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Interaction in Landscape Pattern and Hydrological Process Indices: A Systematic Review

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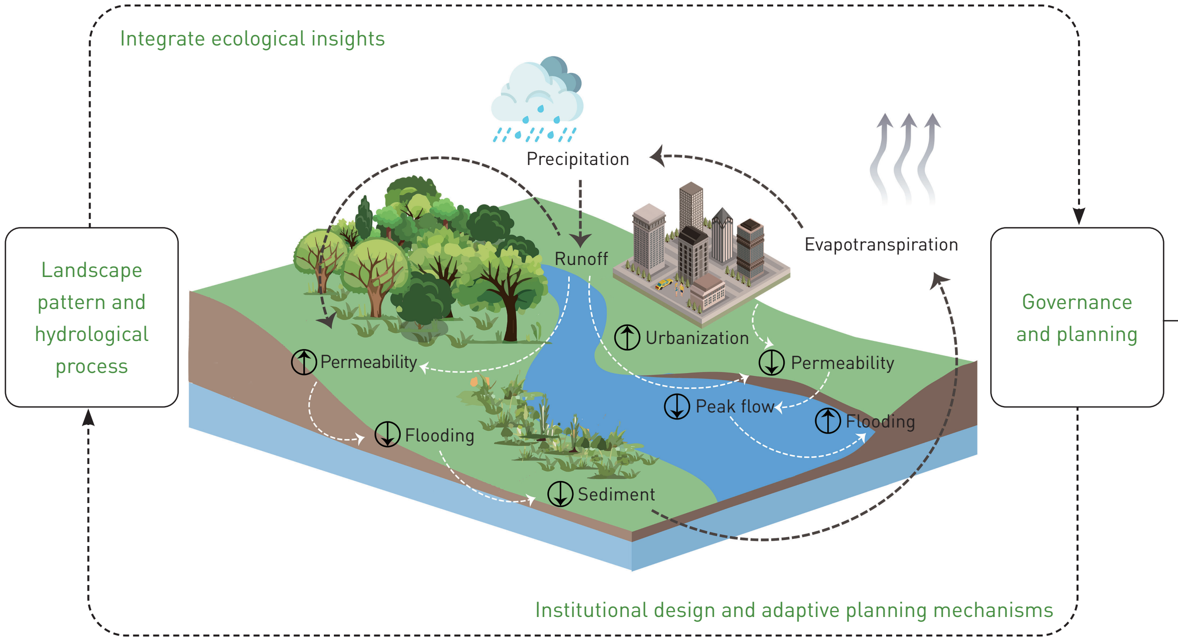
GRAPHICAL ABSTRACT



- **Integrate ecological design principles** by optimizing landscape structures (e.g., permeable surfaces, planting design) to improve hydrological processes and support natural water cycles
- **Adopt cross-scale design strategies** that coordinate hydrological processes across different scales, with priority on managing runoff, flooding, and sediment issues in rapidly urbanized areas
- **Strengthen institutional and adaptive planning mechanisms** to enhance hydrological management, particularly for flood control, peak-flow regulation, and their landscape impacts

ABSTRACT

There are complex landscape pattern and hydrological process (LPHP) interactions, which exhibit different coupling mechanisms across multiple temporal and spatial scales. However, in-depth understanding of the LPHP interactions is currently lacking. This research conducted a systematic review of 198 empirical studies to explore the LPHP interactions. The findings reveal that: 1) global LPHP research was concentrated in temperate regions, with tropical and cold regions underrepresented; 2) LPHP interactions showed temporal and spatial scales differentiation, with the majority of studies occurring at long-term local and regional scales, and the relationship between agricultural land expansion and surface runoff was a key point. This research proposed a dual-path driving model that captures both landscape pattern-driven hydrological processes and hydrological process-reshaping landscape patterns. In natural areas, high cohesion and aggregation patterns should be protected and enhanced. In urban areas, landscape fragmentation should be controlled and green infrastructure should be promoted to strengthen hydrological resilience. Additionally, soil erosion and floods not only alter the landscape composition but may also trigger dynamic changes in landscape configuration, forming feedback loops, which are particularly pronounced at the local scale. Identifying these key pathways enhances the understanding of the coupled human–nature system, facilitating more robust predictions and responses to future changes and challenges.

KEYWORDS

Multiscale; Spatiotemporal Scale; Landscape–Hydrology Interaction; Landscape Pattern; Hydrological Process; Indices; Hydrological Resilience

HIGHLIGHTS

- Current LPHP research mainly focuses on temperate regions, with fewer studies on tropical and cold areas
- Landscape patterns and hydrological processes have a bidirectional feedback loop
- Landscape composition drives long-term hydrological regulation, and configuration affects short-term feedback
- Spatial heterogeneity nonlinearly affects hydrological processes, emphasizing cross-scale feedback

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1 Introduction

The coupled human–nature system has emerged as a critical framework for understanding interactions between human activities and the environment[1–2]. Human land-use decisions have altered the spatial structure of landscapes, profoundly impacting biodiversity, energy flows, and material cycling within ecosystems. These changes in the earth's surface system create diverse hydrological processes[3–5], which in turn shape surface landscape patterns. The interaction between landscape pattern and hydrological process (LPHP) illustrates the intricate relationships embedded in the coupled human–nature system[5–6].

A landscape–hydrological framework has been proposed to explore how landscape patterns influence ecosystem functions through hydrological processes[7–8]. This framework has since been developed, revealing dynamic relationships between landscape configuration and hydrology, particularly in the context of water resource management[9–10]. Existing studies have analyzed how landscape and land changes affect the spatiotemporal distribution of hydrological processes across local to global scales[11–14], highlighting their significant impacts[15], especially through effects at catchment and regional scales[16]. Scholars have also noted that while changes in landscape configuration have direct impacts on hydrological processes at local scales[17–19], their role becomes even more critical at broader scales[20], indicating significant differences in the pathways and intensities of LPHP interactions across scales. However, existing studies remain limited on single-scale analyses and have yet to thoroughly address the complexity of multi-scale LPHP interactions[21] or the associated cross-scale feedback mechanisms, especially the causal relationships between scales[7]. Addressing this gap is not only a complement to existing theoretical frameworks but also an urgent need for effective water resource management and ecological conservation.

Thus, this study aims to reveal the complexity of LPHP interactions across different spatiotemporal scales and explore their key interacting patterns through a systematic review of existing empirical research. The outcomes can contribute to a deeper understanding of internal mechanisms of LPHP interactions and provide both theoretical foundations and practical guidance for future landscape planning and hydrological management.

2 Methods

In this study, LPHP interactions were systematically collected and analyzed through three stages (Fig. 1). In the first stage, the literature search was performed on June 6, 2023, using the Web of Science (WoS) and Scopus databases and limited to English-language research articles published between January 1, 1990 and June 6, 2023. After the initial search, the literature was screened according to predefined criteria emphasizing empirical evidence of LPHP interactions and their mechanisms, rather than model construction or optimization. A total of 198 articles were retained

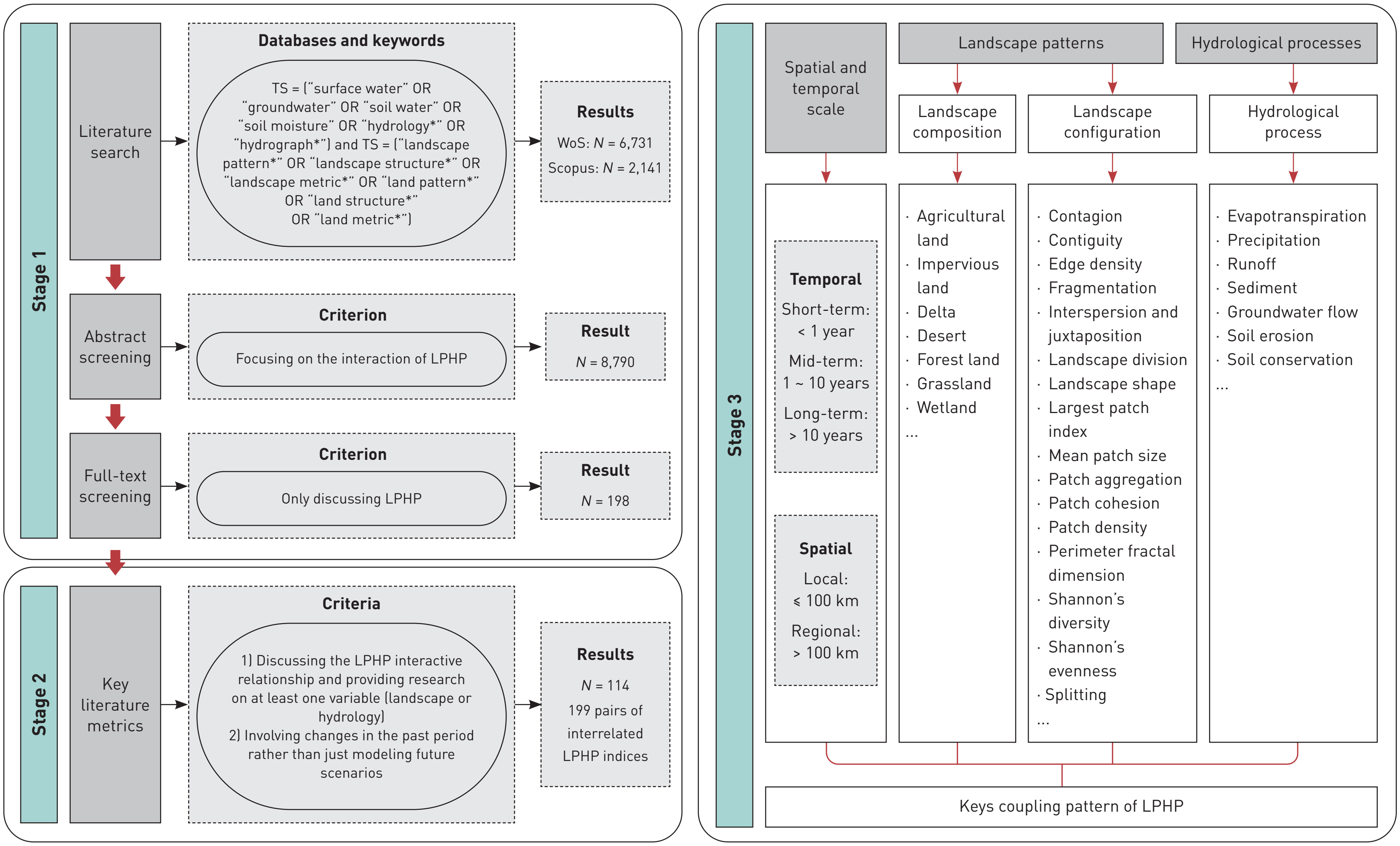

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Fig. 1 Research framework of the LPHP study.

after the initial search, abstract review, and full-text review. These publications were mostly concentrated in 2011–2023, with a peak from 2017 to 2022 (Fig. 2), reflecting the steady growth over the past three decades. In the second stage, 114 studies mentioning the temporal span and spatial extent were extracted to investigate the spatiotemporal scale sensitivity of LPHP interactions. Then, data and indicator attributes in the articles were collected, resulting in 199 pairs of interrelated LPHP indices. In the third stage, these paired indices were categorized by landscape composition and configuration, vertical and horizontal hydrological processes, and the direction within each LPHP indicator pair. Landscape composition indices refer to the amount and proportion of different land use and land cover (LULC) types, while configuration indices describe the spatial characteristics and interrelationships of landscape patches. Hydrological process indices can be classified

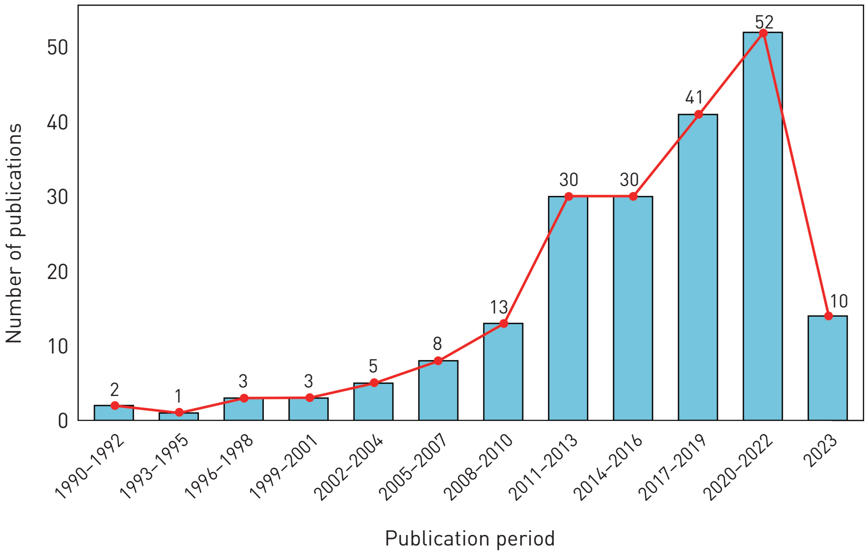

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Fig. 2 The number of publications on LPHP.

into meteorological, surface, and groundwater processes based on their spatial domains, reflecting multi-level hydrological responses. Furthermore, the LPHP interaction indices were investigated across three temporal scales—short-term (< 1 year), mid-term (1 ~ 10 years), and long-term (> 10 years), and two spatial scales—local (≤ 100 km) and regional (> 100 km)① scales[22].

3 Results

3.1 Global Distribution of LPHP

This study mapped the geographical distribution and spatial coverage of the screened research to better understand the LPHP interactions (Fig. 3)②. Globally, LPHP research was primarily concentrated in temperate zones. The majority of studies were conducted in Asia (50.0%), Europe (18.7%), and North America (16.8%), with particular focus on the eastern coast and the Yangtze River Basin of China, developed countries in western and central Europe, and the east and west coasts of the USA. In contrast, research in tropical zones was less prominent, mainly distributed along the southeastern coast of Brazil and in parts of Southeast Asia. At the same time, studies in cold zones remained limited. At finer spatial scales, research displayed distinct local clustering, with relatively few studies conducted in inland and arid areas.

The results suggest a significant deficit of research on LPHP interactions in tropical and cold zones. This geographical uneven distribution limits a comprehensive understanding of global LPHP dynamics. As biodiversity hotspots, tropical zones strongly influence hydrological processes due to their distinctive climatic conditions and ecosystems. Similarly, cold zones, with their unique permafrost and hydrological characteristics, are crucial to global climate and water resource management. In contrast, coastal areas characterized by frequent water exchange have become major research foci. These hydrologically active coastal regions, particularly those under maritime and monsoon influences (e.g., the western coast of the USA, the eastern coast of China, Japan), play a key role in LPHP. Furthermore, regions experiencing rapid economic, social, and urban development, including North America, Central and Eastern Europe, and several urban centers in East Asia, were also research hotspots. Overall, LPHP studies are concentrated in temperate, coastal, and economically developed areas, whereas inland, arid, and cold zones remain underrepresented.

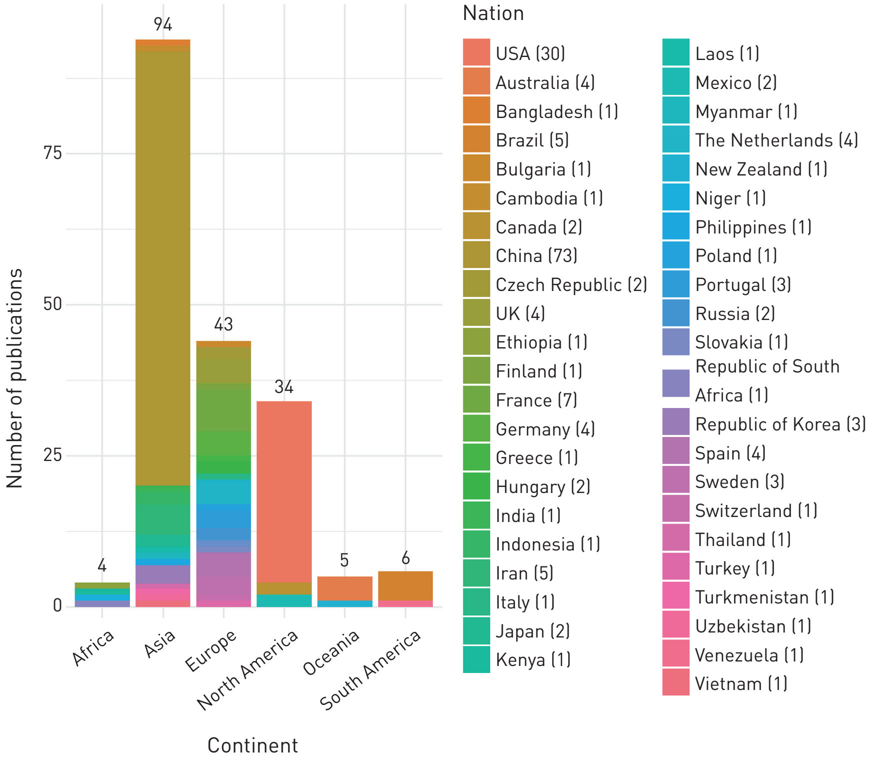

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Fig. 3 Global geographic distribution and the number of publications of screened research.

3.2 Correlation of LPHP Indices Across Spatiotemporal Scales

3.2.1 Spatiotemporal Scales

The temporal and spatial scale classification results (Table 1) show that the short-term studies, focusing on impacts and responses to single extreme precipitation events, were primarily at the local scale, with a complete absence at the regional scale. This finding indicates the limited feasibility of cross-regional synchronous monitoring over a short temporal span. Short- and mid-term studies remained at the local scale, with no coverage at the regional scale, suggesting a potential bottleneck in constructing continuous observation networks at the catchment scale. However, long-term analyses, such as those examining the cumulative effects of forest succession on runoff, presented significant research clusters at both local and regional scales, reflecting the cross-spatial scalability of landscape–hydrological linkages over decadal to centennial periods. Moreover, long-term studies conducted at the local scale

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① The spatial scale was derived from the radius of study area reported in each article.

② This study classified research distribution across six continents (excluding Antarctica, due to the lack of LPHP-related studies). Moreover, not all publications reported specific study areas; therefore, the number of publications in Fig. 3 does not fully correspond to the total number of reviewed articles.

Table 1: The temporal and spatial scale of the 199 paired indices

Temporal scale	Spatial scale	
	Local	Regional
Short-term	3	0
Mid-term	49	0
Long-term	96	51

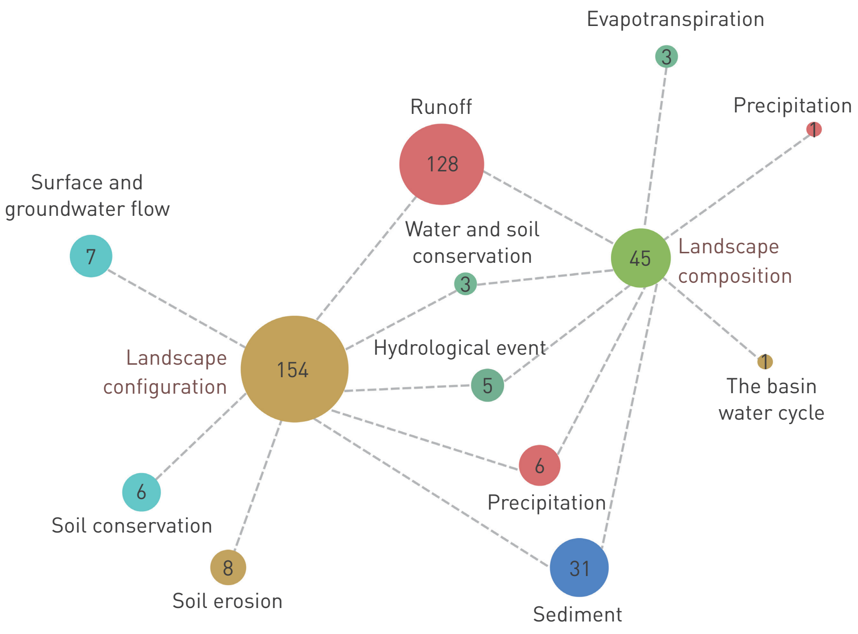
accounted for the largest proportion (48.2%), indicating that the current research on LPHP interactions primarily focusing on meso-scale changes.

3.2.2 LPHP Interaction Indices

The LPHP interactions have received varying degrees of attention. Among them, landscape configuration has most frequently been examined in relation to hydrological process indices (Fig. 4), particularly runoff, followed by sediment and soil erosion. These results indicate that changes in landscape configuration can directly affect runoff generation as well as soil erosion and deposition processes. In contrast, landscape composition has been studied mainly in relation to hydrological events and water cycle processes at the catchment scale, dominated by runoff. In addition, evapotranspiration and water cycle have only been studied in connection with landscape composition. Overall, the literature highlights a predominant focus on the landscape configuration–runoff interaction, while also pointing to growing interest in how landscape composition affects hydrological events and the water cycle.

Specifically, runoff has a strong controlling effect. Research has shown that larger and more continuous woodland patches can reduce surface runoff, consistent with the path-blocking effect described in the source-sink landscape theory[23]. Sediment dynamics exhibited threshold dependence, characterized by nonlinear saturation effects[24]. As landscape fragmentation increased, gully erosion intensity tended to stabilize. Although documented in only a limited number of cases (4.0%), terraced agriculture has been shown to reduce the slope erosion modulus[25]. In contrast, a 10% increase in forest cover can lead to a 14% reduction in annual runoff depth. Groundwater flow (3.5%) was more closely linked to landscape composition than to configuration indices, mainly because LULC directly governs the preferential flow paths. Generally, landscape composition plays a stronger role in driving the macro-scopic redistribution of the hydrological cycle, primarily through the reconstruction of the catchment-scale hydrological cycle and the coordinated regulation of surface and groundwater flow, whereas landscape configuration regulates hydrological fluxes across multiple scales.

Fig. 4 Heatmap of the LPHP interactions. The node sizes reveal the number of occurrences of LPHP interaction indices and the dashed lines show their connections.



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3.2.3 Multi-Scale Interaction

At multiple temporal and spatial scales, landscape composition and configuration interact with hydrological processes via differentiated paths (Fig. 5), underscoring the importance of landscape structures in shaping hydrological dynamics. Runoff correlates with multiple landscape pattern indices, among which the associations with agricultural land and landscape pattern index were more significant. At the short-term local scale, increased fragmentation of wetland patches directly leads to higher runoff and sediment transport. Meanwhile, the expansion of agricultural land results in the pulsed release of surface runoff through the changes in the connectivity of canal systems. At the long-term regional scale, the increased spatial continuity of vegetation coverage (e.g., forests, grasslands) restructures the water cycle through interception, evaporation, and infiltration recharge. Therefore, landscape composition changes contribute to the accumulation of groundwater runoff over interannual temporal scales. In contrast, changes in landscape configuration have a more

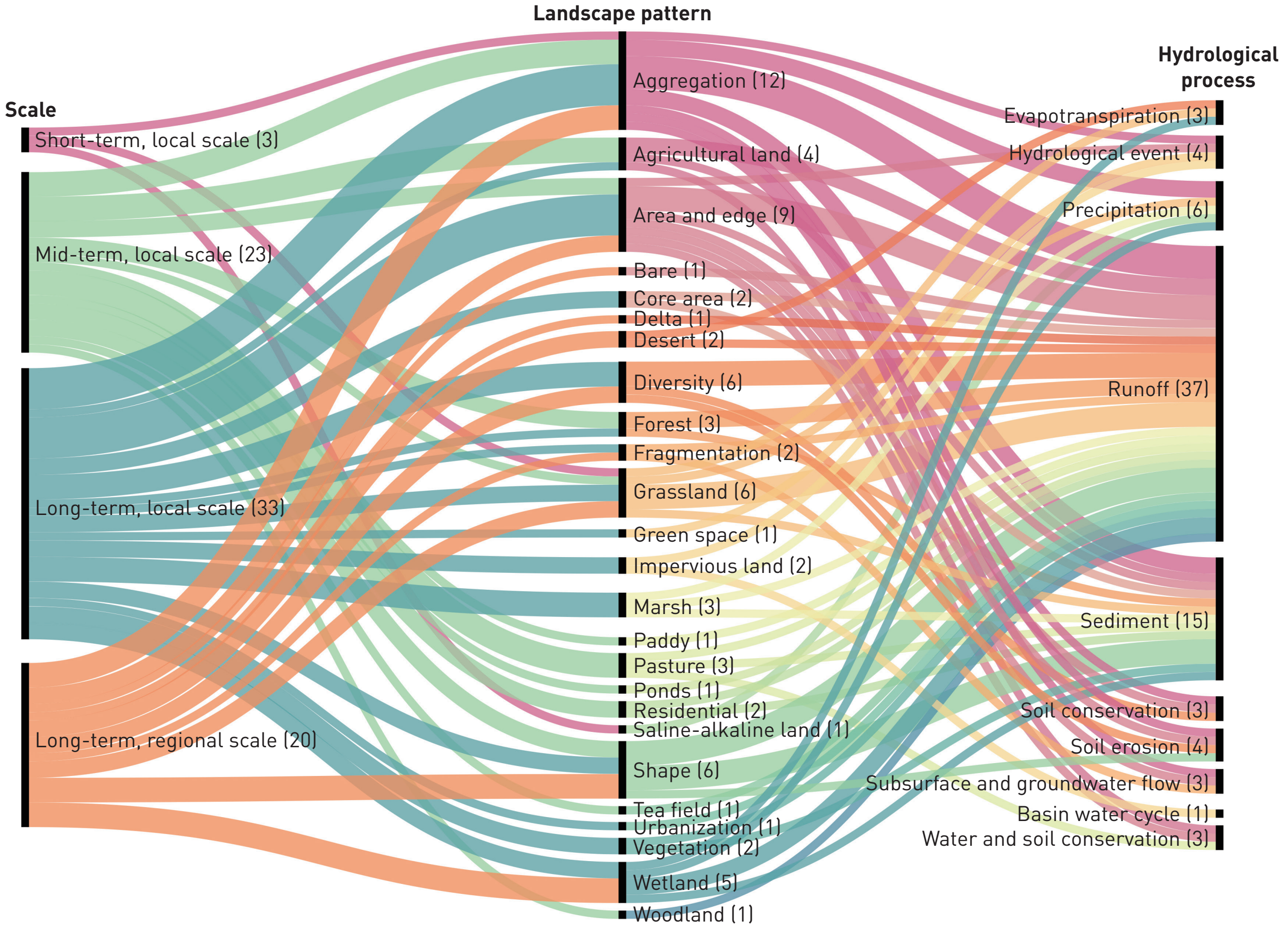

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Fig. 5 Sankey diagram of LPHP interaction indices (the length of the black vertical lines indicates the occurrence number).

pronounced effect on the instantaneous response to surface runoff during heavy rainfall events. These LPHP interactions, characterized by temporal and spatial variability, collectively influence water cycle and runoff dynamics, highlighting the impact of multiscale changes on both landscape composition and configuration in regulating hydrological processes.

Significant differences have been observed in correlations of identical indices, showing strong context-dependent regulation (Fig. 6). Changes in the composition of desert, delta, impervious land, wetland, and green space are positively correlated with runoff, sediment, and precipitation. In contrast, wetland and green space patches formed a dynamically connected network with hydrological processes through their interception and infiltration functions. Agricultural and forest lands exhibit typical bidirectional effects on runoff and sediment. While the expansion of agricultural patches generally exacerbates runoff and sediment load in highly vegetated areas, it negatively correlated with canopy interception and the soil-fixing effect of forest root systems. Indices characterizing landscape fragmentation are positively associated with runoff, whereas the largest patch size and Shannon's evenness are negatively correlated with soil erosion. Shannon's diversity, Shannon's evenness, and the splitting indices all exhibit positive correlations with runoff.

Furthermore, heterogeneity indices (i.e., patch density, contagion) and diversity indices (i.e., Shannon's diversity, Shannon's evenness) showed significant threshold fluctuations in their correlations with hydrological processes. These threshold intervals are concentrated in transition zones where abrupt landscape changes occur. Such bidirectional interactions indicate that landscape spatial heterogeneity modulates hydrological processes through mutual influences, generating hierarchical regulation shaped by multi-factor synergies and threshold-dependent feedbacks. Therefore, this review tentatively concludes that LPHP interactions are intensified by landscape fragmentation but weakened by spatial continuity. This reflects how landscape configuration governs the strength and pathways of LPHP interactions through the dynamic interplay between fragmentation and connectivity.

The expansion of desert and impervious surfaces intensifies runoff by altering surface energy exchanges and increases the

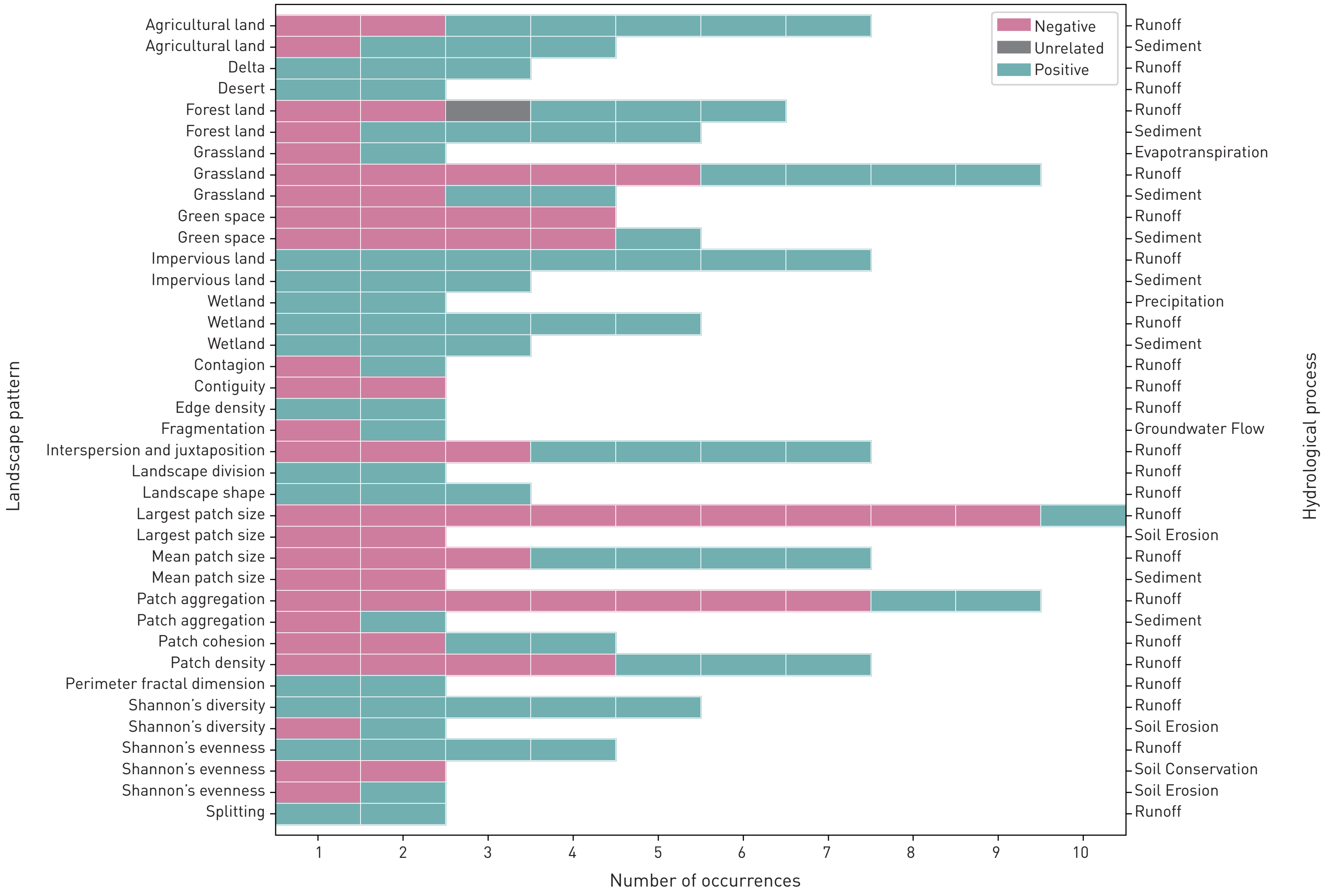

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Fig. 6 Correlations of LPHP indices.

water loss rate. In contrast, natural vegetation and large continuous patches act as biophysical barriers that generate hydrological resistance. Together, these influences establish multiple stable states between landscape patterns and hydrological processes, mediated by alternating enhancement and inhibition effects along spatial heterogeneity gradients.

3.3 Key Patterns of LPHP Interactions

Existing research has revealed two core LPHP interaction paths (Fig. 7) that illustrate the mutual feedback between landscape and hydrology. Understanding these bidirectional interactions is crucial for uncovering the mechanisms that sustain landscape–hydrological equilibrium.

Landscape composition and configuration directly influence hydrological systems by altering key processes such as infiltration, runoff, flooding, and sediment transport[7]. Natural landscape composition (e.g., agricultural land, forest land, wetland) promotes hydrological balance by enhancing infiltration and reducing sediment through large continuous patches that support a percolation-dominated flow pattern. However, intensive human activities may alter catchment structure, leading to excessive runoff and triggering flooding and erosion[26]. This contrast underscores the role of landscape configuration's topological structure as a key determinant of hydrological processes. Indices such as patch cohesion and fractal dimension have been proved to be correlated with hydrological variables, indicating the role of landscape configuration in shaping hydrological processes[27]. Large forest patches can reduce runoff velocity and soil erosion by maintaining vertical soil connectivity, thereby improving soil health[28]. Importantly, these indices do not function as unidirectional control variables. When the annual runoff depth in the catchment exceeds a certain threshold, patch cohesion declines nonlinearly, while the perimeter fractal dimension increases. Concurrently, hydraulic erosion increases

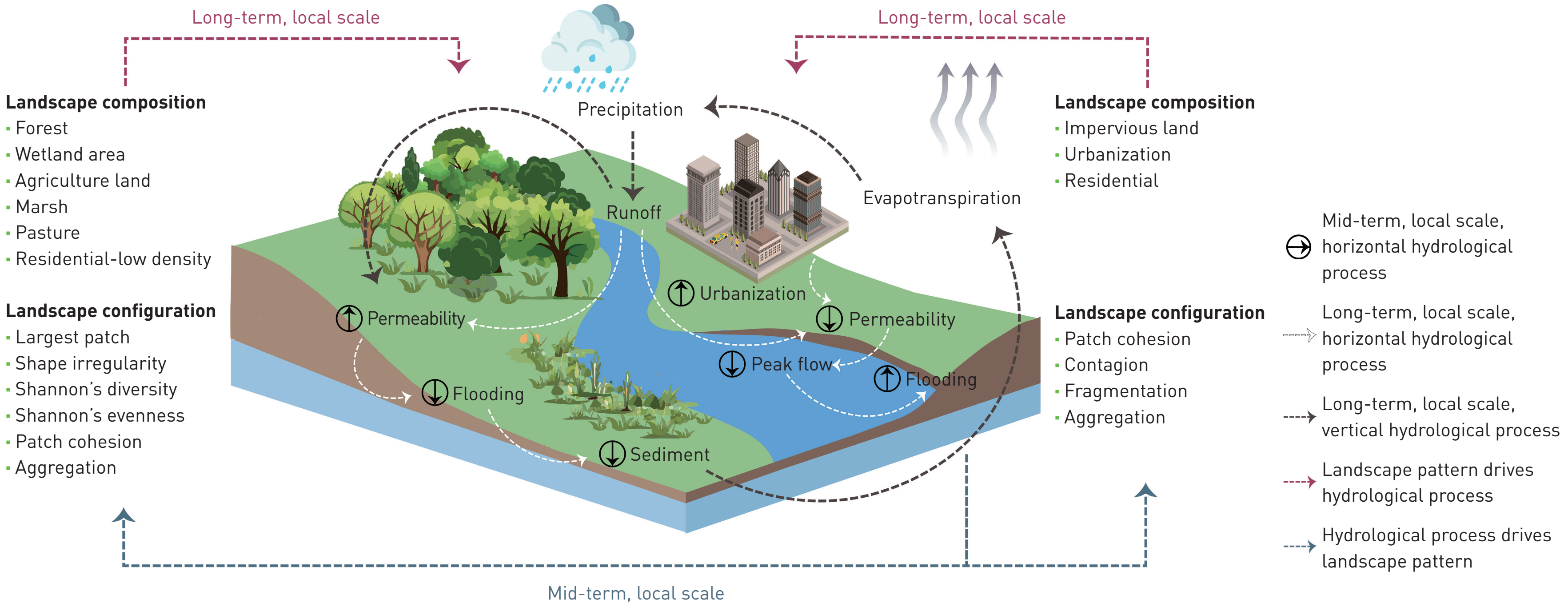

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Fig. 7 The key patterns of LPHP interactions.

entropy along landscape edges, forming negative feedback loops including runoff overload, structural instability, and progressively intensify erosion.

Hydrological processes also exert a profound influence on landscape patterns. For example, periodic floods can expand wetland patch boundaries and enhance landscape connectivity[29]. In contrast, sediment deposition in alluvial fans significantly increases the fractal dimension of adjacent agricultural patches, thereby reshaping the landscape structure[30]. These interactions underscore the dynamic nature of landscape–hydrology feedback[7]. Moreover, LPHP interactions exhibit time-lag effects. Variations in runoff typically lag behind changes in landscape configuration[31], while the effect of sediment on patch cohesion follows a negative feedback loop[32]. These findings imply that progressive landscape restructuring driven by hydrology should be incorporated into the temporal framework of LPHP interactions, which refers to the interplay among the continuum permeability dominance, the fragmentation of connected landscape patches, and the influence on the complex network of multiple hydrological processes.

Altogether, the bidirectional feedback between landscape and hydrology not only reinforces their interdependency but also underlines the need for considering both landscape composition and configuration, along with the time-lag effects, in hydrological models.

4 Discussion

This review illustrates the global geographical distribution, spatiotemporal scales, intrinsic interconnections, and key patterns of LPHP interactions. These interactions form a continuous, closed-loop chain of a "pattern–process–feedback–restructuring" cycle. Therefore, modeling the interactions can help identify key feedback paths and mechanisms within the systems, while also providing new perspectives for understanding the expression of these couplings at different temporal and spatial scales.

4.1 Dual-Path Driving Model

Based on the LPHP interactions, this study summarizes management strategies via differentiated pathways. Given that landscape patterns can drive hydrological changes, natural areas should prioritize the protection and optimization of highly cohesive and aggregated landscape configurations to maintain hydrological stability[9]. In urban areas, landscape fragmentation should be mitigated[33], and the construction of green infrastructure should be promoted to strengthen hydrological resilience[34–36]. Additionally, LPHP feedback mechanisms exhibit significant spatiotemporal lag effects[12,37], underscoring the need to account for historical conditions and their impacts into management decision-making to ensure long-term effectiveness across scales.

Several international examples underscore the relevance of these findings. In the Netherlands, the “Room for the River Program” demonstrated how hydrological risks (e.g., flooding) can drive landscape restructuring through adaptive spatial planning[38], illustrating the two-way feedback between water and land emphasized in our framework. In the Amazon Basin, deforestation has reduced evapotranspiration and increased runoff, disrupting regional hydrological cycles and exemplifying composition-driven hydrological transformation[39–41]. Australia’s Murray–Darling Basin showed how intensive irrigation and land conversion cause wetland desiccation and salinization, triggering landscape-level feedbacks[42]. Similarly, China’s Loess Plateau restoration projects showed how vegetative patch cohesion can reduce runoff and sedimentation over decades[43]. In the Arctic, permafrost thaw has reshaped landscape connectivity and water flow[44–46]. These cases confirm that LPHP interactions are not only ecological processes but are also embedded within governance and planning frameworks. Thus, effective water-landscape management requires the integration ecological insights with institutional design and adaptive planning mechanisms[47].

4.2 Spatiotemporal Scale Sensitivity and Planning Application

Driven by spatiotemporal heterogeneity, LPHP interactions vary significantly across scales. At the long-term local scale, landscape composition such as forest land dominates hydrological regulation through prolonged cumulative effects[18]; at the mid-term local scale, changes in landscape configuration would influence the intensity of feedback[48]; whereas at the short-term scale, configuration exerts more immediate but less persistent effects[43,49–50]. The presence of temporal lags in these responses highlights the need for monitoring strategies spanning multiple decades[37,51].

These findings have practical planning implications. In urban areas, reducing landscape fragmentation with green–blue infrastructure can buffer against runoff surges[35–36]. In agricultural areas, maintaining patch integrity and vegetative cover helps stabilize erosion and enhance water retention[52]. In fragile ecological areas, restoring hydrological corridors and minimizing artificial surfaces can enhance system resilience. Embedding these spatial principles into zoning and planning can support adaptive and scalable land-water systems[47].

4.3 Future Direction

To advance the understanding and application of LPHP interactions, future research should prioritize the following aspects. First, it is essential to conduct global-scale cross-climate zone validation. Most existing studies are concentrated in temperate zones, leaving tropical and cold zones such as the Amazon Basin, Arctic tundra, and Southeast Asia significantly underrepresented. These regions offer unique climatic and ecological contexts that could deepen insights into LPHP variability[13,53–54]. Expanding long-term monitoring networks, improving remote sensing capabilities, and enhancing data sharing across climate zones will be critical[40,54].

Second, multi-scale integrated planning within catchment units should be strengthened. Research should focus on capturing LPHP interactions across scales within the same geographical region to identify critical thresholds, tipping points, and cross-scale feedback chains[55]. Spatial strategies such as the patch–corridor–matrix model and nested spatial interventions (e.g., retention basins in cities, buffer strips in farmland, wetland corridors in peri-urban zones) can help address landscape fragmentation and hydrological instability. Future planning frameworks should include scale-sensitive design, dynamic feedback monitoring, and adaptive policy instruments that respond to changing LPHP interactions.

4.4 Limitations

Despite the comprehensive scope of this systematic review, several limitations should be acknowledged. First, the analysis was restricted to English-language peer-reviewed literature, which may have excluded relevant findings published in other languages or gray literature sources. Second, although the study attempted a global synthesis, there is a geographical bias underlying in the dataset, over-representing temperate regions while underrepresenting tropical and cold zones[13,54]. Third, while the dual-path model has been informed by empirical evidence, it remains a conceptual framework that requires further quantitative validation through modeling, longitudinal field studies, and integrative landscape-hydrology simulations. Finally, the exclusion of studies based solely on future scenario modeling may limit the anticipatory relevance of the findings for climate adaptation and future planning needs.

5 Conclusions

Based on a systematic review and multi-scale analysis of global LPHP interactions, this study proposes a dual-path driving model that revealed the spatiotemporal heterogeneous effects of landscape composition and configuration on hydrological processes. Case studies from diverse global regions—including the Netherlands, Brazil, Australia, China, and Arctic permafrost zones—demonstrate how LPHP interactions unfold under different climatic and geographical distribution. At the macro-scale, landscape composition governs long-term hydrological regulation; at the meso-scale, configuration is more sensitive to hydrological feedback; and at the micro-scale, effects are immediate but transient. These interactions also show significant time-lagged responses, emphasizing the need for long-term, adaptive strategies. To effectively integrate the LPHP model into policy and design, planning must address spatiotemporal thresholds, lag effects, and feedback structures. This calls for interdisciplinary integration across landscape ecology, hydrology, and governance, supported by region-specific monitoring and planning tools. By incorporating LPHP feedback mechanisms into land and water management, we can design more resilient landscapes in the face of hydrological extremes and global environmental changes.

ELECTRONIC SUPPLEMENTARY MATERIAL

Supplementary material is available in the online version of this article at https://doi.org/10.15302/J-LAF-0-020044.

Competing interests | The authors declare that they have no competing interests.

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景观格局和水文过程指标间的相互作用：系统性文献综述

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摘要

景观格局和水文过程（LPHP）具有复杂的相互作用，其耦合机制在多时空尺度上呈现差异，且目前对这些相互作用缺乏深入了解。本研究系统回顾了198项实证研究，以探讨LPHP的相互作用。结果表明：1）全球LPHP研究主要集中在温带地区，针对热带和寒冷地区的研究不足；2）LPHP的相互作用呈现显著的时空分异，多数研究集中于长期（包括局地和区域）尺度，其中农业用地扩张与地表径流间的相互作用是关键点。本研究提出了景观格局驱动水文过程和水文过程重塑景观格局的双路径驱动模型，阐明了在自然地区应保护和优化具有高凝聚度和聚集度的景观格局，而在城市地区应降低景观破碎度并加强绿色基础设施建设，以提升水文韧性。此外，土壤侵蚀和洪水不仅会改变景观组成，还可能引发景观配置的动态变化，形成在局地尺度上尤为明显的反馈回路。识别这些关键驱动路径，有助于深化对人类–自然耦合系统的理解，并为预测和应对未来变化与挑战提供更可靠的依据。

关键词

多尺度；时空尺度；景观–水文相互作用；景观格局；水文过程；指标；水文韧性

文章亮点

- 景观格局–水文过程研究集中于温带地区，热带和寒冷地区不足
- 景观格局与水文过程存在双向反馈循环
- 景观组成驱动长期水文调节，景观配置影响短期反馈
- 空间异质性对水文过程产生非线性影响，且存在跨尺度反馈

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