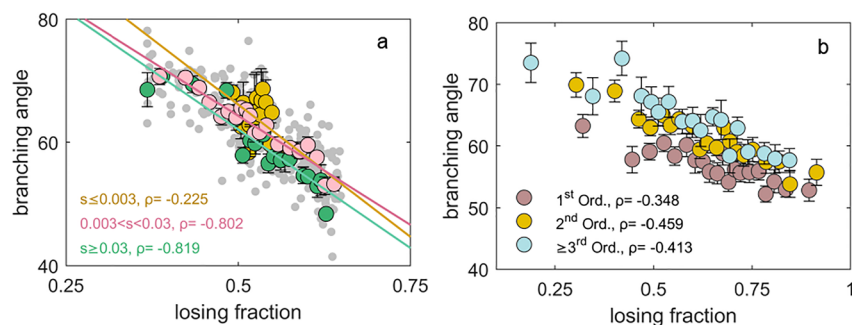

Figure 5. (a) The linear relationship between mean branching angle and losing fraction persists across a wide range in channel gradients (a) and across several stream orders (b). For shallow ($s \leq 0.003$), intermediate ($0.003 < s < 0.03$), and steep ($s \geq 0.03$) channel gradients, mean branching angles are wider where losing fractions are smaller (streams are more gaining). Branching angles between first, second, and third-and-higher order streams (only junctions between streams of the same order are considered), also show a systematic linear relationship with losing fractions. The data shown in both panels are averaged over HUC-6 basins (gray points in panel a) and binned (each large color-coded circle representing 5% of the data for the corresponding slope or stream order class). Spearman correlations are calculated over HUC-6 basins for each slope or stream order class, without binning. Error bars indicate standard errors, where they are larger than the plotting symbols.

higher losing fractions (Figure 5b). As expected, lower-order junctions also tend to have narrower branching angles, primarily because they tend to occur in steeper terrain. To test the possibility of a spurious correlation between losing fractions and branching angle that relates to regional geology, we excluded the extent of the dominant depositional areas across United States, namely the Ogallala group sediments in the western High Plains and the Basin and Range Province, in which channel networks are interpreted to have a deeper geological origin than mature incising (Willett et al., 2018). Our analysis shows that the correlation between branching angle and losing fraction still persists after the exclusion of these predominantly depositional areas (Figures 7–9 in Supporting Information S1).

4. Discussion and Conclusions

Our analysis reveals an empirical linkage between stream-groundwater interactions and the branching geometry of stream networks. Where groundwater levels lie above streams (and thus groundwaters typically feed streamflow), stream branching angles tend to be wider than where groundwater levels lie below streams (and thus streams will tend to lose flow into groundwaters). Our analysis thus helps to clarify mechanisms underlying the observed phenomenological relationship between climatic aridity and branching angles.

We emphasize, however, that our results only emerge from large-sample aggregation over many thousands of individual groundwater and branching angle measurements. One cannot reliably infer groundwater-surface water relationships for individual streams from their branching angles, because individual branching angles reflect the idiosyncratic evolution of individual points on the landscape, as influenced by many factors including small-scale lithological heterogeneity.

Our analysis is based on present-day measurements of streams, aquifers, and valley networks that have evolved over thousands or millions of years. We cannot know the relationships between groundwater and surface water at the time that the drainage pattern first took shape. Nonetheless, it is reasonable to assume that in general (but of course with possible exceptions) the rank ordering of sites in our data has remained relatively stable (wet vs. dry) even if the absolute numbers have changed. That is, streams that were more likely to be gaining (or losing) in the past, relative to others, are also more likely to be gaining (or losing), relative to others, in the present day (once GWP has been taken into account, as our analysis has done). This long-term stability in patterns of groundwater table depths is expected because large-scale patterns of climatic aridity (e.g., the intermountain West of the US is generally drier than the East) have likely persisted for many millions of years. On shorter timescales, our analysis also does not consider the temporal dynamics of groundwater levels relative to streams. However, our source data are based on the medians of all available water level measurements for each well, and thus are likely to be temporally unbiased relative to seasonal and event-timescale variations in groundwater levels. Our analysis also does not address how groundwater levels, relative to streamflow, may vary along individual stream segments (due to differences in topography, for example). In general, streams become more gaining, and branching angles become wider, as streams transition from steep headwaters to gentler lowlands; however, even within restricted ranges of topographic gradients or stream orders, the correlation between losing fractions and valley branching angles still persists (see Figure 5).

Our groundwater well water level data set is dominated by wells that are drilled for water extraction rather than groundwater monitoring, so the stream segments considered in this analysis are likely to oversample irrigated and populated areas. Our analysis is also limited to the contiguous United States due to the limited availability of spatially dense groundwater measurements elsewhere. However, if an adequate global compilation of groundwater data becomes available, it would be useful to extend this analysis to global scale to encompass wider ranges of climate, lithology, and topographic complexity. The systematic relationship between branching angles and losing fractions reveals groundwater's fingerprint in stream network planform geometry and opens an avenue to predict groundwater-surface water interactions in data-scarce areas on Earth and beyond.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Our analyses are based on publically available data. PRISM precipitation and temperature data can be downloaded from (http://prism.oregonstate.edu) at 4 km resolution across United States. NHDPlus stream network and slope attributes (NHDPlus version 2) at 30 m resolution across United States can be downloaded at

http://www.horizon-systems.com/NHDPlus/. Detailed descriptions of the groundwater level data used to estimate the proportion of groundwater wells with water levels that lie below the nearest stream are presented in Jasechko et al. (2021). Stream junctions angles are available in Seybold et al. (2017).

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