Advances in Quantifying Spatial Structure of Watershed Ecosystems and New Indicator Systems

Authors: Wang Zhenhong, Cai Qinghua, Zhao Bin, Xu Yaoyang, Tang Tao, Wang Zhenhong

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Abstract

Watersheds and watershed ecology, as the carriers and theoretical underpinnings of the mountain-water-forest-farmland-lake-grassland life community, are playing an increasingly important role in national ecological civilization construction. Research on the interconnections and progression of watershed ecosystem spatial structure-process-function-mechanism-regulation constitutes the research paradigm of watershed ecology. However, watershed ecology has not established its own discipline-endogenous indicator system model framework for watershed ecosystem spatial structure that organically links various structural components of watershed ecosystems, terrestrial and aquatic systems, upstream and downstream areas, and relationships between terrestrial and aquatic organisms, causing watershed ecology research to be dispersed across freshwater ecology, terrestrial ecosystems, soil and water conservation, agricultural environmental science, hydraulic engineering, and other disciplines, without forming a core theory. This study analyzes the bottlenecks in watershed ecology development, reviews research methods and achievements regarding quantitative characteristics of watershed ecosystem spatial structure based on geography and landscape ecology, and examines the current research status of quantitative characteristics of watershed ecosystem spatial structure utilizing hierarchy theory and meta-ecosystem theory in watershed ecology. It constructs holistic indicators for quantitative characteristics of watershed ecosystem spatial structure, indicators for individual structural components, and indicators for relationships between structural components, providing a methodology for quantifying watershed ecosystem spatial structure and relationships between structural components.

Full Text

Preamble

Review on Quantitative Characteristics of Spatial Structure for Watershed Ecosystem and Corresponding New Index Systems

Wang Zhenhong[1], Cai Qinghua[2], Zhao Bin[3], Xu Yaoyang , Tang Tao[2]

Abstract

As the research scale and carrier for the life community of mountains, waters, forests, farmlands, lakes, and grasslands, watershed ecology is playing an increasingly important role in supporting national ecological civilization construction. The research paradigm of watershed ecology follows the framework of spatial structure-process-function-mechanism-regulation, among which the quantification of spatial structure and the construction of its index system constitute a critical pathway for quantitative research in watershed ecology. Although the index system for watershed ecosystem spatial structure involves multiple disciplines including freshwater ecology, terrestrial ecology, soil and water conservation, agricultural environmental science, and hydraulic engineering, an integrated quantitative framework for ecosystem spatial structure at the watershed scale has yet to be established. This study summarizes research methods and achievements from related disciplines concerning the quantitative characteristics of watershed ecosystem spatial structure, analyzes the challenges in quantifying ecosystem spatial structure at the watershed scale, and constructs a comprehensive index system for watershed ecosystem spatial structure based on hierarchical structure theory and meta-ecosystem theory. This new framework includes overall watershed indices, component indices, and inter-component relationship indices, providing novel methods for quantifying watershed spatial structure and relationships among structural components. This work holds significant scientific value for advancing coupled quantitative research and assessment applications of watershed ecology in the context of the integrated mountain-water-forest-farmland-lake-grassland life community.

Keywords: watershed ecology, watershed spatial structure index system, highland, inter-network zone, river network, mountain-water-forest-farmland-lake-grassland life community

Watershed ecology is a branch of ecology that takes watersheds as research objects, employing modern ecological theories and methods to investigate the structure and function of various components such as highlands, riparian zones, and water bodies, as well as the interactions among these components (Cai et al., 1998; Shang and Gao, 2001). Watershed ecology is closely related to lake (including natural lakes, reservoirs, and ponds) water environmental protection and management, river ecological health, small watershed ecological restoration, and comprehensive management, attracting widespread attention from ecology, environmental science, soil and water conservation, and hydraulic engineering disciplines (Deng et al., 1998; Ward, 1998; Yang, 2018). With the establishment of ecological civilization as a national strategy, particularly since the 19th Party Congress proposed that mountains, waters, forests, farmlands, lakes, and grasslands constitute a life community requiring integrated management, watersheds and watershed ecology have assumed increasingly important strategic roles as the carrier and theoretical foundation for this life community (Yang et al., 2004; Pan, 2019).

Over the past two decades, watershed ecologists with backgrounds in hydrobiology have conducted systematic research on the structure and function of plant, animal, and microbial communities in rivers and lakes, as well as their effects on water environmental quality and underlying mechanisms (Wang et al., 2017). Watershed ecologists from environmental science and chemistry backgrounds have systematically studied water quality changes, hydrochemistry, sediment geochemical cycles, and regulatory mechanisms in rivers and lakes (Yu et al., 2018). Scholars with backgrounds in vegetation ecology, soil and water conservation, and agricultural ecological environments have systematically investigated the regulatory effects and mechanisms of terrestrial plant community structure and function on soil erosion and non-point source pollution (Shang and Gao, 2001; Potter et al., 2004). Researchers from hydrology and hydraulic engineering backgrounds have systematically examined watershed water cycling processes and mechanisms, ecological water conservancy, environmental effects of hydraulic projects, regulatory mechanisms, and management (Chen and Ouyang, 2005; Yin et al., 2018).

Reviewing these research efforts, ecologists have identified a notable characteristic: watershed ecology research and achievements are scattered across different disciplines. There is limited understanding of the relationships and interactions among watershed structural components such as highlands, riparian zones, and water bodies. No endogenous quantitative index system for watershed ecosystem spatial structure exists to quantify watershed structure and relationships among components, which could integrate research from watershed ecologists of different disciplinary backgrounds and form the core theory of watershed ecology (Yan and Wang, 2001; Wang et al., 2012; Yang and Chen, 2016). However, landscape ecology, a sibling discipline, established its quantitative index system for characterizing landscape spatial structure (i.e., landscape pattern indices) early on, including metrics such as patch number, area, shape index, fragmentation, connectivity, proximity index, and diversity index (Forman, 1995; Fu et al., 2011). These landscape pattern indices enable ecologists to study the structure and relationships of matrix, patches, and corridors in landscapes, revealing landscape pattern characteristics (Rukiya et al., 2020). Moreover, based on these indices and combined with population, community, and ecosystem ecology research, relationships between landscape pattern indices and ecological processes/functions can be established to reveal mesoscale ecological functions and mechanisms, with applications in ecological planning (Zhao et al., 2010; Zhao et al., 2012). Consequently, landscape ecology has achieved considerable development. The quantitative index systems and theories for population, community, and ecosystem structure were established even earlier, though their structures are biological (except for abiotic components in ecosystems). Only landscape and larger-scale watershed structures are physical spatial structures.

Many ecologists have used landscape pattern indices to quantify watershed ecosystem spatial structure and link them with watershed ecological processes to reveal process mechanisms (Feng et al., 2010; Gong et al., 2014; Randhir and Tsvetkova, 2011; Rutledge and Chow-Fraser, 2019). However, watersheds have clear boundaries and consist of river networks, inter-network zones, and lakes (reservoirs and ponds) forming catchment areas. Within inter-network zones are collections of ecosystems (meta-ecosystems). Watershed ecological processes, driven by the water cycle, involve relationships between land and water, upstream and downstream, and aquatic and terrestrial organisms at scales much larger than landscapes (Wang et al., 2013; Yang and Chen, 2018). Therefore, watershed ecosystem spatial structure differs from landscapes without clear boundaries and requires different index systems for quantification (Price et al., 2011; Zhao, 2014). With such an index system, watershed ecosystem spatial structure can be well characterized, spatial relationships among structural components can be established, and connections between watershed land and water, aquatic and terrestrial organisms, and upstream and downstream can be developed, advancing the theory of quantitative characteristics of watershed ecosystem spatial structure. Furthermore, under the framework of watershed ecosystem spatial structure index systems, ecological research can be conducted on watershed population, community, ecosystem, and landscape scales regarding water environment, non-point source pollution, and soil erosion issues, revealing the impacts and mechanisms of watershed spatial structure on ecological processes, functions, and health, generating innovative knowledge to guide integrated planning, management, and governance of mountains, waters, forests, farmlands, lakes, and grasslands. Therefore, this study reviews existing research on watershed ecosystem spatial structure, analyzes existing problems, and proposes a new index system.

1. Research Status of Watershed Spatial Structure at Home and Abroad

1.1 Geomorphology-Based Watershed Ecosystem Spatial Structure

A watershed is a closed catchment unit on Earth’ s land surface. Within this objectively defined range, tectonic movements create original landforms, while water flow shaping processes interact with vegetation and human activities to form present-day watershed geomorphology. Geographers analyze watershed ecosystem structural composition from a geomorphological perspective. Based on geomorphological forms, watershed landforms consist of five basic types: mountains, plateaus, plains, hills, and basins. Mountains are further divided into low, medium, high, and extremely high mountains. Plateaus are classified by region and substrate characteristics, such as the Tibetan Plateau and Loess

Plateau. Plains and basins are generally categorized by formation mechanisms, such as alluvial plains, erosion plains, and structural plains; rift basins, graben basins, and foreland basins. Hills are often classified by height and steepness into high hills, low hills, steep hills, and gentle hills. Small watersheds, due to their limited area, often contain only one geomorphological type, while large watersheds may contain all five types. At local scales, watershed geomorphology is described using terms such as valleys, ridges, saddles, peaks, depressions, cliffs, sunny slopes, shady slopes, river valleys, gullies, terraces, deltas, alluvial fans, riverbanks, and riverbeds (Pennock et al., 1987; Lu, 1991).

Quantifying watershed geomorphological structure commonly employs indices such as elevation, slope, aspect, form density, topographic energy value, area size, and gully grade (Xu et al., 1998; Zhang et al., 2010; Price et al., 2011). Jin (1993) focused on quantitative characteristics of river network structure, analyzing relationships between river frequency, length, density, area, and river gradient across different orders, finding strong correlations among these indices. Wondzell et al. (1996) studied how topographic gradients in arid watersheds of the Chihuahuan Desert in North America caused variations in moisture and erosion environments, describing plant community responses and soil erosion regulation. Liu et al. (2015) selected 11 small and medium-sized watersheds in the Huai River basin, using watershed length, form factor, elongation ratio, circularity, watershed slope, horizontal curvature, slope curvature, river network fractal dimension, and area-elevation curve slope to characterize watershed structure and study its impact on runoff characteristics, finding that runoff coefficient was significantly positively and negatively correlated with watershed slope and slope curvature, respectively (Table 1). Some scholars have extracted watershed geomorphological parameters such as area, slope, aspect, geomorphological type, river network indices, and geological factor data based on remote sensing and GIS to quantify watershed structure and establish relationships with hydrological processes (Khanday and Javed, 2017). He et al. (2013) used digital orthophoto map (DOM) and digital elevation model (DEM) data, selecting geomorphological factors including terrain, humidity index, slope length factor, flow power index, aspect, plane curvature, and surface roughness to evaluate soil erosion sensitivity in small watersheds, finding that 96.4% of gullies occurred on sunny slope concave surfaces with large slope length, strong flow power, and low surface moisture. Price et al. (2011) studied the effects of drainage ditch density, colluvial area, topographic variation, and river network percentage on low-flow variations in 35 small watersheds in Georgia, USA.

In this field, traditional methods involve field surveys to delineate different geomorphological units, quantitative measurement of geomorphological characteristics using surveying techniques, and establishment of observation systems such as runoff plots, small catchments, and small watersheds to study relationships between surface material processes and geomorphological features (Hornberger et al., 1985; Fujimoto et al., 2011). However, the development trend in this field is to use remote sensing, GIS, and GPS technologies to extract watershed geomorphological data, quantify geomorphological structural characteristics, and discover watershed geomorphological patterns (Zhang et al., 2010). In terms of applications, combined with watershed hydrological processes and soil erosion, hydrological models and soil erosion models are used to predict the impacts of watershed geomorphological feature differences on surface material processes (Naik, 2012; Krishna et al., 2015).

1.2 Landscape Pattern-Based Watershed Ecosystem Spatial Structure

Landscape pattern refers to the combination of patches, corridors, and matrices of varying sizes, shapes, and arrangements, resulting from complex interactions among physical, biological, and social factors (Fu et al., 2001). Watersheds include various patches, corridors, and matrices at scales larger than landscapes, so watershed structure can be quantified using landscape pattern indices to understand the physical spatial mosaic, diversity, complexity, and dominance of watershed structure (Yen-Chu Weng, 2007). Watershed landscape pattern research includes landscape composition, heterogeneity, inter-patch relationships, pattern hierarchical structure, source-sink landscape patterns, pattern dynamics, and relationships between landscape pattern and function (Luck and Wu, 2002; Xu et al., 2006; Wang et al., 2014). Pattern and process constitute the research core, with landscape pattern indices being the primary method for quantitative analysis of watershed landscapes (Lu et al., 2001; Lee et al., 2009). As objectively defined hydrological response units, watersheds enable the establishment of relationships between landscape pattern and process through observations of outlet runoff, soil erosion, and non-point source pollutant export, with applications in watershed management. Therefore, landscape ecologists often select watersheds as one of the optimal units for landscape ecology research (Chen et al., 2006; Zhang et al., 2012; Kändler et al., 2017).

Specific research has focused on watershed landscape pattern dynamics and driving forces, and relationships between landscape pattern and water quality, runoff, sediment yield, ecosystem service value, and ecological function zoning. For example, Chen et al. (2010) used two-phase KONOS4 multispectral satellite imagery to study forest landscape patterns in the upper Yangtze River shelterbelt project area, including pure forests, mixed forests, bamboo forests, economic forests, cropland, transportation land, water bodies, and construction land, finding excessive pure forests and increased landscape fragmentation. Ren et al. (2017) analyzed landscape pattern dynamics and driving mechanisms in the Yi River basin from 1987-2003 using land cover data, meteorological data, and socioeconomic data, finding that socioeconomic development and population growth were the main drivers of conversion from cropland and unused land to construction land; rising temperatures and increased evapotranspiration were direct causes of water area reduction; and policy was the fundamental cause of changes in forest and grassland landscapes. Zhao et al. (2012) and Liu et al. (2019) used satellite imagery to study relationships between landscape pattern and water quality in the Danshui River basin in Guangdong Province and the Yangtze River basin, respectively, with the former directly observing water quality and the latter using InVEST modeling, finding that landscape composition, configuration, and dominant forest landscape area all affected watershed water quality. Lin (2014) and Sun et al. (2019) used four-phase remote sensing imagery (1995-2015) to quantify watershed landscape patterns, combined with multi-year field measurements to establish relationships between landscape pattern indices and runoff and sediment yield, finding that "source" landscape area continuously decreased while "sink" landscape area continuously increased. Fan et al. (2016) used GIS-based sub-watershed delineation to compare physical, chemical, and biological characteristics of sub-watersheds, dividing Dianchi Lake basin into three-level aquatic ecological function zones, providing a basis for watershed management.

Foreign research has also focused on these aspects. Yen-Chu Weng (2007) studied significant differences in land use from urban centers to peripheries in Dane County, Wisconsin, USA, indicating urbanization-driven landscape pattern changes. Korean research showed that highly dispersed land use types within watersheds led to water quality degradation in watershed wetlands (Lee et al., 2009). In the German-Czech-Polish triangle region, land use cluster analysis could indicate watershed water physicochemical indices, with dense residential areas reducing water quality (Kändler et al., 2017). Gonzales-Inca et al. (2015) used the Separated Land Use/Land Cover Information System to obtain agricultural land, forest land, construction land, water bodies, and other land areas in 16 Finnish watersheds, revealing watershed landscape patterns, observing 21-year water quality indices, and analyzing relationships between water quality and landscape pattern, finding that riparian forest was key to water quality improvement. Cuo et al. studied the effects of forest and roads on runoff in the Nam Mae Rim watershed in Thailand from 1989-2002, finding that deforestation increased annual runoff but had minimal impact on dry season runoff, while roads significantly affected runoff peaks.

1.3 Meta-Ecosystem-Based Watershed Spatial Structure

The meta-ecosystem concept was proposed by French scholars Loreau et al. (2003), referring to "a collection of ecosystems connected across ecosystem boundaries by material flow, energy flow, and organism flow." This concept extends meta-population and meta-community concepts and represents an important analytical approach for studying ecosystem spatial heterogeneity. Chinese scholar Lü (1998) previously proposed a similar concept, suggesting that watershed ecosystems are organic wholes composed of several or all ecosystem types such as mountains, glaciers, forests, grasslands, farmlands, deserts, and lakes connected by water systems, with coupling of material, energy, and information among subsystems. Li (2009) proposed that watershed ecosystems are connected systems of mountains-rivers-seas, where marine ecological processes such as tides and fish migration into rivers also affect rivers and terrestrial riparian zones, with watersheds integrating various patterns and processes. Recent research suggests that meta-ecosystems are suitable for describing and explaining the structure, processes, and functions of watershed ecosystems with specific physical spaces and close interactions among subdivided physical space regions (Jenerette and Lal, 2007; Grave et al., 2010; Yang and Chen, 2018).

Current research on how watershed meta-ecosystems are structured spatially includes three types: horizontal heterogeneous combination, vertical heterogeneous combination, and sympatric combination (Largaespada et al., 2012; Jäger and Diehl, 2014; Ryabov and Blasius, 2014). Horizontal heterogeneous combination refers to different local ecosystems distributed horizontally in watershed space, each with relatively clear boundaries, without requiring structural feature distinction in the vertical direction, but with material, energy, information, and organism flows among ecosystems, such as the physical spatial configuration and connections of forests, farmlands, villages, river networks, and lakes within watersheds. Vertical heterogeneous combination refers to different local ecosystems distributed vertically in space, each with relatively clear boundaries in the vertical direction, without requiring structural feature distinction in the horizontal direction, but also with various flows among ecosystems, such as ecosystems composed of soil animals and microorganisms, surface animals and microorganisms, and birds and insects living within tree canopy spaces in watershed forests. Sympatric combination refers to different local ecosystems overlapping in physical space, but with relatively independent processes overall, connected only through several specific ecosystem processes, such as natural-economic-social composite systems within a watershed where nature, economy, and society are different ecosystems within one physical space.

For quantifying meta-ecosystems, a six-dimensional phase space semi-quantitative method has been developed (Figure 1 [Figure 1: see original paper]) (Yang and Chen, 2018). The first dimension is openness (Mopen), x [0,1], where meta-ecosystems with material flow are open (value=1) and closed (value=0). The second dimension is the number of meta-ecosystems (Mnum), x [2,n], with a minimum of 2 ecosystems and maximum of n ecosystems. The third dimension is heterogeneity of local ecosystems within meta-ecosystems (Mtype), x [1,n], where value=1 indicates the same type of meta-ecosystem (e.g., a watershed composed of multiple grasslands). The fourth dimension is directionality of ecological processes within meta-ecosystems, x [1,2], where x=1 indicates unidirectional material flow from one local ecosystem to another, and x>1 indicates some form of reverse flow (bidirectional). The fifth dimension is hierarchy of meta-ecosystems, x [2,n], typically x=2 indicating a two-level structure of local ecosystem-ecosystem elements and meta-ecosystem-local ecosystem, called "two-level" ; if x>2 indicating finer internal structures within ecosystem elements, called "multi-level." The sixth dimension is meta-ecosystem complexity, Lcomplex [a,b], where a and b represent two boundaries of ecosystem complexity preset here. Meta-ecosystem complexity is composed of six factors: openness, number, homogeneity, internal process directionality, hierarchy, and ecosystem complexity, where complexity is nested—it is one of the six dimensions while simultaneously reflecting the status of the six dimensions.

1.4 Hierarchical Structure-Based Watershed Ecosystem Spatial Structure

In 1997, Cai et al., from a freshwater ecologist perspective, proposed watershed ecology as a science that uses watersheds as units and hierarchical structure theory to study material, energy, and information transfer patterns among highlands, riparian zones, and water bodies within watersheds, aiming to overcome the limitation of traditional freshwater ecology focusing only on water bodies. This concept emphasizes three aspects: first, watersheds are composed of highlands, riparian zones, and water bodies as three horizontally parallel components; second, hierarchical structure theory is used for research, indicating that watersheds have different scale levels from macro to micro (Liu et al., 2012). Hierarchical structure includes structural and functional hierarchies, where lower-level structures form the basis for higher-level structures, and higher-level structures constrain lower-level structures (Deng et al., 1998). From a disciplinary development perspective, there is also a trend of integration among research scopes at different scales, such as development from aquatic ecology to watershed ecology (small to large) and from landscape ecology to landscape genetics (large to small) (Wu and Cai, 1998). Third, the study focuses on material, energy, and information transfer patterns among the three structural components, which belong to ecosystem function categories and inevitably involve abiotic environments, producers, consumers, and decomposers. Therefore, watershed ecology is ecosystem ecology with clear boundaries (watershed divides), and its research methods can be applied to watershed ecology (Shang and Gao, 2001).

In practical research, Wang et al. (2007) used hierarchical structure theory to study topological relationships of gully hierarchical structure sequences in small Loess Plateau watersheds, finding that at the small watershed scale on the Loess Plateau, there exists an optimal range of minimum catchment area and shortest gully length that creates regularity in quantitative characteristics of river network and inter-network zone structures, applicable to gully data extraction based on DEM. Xiong et al. (2011) used GIS to study the hierarchical system of rivers in the Dong River basin of the Three Gorges Reservoir area, dividing the river network into six levels and finding that as streams changed from low to high levels, their physical spatial distribution gradually transitioned from steep, high-elevation areas to gentle, low-elevation areas, with vegetation conditions better along low-level streams than high-level streams. Cohen and Brown (2007) used a hierarchical structure approach to develop a dynamic model simulating watershed wetland flooding and pollutant characteristics, finding that hierarchical wetland networks could increase flood and nitrogen-phosphorus storage by approximately 30%, significantly increasing environmental capacity and reducing water quality degradation and algal bloom probability. Yeo and Guldmann used multi-level optimization methods to optimize land use in different hierarchical watersheds of the Lake Erie (Ohio) basin and output non-point source pollutants, with simulation and application results reducing non-point source pollution peak output by 46%, maintaining protected area at 30% of watershed land area, and controlling urban and agricultural land below 12% and 70%, respectively.

Wang et al. (2013) developed the three structural components of watershed ecosystems—highlands, riparian zones, and water bodies—according to hierarchical structure theory and reductionist thinking in the Maotiao River basin, a second-order tributary of the Yangtze River. Water bodies were divided into river networks and lakes (reservoirs and ponds) with significantly different structures and functions. Highlands were composed of various meta-ecosystems such as broadleaf forests, coniferous forests, sloping croplands, and residential areas. Non-point source pollution observations conducted on different land types revealed that different land use types in inter-network zones have a minimum critical loss rate and loss-adsorption equilibrium value for nitrogen and phosphorus (Wang et al., 2013; Wang et al., 2018). In studies of natural rivers, it was found that natural river networks, especially mountain rivers, are composed of repeatedly occurring rapid-pool-bench systems, whose perimeters and areas show significant correlations between upstream and downstream, with different plant diversity maintenance functions and water purification functions in system components (Ma et al., 2014; Chen et al., 2015; Wang et al., 2019).

For characterizing overall watershed features, watershed circularity and narrowness have been used to depict watershed morphology, and average slope to characterize watershed physical spatial variation (Wang et al., 2012; Yin and Wang, 2012). These practices demonstrate that watersheds as hierarchical structural systems can reveal good patterns in research and achieve good results in applications. Therefore, combined with research from other ecologists and limnologists, and considering that watershed ecology involves both macro and micro scales, a five-level structural system for watershed ecosystems was preliminarily proposed at the first Watershed Ecology Forum under the guidance of hierarchical structure theory and reductionist thinking (Figure 2 [Figure 2: see original paper]; Wang, 2013, 2018). In this system, highlands, riparian zones, and water bodies are developed as second-level structures of watershed ecosystems. Highlands and inter-network zones as equivalent concepts include various meta-ecosystems.

1.4.1 Watershed Ecosystem Spatial Structure Quantitative Research Has Not Formed Its Own System Ecological research demonstrates that ecologists excel at conducting interconnected and progressive "structure-process-function-mechanism-regulation" studies. Well-developed population, community, ecosystem, and landscape ecology have all formed this research paradigm, such as population structure-process-function-mechanism-regulation research. This is because at different scales, "structure" affects "process" and "function," while "process" and "function" provide feedback to structure. Based on understanding "structure-process-function" interactions, "mechanism" can be comprehensively grasped, and "regulation" can be achieved. Currently, watershed ecology has become an important branch of ecology, with considerable work conducted on "process-function-mechanism-regulation" of water bodies or land. For example, freshwater ecology and aquatic environmental science have long focused on river and lake plants, animals, and microorganisms, establishing the river continuum theory and lake water environment dynamics theory, revealing biological community structure and function characteristics and river and lake health mechanisms (Cai et al., 2003; Tang et al., 2004; Ruhala and Zarnetske, 2016; Tao et al., 2018). Terrestrial vegetation, soil and water conservation, and non-point source pollution control research have recognized various effects of vegetation and landscapes on surface material processes, revealing a series of structure-function patterns and engineering effect mechanisms (Potter et al., 2004; Wang et al., 2014; Djuma et al., 2016). With disciplinary development and practical needs for integrated mountain-water-forest-farmland-lake-grassland management, there is a demand to place respective research within the objective watershed scale for holistic, land-water closely connected "watershed ecosystem structure-process-function-mechanism-regulation" studies to develop watershed ecology. However, the current reality is that quantitative research on watershed ecosystem spatial structure lacks its own model framework system, preventing true theoretical integration of watershed water and land to form its own research paradigm. The existing system borrows from landscape ecology and geomorphology (Liu et al., 2012; Khanday and Javed, 2017; Kändler et al., 2017).

A discipline' s vitality stems from establishing endogenous or self-generated conceptual systems and theories. Therefore, innovation is needed in quantitative research on watershed spatial structure.

1.4.2 Limitations of Existing Watershed Ecosystem Spatial Structure Quantitative Theories Although geomorphology- and landscape-based watershed spatial structure quantitative index systems can be borrowed for watershed structure quantification and theoretically integrate land and water research to complete watershed structure-process-function-mechanism-regulation, these index systems belong to endogenous conceptual systems of geomorphology, physical geography, and landscape ecology. In practical applications, research conducted with watershed ecosystems as units instead enriches and strengthens geomorphology, physical geography, and landscape ecology. Moreover, applying geomorphology- and landscape-based watershed spatial structure quantitative index systems to watershed ecology has limitations. Specifically, watershed ecosystem spatial structure characterization commonly uses conceptual systems including highlands, riparian zones, water bodies, river networks, inter-network zones, lakes (reservoirs and ponds), littoral zones, deep-water zones, euphotic zones, rapids, pools, benches, and different types of meta-ecosystems (Figure 3 [Figure 3: see original paper]). Watershed ecologists focus on the hierarchical structure, functions, relationships, and organisms within these structural components. In contrast, geomorphology-based watershed spatial structure composition conceptual systems use geomorphological types such as high mountains, medium mountains, gullies, plains, hills, ridges, and basins, with little consideration of organisms. Moreover, in watersheds, water bodies are not only structural components but also shape watersheds and are key to watershed function and health maintenance—factors not considered in geomorphology-based watershed spatial structure quantitative index systems.

Landscape-based watershed ecosystem spatial structure quantitative indices have many applications in watershed structure characterization, and landscape ecological methods are powerful and widely used in depicting watershed ecosystem structural features (Zhang et al., 2011). However, watershed ecology not only focuses on two-dimensional planar characteristics of watershed structural components (e.g., river networks, inter-network zones, and lakes) but more importantly needs to establish a model framework for spatial relationships among watershed ecosystem structural components to organically connect watershed land-water, aquatic-terrestrial, and upstream-downstream spatial relationships. Watersheds are ecosystems with clear boundaries, and watershed ecology particularly focuses on how overall watershed ecosystem characteristics affect watershed ecological processes. In other words, landscape ecological methods can serve as a model framework for characterizing watershed spatial structure quantitative features but cannot fully meet the requirements of watershed ecosystem research that centers on the water cycle as the core driver and operates at scales larger than landscapes.

Meta-ecosystem- and hierarchical structure-based watershed ecosystem spatial structure research has disciplinary endogeneity, but quantitative research is in its infancy. This study builds upon these developments.

2.1 Watershed Overall Indices

Watershed Narrowness (Wn): Watershed narrowness represents the ratio of the diameter Dr' of a circle with equal watershed area to the maximum axis length Lm parallel to the watershed main axis (Equation 1). When Wn<1, the watershed is elongated; when Wn=1, the watershed is circular; when Wn>1, the watershed is square. Circular watersheds have rapid rainfall runoff, large short-term flood volumes, and wide flood discharge channels (Amazon River basin); elongated watersheds have slow rainfall runoff, smaller short-term flood volumes than circular watersheds of equal area, and relatively narrow flood discharge channels (Yangtze River basin) (Figure 3). Watershed circularity correlates with river network structure indices including channel width, depth, and length, affecting watershed hydrogeochemical cycles and related ecological processes.

(cid:3041) = (cid:3005)(cid:3293) (cid:3013)(cid:3288) 2(cid:3495) (cid:3415) (cid:3417) (cid:3040) (cid:2869).(cid:2869)(cid:2870)(cid:2877)√(cid:3002) (cid:3013)(cid:3288)

Where A is the area of the equal-area circle and is 3.14.

Mean Slope (MS): The weighted average value of different slopes within the watershed (Equation 2). As watershed mean slope increases, surface runoff and surface material (nutrient) export increase, watershed productivity decreases, and cropland and population decrease, which in turn has feedback effects on the watershed ecosystem. Watershed mean slope regulates major ecological processes and functions and has profound impacts on the economy and society.

(cid:3041) MS = (cid:3036) (cid:3036) (cid:3036)(cid:2880)(cid:2869)

Where Pi is the percentage of land area in the ith slope class, and Si is the slope of the ith slope class land.

Topographical Undulating Degree (TUD): Topographical undulating degree is the difference between maximum and minimum elevation within a geographic unit. Watershed average topographical undulating degree is the weighted average of topographical undulating degrees of all geographic units within the watershed (Equation 3). For any two geographic units, the one with larger topographical undulating degree has larger surface area and higher environmental heterogeneity. According to the environmental heterogeneity-diversity principle, it can accommodate more species with different environmental adaptations and has higher biodiversity.

= (cid:3036) (cid:3036) (cid:3041) (cid:3036)(cid:2880)(cid:2869) = (cid:3533) (cid:3036) ((cid:3036)(cid:2879)(cid:3040)(cid:3028)(cid:3051) − (cid:3036)(cid:2879)(cid:3040)(cid:3036)(cid:3041)) (cid:3041) (cid:3036)(cid:2880)(cid:2869)

Where (cid:3036) is the percentage of the ith geographic unit area to the entire watershed area; (cid:3036) is the topographical undulating degree of the ith geographic unit; (cid:3036)(cid:2879)(cid:3040)(cid:3028)(cid:3051) is the maximum elevation of the ith geographic unit; and (cid:3036)(cid:2879)(cid:3040)(cid:3036)(cid:3041) is the minimum elevation of the ith geographic unit.

2.2 Inter-Network Zone Indices

Dominant Ratio of Ecosystem Vertical Distribution (DREVD): Indicates the dominance degree of a certain ecosystem type distributed across different elevation ranges within the watershed (Equation 4). This index can characterize the vertical distribution patterns of watershed ecosystems.

DREVD = (cid:3028)(cid:3284)(cid:3285) (cid:3289) (cid:3284)(cid:3128)(cid:3117) (cid:3002)

Where (cid:3036)(cid:3037) is the area of the ith independent patch of a certain ecosystem type within the jth elevation range, and A is the watershed area.

Coefficient of Variation for Ecosystem Area (CVEA): The variation degree of area sizes of a certain ecosystem type existing separately within the watershed (Equation 5). Larger variation coefficient indicates greater dispersion of ecosystem type areas.

= (cid:2869)(cid:2868)(cid:2868)(cid:3046)(cid:3285) (cid:2923)

Where the numerator is the standard deviation of the jth ecosystem type area existing separately, and the denominator is the mean area of the ith ecosystem type.

Ecosystem Connectivity (EC): Indicates the degree to which separated patches of ecosystem types are physically connected to form combined bodies; calculated at ecosystem type level (Equation 6) and watershed level (Equation 7). This index reflects the material flow level of meta-ecosystems within the watershed.

(cid:3048)(cid:3049) = (cid:3036)(cid:3049)(cid:2879)(cid:3048) (cid:3041)
(cid:3036)(cid:2880)(cid:2869) (cid:3416) (cid:3041) (cid:3036)(cid:3048)
(cid:3036)(cid:2880)(cid:2869) (cid:3040) (cid:3049)(cid:2880)(cid:2869)
(cid:3036)(cid:3049)(cid:2879)(cid:3048) (cid:3041) (cid:3036)(cid:2880)(cid:2869)
(cid:3416) (cid:3040) (cid:3048)(cid:2880)(cid:2869) (cid:3041) (cid:3036)(cid:3048)
(cid:3036)(cid:2880)(cid:2869)

Where (cid:3048)(cid:3049) is the connectivity between the uth and vth ecosystem types; is the connectivity of all ecosystem types within the watershed; (cid:3036)(cid:3049)(cid:2879)(cid:3048) is the arc length connecting the ith patch of the uth ecosystem type with the vth ecosystem type; and (cid:3036)(cid:3048) is the perimeter boundary of the ith patch of the uth ecosystem type.

Ecosystem Heterogeneity Index (EH): Indicates the degree of heterogeneous ecosystem distribution within the watershed (Equation 8). Larger values indicate more ecosystem types and higher heterogeneity; smaller values indicate higher homogeneity.

(cid:3041) = − ((cid:3036)) (cid:3036)(cid:2880)(cid:2869) ((cid:3036))

Where (cid:3036) is the percentage of the ith ecosystem type area to the entire watershed area.

Ecosystem Dispersity (ED): Indicates the degree to which ecosystem types are distributed independently without association with the same ecosystem type (Equation 10). Watersheds include ecosystem types such as cropland, different forest types, grassland, urban areas, and residential areas. Watershed ecosystem type dispersity reflects the resistance of that ecosystem type to disturbances; for example, more separated forest patches provide stronger barriers to forest fires. This index includes two extended indices: Total Ecosystem Dispersity (TED, Equation 11) and Mean Ecosystem Dispersity (MED, Equation 12).

(cid:3036) (cid:3415)

= = (cid:3041) (cid:3036)(cid:2880)(cid:2868) (cid:3416)

(cid:3036) (cid:3041) (cid:3036)(cid:2880)(cid:2868) (cid:3416)

(cid:3036)

Where (cid:3036) is the number of independent or separated patches of the ith ecosystem type; A is the watershed area; and n is the number of ecosystem types.

2.3 River Network Structure Indices

River Density (RD): River length per unit watershed area. This index indirectly reflects watershed surface material export capacity.

Gorge Density (GD): Gorge length per unit watershed area. This index indirectly reflects material export capacity from river source areas.

Mean River Width, Depth, and Length (MRW, MRD, MRL): These three indices indirectly reflect watershed long-distance material export capacity.

Rapid-Pool-Bench Land Area and Perimeter (RPBLA, RPBLP): These indices indirectly reflect the dominance of different habitats in river channels and river function performance.

River Longitudinal Gradient (RLG): The ratio of elevation difference between the highest and lowest points of a river channel to the horizontal distance between these points. This index indirectly reflects river potential energy, flow rate, and water scouring force on channels.

Ratio of River and Gorge Longitudinal Gradient (RRGLG): This index reflects the degree of material generation-deposition within watersheds and lake maintenance capacity. A large ratio indicates steeper upstream channels where materials easily deposit downstream, filling lakes; a small ratio indicates more upstream deposition, reducing sedimentation in mid-downstream lakes.

Riparian Length (RL): This index reflects the capacity of rivers to exert edge effects.

2.4 Lake Structure Indices

Littoral Zone Area (LZA), Deep Water Zone Area (DWA), and Shallow Water Zone Area (SWZA) and Their Ratios: These three indices reflect the sizes and relative importance of different functional zones in lakes. If shallow and littoral zones are dominant, it indicates lake degradation.

Lake Average Water Depth (LAWD): This index reflects the strength of lake water body functional levels.

Lake Perimeter (LP): This index reflects the capacity of watershed lakes to exert edge effects.

Lake Volume (LV): This index reflects watershed lake water resource provision capacity.

2.5 Inter-Network Zone-River Network-Lake Relationship Indices

Average Ecosystem-Lake Distance (AELD): The average distance from the center of a certain terrestrial ecosystem type patch in the lake catchment area to the lake center. For cropland ecosystems, larger index values provide more opportunities for water self-purification during pollutant transport, benefiting lake health; the opposite is detrimental. For forest ecosystems, closer distances benefit lake health.

Terrestrial Ecosystem and Lake Edge Connectivity (TELEC): The degree of connectivity between terrestrial ecosystem types and lakes sharing common boundaries (Equation 12), including calculations for individual lakes and watershed-wide averages. This index reflects the level of potential interactions resulting from connections between different terrestrial ecosystem types and lakes. If a watershed’ s forest ecosystem ELEC is higher than that of cropland or urban ecosystems, it indicates more interactions between forest-lake than between cropland/urban-lake, benefiting lake health.

TELEC = (cid:3036)(cid:3037) (cid:3041) (cid:3036)(cid:2880)(cid:2869) (cid:3415)

Where (cid:3036)(cid:3037) is the length of the ith boundary segment of the jth ecosystem type closely connected to the lake; LE is the lake perimeter.

Lake-Inter-Network Belt Area Ratio (LIBAR): This index reflects the dominance level of lakes and terrestrial ecosystems.

Catchment Ecosystem Type-Lake Area Ratio (CETLAR): The ratio of different ecosystem type areas in the lake catchment to lake area, including calculations for individual lakes and entire watershed values. This index reflects

Note: Figure translations are in progress. See original paper for figures.

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