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AVERAGE DISCHARGE, PERENNIAL FLOW INITIATION, AND CHANNEL INITIATION – SMALL SOUTHERN APPALACHIAN BASINS[1]

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ABSTRACT: Regional average evapotranspiration estimates developed by water balance techniques are frequently used to estimate average discharge in ungaged streams. However, the lower stream size range for the validity of these techniques has not been explored. Flow records were collected and evaluated for 16 small streams in the Southern Appalachians to test whether the relationship between average discharge and drainage area in streams draining less than 200 acres was consistent with that of larger basins in the size range (> 10 square miles) typically gaged by the U.S. Geological Survey (USGS). This study was designed to evaluate predictors of average discharge in small ungaged streams for regulatory purposes, since many stream regulations, as well as recommendations for best management practices, are based on measures of stream size, including average discharge. The average discharge/drainage area relationship determined from gages on large streams held true down to the perennial flow initiation point. For the southern Appalachians, basin size corresponding to perennial flow is approximately 19 acres, ranging from 11 to 32 acres. There was a strong linear relationship ($R^2 = 0.85$) between average discharge and drainage area for all streams draining between 16 and 200 acres, and the average discharge for these streams was consistent with that predicted by the USGS Unit Area Runoff Map for Georgia. Drainage area was deemed an accurate predictor of average discharge, even in very small streams. Channel morphological features, such as active channel width, cross-sectional area, and bankfull flow predicted from Manning's equation, were not accurate predictors of average discharge. Monthly baseflow statistics also were poor predictors of average discharge.
(KEY TERMS: headwater streams; average discharge; channel morphology; baseflow separation; perennial flow; channel initiation.)

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INTRODUCTION

A linear relationship between average discharge and drainage area (assuming similar climate conditions over a basin) is a basic tenet of hydrologic water budgets. As long as the difference between precipitation and evapotranspiration is relatively constant, average discharge necessarily increases linearly with drainage area. Exceptions to this rule are found in areas with large amounts of ground water fracture flow, typically in Karst topography (Evans *et al.*, 2001), and also in arid areas where streams lose flow to ground water recharge. Data from which this relationship has been repeatedly observed come mainly from U.S. Geological Survey (USGS) gages on streams draining tens to thousands of square miles. At the small scale (basins less than 200 acres), there is little observational data to test whether this relationship still holds or whether ground water underflow becomes a significant portion of a basin water budget.

Accurate techniques for estimating average discharge in small ungaged streams are valuable because many regulations, as well as best management practice recommendations, are based on measures of stream size such as average discharge or perennial flow. Furthermore, estimates of average discharge can be valuable in geomorphic characterizations of stream systems and behavior (Jackson and Sturm, 2002; Benda *et al.*, 2003).

We evaluated the average discharge versus drainage area relationship using continuous flow data from 16 small streams in the Southern Appalachians,

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specifically northeast Georgia, southwest North Carolina, and southeast Tennessee. Average discharge was defined as it is used by the USGS – the average of all discharges over the period of record. For sufficiently long records, average discharge is equivalent to mean annual flow. This project was motivated by a regulatory concern that has arisen in Georgia. According to Georgia stream buffer law, small trout streams with average discharge of 0.057 cubic feet per second (cfs) or less are exempt from special streamside buffer requirements (Georgia Department of Natural Resources, 2000, unpublished document). The choice of this regulatory flow threshold (equivalent to 25 gallons per minute) was made arbitrarily by the state legislature without scientific input. This law necessitated development of empirical relations between average discharge and watershed characteristics so that average discharge could be predicted in the absence of flow data.

The objectives of this study were to answer the following four questions:

1. What is the relationship between average discharge and drainage area in small Southern Appalachian streams?
2. What is the range of drainage areas necessary to produce a definable channel and to produce perennial flow in small streams in the Southern Appalachians? This information would provide context for the observed average discharge-drainage area relationships.
3. What is the relationship between mean monthly baseflows and average discharge in small streams of the Southern Appalachians?
4. How do basic channel metrics relate to average discharge in small Southern Appalachian Streams?

Only streams in the Blue Ridge physiographic province in the Southern Appalachian physiographic region were targeted to constrain variation in landscape characteristics such as soil types, climate, and topography that influence streamflow and channel morphology (Dunne and Leopold, 1978; Higgins *et al.*, 1989; Genereux *et al.*, 1993; Bales and Pope, 2001; Potter, 2001).

The overall goal of this research was to determine whether drainage area, average monthly baseflow, or channel metrics could be used as accurate surrogates for average discharge measurements in small ungaged basins. An accurate measurement of average discharge in a stream requires several years of continuous stream gaging data, and a crude measurement of average discharge requires at least a year of continuous flow data. Obviously, many regulatory or best management practice determinations must be made quickly on the basis of map data or a single site visit. The drainage area of a particular stream can be easily measured or estimated using global positioning system (GPS) technology along with USGS topographical maps. This makes drainage area an ideal metric with which to estimate average discharge provided that the drainage area/average discharge relationship holds true for small streams. Baseflows, while variable, can be easily measured at any time of the year. Therefore, seasonal or monthly averaged baseflows, as they relate to average discharge, are potentially useful metrics for estimating average discharge. Similarly, it is much easier to measure variables such as active channel width (ACW), channel cross-sectional area, channel slope, and functional large woody debris (FWD) than to measure average discharge. Relationships between physical characteristics and average discharge would greatly assist in rapid field determinations of average discharge.

METHODOLOGY

Site Description and Selection

Previously monitored flow data was compiled from 13 small streams in the Southern Appalachian Mountains (Swank and Crossly, 1988; U.S. Forest Service Coweeta Hydrologic Research Station, unpublished data; Tennessee Valley Authority, unpublished data). These gage records were identified by interviewing more than 10 southeastern hydrologists and land managers to locate all extant small stream gage records from the southern Appalachians. These streams were located at the U.S. Forest Service (USFS) Coweeta Hydrologic Laboratory near Franklin, North Carolina, and in the vicinity of Ducktown, Tennessee (Table 1). Three additional small streams in North Georgia were selected for monitoring based on drainage area estimates (from USGS topographical maps) and accessibility. One of these streams was located in Stephens County in the Broad River drainage, and the other two streams were located in Fannin County in the Noontootla Creek and Big Creek drainages.

All 16 streams were either first-order or second-order and drained a naturally forested watershed at the time of gaging. The Tennessee streams no longer exist due to strip mining. Drainage areas ranged from 6 to 140 acres, averaging 54 acres (Table 1). Gradients of the existent streams averaged 14 percent and varied from 3.3 to 23 percent (Table 2).

TABLE 1. Location, Source, Data Period, Average Discharge, and Drainage Area of Small Southern Appalachian Streams.

Watershed	Location (county/state)	Source	Years of Data	Data Period	Average Discharge (cfs)	Adjusted Average Discharge (cfs)	DA+ (ac)
A	Macon, North Carolina	CHL	65	1935 to 2000	0.1150	na	29.7
B	Macon, North Carolina	CHL	50	1938 to 1988	0.6627	na	148.0
C	Macon, North Carolina	CHL	62	1936 to 1998	0.1416	na	30.2
D	Macon, North Carolina	CHL	50	1938 to 1988	0.4221	na	79.3
E	Macon, North Carolina	CHL	52	1946 to 1998	0.7444	na	94.7
F	Macon, North Carolina	CHL	57	1943 to 2000	0.8946	na	117.8
G	Macon, North Carolina	CHL	15	1985 to 2000	0.0438	na	18.5
H	Macon, North Carolina	CHL	15	1985 to 2000	0.0248	na	12.8
I++	Polk, Tennessee	TVA	11	1940 to 1951	0.0236	na	15.6
J++	Polk, Tennessee	TVA	5	1940 to 1945	0.0039	na	6.7
K++	Polk, Tennessee	TVA	10	1942 to 1952	0.0049	na	6.5
L++	Polk, Tennessee	TVA	11	1940 to 1951	0.0040	na	5.1
M++	Polk, Tennessee	TVA	16	1935 to 1951	0.0106	na	6.0
N	Fannin, Georgia	UGA	1	2001 to 2002	0.1649	0.2567	30.2
O++	Stephens, Georgia	UGA	1	2001 to 2002	0.0176	0.0274	13.1
P++	Fannin, Georgia	UGA	1	2011 to 2002	0.0541	0.0843	20.8
2178400*	Rabun, Georgia	USGS	38	1964 to 2002	184	na	36160
2177000*	Oconee, South Carolina	USGS	63	1939 to 2002	644	na	132480
3544947*	Towns, Georgia	USGS	17	1984 to 2001	5.35	na	1069
2330450*	White, Georgia	USGS	21	1981 to 2002	128	na	28608

+DA stands for drainage area.
++Streams with intermittent flow in the gage record.
*USGS gage numbers.
Sources: Coweeta Hydrologic Laboratory (CHL), Tennessee Valley Authority (TVA), and The University of Georgia (UGA).
Notes: The adjusted average reported for the UGA gages attempts to eliminate bias from the one-year record monitored during a drought period. Long term USGS records were used to calculate an adjustment factor equal to the average ratio of measured average discharge for water year 2002 to the long term average discharge determined from the whole record.

TABLE 2. Channel Metrics of Small Southern Appalachian Streams Including Active Channel Width (ACW), Slope, Cross-Sectional Area (X-Sec), and the Functional Large Woody Debris Frequency (FWD/ACW).

Watershed	Average Discharge (cfs)	DA (ac)	ACW (ft)	Slope (percent)	X-Section (ft^2)	FWD/ACW
A	0.1150	29.7	4.56	17	3.46	0.63
B	0.6627	148.0	8.27	13	6.73	1.89
C	0.1416	30.2	6.20	12	8.04	1.98
D	0.4221	79.3	6.40	16	6.99	2.34
E	0.7444	94.7	9.41	21	8.08	2.29
F	0.8946	117.8	11.15	18	10.63	3.57
G	0.0438	18.5	8.36	23	8.14	1.40
H	0.0248	12.8	5.58	19	5.30	0.94
N	0.1649	30.2	4.46	4.4	1.93	0.20
O	0.0176	13.1	3.74	3.3	1.71	0.11
P	0.0541	20.8	3.90	5.4	4.84	0.89

Flow Measurement in Newly Monitored Sites

At two of the three newly monitored streams, wooden 90 degree V-notch weirs were installed for measuring flow. Because of bedrock constraints on the bottom of the third stream, a 2-foot H-flume was installed. Pressure transducers measured the gage heights, which were recorded and saved using a CR10X data logger over the course of a year. The loggers and transducers were checked monthly for damage, to change batteries, and to download recorded data. The heights of flow through the weirs were converted to a flow rate using the following equation (USDI, 1981):

$$\text{Discharge (cfs)} = 2.49 * H^{2.48}$$

where H is the gage height measured in feet. The following 2-foot H-flume calibration equation was used to calculate the flow rate from heights through the H-flume (McCuen, 1998):

$$Y = -0.0527 X^5 - 0.1987 X^4 - 0.1558 X^3 + 0.2657 X^2 + 2.2377 X + 0.3522$$

for all heights > 0.0193 feet and discharge > 0.0014 cfs, where $Y = \text{Log}_{10}$ (discharge in cfs) and $X = \text{Log}_{10}$ (height in feet). These equations yielded flow rate in cubic feet per second (cfs). These three stream gages were tied into the stream banks, and thus they did not measure down valley flow through the valley colluvium/alluvium nor did they measure ground water flow (predominantly fracture flow) leaving the basins.

Coweeta and Tennessee Valley Authority Flow Measurements

The Coweeta gages are V-notch weirs with stilling basins tied into concrete dams penetrating through and across the valley alluvium/colluvium. Therefore, the Coweeta gages intercept and record down valley alluvial/colluvial flow. They only miss ground water moving through fractures beneath the valley floor. The Tennessee Valley Authority (TVA) gages no longer exist, and information regarding design of the TVA gages was not located. Because the gages used in the flow analysis feature different designs, there are unaccounted biases in the data sets.

Channel and Perennial Flow Initiation

Thirty streams located throughout North Georgia were surveyed to find points of channel and perennial flow initiation. Channel initiation points were noted as places where a definable channel had formed that drains the landscape. Using a Garmin GPS, channel initiation points were identified and drainage areas were determined from USGS topographical maps. These streams were surveyed again to estimate points of perennial flow initiation between late June and early August, coinciding with the beginning and middle of the usual low flow period. Locations of flow initiation points were also identified using a Garmin GPS and areas were determined from topographical maps.

Flow Analysis

Average discharge values were calculated for each gaged stream by averaging all measured flow values over the entire record. For the TVA and Coweeta gages, discharge records reported daily average flows, and for the University of Georgia (UGA) gages, discharge was measured hourly for stages below 1 foot and at 10 minute intervals for stages above 1 foot. Weighting of the shorter interval measurements was necessary to calculate average discharges for the UGA gage records.

The UGA gages were monitored for only one year (water year 2002), during which the area experienced drought conditions. Therefore, the average discharges measured at the UGA gages during water year 2002 underestimate the long term average discharge for these sites. Therefore, the actual measured averages are reported for these sites as well as an adjusted average calculated by using the local long term USGS gages to determine a correction factor with which to scale water year 2002 average discharges up to long term average discharges. Using the three local USGS long term gages (Table 1), it was determined that the long term average discharge was 55.7 percent higher than the water year 2002 average discharge, so the average discharges from the UGA gages were multiplied by 1.557 to estimate the long term average for these stations.

For the baseflow analysis, a computer program was developed to separate baseflow from storm flow using daily flow values. Storm flow was separated from baseflow using a 1 percent threshold for daily flow changes. If the discharge increased more than 1 percent from one day to the next, the next day's flow

value was considered storm flow and the previous day's value was returned. Conversely, if discharge decreased less than one percent, that day's flow was considered baseflow. This process was repeated for each of the daily flow values in each data set therefore returning only baseflow values.

Baseflow is mainly a result of ground water inputs and diminishes slowly between storms (Dunne and Leopold, 1978). Average baseflows vary monthly. In the southern Appalachians, baseflows are highest January through March and lowest from August through October. Monthly baseflow averages were calculated and the distribution of baseflow values was determined for each month at 14 of the 16 streams. It is assumed that the monthly baseflow values of these 14 streams are similar to those of similar size and location (Southern Appalachians, Blue Ridge Province).

Measurement of Physical Characteristics

Drainage area measurements were determined by walking the drainage area perimeter of each of the three monitored streams with a Trimble GPS. Drainage areas of the 13 streams provided by the Coweeta Hydrologic Lab and the Tennessee Valley Authority were previously determined by those organizations. Geomorphological characteristics were measured along the reach (upslope of the water control structure) of 11 of the 16 streams for a distance of 20 times the active channel width of the channel. The five TVA streams could not be surveyed because they no longer exist. Five active channel widths (ACWs) were taken at regular intervals (four times the ACW) along each reach. Five cross-sectional area measurements were made and the reach average slope was determined using a standard surveying level (slope < 5 percent) or a clinometer (slope > 5 percent). The amount of functional large (diameter > 0.33 ft) woody debris (FWD) was tallied for each reach. The tallied amount of FWD was then divided by the number of ACWs in the reach to get FWD frequency. Correlations and multiple regressions between drainage area, average discharge, and geomorphological characteristics including gradient, ACW, cross-sectional area, cross-sectional area multiplied by slope, bankfull width (based on Manning's equation), and FWD content were determined.

RESULTS AND DISCUSSION

Channel and Perennial Flow Initiation

The range of drainage areas necessary to form a defined channel along with the range of areas apparently needed to produce perennial flow are presented in Figure 1. A definable channel is formed in a basin ranging from 7 to 20 acres (average is 11 acres) while a basin that apparently yields perennial flow ranged from 11 to 32 acres (average is 19 acres). Figure 1 shows a fairly tight distribution of both channel and perennial drainage areas. According to Figure 1, many of the gaged streams in this study would be considered intermittent. Based on actual flow data, streams I, J, K, L, M, O, and P were intermittent (Table 1).

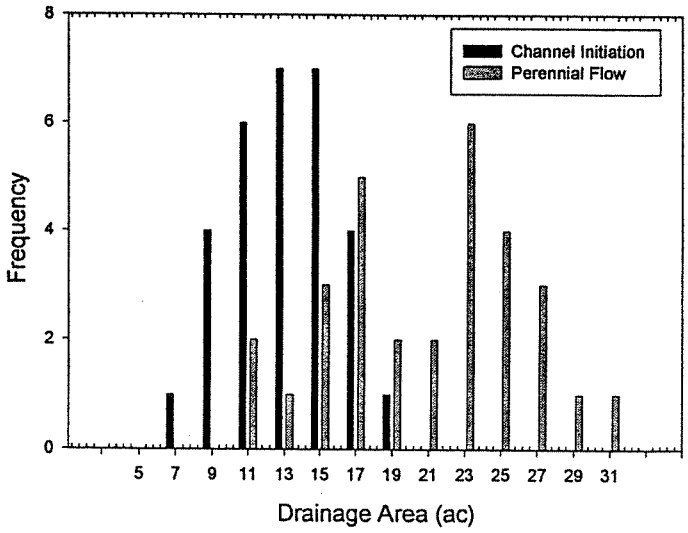

Figure 1. Channel and Perennial Flow Initiation of Small Southern Appalachian Streams.

Drainage Area and Average Discharge

For streams draining more than 16 acres, an area approximately corresponding to the area needed to produce perennial flow, the relationship between average discharge and drainage area is nearly linear and shows little scatter (Figure 2) (including USGS gages, $R^2 = 0.99$, $P < 0.0001$; excluding USGS gages, $R^2 = 0.85$, $P < 0.0001$). Whether the UGA streamflows are adjusted or not adjusted for drought bias makes little difference to the interpretation of the data (Figure 2). Included in Figure 2 are the upper and lower bound of expected average discharge for northeast

Georgia determined from the USGS unit area runoff map for Georgia (USGS, 1982). The unit area runoff map is a contour map with lines of equal average unit area runoff. It was developed from water budget principles using data from larger streams to calibrate evapotranspiration values. According to the USGS unit area runoff map, the average runoff in the Blue Ridge physiographic region of Georgia is in the range of 1.6 to 3.4 cfs/mi^2. For comparison, data from four local USGS gages (draining 1.7, 45, 57, and 207 square miles) are also depicted on the graph (Figure 2). Two of the Coweeta streams lay slightly above the upper value expected from the unit area runoff map, but all the other small streams draining more than 18 acres lie within the expected range of average discharge based on drainage area. The Coweeta streams are four miles north of the Georgia border and do not show up on the Georgia unit area runoff map. It is possible that orographic effects at Coweeta are driving the higher than expected flows in two of the Coweeta streams.

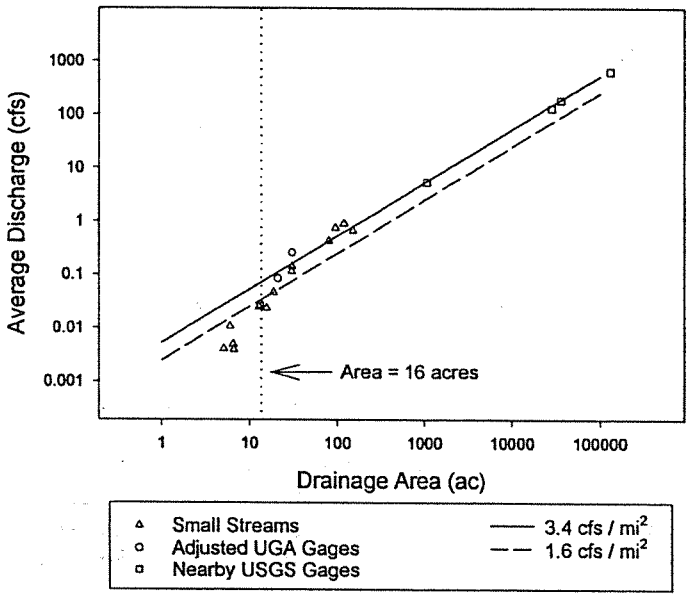

Figure 2. Average Discharge/Drainage Area Relationship Held by Small Southern Appalachian Streams. Including USGS Gages, $R^2 = 0.99$, $P < 0.0001$; Excluding USGS Gages, $R^2 = 0.85$, $P < 0.0001$.

Average discharge in intermittent streams (roughly corresponding to streams draining less than 16 acres) is less than would be expected from regional water balances. In other words, downward extrapolation of average discharge versus drainage area relationships observed in larger streams does not work for intermittent streams in the southern Appalachians. The authors infer that ground water flow beneath the gages becomes a significant portion of the basin water budget in intermittent stream basins.

Baseflow Analysis and Average discharge

Figure 3 depicts box plots of monthly unit area baseflow values separated by a 1 percent difference in daily flow (for about 328 years of flow data taken from 14 small streams), respectively. The high variability in monthly baseflows from year to year renders this statistic useless for average discharge estimation.

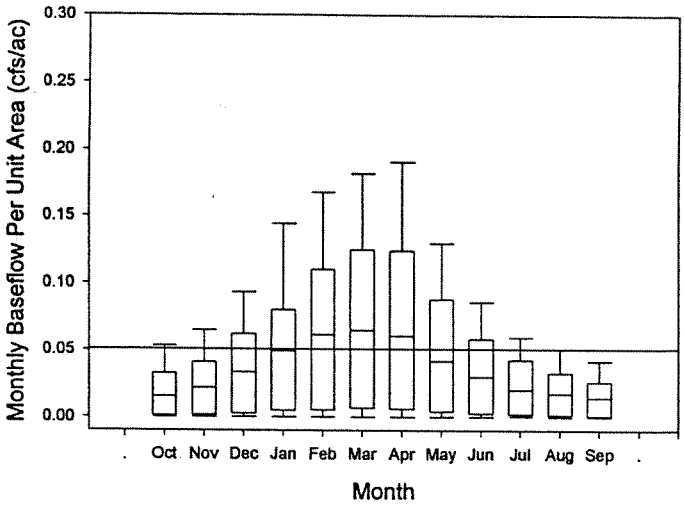

Figure 3. Mean Monthly Baseflow Per Unit Area for 16 Small Southern Appalachian Streams. Baseflow separated at a 1 percent threshold. Solid line indicates average unit area discharge.

Channel Characteristics and Average Discharge

A summary of the channel metric values is presented in Table 2. Average discharge is positively correlated with ACW (Figure 4) ($R^2 = 0.68$, $P = 0.0017$), but the relationship is not nearly as strong as the average discharge – drainage area relationship. As expected, active channel width increases with increased drainage area (Figure 5) ($R^2 = 0.53$, $P = 0.0104$). Cross-sectional area, a metric of cross-sectional area times slope, and bankfull width (based on Manning's equation) were all positively correlated with average discharge ($R^2 < 0.41$, $P > 0.030$) and drainage area ($R^2 < 0.31$, $P > 0.070$), but the relationships were weak.

Active channel width tends to increase with average discharge. However, other investigators have

found that a variety of factors including woody debris frequency, step frequency, and gradient affect ACW (Jackson and Sturm, 2002). In small Southern Appalachian trout streams, ACW seems to be highly correlated with FWD frequency (Figure 6). Actually FWD frequency is a better predictor of channel width than average discharge. Therefore, a two-variable model of ACW verses average discharge and FWD was evaluated (Figure 7) ($R^2 = 0.79$, $P = 0.001$). While active channel width can serve as a crude predictor of average discharge, there is a lot of noise in the relationship based on the 11 points of data used in this study. Woody debris frequency may be responsible for this noise.

All the channel metrics were more closely related to average discharge than to drainage area. This is probably because the formation of these morphological features is directly related to stream power which is a function of discharge and slope. Predicting average discharge based solely on channel metrics is inaccurate, but channel metrics can be used as a check on predictions developed from discharge/drainage area relationships.

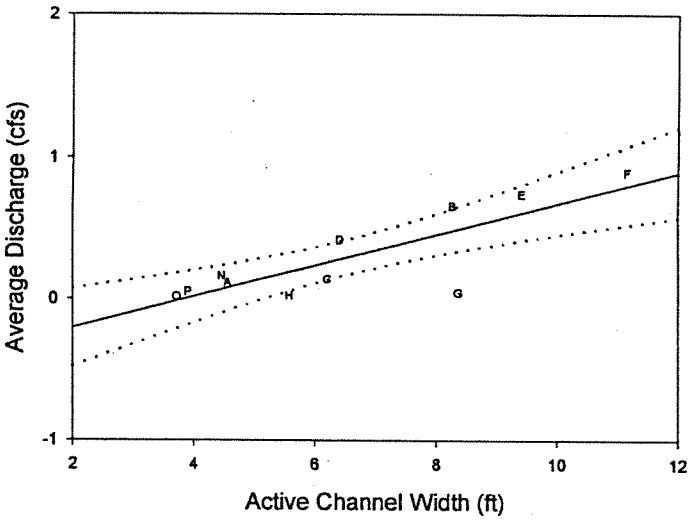

Figure 4. Average Discharge With Regard to Active Channel Width in Small Southern Appalachian Streams. $R^2 = 0.68$, $Y = 0.1096\ X - 0.4188$, $P = 0.0017$. Dotted lines represent 95 percent confidence interval.

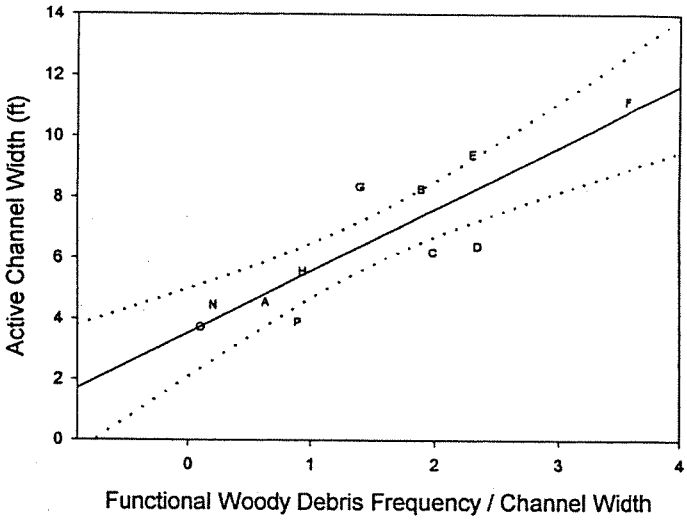

Figure 6. Active Channel Width With Regard to Functional Large Woody Debris Frequency in Small Southern Appalachian Streams. $R^2 = 0.76$, $Y = 0.62\ X - 1.08$, $P = 0.0004$. Dotted lines represent 95 percent confidence interval.

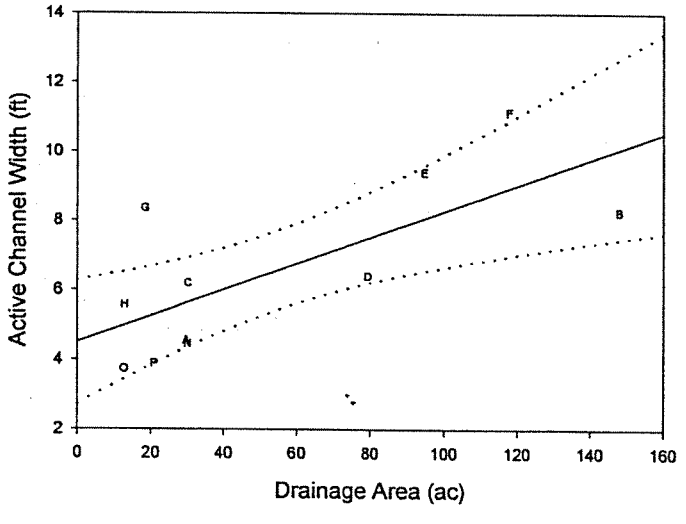

Figure 5. Active Channel Width with Regard to Drainage Area in Small Southern Appalachian Streams. $R^2 = 0.53$, $Y = 0.0376\ X - 4.5121$, $P = 0.0104$. Dotted lines represent 95 percent confidence interval.

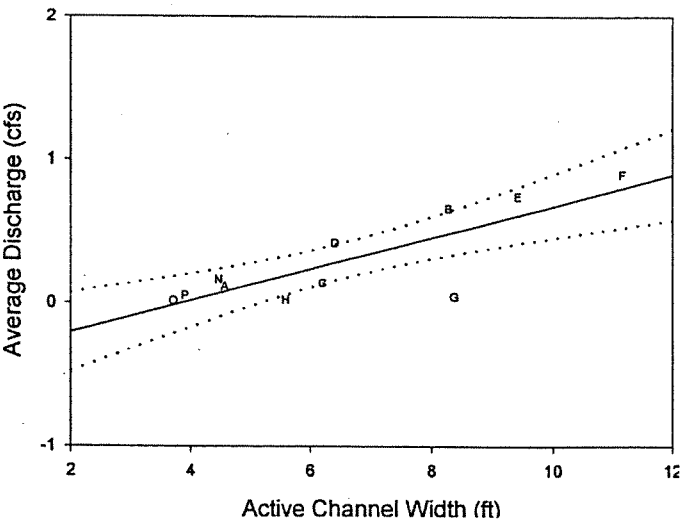

Figure 7. Active Channel Width and Predicted Active Channel Width Determined by Average Discharge and Functional Large Woody Debris Frequency Model. $R^2 = 0.79$, $Y = 0.99\ X - 6.66$, $P = 0.0010$. Dotted lines represent 95 percent confidence interval.

SUMMARY AND IMPLICATIONS

An accurate prediction of average discharge can be useful in management plans (Richter *et al.,* 1997), in geomorphic characterization of streams, and in implementing policies such as those in Georgia stream buffer law. The average discharge-basin flow relationship is an ideal way of predicting average discharge provided that the relationship holds at all scales.

For perennial streams draining more than about 16 acres in the southern Appalachians, the relationship between average discharge and drainage area is linear and consistent with that repeatedly observed in larger streams, indicating that ground water underflow does not become a significant portion of the water budget unless the drainage area is less than about 16 acres and streamflow is intermittent. Therefore, in this physiographic region, drainage area serves as an accurate predictor of average discharge even for very small perennial streams. Active channel width was the only channel morphological feature that was strongly correlated with average discharge. Basic channel metrics are not precise or accurate predictors of average discharge, but can be used to reaffirm estimates based on drainage area.

The average discharge/drainage area relationship show here only applies to the Blue Ridge physiographic region in the Southern Appalachian Mountains. More small stream gage data is needed to develop an understanding of this relationship in small streams in other physiographic regions. It is likely that similar relationships would be found in gaining streams in humid physiographic regions where shallow ground water fracture flow is not prevalent.

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