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Climate and human organization decouple geometric and functional scaling in river networks

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Abstract. Scaling laws are widely regarded as fundamental organizing principles of river networks, however, whether different scaling relationships emerge from common or distinct mechanisms remains unresolved. Using 41,677 rivers across China, we show that geometric and functional scaling exhibit fundamentally different sensitivities to climatic and anthropogenic forcing. The classical Hack's law relationship between river length and drainage area remains remarkably stable across river hierarchies, climatic gradients, and major basins, indicating a highly conserved geometric organization of river networks. In contrast, runoff-efficiency scaling varies systematically with precipitation, transitioning from strongly negative exponents in arid regions to near-zero values in humid environments. This climatic dependence is associated with hydrological connectivity: river-network structure suppresses runoff efficiency, whereas lake systems enhance the scaling efficiency of runoff generation and transport across basin sizes. Furthermore, administrative fragmentation weakens natural geometric scaling while generating apparent functional scaling relationships absent in intact drainage systems. These findings reveal a fundamental asymmetry in river-network organization: geometric scaling remains highly conserved, whereas functional scaling is strongly shaped by climate, connectivity, and human spatial partitioning. Our results suggest that the organizing principles governing river systems are not fixed properties of natural landscapes, but emergent behaviors continually reshaped by climate variability, hydrological connectivity, and human modification.

1 Introduction

Scaling laws are among the most pervasive patterns in natural systems, which provide a powerful framework for understanding how complex structures emerge across spatial scales (West et al., 1997; Wu, 2004; Song et al., 2005; Peckham and Gupta, 1999). River networks represent one of the most iconic examples of such behavior, which exhibits remarkably regular relationships between drainage area, channel length, network topology, and hydrological processes (Devauchelle et al., 2012; Horton, 1945; Maritan et al., 1996; Hack, 1957; He et al., 2024; Robinson and Scheingross, 2024; Perron et al., 2012; Peckham, 1995; Ranjbar et al., 2020; Danesh-Yazdi et al., 2017). Among these relationships, Hack's law has become a cornerstone of

https://doi.org/10.5194/egusphere-2026-4551
Preprint. Discussion started: 5 August 2026

river-network theory and has been documented across a wide range of climatic and geomorphic settings, which links river length to drainage area through a power-law function (Mueller, 1972; Dodds and Rothman, 2000; Dong et al., 2026; Hack, 1957).

Despite decades of research, most studies have focused on describing the existence and universality of river-network scaling laws (Dodds and Rothman, 2000; Rinaldo et al., 2018). Considerably less attention has been devoted to understanding why some scaling relationships remain remarkably stable whereas others vary substantially across environmental gradients. In particular, river networks possess both geometric and functional dimensions. Geometric properties describe the physical organization of drainage systems, whereas functional properties characterize the efficiency with which water is collected, stored, and transmitted through those systems (Bracken et al., 2013; Berghuijs et al., 2014a; Li and Sivapalan, 2014; Woods and Sivapalan, 1999; Zhang et al., 2026; H. Bavojdan et al., 2025; Rodriguez-Iturbe, 1997; Botter and Rinaldo, 2003; Jencso et al., 2009). Whether these two dimensions respond similarly to climatic forcing remains poorly understood.

Climate is widely recognized as a dominant regulator of hydrological processes (Sheffield et al., 2012; Donohue et al., 2007; Eagleson, 2005; Williams et al., 2012; Berghuijs et al., 2014b; Yang et al., 2009). Variations in precipitation influence runoff generation, hydrological connectivity, water storage, and river discharge across landscapes (Milly et al., 2005; Blöschl and Sivapalan, 1995; Bracken et al., 2013; Fu et al., 2017; Berghuijs et al., 2014b; Mcguire and Mcdonnell, 2010; Birkel et al., 2015; Shao et al., 2021; Famiglietti, 2014; Rodell et al., 2018). However, evidence regarding the influence of climate on river-network scaling remains mixed. Some studies suggest that climatic conditions can alter drainage organization and network evolution, which influences drainage density, branching structure, and channel-network development (Tucker and Slingerland, 1997; Hooshyar et al., 2019; Li et al., 2026; H. Bavojdan et al., 2025), whereas others emphasize the remarkable persistence of geometric scaling laws across contrasting environments (Maritan et al., 1996). These contrasting perspectives raise a fundamental question: does climate modify the scaling architecture of river networks, or does its influence emerge primarily through hydrological functioning?

Addressing this question requires moving beyond geometric descriptions alone and examining how hydrological efficiency scales across climatic gradients. Moreover, climatic effects are unlikely to operate directly. Instead, they may be mediated through landscape structures that regulate hydrological connectivity, including river-network organization and surface-water storage systems such as lakes (Bracken et al., 2013; Cohen et al., 2016; Messager et al., 2016; Ali and Roy, 2010; Jencso et al., 2009). Understanding these pathways is essential for linking climatic forcing to the emergence of hydrological scaling relationships.

A further complication arises because hydrological systems are increasingly managed through human-defined administrative units rather than natural drainage basins (Molle, 2009; Warner et al., 2008; Sivapalan et al., 2012). Water allocation, environmental governance, and resource planning fragment naturally connected river systems (Warner et al., 2008). Whether such anthropogenic partitioning alters the scaling relationships observed in natural drainage networks remains largely unexplored, despite its potential implications for hydrological assessment and water-resource management.

https://doi.org/10.5194/egusphere-2026-4551
Preprint. Discussion started: 5 August 2026

Here, using 41,677 rivers distributed across China, we investigate how geometric and functional scaling relationships respond to climatic, structural, and anthropogenic controls. Specifically, we address three questions: (1) whether Hack's law remains stable across climatic and geomorphic gradients; (2) how functional scaling varies along precipitation gradients and what mechanisms underlie this variation; and (3) whether administrative fragmentation reshapes scaling relationships derived from natural river systems. By integrating river-network geometry, hydrological connectivity, and administrative organization, we demonstrate how climate and human spatial partitioning jointly influence the emergence of hydrological scaling laws.

2 Methods

2.1 River and lake datasets

River-network information is obtained from an official river inventory maintained by the Ministry of Water Resources of the People's Republic of China. The inventory provides river length, drainage area, river level, basin affiliation, administrative information, long-term mean precipitation depth, and long-term mean runoff depth for river systems across China. River length (L) and drainage area (A) are extracted directly from the inventory and used throughout the scaling analyses.

Lake information is obtained from an official lake inventory maintained by the Ministry of Water Resources of the People's Republic of China. The inventory contains lake area and administrative information for major lakes across China. To characterize regional lake abundance, total lake area and lake number are aggregated at the provincial level and subsequently link to river records using administrative identifiers.

2.2 Data preprocessing

All analyses are conducted at the river-record level. Records with missing, zero, or negative river length and drainage area are removed. Duplicate records are identified and removed using river identifiers and geometric attributes. Artificial channels and other human-engineered waterways were excluded from the dataset to avoid introducing anthropogenic alterations to river geometry and connectivity, thereby ensuring that the analyses represent natural river-network organization and hydrological functioning.

For analyses involving runoff efficiency, valid precipitation (*P*) and runoff (*R*) information is required. Runoff efficiency (*RP*) is defined as:

$$RP = \frac{R}{P} \quad (1)$$

Only rivers satisfying

$$P > 0, R > 0, A > 0 \quad (2)$$

are retained.

https://doi.org/10.5194/egusphere-2026-4551
Preprint. Discussion started: 5 August 2026

2.3 Geometric scaling analysis

River-network geometry is quantified using Hack's law (Dodds and Rothman, 2000; Rodriguez-Iturbe, 1997; Hack, 1957):

$$L = cA^h \quad (3)$$

where L is river length, A is drainage area, c is a scaling coefficient, and h is the Hack exponent.

Following standard scaling analyses, both variables are logarithmically transformed:

$$\log_{10}(L) = h\log_{10}(A) + c \quad (4)$$

and fitted using ordinary least squares regression.

The resulting slope is interpreted as the Hack exponent. Model performance is evaluated using the coefficient of determination (R^2), significance tests, and 95% confidence intervals.

To assess robustness, bootstrap resampling (1000 iterations) is applied. The median bootstrap estimate and associated confidence interval are used to evaluate uncertainty in h.

To investigate effects of river level, Hack's law is fitted separately for different river-level classes. Additional regression analyses are conducted to assess whether river level contributed explanatory power beyond drainage area alone.

To evaluate climatic influences on geometric scaling, a river-level scaling index is calculated as:

$$h_i = \frac{\log_{10}(L_i)}{\log_{10}(A_i)} \quad (5)$$

and examine along precipitation gradients using correlation analyses and grouped comparisons.

2.4 Climatic modulation of runoff-efficiency scaling

To characterize hydrological functioning, runoff efficiency is related to drainage area through:

$$\log_{10}(R/P) = \beta\log_{10}(A) + c \quad (6)$$

where β represents the runoff-efficiency scaling exponent.

To quantify how β varies across climatic conditions, rivers are sorted according to long-term mean precipitation and analyzed using a moving-window approach. Each window contains 2000 rivers, and adjacent windows overlap by 500 rivers.

For each window, the local scaling exponent β is estimated using ordinary least squares regression. Bootstrap resampling (1000 iterations) is used to quantify uncertainty.

Relationships between precipitation and β are evaluated using Pearson and Spearman correlation analyses. LOWESS smoothing (Cleveland, 1979) is used to visualize continuous variation in runoff-efficiency scaling along the precipitation gradient.

2.5 Hydrological connectivity controls

To evaluate whether hydrological connectivity regulates runoff-efficiency scaling, two complementary analyses are conducted.

(a) River-network structure

River-network structure is characterized using:

https://doi.org/10.5194/egusphere-2026-4551
Preprint. Discussion started: 5 August 2026

$$S = \frac{L}{\sqrt{A}} \tag{7}$$

which represents the relative elongation of drainage pathways (Sassolas-Serrayet et al., 2018).

Runoff efficiency is modeled as a function of basin size, precipitation, and network structure:

$$\log_{10}(RP) = \alpha + b_1 \log_{10}(A) + b_2 \log_{10}(P) + b_3 S \tag{8}$$

The contribution of network structure is evaluated using changes in R^2, information criteria, and nested model comparisons. Partial-regression analyses are used to isolate the independent effect of network structure after accounting for basin size and precipitation.

(b) Lake-density effects

Lake density is used as an indicator of regional water storage and hydrological connectivity:

$$D_L = \frac{A_{\text{lake}}}{A} \tag{9}$$

where A_{lake} represents aggregated lake area and A is drainage area.

To examine whether lake systems influence runoff-efficiency scaling, rivers are ranked according to lake density and analyzed using the same moving-window framework described above. Local values of β are estimated for each window and related to mean lake density using Pearson and Spearman correlations.

Because lake information is aggregated at the provincial scale, these analyses are interpreted as statistical associations rather than causal estimates.

2.6 Administrative fragmentation experiment

To investigate the influence of anthropogenic spatial partitioning on hydrological scaling, a fragmentation experiment is performed.

The number of administrative units traversed by each river is first identified. For rivers crossing multiple administrative regions, river length and drainage area are partitioned equally among administrative fragments:

$$L_{admin} = \frac{L}{n} \tag{10}$$

$$A_{\text{admin}} = \frac{A}{n} \tag{11}$$

where n represents the number of administrative units intersected by the river.

Hack's law is then re-estimated using the fragmented representation:

$$\log_{10}(L_{\text{admin}}) = h_{\text{admin}} \log_{10}(A_{\text{admin}}) + c \tag{12}$$

Similarly, runoff-efficiency scaling is evaluated using:

$$\log_{10}(RP) = \beta_{admin} \log_{10}(A_{admin}) + c \tag{13}$$

Differences in slope and explanatory power between natural and fragmented systems are used to quantify the influence of administrative partitioning on hydrological scaling.

https://doi.org/10.5194/egusphere-2026-4551
Preprint. Discussion started: 5 August 2026

This experiment is intended as a sensitivity analysis of spatial fragmentation rather than a physically explicit representation of water management processes.

3 Results

3.1 Climate-constrained geometric scaling

River length increases systematically with drainage area across the Chinese river network, following the classical Hack's law scaling relationship (Fig. 1a). Using 41,677 rivers, we identify a robust power-law relationship between river length and drainage area, which yields a Hack exponent of $h = 0.573$ ($R^2 = 0.72$, $p < 0.001$). The estimated exponent falls within the range commonly reported for river networks worldwide (Rigon et al., 1996; Sassolas-Serrayet et al., 2018), which indicates that Chinese river systems conform to a highly consistent geometric scaling structure despite substantial environmental heterogeneity.

To examine whether this scaling relationship varies across river levels, we estimate Hack exponents separately for different river-level classes (Fig. 1b). Although river morphology differs substantially among levels, the estimated exponents remain relatively stable, ranging from approximately 0.56 to 0.62. Most river levels cluster closely around the network-wide mean value ($h \approx 0.58$), with only a modest increase observed for higher-level rivers. These results indicate that the length–area scaling relationship is largely preserved across different levels of drainage-network organization.

To further visualize the geometric implications of these estimates, representative river-network structures corresponding to different river levels are compared (Fig. 1c). Despite large differences in branching complexity and network architecture, the associated Hack exponent varies by less than 0.06 across all levels.

We then evaluate the climatic sensitivity of Hack scaling by stratifying rivers according to long-term mean precipitation (Fig. 1d). Hack exponents exhibit a significant positive relationship with precipitation (slope = 7.34×10^{-6}, $p < 0.001$, see Fig. S1 in the Supplement), which indicates that wetter regions tend to support slightly stronger length–area scaling. However, the magnitude of variation remains modest relative to the overall stability of the scaling relationship. Across the full precipitation gradient, h remains confined within a narrow interval, which suggests that climatic conditions systematically regulate river-network geometry but do so within a highly constrained geometric framework.

These analyses reveal that Hack scaling is both remarkably stable and climatically responsive. River-network geometry exhibits strong persistence across river levels, network structures, and major river basins, while simultaneously retaining a measurable sensitivity to hydroclimatic conditions. Similar scaling exponents are obtained when the analysis is restricted to representative main-stem rivers (see Fig. S2 in the Supplement), and river-level effects on the length–area relationship remain generally small (see Fig. S3–S4 in the Supplement), which indicates that the observed Hack's law is robust to both river selection and river level. Furthermore, incorporating river-level information into regression models results in only marginal improvements in explanatory power (see Table S1 in the Supplement). Overall, these findings indicate that the relationship

https://doi.org/10.5194/egusphere-2026-4551
Preprint. Discussion started: 5 August 2026

between river length and drainage area represents a fundamental organizational property of river networks that is robust across diverse environmental settings. The modest but significant climatic regulation of Hack exponents further suggests that climate influences river-network geometry through gradual adjustments to scaling behavior rather than through large-scale reorganization of drainage structure.

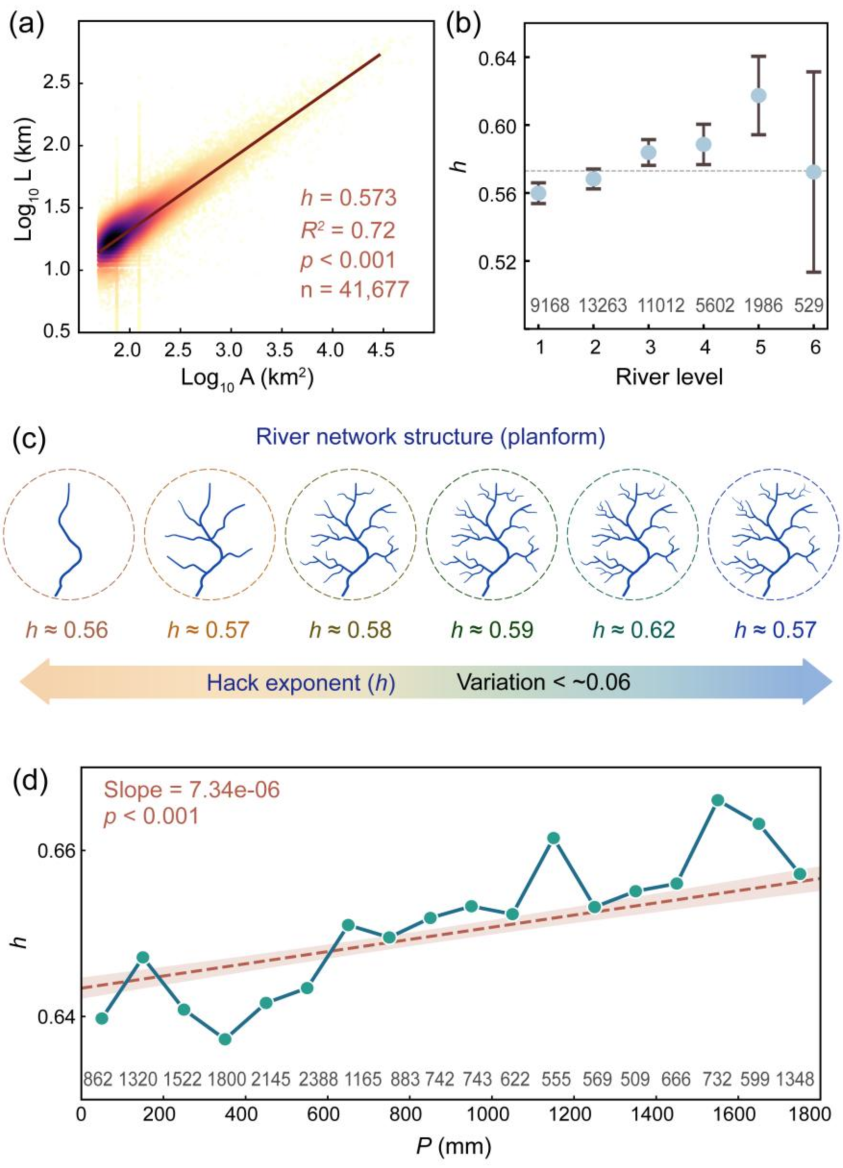

Figure 1. Robust Hack scaling across river levels and climatic gradients in Chinese river networks. (a) Power-law relationship between river length (L) and drainage area (A) for 41,677 rivers across China. The fitted Hack exponent is h = 0.573 (R^2 = 0.72, p < 0.001), which indicates a highly organized length–area scaling structure. (b) Hack exponents estimated

https://doi.org/10.5194/egusphere-2026-4551
Preprint. Discussion started: 5 August 2026

separately for different river levels. Error bars denote 95% confidence intervals and numbers indicate sample sizes. Scaling exponents remain relatively stable across levels despite substantial differences in network morphology. (c) Conceptual illustration of increasing river-network complexity across levels. Despite substantial differences in branching architecture, corresponding Hack exponent remains confined within a narrow range (h = 0.56–0.62), illustrating the persistence of geometric scaling across contrasting network structures. (d) Variation of Hack exponents along the long-term mean precipitation gradient. The fitted trend (dashed line) indicates a significant positive relationship between precipitation and h ($p < 0.001$), suggesting that climate systematically regulates river-network geometry while preserving the overall stability of Hack scaling.

3.2 Climate-dependent functional scaling

We then investigate whether climatic forcing manifests through the hydrological functioning of river networks. Runoff efficiency (R/P) exhibits a pronounced climatic dependence that contrasted sharply with the stability of Hack scaling (Fig. 2a). Along the precipitation gradient, the runoff-efficiency scaling exponent β varies systematically with mean annual precipitation (Pearson r = 0.394, p = 0.019; Spearman ρ = 0.424, p = 0.011). The lowest β values occur under dry regions, whereas β increases rapidly with precipitation and gradually approaches a stable plateau under humid regions. These results indicate that climatic wetness fundamentally alters the relationship between runoff efficiency and drainage area. The moving-window analysis exhibits consistently high goodness-of-fit and nearly constant sample sizes across the precipitation gradient, which confirms that the observed patterns are not driven by local variations in sample availability (see Fig. S5 in the Supplement).

The climatic transition observed in Fig. 2a ultimately leads to two contrasting hydrological scaling regimes (Fig. 2b). In arid regions (see Table S2 in the Supplement), runoff generation is limited by water losses through evaporation, infiltration, and channel transmission. As basin area increases, these cumulative losses offset the potential collection advantage of larger drainage networks, resulting in strongly negative β values. By contrast, humid regions (see Table S3 in the Supplement) exhibit more persistent runoff generation and stronger hydrological connectivity. Under these conditions, river networks maintain efficient water collection and routing across scales, causing β to increase toward near-zero values and remain comparatively stable. The significant difference between arid and humid regions highlights a fundamental hydroclimatic control on functional scaling.

A conceptual framework emerging from these results is illustrated in Fig. 2c. Along the precipitation gradient from arid to humid regions, river networks transition from weakly connected systems characterized by limited runoff generation to highly connected systems capable of efficiently collecting and conveying water. Therefore, functional scaling is not an intrinsic geometric property of river networks but rather an emergent functional characteristic shaped by long-term hydroclimatic conditions. Combined with Fig. 1, these findings reveal a fundamental distinction between geometric and functional scaling in river systems. While river-network geometry remains remarkably conserved across climatic gradients, hydrological functioning exhibits strong climatic sensitivity.

The strong climatic dependence of β further raises an important question: What physical pathways mediate the influence of

https://doi.org/10.5194/egusphere-2026-4551
Preprint. Discussion started: 5 August 2026

precipitation on functional scaling? Addressing this question requires moving beyond climatic forcing itself to examine the landscape structures that mediate water movement through river systems.

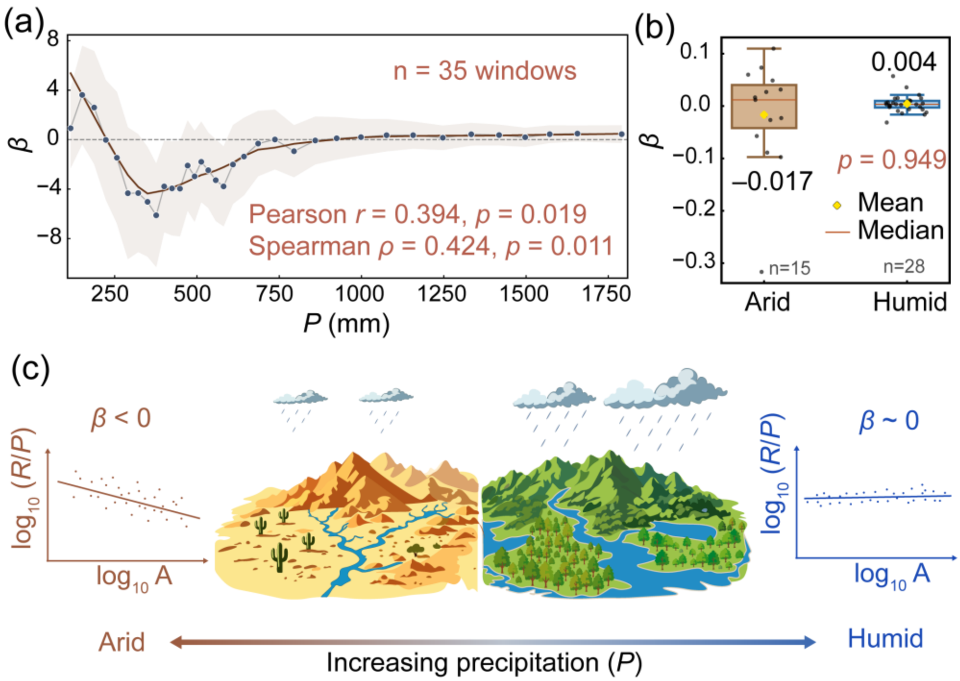

Figure 2. Runoff-efficiency scaling exhibits strong climatic dependence and transitions across hydroclimatic regimes. (a) Variation in the runoff-efficiency scaling exponent (β) along the mean annual precipitation gradient. Points represent moving-window estimates and the brown solid line denotes LOWESS smoothing. Shaded areas indicate 95% confidence intervals. Both Pearson and Spearman correlations reveal a significant positive relationship between precipitation and β, which indicates systematic climatic regulation of runoff-efficiency scaling. (b) Comparison of β between arid and humid regions. Boxes indicate interquartile ranges, whiskers represent 1.5 × IQR, and symbols denote mean values. Arid regions exhibit predominantly negative β values, whereas humid regions show β values close to zero, reflecting distinct hydrological scaling regimes. (c) Conceptual framework illustrating climate-controlled emergence of runoff-efficiency scaling. Along the precipitation gradient, river systems transition from weakly connected networks characterized by limited runoff generation and negative β values to highly connected networks with efficient water collection and transport, causing β to increase toward near-zero values. These results suggest that runoff-efficiency scaling is an emergent functional property governed by hydroclimatic conditions rather than an intrinsic geometric characteristic of river networks.

https://doi.org/10.5194/egusphere-2026-4551
Preprint. Discussion started: 5 August 2026

3.3 Hydrological connectivity regulates functional scaling

The strong climatic dependence of runoff-efficiency scaling identified in Fig. 2 suggests that precipitation is a key regulator of β. However, climatic forcing alone cannot explain how hydrological functioning emerges across river networks. We then investigate whether landscape hydrological connectivity provides an additional control on functional scaling.

After controlling for basin area and precipitation, runoff efficiency (R/P) remains significantly associated with river-network structure (Fig. 3a). The network-structure proxy (S) exhibits a significant negative relationship with runoff efficiency, which indicates that river-network organization exerts an independent influence on hydrological performance beyond the direct effects of climate and basin size. Although the effect size is relatively modest, incorporating river-network structure into regression models consistently improved explanatory power, while precipitation remains the dominant predictor of runoff efficiency (see Fig. S6 in the Supplement).

Notably, the influence of river-network structure is negative rather than positive. Basins characterized by larger S values tend to exhibit lower runoff efficiency, which suggests that longer effective transport pathways do not necessarily enhance runoff collection. Instead, extended flow paths may increase opportunities for evaporation, infiltration, transmission losses, and flow dispersion, thereby reducing the effective delivery of runoff through the drainage system. These results indicate that river-network structure affects not only geometric organization but also the functioning of water-cycling processes.

We then examine whether large-scale hydrological connectivity influences functional scaling. Lake density exhibits a strong positive association with the runoff-efficiency scaling exponent β (Fig. 3b). Sliding-window analyses reveal that β increased significantly with lake density (Pearson r = 0.637, p < 0.001; Spearman ρ = 0.580, p < 0.001). Regions with sparse lake coverage generally exhibit negative β values, whereas β increases rapidly with increasing lake density before stabilizing under lake-rich conditions. This nonlinear transition suggests that abundant surface-water storage systems enhance the ability of river networks to maintain efficient runoff collection across scales.

The contrasting effects of river-network structure and lake density reveal two complementary dimensions of hydrological connectivity. River-network structure primarily regulates the efficiency with which runoff is conveyed through drainage pathways, whereas lake systems regulate how that efficiency scales with basin size. These findings indicate that functional hydrological scaling emerges not only from climatic forcing but also from the organization of hydrological connectivity across landscapes. While climate determines the overall availability of water (Fig. 2), connectivity governs how effectively that water is stored, transmitted, and collected within river systems.

https://doi.org/10.5194/egusphere-2026-4551
Preprint. Discussion started: 5 August 2026

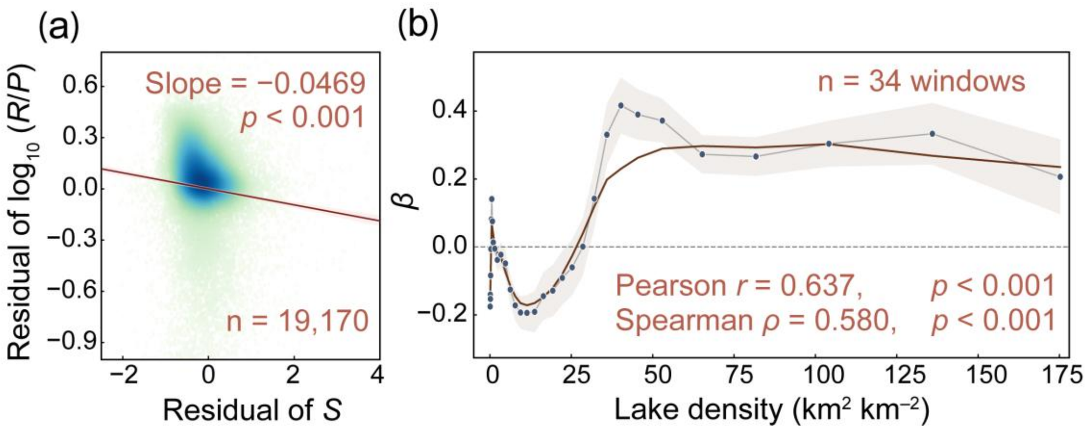

Figure 3. Hydrological connectivity mediates the climatic regulation of runoff-efficiency scaling. (a) Partial-regression relationship between river-network structure (*S*) and runoff efficiency (*R*/*P*) after accounting for basin area and precipitation. The negative slope indicates that longer effective transport pathways are associated with reduced runoff efficiency. (b) Relationship between lake density and the runoff-efficiency scaling exponent β. Points represent moving-window estimates and the brown solid line denotes LOWESS smoothing. Shaded areas indicate 95% confidence intervals. β increases rapidly with lake density before approaching a stable plateau under lake-rich conditions, suggesting that hydrological connectivity exerts a strong control on functional hydrological scaling.

3.4 Human fragmentation reshapes geometric and functional scaling

The preceding analyses demonstrate that hydrological scaling emerges from the interaction between climate, hydrological connectivity, and river-network organization. Importantly, all of these relationships are derived from natural drainage systems, within which hydrological connectivity is preserved by basin boundaries. In practice, however, water governance, resource allocation, and environmental management are rarely organized according to natural river basins. We then examine how administrative fragmentation influences the geometric and functional scaling relationships identified above.

As expected, natural river basins exhibit a strong and well-defined Hack relationship between river length and drainage area (Fig. 4a). Consistent with the results presented in Fig. 1, river length increased with basin area following a robust power-law relationship (h = 0.573, R^2 = 0.72). However, when the same river networks are partitioned according to administrative boundaries, the scaling relationship weakens substantially (Fig. 4b). The Hack exponent declines from 0.573 to 0.473, accompanied by a marked reduction in explanatory power (ΔR^2 = −0.17). These results indicate that administrative fragmentation disrupts the natural geometric organization of river networks and weakens the emergent scaling structure that characterizes drainage systems in continuous hydrological space.

Functional scaling exhibits the opposite response (Fig. 4c–d). Under natural basin organization, runoff efficiency shows little dependence on drainage area, yielding a near-zero scaling exponent (β = 0.008). Following administrative partitioning, a

https://doi.org/10.5194/egusphere-2026-4551
Preprint. Discussion started: 5 August 2026

systematic positive area dependence emerges, which increases the scaling exponent to $\beta = 0.022$ ($\Delta\beta = 0.016$). Although the magnitude of change is modest, the direction of the response contrasted sharply with that observed for Hack scaling. Because the fragmentation experiment alters spatial organization without modifying the underlying runoff and precipitation information, the enhanced β reflects a reorganization of the observed scaling relationship rather than a change in hydrological forcing itself. A conceptual interpretation of this mechanism is illustrated in Fig. 4e. In natural basins, water, storage, and flow pathways are organized within a connected drainage network, which allows geometric and functional scaling relationships to emerge from intrinsic hydrological connectivity. Administrative partitioning, by contrast, reorganizes rivers into fragmented spatial units that no longer correspond to natural drainage structures. This reorganization reduces the coherence of geometric scaling while enhancing apparent functional scaling, thereby reshaping the observed scaling properties of river systems. Overall, these findings demonstrate that hydrological scaling is governed not only by climate and landscape connectivity, but also by the spatial framework through which river systems are defined and managed. Human boundaries therefore represent an additional and previously overlooked effect on the emergence of river-network scaling laws.

https://doi.org/10.5194/egusphere-2026-4551
Preprint. Discussion started: 5 August 2026

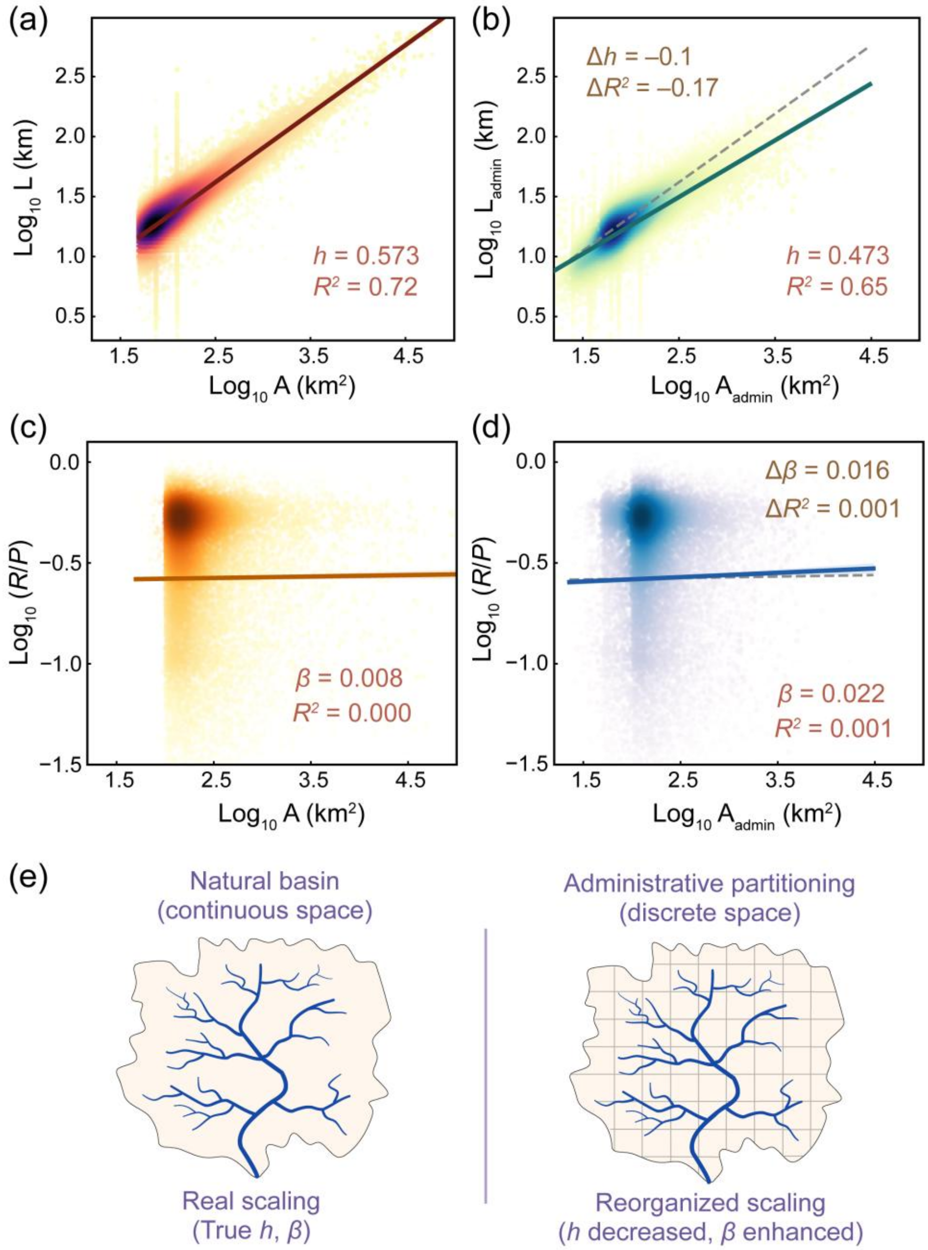

Figure 4. Administrative fragmentation weakens geometric scaling while enhancing functional scaling in river systems. (a) Natural river basins exhibit a robust Hack relationship between river length (L) and drainage area (A), yielding a scaling exponent of h = 0.573. (b) Re-estimated Hack scaling after administrative partitioning. Fragmentation reduces the Hack exponent (Δh = −0.1) and decreases explanatory power (ΔR^2 = −0.17), which indicates a weakening of the natural geometric organization of river networks. (c) Functional scaling under natural basin organization. Runoff efficiency (R/P) shows little dependence on drainage area, resulting in a near-zero scaling exponent (β = 0.008). (d) Functional scaling after administrative

https://doi.org/10.5194/egusphere-2026-4551
Preprint. Discussion started: 5 August 2026

partitioning. Fragmentation strengthens the observed area dependence of runoff efficiency, increasing the scaling exponent ($\Delta\beta$ = 0.016) despite no change in the underlying hydrological forcing. (e) Conceptual framework illustrating how administrative partitioning reorganizes river systems from continuous hydrological space into discrete management units. This reorganization weakens geometric scaling (h) while enhancing apparent functional scaling (β), thereby reshaping the observed scaling behavior of river networks.

4 Discussion and conclusion

Scaling laws are widely regarded as signatures of self-organization in natural systems, which reflects how complex structures emerge and function across scales (Barabási, 2009; Song et al., 2005). River networks have long served as one of the most iconic examples of such behavior, however, previous studies have largely treated river scaling as a single phenomenon (Sassolas-Serrayet et al., 2018; He et al., 2024; Rodriguez-Iturbe, 1997). By simultaneously examining river-network geometry, functional scaling, hydrological connectivity, and administrative fragmentation, our results reveal that river scaling is governed by multiple organizing principles rather than a single universal mechanism. Geometric and functional scaling emerge from fundamentally different processes and therefore respond differently to climatic and anthropogenic forcing. This distinction helps explain why some scaling relationships remain remarkably stable across environmental gradients whereas others vary systematically with climate and landscape organization.

This study shows that geometric scaling exhibits remarkable resilience to environmental variability. Despite substantial differences in precipitation, river level, and basin identity, Hack exponents remain highly constrained across all examined conditions (Fig. 1). Although precipitation exerts a detectable influence on scaling behavior, the magnitude of variation is small relative to the overall stability of the length–area relationship. These results suggest that river-network geometry is governed primarily by long-term geomorphic self-organization rather than contemporary climatic forcing (H. Bavojdan et al., 2025; Mantilla et al., 2010). Such behavior is consistent with theoretical perspectives that view river networks as emergent structures arising from persistent erosion, drainage integration, and topographic adjustment (Ranjbar et al., 2020; Rinaldo et al., 2014; Seybold et al., 2021; H. Bavojdan et al., 2025; Benda et al., 2004). While climate undoubtedly shapes runoff generation and landscape evolution, its influence appears insufficient to fundamentally reorganize the geometric architecture of drainage systems. The persistence of Hack scaling across broad climatic gradients therefore supports the view that geometric scaling laws represent emergent properties of river-network organization that are largely conserved across environmental settings.

In contrast, functional scaling exhibits strong climatic sensitivity. The runoff-efficiency scaling exponent β varies systematically along the precipitation gradient, which transitions from negative values in dry regions toward near-zero values in humid regions (Fig. 2). Unlike Hack scaling, runoff-efficiency scaling is not an intrinsic geometric property of river systems. Instead, it represents an emergent functional characteristic arising from the interaction between climate and hydrological connectivity. This distinction reveals an important asymmetry in river-network organization: climate exerts only limited

https://doi.org/10.5194/egusphere-2026-4551
Preprint. Discussion started: 5 August 2026

influence on geometric structure but strongly regulates hydrological functioning (Berghuijs et al., 2014a; Gudmundsson et al., 2021; Blöschl et al., 2017; Hooshyar et al., 2019; Li et al., 2026). Consequently, river networks may maintain similar geometric architectures while exhibiting fundamentally different capacities for collecting, storing, and transmitting water.

Our results further suggest that hydrological connectivity provides the missing mechanism linking climate to functional scaling (Fig. 3). Combined with the observed effects of river-network structure on runoff efficiency, these findings indicate that climatic regulation of hydrological scaling operates indirectly through landscape organization. Not all forms of connectivity play equivalent roles, however. River-network structure primarily regulates the efficiency with which runoff is conveyed through drainage pathways, whereas lake systems regulate how that efficiency scales across basin sizes. This division of labor within hydrological connectivity helps explain why climatic gradients generate systematic differences in hydrological performance without substantially altering river-network geometry.

Beyond natural controls, our analyses reveal that hydrological scaling is also shaped by the way humans organize space (Fig. 4). Administrative fragmentation weakens the geometric scaling observed in natural drainage systems while simultaneously enhancing apparent functional scaling relationships. Because the fragmentation experiment alters spatial organization without modifying the underlying hydrological variables, these changes emerge entirely from the redefinition of observation units. This finding carries important implications. Some observed scaling relationships may reflect anthropogenic spatial organization as much as intrinsic river-network processes. Human-defined boundaries therefore represent an additional and previously overlooked control on the emergence of hydrological scaling patterns.

Overall, our results support a framework for understanding river-network scaling. Geometric scaling emerges primarily from the self-organized architecture of drainage networks and remains remarkably robust across environmental gradients. Functional scaling, by contrast, arises from climate-dependent hydrological connectivity and therefore varies systematically across hydroclimatic regimes. Beyond these natural controls, human spatial partitioning can further reorganize the scaling relationships that are ultimately observed and managed. River-network scaling should be viewed not as a single universal phenomenon, but as the outcome of interacting geometric, hydrological, and socio-spatial processes. It is essential for understanding how river systems respond to environmental change and for interpreting hydrological scaling relationships in an increasingly human-modified world.

Code and data availability

The compiled river-network and lake datasets supporting the findings of this study are available from the corresponding author upon reasonable request, subject to scientific review and the completion of a material transfer agreement. Requests should be directed to shaoww@iwhr.com. The code for reproducing the analyses presented in this study is publicly available at https://github.com/LaianLaian/river-scaling-decoupling.

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Author contributions

Weiwei Shao, Rui Shao, and Jiaqi Li conceived the study. Rui Shao and Jiaqi Li developed the methodology. Rui Shao, Jiaqi Li, and Weiwei Shao performed the formal analysis and visualization. Weiwei Shao and Haibing Wu curated the data. Rui Shao, Jiaqi Li, and Weiwei Shao wrote the original draft. Weiwei Shao acquired the funding. Weiwei Shao supervised the project and administered the project. All authors reviewed and edited the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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Review statement

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