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美国大陆五个山区集水区的河溪结构分析

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摘要 河溪结构及其关联的空间特征，是研究集水区中能量和物质移动规律所不可缺少的内容。利用美国地质调查局的水文数据库和地理信息系统(ARC/INFO)，对美国大陆5个主要山地中典型集水区河溪的数量、密度、分布结构以及河溪岸边带的组成，进行了分析和比较。5个山地分别是：西北太平洋沿岸，西部卡斯卡特山、中部落矶山、东部阿巴拉契亚山和南部欧扎克山。发现这5个集水区中的河溪网络结构非常相似。一级河溪大约占河溪总长度的60%左右。东部山地地质历史比较长，其集水区中河溪总长度、密度、高差以及河溪片段数量，都比西部相对年轻的集水区要高。此外，尽管其中河溪边岸域总面积随边岸域宽度线性增长，但它们在面积中的相对比例仍然很小(<12%)。因此，在森林经营中保护河溪边岸植被，并不会对木材生产造成太大的威胁。

关键词 河溪结构，山区集水区。

STREAM STRUCTURE ACROSS FIVE MOUNTAINOUS WATERSHEDS IN THE CONTINENTAL UNITED STATES

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Abstract Stream geometry and related measurements are the baseline information needed for ecological analysis of materials and energy movements within a watershed landscape. Using the United States Geological Surveys (USGS) hydrography database and a geographic information system (ARC/INFO), we examined and compared the distribution of streams, stream sections, total numbers, density, and riparian zones, in five mountainous watersheds in the continental United States; the Pacific Coastal Range, Cascades, Rockies, Appalachian Mountains, and Ozarks. Stream networks were found to be similar among the watersheds, with first order streams comprising up to 60% of the watersheds. The two watersheds in the eastern US had smaller stream length, basin relief, and higher stream densi-

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ty and section density than western watersheds. The amount of riparian area linearly increased with buffer width and did not account for larger amounts of the land area. Only seven to twelve percent of a total watershed area was included in riparian areas when a 60m buffer width was applied. Riparian zone distribution was related to watershed geomorphology. Emprirical models were developed to predict the proportions of stream, stream density, and changes in riparian areas with stream order within each watershed. Applications of these results in ecosystem analysis at watershed scales and riparian zone management are discussed.

Key words stream structure, watersheds.

1 INTRODUCTION

The importance of understanding ecosystem behaviors at large spatial and temporal scales for natural resource management has recently received special attention in ecology, forestry, wildlife management, and conservation. Concurrently, watershed analysis, as pioneered by Bormann and Likens[1] at the Hubbard Brook Experimental Forest in New Hampshire, has been widely accepted as both a logical approach in ecosystem science and as a basic unit in resource management[2]. Scientific investigations of many ecological processes (e.g., evapotransporation, mass movement, disturbance, vegetation dynamics of watersheds) are especially recommended and sought in the literature[1~5]. In practice, the Forest Ecosystem Management Team[6] uses the watershed approach with a central focus on stream networks and the associated riparian habitats region wide as a part of integrated ecosystem management[7,8].

The structure and function of a stream and riparian ecosystem are key issues in a watershed study. Many authors have suggested streams and riparian areas to be the "blood system" and "hot-spots" of a landscape[9,2]. These terms originated because riparian areas form a highly connected network which predominately affects the overall function of a landscape. Examples include distribution and movement of species, nutrients, sediment, cumulative effects, and disturbance events[10,11]. The development of "river continuum concept" by Vannote *et al.* and others[5,12~15], which defines the existence of gradients of ecosystem composition, structure, and function as one moves from the head waters to large rivers, provides a mechanical framework for exploring stream functions.

Recognition of the importance of stream networks in landscapes has also lead to scientific interest in the examination of riparian zones and their influences on both aquatic and terrestrial ecosystems. Riparian zone functions include providing shade, fine and coarse organic materials, nutrients, stream sediments, and diverse habitats for plants and wildlife, and corridors for seed and animal dispersal[16~19,42]. Management efforts to help riparian zone functions include leaving riparian buffers on both sides of a stream during timber harvest and avoiding detrimental human activities. These management efforts have become a generally practied management guideline in North America with the area involved sometimes referred to as riparian management zones[20]. For the Pacific Northwest, FEMAT proposes that buffer width be dependent upon stream order, geological settings, and surrounding topography. The buffer width may vary according to geomorphic features which has resulted in the proposed buffer width of 50ft to 300ft (i.e., ≈10~50m). Management objectives and guidelines concerning riparian zones are optional and differ between timber industries and environmental groups[21].

Despite the theoretical and practical debates on management criteria for buffers, there is a lack of basic information about the structure and spatial distributions within a watershed or landscape. For example, how many streams and how much riparian areas given specific widths are in watersheds? Are stream segments proportionally divided by stream orders? For mountainous areas, what are the roles of basin relief (i. e., elevation) in characterizing stream and riparian networks?

Using public-domain hydrological and elevation databases maintained by the United Staes Geological Service (USGS), this study was initiated to examine the stream networks of mountainous watersheds in five major mountain ranges in the continental United States: the Pacific Coastal Range, Cascades, Rockies, Appalachian Mountains, and Ozarks. Specifically our objectives were to: (1) compare the differences and similarities of stream networks in mountainous watersheds; (2) evaluate the influences of streams and rivers by order in the above landscapes (i. e., elevation) by developing width-varying riparian zones; and (3) provide a conceptual framework for understanding streams, riparian zones, and their potential applications in ecological research or natural resource management. Our working hypothesis was that streams and stream networks of the five mountainous landscapes have similar structures and influences (i. e., riparian zones) across watersheds in the above ranges.

2 METHODS

2.1 Study Areas

Five watersheds were included in this study (Fig. 1): the Queets River watershed in the western portion of the Olympic Peninsula (WA), the McKenzie River watershed in the central Cascades (OR), the Stillwater River watershed in the northern Rockies (MO), the Current River watershed in the western Ozarks (MO and AK), and the Litter River watershed in the southern portion of the Appalachian Mountains (TN and NC). Selection of these watersheds was based on extensive research determined in the past and on-going research projects at these sites.

The Queets River watershed in located on the west end of the Olympic Peninsula (124°10′N and 47°40′W). The climate is mild, between 0℃ and 25℃ and rarely freezes. The yearly average rainfall is close to 500cm. Elevation ranges from sea level to 2434m on Mount Olympus over a horizontal distance of 55km. The high rainfall and effects of the Pacific Ocean jointly produce the rare temperate rain forest that is dominated by sitka spruce (*Picea sitchensis*), western hemlock (*Tsuga heterophylla*), and western redcedar (*Thuja plicata*). Douglas-fir (*Pseudotsuga menzisti*), subapine fir (*Abies laciocarpa*), and Alaska yellow cedar (*Chamaecyparis nootkatensis*) become more dominant with increasing elevation. The unique active glaciers, maritime climate, rainforest, and soil provide diverse habitats for flora and fauna.

The McKenzie River watershed is located in the densely wooded, central portion of the western slope within Oregon's Cascade Range (44°15′N and 122°10′W). Elevation ranges from 420～1630m and the terrain is extremely rugged with steep slopes and deeply incised streambeds. The area has a quasi-Mediterranean climate with mild moist winters and warm dry summers. The average annual temperature is 8.5℃. Only six percent of the mean yearly precipitation (230cm) falls from June to August. Most soils in the area are classified as Inceptisols, but some Alfisols are present. These soils are highly porous, with 60%～70% porosity in surface soil and 50%～60% porosity in subsoils. High porosity also provides storage for 30～40cm of water in the upper 120cm soil, which serves as a water source for the forest during summer drought[21]. Vegetation in this area is stratified into two major zones, resulting from the altitude temperature gradient. The *Tsuga heteropylla* (Raf). Sarg. zone is generally below 1050m and has abundant western hemlock and Douglas fir[22]. The Pacific silver fir (*Abies amabilis* Dougl. ex Forbes) zone is found above 1050m.

The Stillwater River watershed (48°30′N and 114°42′W) is located in the northern Rockies and serves as a drainage for the Beartooth Mountains. Starting elevations of the headwaters (located 40km south of Cooke City, MT) are in excess of 3300m. Precipitation is mostly in the form of snow at or near the headwaters and exceeds 247cm annually. The Stillwater River flows northeast for approximately 105km before emptying into the Yellowstone River east of Columbus, Montana. The elevation of this juncture is estimated to be 990m with annual precipitation here being only 35cm. Geologic formations of the watershed are comprised of some of the oldest known rocks. Vegetation along this watershed varies greatly and is mostly determined by elevation. Lodgepole pine (*Pinus contorta*) is the most frequent and dominant species in the watershed with subalpine fir (*A. laciocarpa*) and whitebark pine (*P. albicaulis*) in the subalpine areas. Much of the lodgepole area is in a regenerative state due to the 1988 Yellowstone fires. Over 55 680hm^2 of lodgepole forests in the Stillwater watershed were burned and are recently showing signs of regeneration.

The Current River watershed is located in the eastern portion of the Ozark Mountains in southeastern Missouri and northeastern Arkansas (36°15'N and 90°33'W). The region has a humid continental climate with hot, humid summers and cool winters. Average annual precipitation is 112cm, the majority being rain during spring and summer[23]. Dolomitic limestone imbedded with large quantities of chert dominated of the watershed. The soil is clay or clay loams containing chert on the surface[24]. Southern hardwood forests remain relatively unfragmented, and importain species include oaks (*Quercus* spp.), hickories (*Carya* spp.), and shortleaf pine (*Pinus echinata*).

The Little River watershed is one of 45 major watersheds in the Great Smoky Mountains (83°35'W and 35°40'N). Aquatic resources include a gradient from extremely soft-water, first order streams to more buffered third and fourth order rivers. The Smokies are located along the border of Tennessee and North Carolina and lie along the backbone of the southern Appalachian Mountains. It is underlain by a diversity of igneous, metamorphic and sedimentary bedrock types. The climate is characterized by high precipitation (> 150cm per year), cool summers, and cold winters. Soils are shallow Inceptisols with a thich organic horizon. The Great Smoky Mountains are also rich in plant and wildlife diversity. Approximately 1200 native vascular plant species and about 130 trees, 450 known bryophyte and over 3400 lichen species[25] exist there. A variety of forest cover types are distributed within the watershed, including the largest undisturbed area of the remnant red spruce-fraser fir (*Picea rubens*, and *Abies frsaeri*) forest in the world[26,27].

2.2 Data Acquisiton and Analysis

Our major data sources included 1:100 000 scale digital line graph (DLG) of hydrology and 1:250 000 scale digital elevation models (DEM) of the GeoDatabased maintained by the USGS through electronic listserve. These data were retrieved using anonymous File Transfer Protocol (FTP), decoded, and imported into an ARC/INFO Geographic Informations System (GIS) on a UNIX platform. Originally, these data were stored in eight files per pixel of onedegree regulary speced intervals. ARC coverages imported from these files were merged into one file for each basin. Using USGS 1:100 000, scale topography maps as a hardcopy reference, dangling arcs, lakes, reservoirs, man-made canals and other anomalies were removed. Stream order was then assigned to each stream section based on Strahler[28]. Standard buffer widths of 10, 20, 30, 45, 60, 90 and 120m were applied to sections across the watersheds to generate riparian coverages. Variable widths were used to examine the amount of riverine forests in the watershed/landscape under different management scenarios that are currently applied on public lands.

The DEM lattice was used to delineate watershed boundaries using "FLOWDIRECTION" and "WATERSHED" commands of the GRID Module in ARC/INFO. This boundary coverage was used to calculate watershed size and to clip a DEM of the watershed. The DEM lattice then was used to generate an elevation coverage, which was later unioned with stream and riparian coverages to explore the spatial distribution of streams and riparian zones in each watershed. All coverages and lattices were projected to the Universal Transverse Mercator(UTM)coordinate system.

Watershed size, stream length by order, area of riparian zones, and their spatial distribution of streams along the elevation were downloaded into ASC Ⅱ files from the INFO Module for further analysis. Absolute and relative length of streams by stream order, and area of riparian zones by seven widths and elevation were tabulated and summarized using Statistical Analysis System(SAS). Linear regression analysis was completed to develop empirical models to predict the changes in stream length, stream density, and area of riparian zones with stream order in each watershed.

3 RESULTS

The five mountainous watersheds are clearly different in their size(423~6888km^2), shape, basin relief (4308 to 3142m), and stream density(Fig. 1, Table 1). The Current River and the Little River watersheds are two extreames in their size and topography. The Current River watershed is the largest(6888.04km^2) with the smallest relief ratio, while the Little River watershed is the smallest(423.47km^2)with larger relief ratio. The Current Rriver watershed has the lowest elevation difference(408m)compared to a drop of over 3000m in the McKenzie River watershed(Table 1). The two watersheds(the Little and Current rivers)in the eastern states seemed to have significantly higher stream density, shorter streams, higher section density, and smaller basin relief than the three western watersheds. A simple logarithmic linear regression proved to be an effective model to predict the changes in stream length and density for each stream order (Table 2).

Table 1 Watershed location, area, elevation, length, and density calculations for five mountainous riparian areas of the continental United States

Study area (River Name)	Location (State)	Basin Area (km^2)	Elevation Max. (m)	Elevation Min. (m)	Rasin relief (m)	Relief ration (m/km^2)	Stream density (m/km^2)	Mean length (m)	No. Of streams (N)	Section density (N/km^2)
Current	Missouri	6888.04	484	76	408	0.006	971.04	1911	3360	0.49
Little	Tennessee	423.47	2009	280	1729	4.08	896.66	1954	225	0.53
McKenzie	Oregon	3136.78	3142	62	3080	0.98	623.21	2384	820	0.26
Queets	Washington	1171.41	2134	0	2134	1.82	651.89	3222	237	0.20
Stillwater	Montana	2802.48	2086	1.097	989	0.35	593.44	2670	623	0.22

Table 2 Parameters from logarithmic and linear regressional analysis using buffer width as independent variable to estimate proportion, stream density, and proportion riparian area of the specified watershed

Study area	Proportion①				Stream density①				Proportion riparian Area②		
	b_0	b_1	MSE	adjR^2	b_0	b_1	MSE	adjR^2	b_1	MSE	adjR^2
Queets	4.104	−1.523	3.747	0.927	5.919	−1.185	2.267	0.670	0.128	153.642	0.999
MacKenzie	4.129	−1.764	5.027	0.971	5.968	−1.786	5.152	0.966	0.122p	140.991	0.999
Stillwater	4.170	−1.748	4.936	0.887	5.864	−1.555	3.909	0.961	0.115	124.745	0.999
Current	4.065	−1.664*	4.475	0.991	6.352	−1.674	4.637	0.994	0.190	339.306	0.999
Little	3.991	−1.440	3.349	0.961	6.594	−2.325	8.733	0.735	0.202	386.633	0.999

①Model used: $\ln(y)=b_0+b_1\ln(x)+\varepsilon$

②Model used: $y=b_1x+\varepsilon$

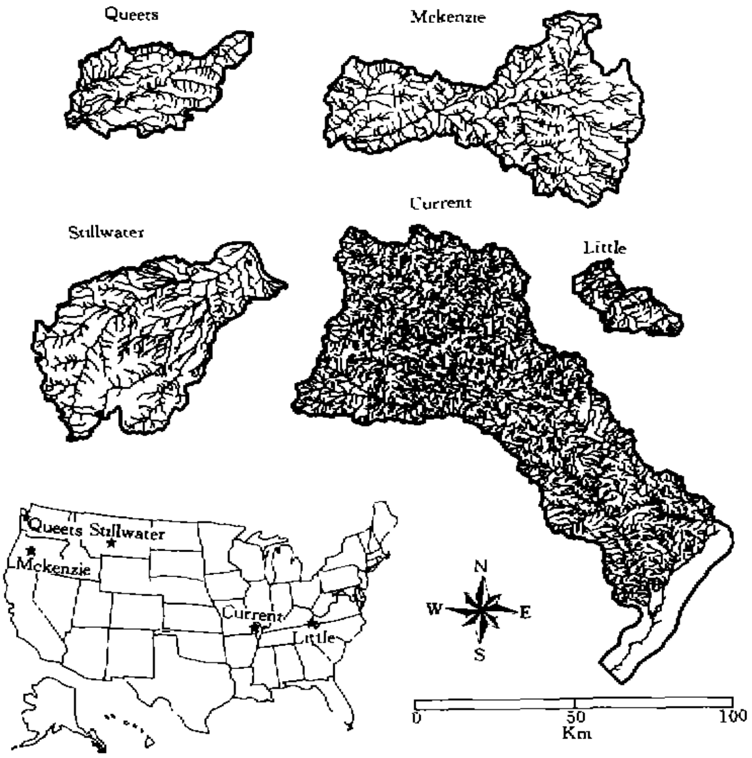

Fig. 1 Geogaphic distribution of streams in five mountainous watersheds of the continental United States

Two of the smaller watersheds (Queets and Little) extend to fourth order streams only, while the Stillwater and Current extend to sixth-order streams (Table 3). As expected, the total length of streams was linearly related to basin size ($R^2=95.8$) and the proportion of streams in all five watersheds decreased exponentially with stream order (60%, 18%, and 10% for first, second, and thrid order streams, respectively) (Fig. 2a). There is no clear difference in the distribution of streams by order among the five watersheds. Changes in stream density with stream order also show exponentially decreasing trends at these watersheds but the Current and Little River watersheds have higher density for the first order streams (Fig. 2b). Stream density for higher order streams among the five watersheads was not different.

The amount of area contained within the 7 buffer zones increased linearly with basin size ($R^2=95.4\%$ ~96.5%) and buffer width in all five watersheds (Table 3). For example, in our smallest watershed (i.e., the Little River), using a medium buffer width of 60m or about 200ft, there are 5235hm^2 of riparian area. Riparianarea increased to 79350hm^2 in the Current River watershed, which is the largest (Table 4). Two distinct increasing patterns in buffered area with buffer width were apparent as noted in stream length in Fig. 2b. Changes in proportion of riparian area of the watershed are greater in the two eastern watersheds than those in the west (Fig. 3). Our confidence in predicting the amount of riparian area by stream order was greater than 99.9% (Table 2).

Spatial distribution of stream and riparian areas in the watersheds indicate a very unique pattern within the Current River watershed (Fig. 4). The majority of riparian areas are distributed in the mid to lower areas of the landscapes and decreases exponentially with increasing in elevation. In the Current River watershed, however, the distribution of riparian area in the landscape is relatively even within the range of 200m to 400m in elevation with smaller amounts extending into the high and low extremes. The above relationship appeared to be independent of buffer width. Similar distribution of land areas along the elevational gradient in each watershed existed (Fig. 5), indicating that mountainous streams are independent of spatial locations and elevation.

4 DISCUSSION

Streams and related concepts and theories are becoming the key components in ecology as we extend our interest in ecosystem processes to broader scales[2]. Many issues, such as water quality control and maintenance of biological diversity, cannot be properly addressed without baseline information on the geometrical structure of stream networks in a watershed[29]. A combination of the DLG information from USGS GeoDatabase and applications of geographic information systems are promising for quantifying stream structure and associated riparian zones at the watershed, landscape, and regional scales[10]. Completion of the GeoDatabase country-wide in the near future will allow us to systematically examine the stream networks of each geological region.

A limitation of using the GeoDatabase to delineate stream networks is that most first and second order streams are not included in the database because of its coarse resolution (i.e., 1 : 100000). Other more accurate approaches, might involve delineation of stream networks using high resolution digital elevation models based on geomorphic and hydrologic processes[30,31], mapping topographic cues on fire scale maps (i.e., 1 : 24000), or resorting to field mapping to ground truth the date.[6] Despite the controversial debates on various models and approaches[32], the GeoDatabase is the only available database to provide relative good quality and consisten precison when making comparisons across regions.

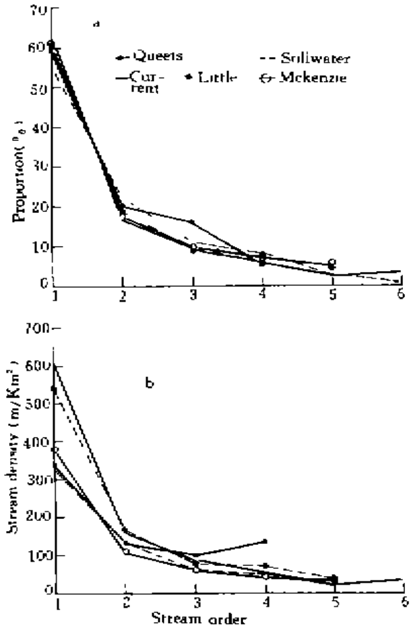

Fig. 2 Correlation between proportion of stream segments (a) and stream density (b) of total watershed for each stream order represented in the five mountainous watersheds analyzed

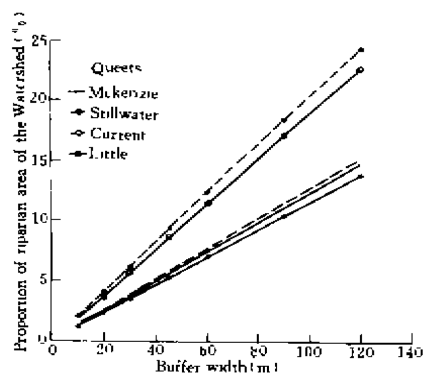

Fig. 3 Proportion of watershed area included for each buffer widths for five mountainous watershed from the continental United States

Table 3　Stream length by order and total stream length for five mountainous watershed areas in the continental United States

Study area	Stream order						Total (km)
	1 (km)	2 (km)	3 (km)	4 (km)	5 (km)	6 (km)	
Current	4217.94	1090.02	616.64	374.59	158.17	231.22	6688.58
Little	228.89	70.27	33.04	16.77	—	—	379.71
McKenzie	1187.01	338.03	186.79	132.48	110.57	—	1954.88
Queets	451.68	152.52	119.11	40.33	—	—	163.63
Stillwater	910.57	366.76	177.51	143.16	48.30	16.81	1663.12

Table 4　Watershed area(km^2) calculated for five mountainous watersheds using 10,20,30,45,60,90 and 120m buffer widths

Study area	Buffer widths						
	10(m)	20(m)	30(m)	45(m)	60(m)	90(m)	120(m)
Current	130.01	249.03	397.38	596.30	793.50	181.06	1560.17
Little	8.75	17.52	26.31	39.39	52.35	77.92	103.00
McKenzie	38.92	78.13	117.12	175.46	233.28	348.86	462.93
Queets	15.42	29.05	45.36	68.07	90.70	135.20	179.13
Stillwater	38.92	78.13	117.12	175.46	233.28	348.86	462.93

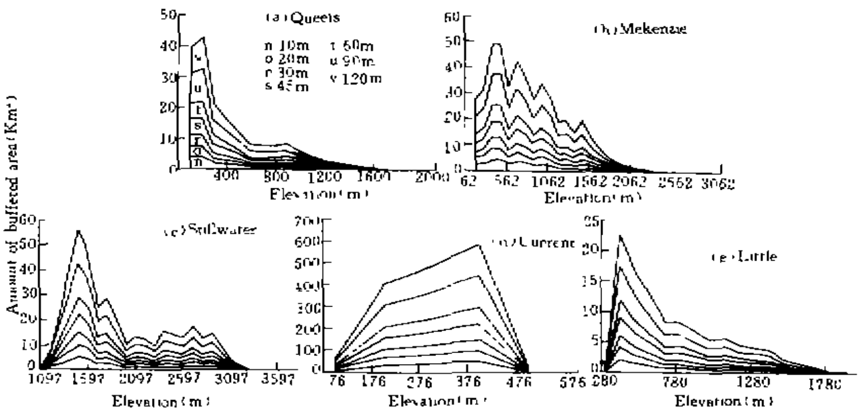

Fig. 4　Total area distribution by elevation of each buffer zone for the five mountainous watershed investigated

Our results may therefore be significantly biased due to missing smaller streams in the GeoDatabase. For the Coastal range and Cascade Mountains in the Pacific Northwest, the FEMAT team[6] reported that stream density ranged from 1.82 to 5.56km per square km based on 53 small watersheds in Washingtonand Oregon. Results from the GeoData base for the Queets and McKenzie River watersheds are only 0.652 and 0.623km/km², respectively (Table 1), suggesting that the GeoData base probably missed at least 60% of small streams. As a result, the amount of smaller streams and associated riparian areas reported in the study is underestimated. However, it appears that the pattern of changes in stream length by order remains the same, suggesting that stream networks constructed using the Geo Database are valid and comparisons can be made among our five selected watersheds. Clearly, a high quality stream network database is the key for future studies relating stream networks and their relationships to various ecosystem processes and management practices.

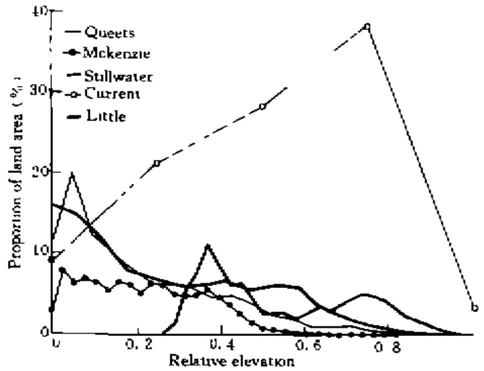

Fig. 5 Distribution of land area relative to basin size along the elevation. The x axis represents a relative elevation gradient which is computed using elevation data as: (maximum-minimum)/(basin relief)

Consistency in proportion of streams by order suggests mountainous streams have very similar structures (Fig. 2a and Table 4), regardless of watershed size and differences in stream density (Fig. 2b) among the five mountainous watersheds. There results matched precisely with findings in coastal watersheds of western Washington where the percentages of first and second order streams are about 60% and 18%, respectively[33]. These results support our hypothesis that streams are organized in a similar structure across mountainous watersheds. [34]related these similarities to a higher level of processes (i. e. , self-organization). We argue that basin morphometry, such as the size and drops of sub-basins and slope, may have equal contributions[35]. Obviously, conclusions cannot be made without including more watersheds and analyses in similar and different geological settings. Similarly, our conclusion that the western watersheds have a lower stream density also needs further research.

Special attention needs to be paid to the spatial distribution of streams within the context of elevation in the watersheds. We found that a majority of streams were distributed in the lower elevations of the Queets, McKenzi, Stillwater, and Little watersheds, where there are steep slopes and larger elevation drops. However, the streams in the Current River watershed were more or less evenly distributed in the landscape, largely because the geological settings are more uniform (e. g. , smaller basin relief, Fig. 5) compared with the other four watersheds[24]. Nevertheless, high correlations between the spatial disribution of riparian zones and total land areas, along elevation gradients (Fig. 4 and Fig. 5) supports a conclusion that predictable models can be developed based on the size of the sub-watersheds in a basin; that is the relation of reparian zone with elevation is correlated with the total watershed area.

Direct applications of our results on stream structure in nutural resource management are multi-fold. Parameters estimated from this study, such as stream length, basin relief, and relief ratio, are commonly used to study basic geomorphic processes[35,36]. For example, mean annual runoff was suggested to be a linear function of stream density; sediment discharges can be calculated by basin size and relief ratio[37]; and the number of species, amount of suitable wildlife habitat, or catchment of materials by riparian vegetation from terrestrial lands into the stream may be estimated based on the amount of riparian zones in the landscape[29,38].

In ecology, extensive efforts have been made to study the distribution of coarse woody debris[23,40], aquatic species, productivity/respiration rate[12], and nutrients[14] along a continuous river network by selecting and sampling a number of streams in the landscape. Results from these empirical studies can be readily extrapolated to watershed scales using the stream geometry findings of this study. For example, overlaying stream and riparian networks on top of a vegetation coverage will provide us with first hand information on the contributions(e.g., organic matter and quality) of each vegetation type to the watershed. Such information is critical in forest practice when alternative management scenarios are developed and applied at landscape levels. At regional scales, estimation of stream flows, sediment sccumulation, and discharge regimes are also possible using the empirical results(Fig. 2~4) and models(Table 4) developed here. Additional information on watershed size and distributions in a region can also be obtained through the results of this study[41].

As denoted by high species diversity, riparian zones serve as important pools and corridors for the plant and wildlife species within landscapes. Gregory *et al.*[17] reported that total number of plant species peaks in riparian zones and decreases as one moves away from the stream. Nilsson found 13% of Sweden's vascular plants are distributed along the streams and rivers. Naiman *et al.*[33] also reported that 68% of plant species sampled along gradients from small streams to the uplands in western Washington were located within 10m of the stream. This suggests a majority of species can be properly maintained by managing a small proportion of the landscape(i.e., the riparian zones).

A frequently debated issue in forest landscapes concerns manipulations of riparian vegetation[8,20]. These areas contain high timber production but play crucial roles in maintaining water quality control and providing diverse habitats for wildlife, and so forth[17,16]. A general argument is that preservation of riparian forests can only be made at the cost of timber production. While such an argument is valid, economic gains must be balanced with ecological losses. More effort has to be made to quantify the amount of riparian zones in a landscape. For example, many management plans[6] recommend very narrow riparian buffers(< 60m) for reservation, indicating a minor proportion of the land areas will be omitted when calculating timber production. A management plan setting aside 21% of forests for reserve allows us to leave 60m buffers for all streams in the Current or the Little watersheds in the eastern United States, and more than 100m buffers in the Queets, McKenzie, and Stillwater watersheds(Fig. 3).

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