A Regional Analysis of the Physical Characteristics of Streams
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Source: *Journal of the North American Benthological Society*, Vol. 16, No. 1 (Mar., 1997), pp. 87-95
Published by: The University of Chicago Press on behalf of the Society for Freshwater Science
Stable URL: http://www.jstor.org/stable/1468240
Accessed: 01-07-2015 15:29 UTC

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A regional analysis of the physical characteristics of streams

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Physical characteristics of streams are determined by complex interactions between climate and geology, often indirectly mediated by vegetation. These characteristics vary considerably among regions of the world. For example, Wolman and Gerson (1978) suggested that stream geomorphology is driven by the frequency of extreme events and the timing and capacity for recovery. In temperate regions, extreme storms and floods that scour and widen the stream channel typically occur at 50- to 200-y intervals. Time between events may therefore be long enough for streamflow, vegetation, and hillslope slumps to return the channel to pre-storm widths. In contrast, arid regions experience severe flooding more frequently. With little time between floods, slow vegetation growth, and often no flow at all between floods, these arid land channels tend to widen to a greater extent than streams in temperate regions. Interactions of climate and geology with their effects on vegetation and physical stream characteristics are the prime determinants of organic processes occurring in streams. In this chapter we describe and compare 8 physical characteristics of the 35 streams described in the preceding chapters. Because of the limited geographic extent of the streams, this analysis is not a comprehensive treatment of the physical characteristics of streams. The primary purpose of this paper is to provide a background for the analyses of organic matter processes presented in subsequent chapters.

Methods

This analysis was based on the 35 streams described in the previous chapters. We examined

TABLE 1. Physical characteristics of the streams used in this study.

	Number of streams	Mean	Median	Maximum	Minimum
Latitude (degrees)	35	44.0	44.0	78	18
Stream order	35	2.9	2	9	1
Mean annual water temperature (°C)	32	9.4	8.2	22.0	1.0
Watershed area (ha)	34	90,400	662	1,987,100	7.5
Precipitation (cm)	35	136	110	438	10
Mean annual discharge (L/s)	34	18,300	59.5	466,100	1.7
Stream width (m)	32	29.0	2.5	400	0.3
Stream gradient (m/m)	34	0.08	0.024	0.45	0.0002

8 characteristics of the streams—latitude, stream order (Strahler 1957), mean annual water temperature, watershed area, mean annual precipitation, mean annual discharge, stream width at mean annual discharge, and stream gradient (Table 1). While this is a very limited set of characteristics to physically describe streams, they were the only characteristics that were available for all or most of the 35 streams. We analyzed the data using linear regression. Regressions on log-transformed data are reported if transformation improved the fit of the regression line. In addition, we used the physical characteristics of the streams in a principal components analysis to look for general patterns characterizing these streams. As necessary we transformed the data to generate normal distributions (Kolmogorov-Smirnov test, $p > 0.04$). Stream order and width could not be normalized and were not included in the analysis. Also, any streams with missing data could not be included (Creeping Swamp, Quebrada Sonadora, and Rio Icacos—temperature; Canada Stream—watershed area and slope; Deep Creek—discharge).

Results

Latitude

The average latitude of the 35 streams is 44°. All but 2 (Canada Stream, Antarctica, and Keppel Creek, Australia) are in the northern hemisphere. High latitude streams include Canada Stream (78°S) and the Kuparuk River, Alaska (70°N). The only streams in the tropics are 3 streams in Puerto Rico (18°). Most of the streams are in the temperate region (Fig. 1).

Stream order

Strahler stream order of the streams used in this analysis ranges from 1st to 9th; however, most of the streams are 1st and 2nd order. The larger streams include the 9th-order Moisie River, Quebec, 7th-order McKenzie River, Oregon, and 6th-order Ogeechee River, Georgia, and Matamek River, Quebec.

Temperature

Annual water temperature averaged 9.4°C, ranging from 1.0°C (Caribou Creek, Alaska) to 22.0°C (Quebrada Toronja, Puerto Rico). There was a strong relationship between temperature and latitude (Fig. 1, $r^2 = 0.69$, $p < 0.001$, $n = 33$). The temperature for Canada Stream fell well off the line because the reported temperature was for the ice-free period only. Omitting this one stream improved the regression ($r^2 = 0.74$, $p < 0.001$, $n = 32$). The desert streams (Sycamore Creek, Arizona, Deep Creek, Idaho, and Rattlesnake Springs, Washington) fell above the regression line, whereas mountain streams (e.g., Devil's Club Creek and Mack Creek, Oregon) fell below the line.

Watershed area

The watershed (= catchment) areas of the streams are highly variable. While most of the watersheds are small (median = 662 ha), the larger order streams have very large watersheds (Fig. 2). Watershed area ranges from 7.5 ha for 1st-order Satellite Branch (North Carolina) to nearly 2 million ha for the 9th-order Moisie River. The statistical relationship be-

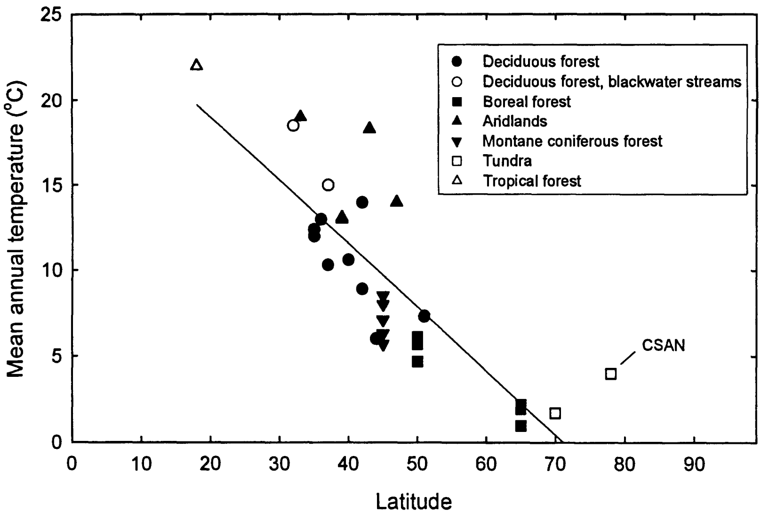

FIG. 1. Mean annual water temperature versus latitude for the streams used in this study. The value for Canada Stream (CSAN) is for the ice-free period only.

tween watershed area and stream order was surprisingly good (Fig. 2, $r^2 = 0.60$, $p < 0.001$, $n = 34$, watershed area log-transformed) considering the wide range in precipitation. However, for both 1st- and 2nd-order streams, watershed area varied over about 4 orders of magnitude. The streams with the largest watershed area relative to their order were the desert streams. Compared with data for all streams (Leopold et al. 1964), the streams used in our study generally had smaller watersheds for a specific order (Fig. 2). The difference is undoubtedly due to the effect of map scale. Whereas the data given by Leopold et al. were based on 1:62,500 scale maps, which generally do not show 1st- and 2nd-order streams, stream ecologists typically use finer-scale maps or actual knowledge of existing streams to determine stream order.

Precipitation

Precipitation in the watersheds of the streams ranged from 10 cm (Canada Stream) and 14 cm (Rattlesnake Springs) to over 400 cm in 2 of the streams in Puerto Rico. There was a significant decrease in precipitation with latitude ($r^2 = 0.55$, $p < 0.001$, $n = 35$, precipitation log-transformed) due to the high precipitation in Puerto Rico and the low precipitation in the Dry Valleys of Antarctica (Canada Stream), the North Slope of Alaska (Kuparuk River), and interior Alaska (Monument and Caribou Creeks). When we excluded these extremes, there was no significant relationship between precipitation and latitude ($r^2 = 0.03$, $p = 0.41$, $n = 27$, precipitation log transformed).

Discharge

Mean annual discharge of the streams averaged 18,300 L/s, but like watershed area the distribution was highly skewed. Most streams had low discharge (median discharge = 59.5 L/s), but a few had very high discharge. Lowest discharge streams were Devil's Club Creek and Satellite Branch at 1.7 L/s, and the Moisie River had the highest discharge (466,000 L/s). We found the expected strong statistical relationship between discharge and watershed area (Fig. 3, $r^2 = 0.84$, $p < 0.001$, $n = 33$, both variables log transformed), and, as expected, desert streams fell below the line and Puerto Rican streams fell above it.

We converted discharge to discharge per unit area by dividing by watershed area. When we regressed areal discharge on precipitation (Fig. 4A, $r^2 = 0.67$, $p < 0.001$, $n = 33$), we found a significant relationship between these 2 variables with an average of 60% of precipitation to these watersheds ending up as stream discharge. This is high compared to a global average of 36% (e.g., Schlesinger 1991). However, looking at discharge as a percent of precipita-

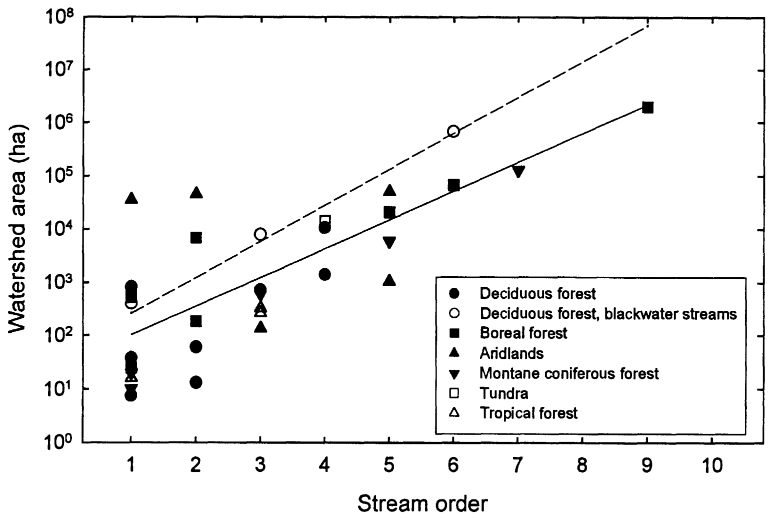

FIG. 2. Watershed area versus stream order for the streams used in this study. The dashed line represents the streams used by Leopold et al. (1964).

tion compared with precipitation (Fig. 4B) suggests several sites with anomalous data, i.e., discharge exceeded precipitation (several of the Quebec and Oregon streams, the Kuparuk River, and Monument Creek). These anomalies could result from inaccurate measurements of watershed area, precipitation, or discharge. In several cases they probably result from comparing short- and long-term data. For example, the precipitation value for Monument Creek is a long-term average while the discharge value is from a single year of higher than average discharge (J. G. Irons, University of Alaska, personal communication). For the Kuparuk River, precipitation was based on an average for the North Slope whereas the Kuparuk River watershed probably receives greater precipitation than that average (B. J. Peterson, Marine Biological Laboratory, Woods Hole, personal communication). Taking these 2 streams, the Oregon River Continuum sites, and the Quebec sites out of the analysis greatly improved the

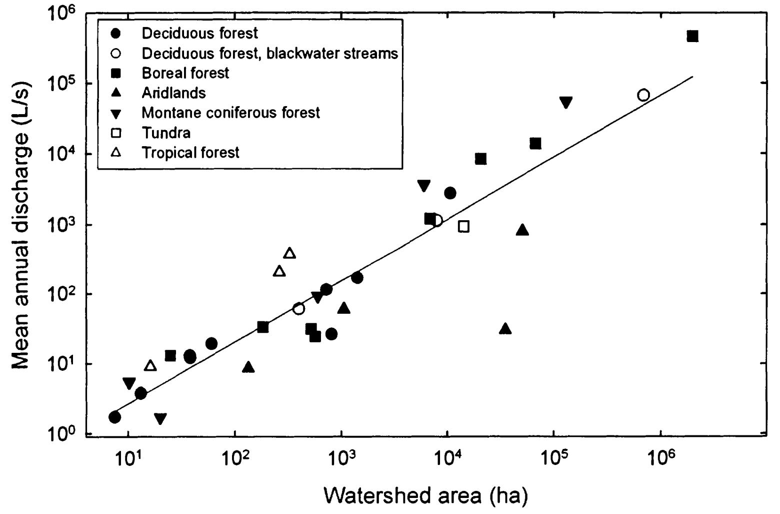

FIG. 3. Mean annual discharge versus watershed area for the streams used in this study.

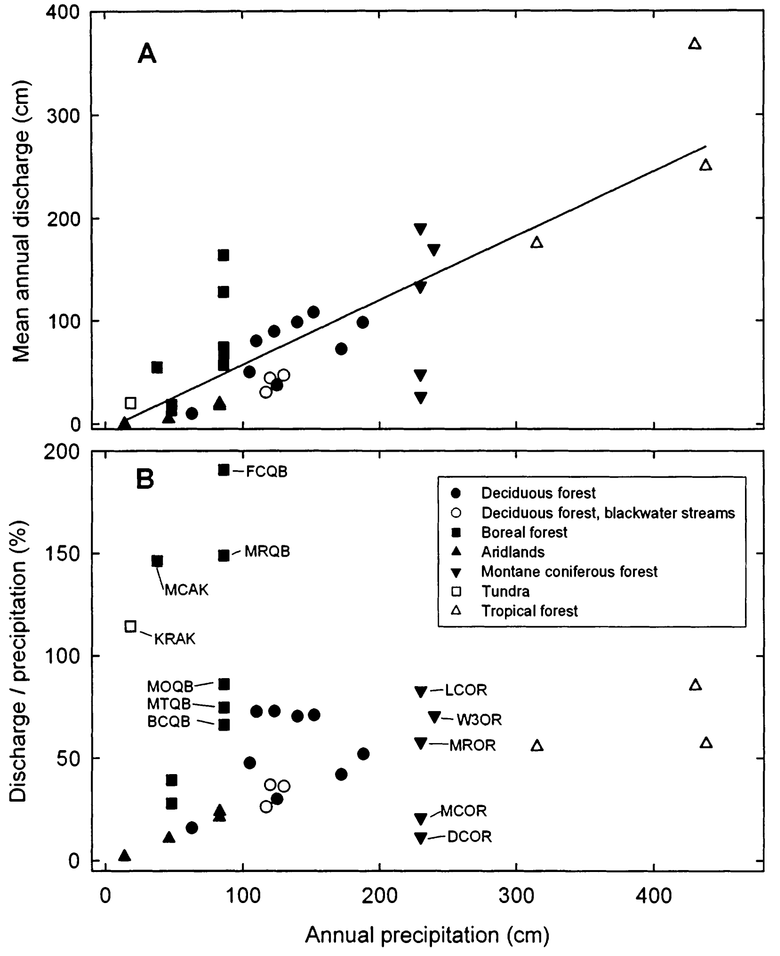

FIG. 4. Mean annual discharge (A) and discharge as a percent of precipitation (B) versus annual precipitation. Site acronyms are defined in the first chapter of this paper (Webster and Meyer 1997).

regression between discharge and precipitation ($r^2 = 0.91$, $p < 0.001$, $n = 22$). Also, there was then a significant relationship between discharge as a percent of precipitation and precipitation ($r^2 = 0.55$, $p < 0.001$, $n = 22$, precipitation log-transformed), indicating that the higher the precipitation the higher the percent of that precipitation that goes to stream discharge.

Gradient

Stream gradient ranged from 0.0002 m/m for the Ogeechee River to 0.45 m/m for WS 10 (Oregon); however, most streams were rather low gradient (median = 0.02 m/m). Regression analysis showed that gradient was related most closely to discharge (Fig. 5A, $r^2 = 0.46$, $p < 0.001$, $n = 33$, both variables log-transformed). The relationship between gradient and order was significant but not as good ($r^2 = 0.24$, $p = 0.003$, $n = 34$, gradient log transformed). Gradient was also significantly related to precipitation ($r^2 = 0.20$, $p = 0.007$, $n = 34$).

Width

Stream widths were highly skewed because of 2 very wide streams (Creeping Swamp, North Carolina, 400 m wide, and Moisie River, 208 m wide). Most streams were less than 3 m wide (median = 2.5 m). Not including Creeping Swamp, stream width was significantly related to other measures of stream size: discharge (Fig.

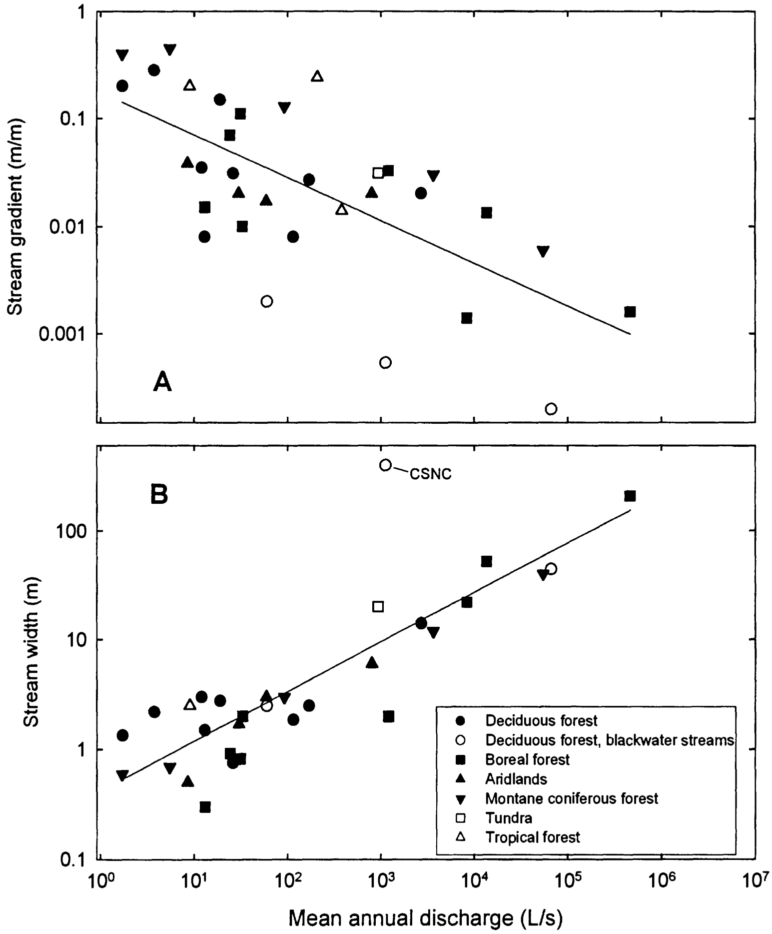

FIG. 5. Stream gradient (A) and width (B) versus mean annual discharge. Creeping Swamp (CSNC) was not included in the regression analysis.

5B, $r^2 = 0.82$, $p < 0.001$, $n = 30$, both variables log-transformed), order ($r^2 = 0.75$, $p < 0.001$, $n = 31$, width log-transformed), and watershed area ($r^2 = 0.64$, $p < 0.001$, $n = 31$, both variables log-transformed).

Discussion

Clearly the 35 streams used in this study are not a random sample of streams through the world. The set of streams is biased becaused the streams are mostly small and are located primarily in the temperate zone of the northern hemisphere. However, our range of streams is quite large and covers most of the stream types found in the world, perhaps with the exception of very large rivers, especially large tropical rivers. In our analyses of the physical data, we found relationships that would be expected in any similar sized sample of streams.

Dunne and Leopold (1978) pointed out that the exponent of the power function indicated by the log–log relationship between discharge and watershed area was about 1.0 for streams in eastern United States. An exponent value of 1.0 means that discharge increases in direct proportion to watershed area. However, extending this analysis over a large area that is not hydrologically homogeneous results in exponent values slightly less than 1.0 (Dunne and Leopold 1978, Leopold 1994). In Fig. 3, the exponent (slope of the log–log curve) is 0.88. If we exclude Rattlesnake Springs and Sycamore Creek, which are both flashy desert streams, the exponent becomes 0.96 ($r^2 = 0.93$, $p < 0.001$, $n = 31$).

The relationship between discharge and pre-

TABLE 2. Results of principal components (PC) analysis of the physical charactersitics of the streams.

	PC 1	PC 2	PC 3	PC 4
Correlations between PCs and original variables				
Temperature	−0.185	0.603	−0.417	0.233
Ln (watershed area)	0.538	0.217	0.067	0.455
Ln (stream gradient)	−0.436	−0.339	0.109	0.817
Square root (latitude)	0.318	−0.579	0.082	−0.028
Square root (precipitation)	−0.364	0.271	0.803	−0.138
Ln (discharge)	0.503	0.258	0.400	0.227
Proportion of variance explained by PC	0.474	0.345	0.119	0.053
Cumulative proportion of variance explained	0.474	0.819	0.938	0.991

cipitation shown by Fig. 4 is interesting and complex. In areas of low precipitation, direct evaporation is high and little precipitation goes to stream flow. In some areas and some years, total evaporation may equal precipitation resulting in endorheic basins. With higher precipitation, there is more terrestrial vegetation and plant transpiration becomes the dominant evaporative process. However, our data suggest that in regions of higher precipitation, total evapotranspiration (direct evaporation plus transpiration and interception) is a lower percent of precipitation than in more arid climates. Similar analyses are usually done on a much smaller scale than our global analysis. For example, at Coweeta Hydrologic Laboratory (North Carolina), higher elevation watersheds have higher precipitation. Because these watersheds are cooler, there is less evaporation and a shorter growing season (less transpiration) (Swift et al. 1988), and therefore a greater percent of precipitation goes to discharge. Looking at one watershed at Hubbard Brook Experimental Forest (New Hampshire) over several years of varying precipitation, Likens and Bormann (1995) found that stream discharge was directly proportional to precipitation. This relationship means that discharge as a percent of precipitation would be asymptotic, with a graph similar to the data in Fig. 4B (anomalous points excluded). Our results and the 2 cited studies show very different patterns at different scales, but all emphasize the strong regulatory role of terrestrial vegetation on stream discharge.

Measurements of gradient made on a single stream usually indicate a graded condition, that is, a smooth decrease in gradient downstream (e.g., Morisawa 1968), though deviations from this pattern can occur as a stream passes over varying geologic surfaces. Extending this sort of analysis to a comparison of many streams points out distinctive characteristic of some streams. For example, the low gradient coastal-plain streams (Buzzards Branch, Virginia, Creeping Swamp, and the Ogeechee River) fall well below the line in Fig. 5A. The mountain streams of Puerto Rico and Oregon fall above the line.

Extensive analyses have compared stream width with various measures of stream size (order, discharge, watershed area) (e.g., Leopold et al. 1964, Morisawa 1968, Strahler 1975, Leopold 1994). Because of differences in determining stream order in various geographic areas, order is probably the least useful measure of stream size when making comparisons beyond a single basin. Also, when making comparisons among streams with widely varying precipitation, watershed area is not very useful. Comparisons of width to discharge, whether done within a basin or on a larger regional scale, always show relationships similar to Fig. 5, a straight line on a log–log plot. The exponent of the implied power function is typically around 0.5 for downstream comparisons (Leopold et al. 1964, Leopold 1994). The exponent value from Fig. 5B is 0.42, well within the range of typical values reported by Park (1977).

In the principal components analysis, principal component 1 (PC 1) was well correlated with stream size (discharge and watershed area, Table 2). This principal component explained 47% of the variation among streams. An additional 34% of the variation among streams was explained by PC 2, which was correlated with water temperature and latitude (Table 2) but was not related to just these 2 variables. For example, Hugh White Creek and Satellite Branch (both at Coweeta Hydrologic Laboratory, North

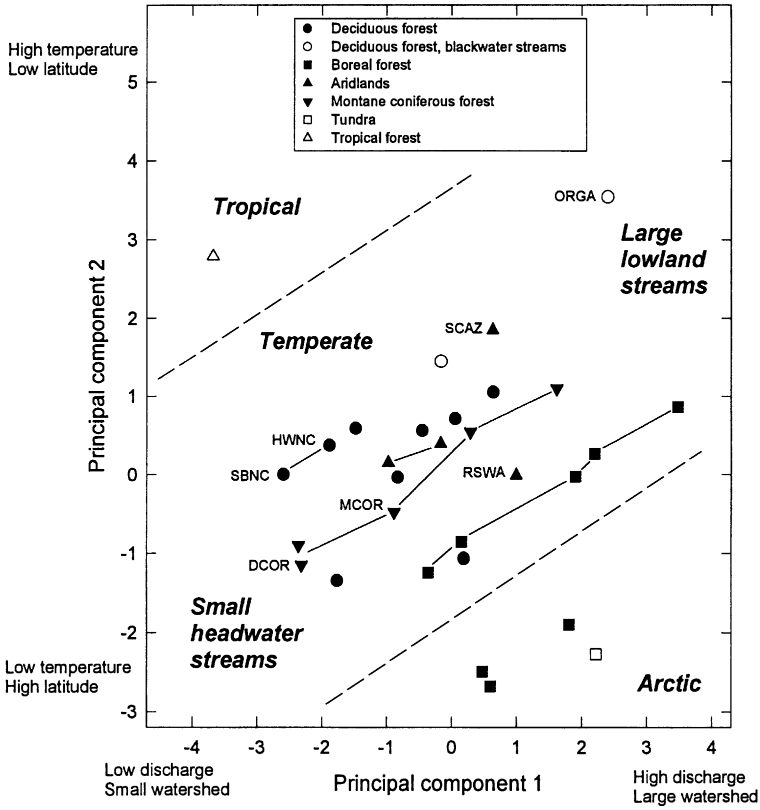

FIG. 6. Principal components (PC) analysis of the physical characteristics of the streams. PC 1 was well correlated with stream size (discharge and watershed area) and PC 2 was correlated with water temperature and latitude. The dashed lines separate tropical, temperate, and arctic zones. Solid lines connect streams within the same or adjacent drainages. Site acronyms are defined in the first chapter of this paper (Webster and Meyer 1997).

Carolina) are at the same latitude. However, the plot of Hugh White Creek was higher than that of Satellite Branch on PC 2 although the average temperature reported for Hugh White Creek is slightly cooler than that of Satellite Branch (Fig. 6). Similarly, Mack Creek is slightly cooler than Devil's Club Creek (both at Andrews Experimental Forest, Oregon) but its plot was higher on PC 2 (Fig. 6). PC 3 was strongly correlated with precipitation and explained 12% of the variance, and PC 4 was correlated with stream gradient and added 5% to the explained variance (Table 2). Graphing PC 1 versus PC 2 (Fig. 6) shows a clear separation among tropical, temperate, and arctic streams on a diagonal from upper left to lower right. The other diagonal (lower left to upper right) represents the continuum from small headwater streams to large lowland streams. The solid lines drawn in Fig. 6 connect streams within the same or adjacent drainages: Hugh White Creek and Satellite Branch at Coweeta; the prairie and gallery forest sites on Kings Creek at Konza Prairie, Kansas; the 5 Oregon sites in the McKenzie River basin; and the 5 Quebec sites. These lines are nearly parallel, in each case extending from lower left to upper right as one goes from upstream to downstream. The 2 sites that seem most out of place in Fig. 6 are the desert streams, Rattlesnake Springs and Sycamore Creek, but these 2 sites separated out clearly in the 3rd principal component.

Cushing et al. (1980) made a similar analysis of 35 streams using a broader suite of variables including nutrients and CPOM input. They also found that their 1st principal component was strongly correlated with watershed area, though a variety of other variables were also important.

Temperature fluctuation and nitrate were highly correlated with their 2nd principle component. One difference between their analysis and ours was that precipitation was highly correlated with their 1st principle component but didn't come into our analysis until the 3rd principle component. The lack of a temperature effect and the greater importance of precipitation in the study by Cushing et al. were probably results of the more limited latitudinal extent of their sites.

Conclusions

The 35 streams used in this study were not chosen to represent the range of physical conditions of streams throughout the world. Rather, they were chosen because of the availability of data on organic processes. However, where comparisons were possible, relationships among physical variables of the 35 streams were similar to the relationships among the same variables in more extensive studies. Stream size, water temperature, and precipitation appear to be the most important variables physically characterizing the streams. These variables set the template for organic processes occurring in streams. However, as becomes evident in analyses of organic processes, the influence of these physical processes is largely indirect through their effects on terrestrial vegetation.

Acknowledgements

This work was supported by the Coweeta Long Term Ecological Research grant from the National Science Foundation. Bert Cushing and Judy Meyer provided helpful comments on an earlier version of this chapter.

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A comparison of primary production in stream ecosystems

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The objective of this paper is to identify physical, chemical, and biological variables that might help explain the wide range of primary production observed in streams from a variety of biomes and locations throughout the world. We used regression approaches to search for predictive, statistical relationships that might reveal how aquatic, riparian, and watershed vari-