Advances in Research on Eco-hydrological Processes in the Loess Plateau: Postprint

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Abstract

Taking hydrological processes in the Loess Plateau as the main thread and addressing characteristics such as water resource scarcity, uneven distribution, complexity, and non-stationarity, this study reviews the current status and research progress of hydrological processes in the region, including water resource distribution, water balance, and hydrological cycling; integrates eco-hydrological scale effects to synthesize and summarize eco-hydrological processes across scales from soil, microorganisms, and plant canopy to slope, watershed, and landscape; proposes that future research should, in light of the spatiotemporal heterogeneity of eco-hydrological processes in this region, employ multidisciplinary cross-integration approaches to strengthen integrated and networked studies of macroscopic and microscopic processes; advocates comprehensive observation and simulation methods encompassing multiple scales, elements, and spatiotemporal dimensions to quantify water carrying capacity and ecological thresholds in key ecological functional zones; seeks to reveal water transfer and distribution characteristics across different spatiotemporal scales from both ecological and hydrological perspectives; and thereby provides a theoretical foundation for macroscopic regulation and optimal allocation strategies for water resources in the Loess Plateau.

Full Text

Preamble

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Abstract

Focusing on hydrological processes in the Loess Plateau, this review examines the current status and research progress of water resources distribution, water balance, and hydrological cycling, addressing issues of water scarcity, uneven distribution, complexity, and non-stationarity. Integrating scale effects of ecohydrology, we synthesize findings across watershed and landscape scales. Given the spatiotemporal heterogeneity of ecohydrological processes in this region, future research should employ multidisciplinary integration, strengthen coupling between macro- and micro-processes through networked studies, and utilize multi-scale, multi-factor, and multi-temporal-spatial comprehensive observation and simulation approaches. We propose that future efforts must: (i) quantify water carrying capacity thresholds and ecological thresholds in key functional zones; (ii) reveal water transfer and distribution characteristics across different spatiotemporal scales from ecological and hydrological perspectives; and (iii) provide theoretical foundations for macro-level water resource regulation and optimal allocation patterns in the Loess Plateau.

Keywords: ecohydrological processes; scale effect; Loess Plateau

Water is the primary driver of material cycling and energy exchange among Earth' s spheres, playing a critical regulatory role in ecosystem service functions [1-2]. The hydrological cycle, particularly terrestrial water cycles, is highly sensitive to global change [3]. Evolution of terrestrial water cycles and their role in global change represent important foundations for global climate governance and addressing water crises, forming major research frontiers in international programs such as the International Geosphere-Biosphere Programme (IGBP) [4-5]. Under intensifying climate change and human activities, terrestrial hydrological processes and fluxes have undergone significant alterations, triggering a series of ecological and environmental effects [6]. Ecohydrology, an emerging interdisciplinary field, primarily investigates interactions between ecological and hydrological processes across spatiotemporal scales. Since its development, ecohydrology has demonstrated frontier superiority in understanding hydrological process mechanisms, driving forces, and model coupling, gaining widespread attention in practical applications [6-7]. Since its emergence in the 1990s, ecohydrology has played important roles in addressing scientific questions concerning processes and patterns [7]. The 2008 special issue on hydrological cycling in *Ecohydrology* journal strongly advanced the field [8-9]. International workshops by the International Association of Hydrological Sciences (IAHS) in 2013 and academic conferences by the Chinese National Committee for IAHS (CNC-IAHS) in 2016 particularly emphasized the significance of cross-disciplinary integration between ecology and hydrology [5].

Ecohydrological processes involve numerous atmospheric, biological, and other elements characterized by multi-directional feedbacks and dual influences from natural and human activities, exhibiting complex spatiotemporal heterogeneity and non-stationarity [10-11]. Since 2008, research has transitioned from separate to integrated approaches, with ecohydrological processes gradually shifting toward coupled pattern-process paradigms. Scale effects have become increasingly prominent. The Loess Plateau, one of the world' s most severely eroded regions, has been a focus of international research. Early studies primarily examined one-way coupling [3-5], but with disciplinary integration, the region' s ecohydrological processes have attracted increasing attention under coupled pattern-process and scale-effect frameworks. This review synthesizes current research from soil, watershed, and landscape perspectives, integrating scale effects to provide a comprehensive conceptual and theoretical understanding of vegetation-soil-microorganism interactions in hydrological processes, offering foundational references for macro-level water resource regulation and optimal allocation.

1. Key Scientific Questions

Ecohydrological processes in the Loess Plateau drive material cycling and energy exchange while playing crucial roles in ecosystem services [12]. Climate change and human-induced land-use changes significantly impact these processes and environmental evolution. The 2016 National Ecological Environment Change Survey Report (2000-2010) indicated that ecosystem quality and service functions have declined over the past decade [12,14]. Environmental quality assessments by the Chinese Academy of Sciences' Research Center for Eco-Environmental Sciences show that the Loess Plateau remains ecologically fragile, with prominent environmental issues including intensified artificialization and severe land degradation such as desertification [15-16]. Since implementing the Grain-for-Green Program, vegetation coverage has increased significantly, altering ecosystem processes, structure, and function [17]. These changes affect energy and material exchange across the biosphere [18-19].

Hydrological processes in the Loess Plateau are strongly influenced by precipitation patterns with high uncertainty and intermittency in timing, intensity, and duration, creating uneven and non-stationary hydrological characteristics [17,20]. Combined with unique topography and human activities, these processes exhibit distinct regional features [21]. While numerous studies have established relatively complete frameworks for Loess Plateau hydrology, scale effects have often been overlooked. Soil serves as the carrier for ecosystem life activities and the primary reaction site connecting biological, physical, and chemical processes [22-23]. Hydrological processes greatly influence and control plant metabolism and microbial activity through multi-interface network systems encompassing surface runoff and transformations between free and bound water, with coupling and feedback mechanisms exhibiting spatiotemporal scale effects [16-17]. Investigating ecohydrological processes from soil, vegetation, and microbial perspectives is key to understanding the Loess Plateau' s water cycle.

[Figure 1: see original paper] The importance of hydrological processes in the Loess Plateau (China map from Ouyang et al. [12]; Loess Plateau map from Feng et al. [13])

Key scientific questions include: (1) How do vegetation restoration processes affect precipitation and evaporation? (2) How do different interfaces influence transpiration and surface runoff to affect ecosystem water balance? (3) How does vegetation restoration impact slope and watershed hydrological processes? (4) How can we balance vegetation restoration with water carrying capacity? (5) How do soil water balance and groundwater recharge interact? (6) How do precipitation effectiveness and evapotranspiration contribute to hydrological processes? (7) How do microbial communities feedback and regulate water cycling? (8) What microbial ecological models should be developed for the future?

1. Water Balance of the Loess Plateau

Soil hydrological processes include evapotranspiration, infiltration, and percolation, which collectively determine soil water balance [22-23]. The deep soil layers of the Loess Plateau can retain most infiltrated water, significantly reducing deep percolation. With scarce precipitation and no deep groundwater recharge, precipitation and evapotranspiration become the most important factors affecting water balance [23]. Large-scale ecological restoration has invested substantial resources to improve water utilization efficiency and establish protective forests. In the loess hilly-gully region of northern Shaanxi, the sum of canopy interception, surface runoff, and evapotranspiration in *Robinia pseudoacacia* forests far exceeds rainfall, often creating soil water deficits and moisture stress [27].

Huang et al. [3] studied relationships between hydrological processes and groundwater recharge in the Loess Plateau, finding that: (1) groundwater recharge occurs primarily during specific periods; (2) water movement rates in loess soils are 0.2-0.3 m/a, requiring decades to reach the water table; and (3) shrubs and other vegetation significantly reduce infiltration. Liu et al. [28] studied water balance in artificial grasslands in the Weibei dry plateau, finding that *Medicago sativa* consumes deep soil moisture through high evapotranspiration, easily forming dry soil layers. In the western Shanxi loess residual plateau, evapotranspiration from artificial coniferous forests exceeds precipitation input, causing water stress, while shrubs like *Ostryopsis davidiana* and *Hippophae rhamnoides* show less stress [29].

[Figure 2: see original paper] Hydrological processes at different scales in the Loess Plateau

During the growing season in loess hilly regions, transpiration accounts for 76.1% of rainfall. Soil water storage has both inputs (precipitation, canopy interception, infiltration, minor condensation and groundwater recharge) and outputs (evapotranspiration, surface runoff, deep percolation), with the difference reflecting dynamic changes in soil water storage [22-23]. Due to deep groundwater, atmospheric precipitation is the main income source. However, expenditure often exceeds income, with shallow and effective soil water reservoirs experiencing severe deficits [31]. The thick loess layer provides large deep reservoir capacity, but dry soil layers can block vertical water exchange [32], causing vegetation to over-consume water early in the growing season and rely on effective storage later. This leads to vegetation degradation or death due to water shortage, creating ecosystem degradation and uneven water distribution patterns [33-35], despite the soil reservoir’ s regulatory function.

2. Vegetation Regulation of Ecohydrological Processes

Understanding vegetation-water relationships began with Walter and Stadelmann’ s [36] water partitioning theory, which suggested small precipitation events replenish shallow reservoirs while large events recharge deep soil reservoirs. Shallow-rooted herbs primarily use shallow soil water, while deep-rooted shrubs and trees utilize deep reservoirs through hydraulic lift—where water moves upward through root systems driven by water potential differences, effectively transferring deep water to surface layers [37]. However, research on water sources and transfer mechanisms remains inconclusive. Brooks et al. [38] found that plant-utilized water differs from directly infiltrated water, challenging traditional soil water movement concepts. Ryel et al. [39] proposed that soil water comprises both plant-available reservoirs and surface infiltration pools, with shallow layers for plant use and deep layers maintaining soil water storage.

Chinese researchers have made substantial progress in soil water heterogeneity, soil-plant water relations, and water carrying capacity. Fu et al. [40] investigated soil moisture spatial variability across plot to regional scales, finding that spatiotemporal heterogeneity in soil physicochemical properties causes scale-dependent mechanisms. Kang and Kang [41] demonstrated root interface effects on single-root water uptake in winter wheat. Shao et al. [42] developed root water uptake models, while Kang et al. [43] established winter wheat models based on root depth, density, and soil moisture data. Xia and Shao [44] coupled ecohydrological and biogeochemical cycles to model soil water-vegetation carrying capacity in small watersheds. Recently, Fu’ s group [15] used land surface temperature triangles to characterize vegetation drought, revealing soil moisture spatiotemporal patterns and identifying areas with severe moisture decline, particularly at forest-grassland transition zones, providing methods for large-scale vegetation restoration assessment. However, most studies focus on single functional levels, with limited research on integrated water transfer coupling across levels and persistent regional and temporal lags.

3. Soil Microorganism Regulation of Ecohydrological Processes

Water provides essential conditions for soil microorganisms, promoting metabolic activity and driving nutrient cycling and hydrological processes

[45-46]. Microbial communities occupy different ecological niches, forming network systems through food webs. Water effects on microbial community structure and interactions can be additive, synergistic, or antagonistic [47]. Bi et al. [30] found synergistic effects of water on microbial carbon utilization in temperate grasslands, with rainfall increasing soil moisture and altering community structure while decreasing fungi:bacteria ratios [46]. However, some studies found no community composition changes with rainfall variation [48]. De Nobili et al. [49] summarized moisture effects in two phases: (1) increased moisture enhances microbial metabolism up to saturation; (2) further moisture increase reduces soil porosity and oxygen, inhibiting aerobic microbes.

Soil microbial responses to moisture are complex and sensitive. Drought stress alters aerobic:anaerobic bacteria ratios, while waterlogging inhibits fungal metabolism. Microorganisms exhibit plasticity to drought and moisture-temperature fluctuations [50]. Despite decreasing bacterial abundance with moisture gradients in loess soils, diversity remains independent of moisture, indicating buffering capacity [50]. Fungal community structure shows significant moisture responses, while actinomycetes vary seasonally and annually [51], demonstrating that not all communities are equally sensitive. These varied response mechanisms highlight microorganisms' important roles in hydrological processes.

[Figure 3: see original paper] Hydrological processes dominated by microorganisms

At the soil colloid scale, microbial activity alters surface properties by enhancing hydrophobicity and changing porosity, affecting water film thickness and microbial transport. Microbial-induced pore clogging and hydrophobicity changes influence microbial distribution patterns and landscapes, subsequently affecting soil structure and hydrology. Microorganisms thus serve as critical links regulating water distribution and transfer, bridging physical and biological processes —an important future research direction.

4. Canopy Regulation of Ecohydrological Processes

Vegetation canopy is a critical link in ecohydrological processes, altering hydrology through interception, throughfall, and stemflow while being influenced by hydrology in population expansion, structure, and evolution [52-53]. Canopy-scale hydrology essentially redistributes precipitation—some is intercepted while the remainder becomes throughfall or surface runoff [54]. Intercepted water evaporates back to the atmosphere, while root water uptake through transpiration releases vapor, forming soil-plant-atmosphere water transfer systems. Canopy cover reduces bare soil evaporation through litter layer interception and canopy storage [55-56].

Precipitation characteristics significantly influence these processes: large, frequent, long-duration events versus small, sporadic, short events affect throughfall and runoff generation [57]. Canopy interception correlates positively with precipitation but varies greatly with canopy structure, functional type, and precipitation characteristics [58-59]. Tall vegetation generally intercepts more precipitation [60]. Studies show North American forest interception rates of 10-35%, European beech up to 34.34%, and Chinese forest ecosystems ranging 11.40-34.34%, with deciduous broadleaf forests having lower rates than subtropical evergreen coniferous forests [61-62]. In the Loess Plateau, shrub and herb interception rates vary significantly, with Liupanshan shrubs intercepting 1.8-12.8% [63]. Wang et al. [65] studied hydrological processes along precipitation gradients from north to south in loess hilly regions, finding decreasing litter storage and water absorption rates, demonstrating clear zonation. While aboveground processes are well-studied, root-soil interface processes remain poorly understood due to observation difficulties, requiring integrated aboveground-belowground research.

5. Slope Regulation of Ecohydrological Processes

Slopes connect watersheds and patches as important landscape units. Slope-scale hydrological processes are influenced by precipitation, spatial heterogeneity, and human disturbance [66]. Vegetation reduces rainfall impact, decreases Darcy resistance and Manning roughness, and transforms flow regimes from laminar to transitional as discharge increases [67]. Infiltration, runoff generation, and evapotranspiration show strong scale effects and nonlinearity [68]. At patch scales, bare and vegetated patches create mosaic patterns affecting water storage, infiltration, and runoff differently—vegetation patches enhance infiltration while bare patches increase runoff [69]. At slope scales, runoff from patch mosaics is intercepted by vegetation, with some infiltrating to deep soil reservoirs and some generating overland flow [70-71].

Loess Plateau slope hydrology lacks in-depth analysis of runoff frequency and generation mechanisms, particularly regarding soil uniformity and water movement patterns. Soil uniformity is key to understanding slope processes, yet traditional models (Richards equation, Darcy law) assume homogeneous soil, causing deviations in understanding flow velocity and sediment yield. Future research should use physical models and field observations to identify how vegetation patches and types co-regulate hydrology, fitting spatial network structure equations to provide theoretical foundations for slope-scale models.

6. Watershed Regulation of Ecohydrological Processes

Watershed-centered hydrological processes represent an international research frontier, with comprehensive observation and modeling programs worldwide. In the Loess Plateau, watersheds are fundamental hydrological units complexly influenced by land use and human disturbance [72]. Early research focused on land use impacts on floods and runoff, using field observations and models requiring further validation [73]. Under global change and large-scale human activities, water resources are decreasing while vegetation restoration regulates water balance, reduces peak flows, and decreases runoff [29].

Zhou [74] developed new methods measuring watershed outlet velocity to determine discharge and established small watershed rainfall-runoff models. Li [75] applied improved ecohydrological models to the Lüergou watershed, showing seasonal precipitation and runoff patterns with decreasing trends, while climate fluctuations increasingly influence runoff relative to land use changes. Recent studies indicate severe impacts from human activities (check-dam construction) and increasing water demand, creating conflicts between water balance and carrying capacity [16]. Fu' s group coupled observations and modeling to reveal water resource thresholds, proposing that watershed-scale water yield and sediment management should shift from small watershed control to whole-basin coordination [13].

7. Landscape Pattern Regulation of Ecohydrological Processes

Loess Plateau hydrological processes are tightly linked with landscape patterns, forming a nexus between landscape ecology and ecohydrology [29,76-78]. Landscape patterns affect hydrology through vegetation distribution and land-use changes, while hydrology drives landscape dynamics through erosion and microtopography [79]. Hydrological models have analyzed these impacts: Gerner et al. [80] showed Amazon land-use changes altered surface hydrology and indirectly affected surrounding ecosystems; Giertz et al. [81] built climate-responsive hydrological models; Savary et al. [82] identified runoff and erosion as key hydrological components, with forest cycles being more complex than agricultural ones.

Landscape metrics have been applied to hydrological studies. van Nieuwenhuyse and Wyseure [84] developed virtual landscape-hydrology network models. Li and Zhou [85] coupled landscape pattern analysis with hydrological processes in the Yanhe watershed, finding landscape indices contributed little to runoff with regional variation [86]. Yang et al. [87] demonstrated that forest landscape patterns in the Qilian Mountains created higher hydrological complexity than grasslands or shrubs. Xu et al. [88] built coupled land-use-ecohydrology models for crop-pasture zones, while Suo et al. [89] analyzed forest fragmentation impacts on hydrological regulation in the Sanshui River basin. Fu et al. [73] used scaling methods to establish soil erosion evaluation systems, and Chen et al. [90] introduced landscape spatial load contrast indices into hydrological modeling. Future research must identify appropriate landscape indices, integrate them into hydrological models, and analyze coupling mechanisms across scales.

3. Existing Problems

Large-scale vegetation restoration in the Loess Plateau has altered water and vegetation patterns, with increased organic matter input significantly improving soil quality and nutrients, fundamentally changing water carrying capacity.

However, environmental variability and technical limitations create challenges. The region' s hydrological processes exhibit unevenness and non-stationarity, requiring scale effect integration for proper understanding. Ecosystem complexity and precipitation variability (with amplified interference from decreasing rainfall) combined with regional incomparability mean that results from one watershed may not apply elsewhere, sometimes yielding opposite conclusions. Eliminating geographic and climatic influences to complete scale transformation from micro to macro processes remains a critical challenge.

4. Outlook

While ecological restoration has achieved success, multi-scale ecohydrological process research remains in early stages. Microorganisms are key regulators linking hydrological and biological processes, making microbial perspectives crucial for understanding the Loess Plateau water cycle. Future research should integrate:

1. **Mathematical-physical network models** of ecological-hydrological interactions as disciplinary foundations, with scale transformation as a key challenge. Coupling interface and node processes will improve prediction accuracy and sensitivity, revealing hydrological mechanisms.
2. **Multi-scale, multi-factor coupling frameworks** that incorporate scale effects, identify regulatory mechanisms across scales, and complete transformations from soil to landscape scales.
3. **Watershed-scale observations and modeling** as fundamental units, with long-term monitoring of key interface processes, development of watershed-specific models, and upscaling to the entire Loess Plateau.
4. **Advanced technologies** including water stable isotope tracing and probe techniques to reveal water transfer patterns across interfaces from mass balance perspectives, quantifying regional water thresholds and carrying capacities.
5. **Integrated networking studies** using multi-scale observation and simulation to reveal ecohydrological processes from micro to macro scales, supported by precise experimental design, long-term observations, and interdisciplinary integration.

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