ABSTRACT

BRUTON, JEFFREY GRIFFIN. Headwater catchments: Estimating surface drainage extent across North Carolina and correlations between landuse, near stream, and water quality indicators in the Piedmont physiographic region. (Under the direction of James D. Gregory.)

Headwater drainages are an important part of larger river networks because of their linkage to the surrounding landscape. Most of the drainages are not shown as blue-lines on the commonly used USGS 1:24,000 scale topographic map series, especially in finely dissected terrain. In a preliminary study, the traditional contour crenulation (T-CC) method was used to map-measure drainage lengths in seven first-order blue-line (FO-BL) drainage areas located in the Piedmont (P) physiographic region of North Carolina (NC). They were compared to field-measured lengths. Results indicated a strong correlation between the lengths ($R = 0.98$). Results also indicated strong correlations between lengths and areas for both methods (Field Measured, $R = 0.99$ and T-CC, $R = 0.97$). Drainage densities (Dds) for each method were compared using ANOVA and Tukey-Kramer procedures. Mean field-measured and T-CC Dds were not significantly different. Both were significantly greater than the mean FO-BL Dd.

The preliminary study was expanded and included 122 randomly selected FO-BL catchments across five topographically diverse physiographic regions. Results indicated that catchment size and map contour intervals were also important factors in predicting T-CC lengths from areas. T-CC length prediction equations were tested in the Piedmont and Mountain regions. T-CC and predicted Dds were compared. Results indicated that mean T-CC and predicted Dds were not significantly different for either region. By region, the T-CC lengths were 2 to 4 times greater than FO-BL lengths.

Macroinvertebrates family taxa richness (FTR) and Hilsenhoff family biotic index (FBI) values were used to assess the near-stream habitat and average runoff condition of 33 headwater catchments located in the upper Neuse River basin of NC. Near-stream habitat condition (HR) was rated using elements of the US Environmental Protection Agency (US EPA) Rapid Bioassessment Protocols; bank stability, bank vegetation protection, riparian zone width, and riparian zone vegetation structure. Catchment runoff condition was estimated using the US Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS) curve number (CN) method. Three reference sites were selected to represent small, medium, and large size-class reference conditions. Catchment areas and the four assessment variables (CN, HR, FTR, and FBI) were normally distributed within each of the catchment size-classes, as were the CN and FBI variables for the 33 catchments combined.

The relationship between the curve number (CN) and each of the assessment variables (HR, FTR, and FBI), as well as between each of the assessment variables was examined using linear regression. The analysis was performed for each catchment class-size and for all 33 catchments combined. A strong negative correlation between the CN by HR combination suggested that increased runoff condition is related to decreases in near-stream habitat quality. The strong negative correlation between the HR by FBI combination suggested that as habitat quality is reduced, water quality is also reduced. The very strong positive correlation between the CN by FBI combination suggested that increased runoff condition is related to decreases in overall water quality.

Examination of the three reference sites showed progressive increases in FTR (15, 27, and 33) with increases in catchment area (28, 76, and 286 acres), while maintaining low FBI values (3.64, 3.04, and 3.67) and excellent water quality (WQ) ratings. These results suggested that higher FTRs were found in larger catchments, however, the higher FTRs in the impacted catchments were due to the presence of higher numbers of tolerant macroinvertebrate families. Linear regression equations were developed to predict FBIs using CNs for each of the size-classes and with all 33 catchments combined.

HEADWATER CATCHMENTS: ESTIMATING SURFACE DRAINAGE EXTENT ACROSS NORTH CAROLINA AND CORRELATIONS BETWEEN LANDUSE, NEAR STREAM, AND WATER QUALITY INDICATORS IN THE PIEDMONT PHYSIOGRAPHIC REGION

by
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A dissertation submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the
Degree of Doctor of Philosophy

FORESTRY

Raleigh

2004

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DEDICATION

This dissertation is dedicated to my loving wife Janice Ellen Odom whose never-ending confidence in my abilities and persistent positive encouragement through the years was instrumental in its completion.

BIOGRAPHY

Jeffrey Griffin Bruton was born August 31, 1953 and was raised in Fayetteville, North Carolina. He graduated from Terry Sanford Senior High School in 1971 and then served four years as a military policeman in the United States Air Force. After serving in the military he was able to attend college with financial assistance provided through provisions of the GI Bill. He received an Associate in Science degree from Sandhills Community College in 1978, a Bachelor of Science degree in Conservation from North Carolina State University in 1980, and a Master of Science degree in Ecology from North Carolina State University in 1988. Since 1990, he has worked as an Environmental Specialist for the North Carolina Department of Environment and Natural Resources, Division of Water Resources, administering the Water Resources Development Project Grant Program and managing the program's stream restoration activities.

ACKNOWLEDGEMENTS

I would like to thank the following individuals for their contributions towards this academic endeavor: Dr. Sam Mozley for the initial inspiration, Dr. Jim Rice, whose criticisms forced me to reevaluate my interests and goals, Mr. John Sutherland for allowing me to incorporate such an endeavor into my professional work environment, committee member Dr. Jean Spooner for her thorough reviews and never-ending enthusiasm, committee member Dr. Garry Grabow for his assistance in the field (literally) and with statistical lessons and editorial reviews, committee member Dr. Greg Jennings for his invaluable assistance through transitions and trying times, and committee chair Dr. Jim Gregory, who stuck with me from the beginning and added greatly to final product.

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CHAPTER ONE

USING CATCHMENT RUNOFF CONDITION AND NEAR STREAM HABITAT RATINGS TO PREDICT MACROINVERTEBRATE WATER QUALITY INDICATOR VALUES IN PIEDMONT HEADWATER STREAMS

Abstract

Macroinvertebrates family taxa richness (FTR) and Hilsenhoff family biotic index (FBI) values were used to assess the near-stream habitat and average runoff condition of 33 headwater catchments located in the upper Neuse River basin of North Carolina. Near-stream habitat (bank and riparian habitat) condition was rated (HR) using elements of the US Environmental Protection Agency (US EPA) Rapid Bioassessment Protocols: bank stability, bank vegetation protection, riparian zone width, and riparian zone vegetation structure. Catchment runoff condition, the weighted average runoff curve number (CN), was estimated using the US Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS) curve number method. Three reference catchments were selected to represent small, medium, and large size-class conditions. The relationship between these biological and runoff assessment variables was examined with linear regression.

The results of the matched pair regressions showed that correlations were strongest for the HR by FBI, CN by HR, and CN by FBI combinations. Within each of those combinations, the results were similar for each of the three size-classes of catchments except for the HR by FBI combination where the r^2 value for the large size-class was greater than those for the small and medium size-classes. The correlation for the CN by FBI combination was the strongest and most consistent within size-classes of catchments.

The strong negative correlation of the CN by HR regression suggested that higher runoff/rainfall condition is related to lower near-stream habitat quality. The strong negative correlation of the HR by FBI regression suggested that lower habitat quality is related to lower water quality. The very strong positive correlation of the CN by FBI regression suggested that higher runoff/rainfall condition is related to lower overall water quality.

An examination of the three reference catchments showed progressively greater FTR (15, 27, and 33) with greater catchment area (28, 76, and 286 acres), while maintaining low FBI values (3.64, 3.04, and 3.67) and excellent water quality (WQ) ratings. Those results suggested that higher FTR was found in larger catchments, however, the higher FTR in the catchments impacted by development was due to the presence of higher numbers of tolerant macroinvertebrate families.

This study demonstrated the utility of rapid bio- and habitat assessment procedures to assess water quality in headwater streams, which are currently not being evaluated in NC. It demonstrated the usefulness of using HRs and CNs in screening and setting headwater rehabilitation and protection priorities that could greatly reduce the resource and temporal requirements typically associated with rapid bioassessments. It also provided a tool for stream restoration practitioners to use in setting achievable restoration outcome measures. The study should be expanded to evaluate additional headwater catchments across the state.

Introduction

Headwater streams are located throughout a basin and originate near catchment divides. These small streams join together to form larger streams and rivers or run directly into larger rivers and lakes. Headwater streams are an important part of larger river networks because of their linkage to the surrounding landscape (Hynes 1970, Hynes 1975, Vannote et al. 1980, Webster et al. 1992, Allan and Flecker 1993, Bonell 1993, Allan et al. 1997, Bolstad and Swank 1997, Liken et al. 1997, Pringle 1997). For example, first through third order streams represent approximately 95% of the number and about 75% of the total length of stream channels on the landscape and carry as much as 90% of the excess flow, or runoff, in the US. Therefore, runoff from headwater areas can impact both the quantity and quality of the water received downstream and may impose important constraints on hazard control (i.e., flooding) as well as resource development on the main river (Strahler 1957, Leopold et al. 1964, Dunne and Leopold 1978, Kirkby 1978, Leopold 1994, Daniels and Gilliam 1996, Naiman 1983, Clinnick 1985, Cooper et al. 1987, Burt 1992, Webster et al. 1992, Kusler and Larson 1993, Gilliam 1994, Lenat and Crawford 1994, Gilliam et al. 1997, Wenger 1999, Alexander et al 2000, Peterson et al. 2001).

Until recently, regulatory agencies did not recognize the hydrological and ecological importance of small streams. As a consequence, headwater streams were largely overlooked and many have been lost from the landscape by human activities (Meyer and Wallace 2001). One reason that they continue to be overlooked in North Carolina (NC) is because water resource managers often rely on the blue-line symbols shown on US Geological Survey (USGS) 1:24,000 scale topographic maps for accounting, regulatory, and restoration purposes. For example, the NC Department of Environment and Natural Resources (DENR); Division of Water Quality (DWQ), Basinwide Planning Program uses the blue-lines to catalogue the use-support ratings of stream reaches across the state (NC DENR 2002a), however, any stream with a base flow wetted width of less than 3 meters is not rated. The

NC DWQ Wetlands/Water Quality Certification Unit uses the blue-lines in conjunction with stream-lines shown on county soil surveys to manage riparian buffers in the Neuse River and Tar-Pamlico River basins (NC DENR 2002b). The NC DENR Ecosystem Enhancement Program requires that potential stream restoration projects be located along a USGS designated perennial blue-line drainage to be eligible to receive stream restoration resources (NC DENR 2002c).

Because they are largely overlooked, headwater streams are susceptible to adverse impacts associated with urbanization, which include extensive changes in hydrology, channel morphology, and water quality (Leopold 1968, Hammer 1972, Hollis 1975, Klein 1979, Arnold et al. 1982, Booth 1991, Bolstad and Swank 1997, Booth and Jackson 1997, Doll 2002). For example, since headwater streams are direct receivers of runoff from the landscape their lack of inclusion in regulatory protection has resulted in their frequent filling, piping, moving, etc. associated with various changes in landuse. The impacts are typically gradual, operating at different spatial scales in a watershed, and influence instream conditions via multiple processes (Allan et al. 1997). As urbanization occurs, a watershed's response to precipitation is altered with the most common effects being reduced infiltration and decreased travel time, which significantly increases mass runoff and peak discharge. Increased stormflow, in turn, results in increased channel erosion and the degradation of in- and near-stream habitats. Thus, it has been suggested that the leading cause for decreases in the biological condition of urbanizing streams and the near-stream habitat is changes in a watershed's hydrologic regime (May et al 1997).

Recent catchment-wide assessments have used watershed imperviousness as an indicator of overall stream health (see review in Schueler 1994). For example, the amount of impervious surface in a watershed has been linked with stream quality measures such as macroinvertebrate community composition, macroinvertebrate community taxa richness, number of pollution intolerant taxa, diversity, and overall biological health (Benke et al. 1981, Pitt and Bozeman 1983, Pedersen and Perkins 1986, Jones and Clark 1987) as well as changes in physical and chemical characteristics of streams (Schueler 1994, May et al. 1997). Recent studies have suggested that good water quality is maintained at an impervious threshold of 8 to 15 percent (Benke et al. 1981, Schueler and Galli 1992, Shaver et al 1995, Wang et al. 2000, Stepenuck et al. 2002, Roy et al. 2003, Wang and Kanehl 2003). Minor increases in imperviousness above that threshold have been associated with declines in water quality and sharply lower aquatic insect diversity when imperviousness reached 25 to 30 percent (Jones and Clark 1987, Black and Veatch 1994).

The importance of considering the cumulative effects of various landuses in catchment-wide assessments was demonstrated by Bolstad and Swank (1997). They studied a rural watershed that was predominantly forested and had less than 6 percent of the total land area dedicated to developed and agricultural landuses. They found consistent downstream changes in water quality concomitant with downstream changes in landuse. During base-flow conditions stream water quality was high, however, during stormflow, water quality declined significantly. Bolstad and Swank (1997) suggested that the decrease in water quality during stormflow was due to increased overland flow and transport of materials directly to the stream.

The emphasis on macroinvertebrates in biological monitoring is because they are found in all aquatic environments, are less mobile than many other groups of organisms, are of a size that makes them easily collectable, and they show responses to a wide array of potential pollutants. Moreover, many macroinvertebrates have life cycles of a year or more so that short-term fluctuations in water quality is reflected in community composition. The most widely used macroinvertebrate metrics are taxa richness and taxa biological indicies (Lenat 1993). Since watershed imperviousness and stormwater runoff are directly related to water quality and near-stream habitat condition, macroinvertebrate monitoring has been recommended as a tool for watershed planners (Schueler 1994, Arnold and Gibson 1996, Lammert and Allan 1999, Stepenuck et al. 2002).

This study used weighted average runoff curve number (CN) as an indicator of catchment hydrologic condition, rather than percent imperviousness. All of the drainage area was used and major landuses were divided by hydrologic soil groups. The purpose of the study was to measure the accuracy of predicting the outcome of commonly used rapid bioassessment water quality indicators using a potential rapid catchment-wide assessment tool (i.e., runoff CNs).

Methods

A total of 33 headwater catchments located in Wake County, NC were selected for evaluation. The catchments were located within the Piedmont physiographic province on crystalline rock geology where Ultisol soils predominate. Annual rainfall averages approximately 45 inches per year. Formerly dominated by agriculture and forest, the region has experienced rapid urbanization in the last few decades. Landuses within each catchment ranged from completely wooded to highly urbanized with a wide variety of mixed landuses in between. Table 1 shows the catchment summary statistics and includes the primary landuses within each catchment.

Catchments were not randomly selected. Three of the catchments, WBU01, WBU02, and WBU03, were located at William B. Umstead State Park. The 5,500-acre park was established in 1934 under the Resettlement Administration. At the time, much of the previous oak-hickory-beech forest had become submarginal agricultural land due to poor cultivation and one-crop production practices. The three park sites were used as reference conditions and were located in a section of the park where the oak-hickory-beech forest has regenerated over the past sixty years.

The establishment of suitable references is an essential component of sampling design for biomonitoring and it has been suggested that local stream conditions be compared to regional reference reaches (Resh and McElravy 1993, Resh et al. 1995, Barbour et al. 1999). The drainage area sizes of the three reference catchments were 28 acres, 76 acres, and 286 acres, respectively, and were selected for their range in sizes and having a main stem stream with perennial flow. It was assumed that larger catchments would have the potential for greater taxa richness of stream macroinvertebrates (Vannote et al 1980); however, according to Lenat (1993), biotic indices are more reliable than taxa richness when water quality ratings are assigned to smaller streams.

The remaining 30 impacted catchments were selected based on their sizes being close to that of the reference sites, the need to include a variety of landuses, and having access to property for sampling and habitat evaluations. The areas of the 30 impacted catchments

Table 1. Catchment summary statistics. The table includes the catchment name, drainage area (acres), size-class (small, medium, or large), and major landuses.

Name	Area (acres)	Size-class	Major Landuse(s)
WBU_02	76	Medium	Forest
WBU_01	28	Small	Forest
WBU_03	286	Large	Forest
LW_11	121	Medium	Forest/Forestry/Rural Residential/Pasture
CC_01	42	Small	Forest/Rural Residential
CC_04	112	Medium	Forest/Abandoned Ag.
SF_01	14	Small	Forest/Forestry
LW_10	681	Large	Forest/Forestry/Rural Residential
WC_02	188	Large	Forest/Low Density Resdental
SF_02	142	Large	Forest/Forestry
WC_01	37	Small	Forest/High Density Resdental
WC_04	81	Medium	Forest/Open Field/Interstate Hwy.
LW_09	816	Large	Forest/Forestry/Pasture/Rural Residential
CC_03	495	Large	Forest/Forestry/Abandoned Ag./High Density Residential
CC_02	702	Large	Forest/Forestry/Abandoned Ag./High Density Residential
CSC_01	40	Small	Moderate Density Residential/School Yard
WC_05	81	Medium	Forest/Interstate Hwy.
LW_06	24	Small	Pasture/Row Crop/Forest
LW_01	82	Medium	Pasture/Forest/Concentrated Livestock Facility
WC_03	148	Large	Forest/High Density Residential/Interstate Hwy.
WC_08	91	Medium	Moderate Density Residential
LW_05	53	Small	Pasture/Row Crop/Forest
FGR_01	102	Medium	Moderate Density Residential
LW_03	98	Medium	Pasture/Concentrated Livestock Facility
BC_01	366	Large	Moderate Density Residential/High School
LW_08	60	Small	Pasture/Concentrated Poultry Facility
WC_07	661	Large	Moderate Density Residential/Commercial
LW_02	32	Small	Pasture/Concentrated Livestock Facility
LW_07	33	Small	Pasture/2-lane Hwy.
WC_06	25	Small	Moderate and High Density Residential
LW_04	66	Medium	Pasture/2-lane Hwy.
PH_01	160	Large	Moderate Density Residential/Commercial
DC_01	124	Medium	Moderate and High Density Residential

ranged from 14 acres to 816 acres in size with a mean of 184 acres. Three of the impacted catchments, LW11, LW10 and LW09, were defined by different sites located on the same stream with increasing drainage areas, respectively, as were catchments LW06 and LW05. The remaining sites were located on separate drainages.

The impacted sites were divided into three catchment size-classes each having 10 sites that roughly corresponded in size to one of the reference sites. The small catchments ranged from 14 to 60 acres in size with a mean size of 35 acres. The reference catchment for the small size-class was WBU_01, which was 28 acres. The medium catchments ranged from 66 to 124 acres in size with a mean of size of 94 acres. The reference catchment for the medium size-class was WBU_02, which was 76 acres. The large catchments ranged from 142 to 816 acres in size with a mean of size of 422 acres. The reference catchment for the large size-class was WBU_03, which was 286 acres. Areas within each size-class, as well as with all catchments combined were normally distributed using the Shapiro-Wilk W test.

Once catchments were selected, their boundaries were digitized from the digital raster graphic version (DRG) of the USGS 1:24,000 scale topographic maps using ArcView GIS 3.1 (ESRI). The 1:24,000 scale digital soils maps for Wake County and color infrared 1:24,000 scale USGS digital orthographic quarter quadrangles (DOQQs, 1998 photography, 1 meter resolution) were obtained from the NC Center for Geographic Information and Analysis (CGIA). Soil mapping units for each catchment were separated into hydrologic soil groups (USDA 1986) and used as a GIS layer over the Wake County DOQQs. Weighted average curve numbers, which represented weighted average runoff condition, were estimated for each catchment using the USDA, NRCS TR-55 model (USDA 1986).

Instream benthic macroinvertebrate sampling used a variation of the single habitat approach recommended by Barbour et al. (1999). Organisms were collected during March and April of 1999 using a kick-net with a 1,000 micron mesh opening and an fourteen pronged garden rake. Samples were collected at three riffle/run locations in the main stem stream of the catchment within a 100-200 yard reach upstream of the catchment mouth.

The months of March and April occur during the Spring macroinvertebrate sampling period for NC (NC DENR 2002d), which represents the biologically optimal sampling season when the habitat is utilized most heavily by later instars of insect macroinvertebrates and the food resource has stabilized to support a balanced indigenous community. The riffle/run habitat type was sampled because of the high taxa richness and abundance of organisms that occur there and because the single habitat approach provided some habitat stratification and therefore reduced sample variation for inter-site comparisons (Resh and Jackson 1993).

At each sample location the wetted width of the stream channel was measured and the equivalent of one square meter of habitat was sampled. Organisms from the three samples were pooled for each site location. Organisms were picked and counted in the field, preserved in 95% ethanol, and transported to the lab for identification to the family level. Chironomidae were further identified in the field as “blood-red” and “other” following Hilsenhoff (1988). High populations of blood-red midges are often used as a pollution indicator. While most chironomid larvae are yellowish or green, a few (*Chironomus plumosus* group) have hemoglobin in their blood that carry oxygen, which allows them to live in water that is low in oxygen (Ward 1992). Family identifications were based on

Merritt and Cummins (1996). Abundance values were assigned as follows: rare = 1 (1-2 specimens), common = 3 (3-9 specimens), or abundant 10 (10 or more specimens) (Lenat 1993). Family biotic index (FBI) calculations were based on the following NC DWQ equation (NC DENR 2002d):

$FBI = Sum (TV_i)(n_i)/N$	TV_i = $_i$th taxa's tolerance value n_i = $_i$th taxa's abundance value (1, 3 or 10) N = sum of all abundance values.

FBI values range from 0 to 10, with lower values indicating less tolerant taxa. A family taxa richness (FTR) value was also determined for each catchment by summing the number of taxa in each composite sample.

Family tolerance values and the family biotic index for water quality rating scale followed Hilsenhoff (1988). The Hilsenhoff (1988) procedures were used instead of NC procedures for several reasons. The NC biotic index was developed for a lower level of taxonomic identification (genus and species), NC DWQ procedures stipulate that streams 3 meters or less in width should not be rated, the NC rating scale was developed for summer collections, and the NC scale has five water quality rating increments rather than seven like the Hilsenhoff (1988) scale. The Hilsenhoff (1988) index was initially developed to assess the impacts of organic and nutrient pollution in streams. However, it is commonly used and is considered an effective measure of the general quality of macroinvertebrate stream communities (Stepenuck et al. 2002, Roy et al. 2003, Wang and Kanehl 2003).

Within the sample reach the bank and riparian habitats (near stream habitat) were assessed following US EPA Rapid Bioassessment Protocols (Barbour et al. 1999). Four conditions were assessed, bank stability, bank vegetative protection, riparian vegetative zone width, and riparian vegetation structure, and combined into a single habitat rating (HR) metric for analysis. Each condition was rated on a scale from 0 to 10 for each bank for a maximum score of 20 per reach and a maximum cumulative HR score of 80.

The relationship between the catchment weighted average curve number (CN) and each of the stream assessment variables (HR, FTR, and FBI), as well as between each of the stream assessment variables was examined using linear regression (JMP 2000). The analysis was performed for each catchment class-size and for all 33 catchments combined.

Results

Catchment areas and the four stream assessment variables (CN, HR, FTR, and FBI) were normally distributed within each of the catchment size-classes, as were the CN and FBI variables for the 33 catchments combined. The variables are summarized by catchment in Table 2.

The results of the linear regression analyses by matched pair combinations are shown in Table 3. Correlations were low to moderate for the HR by FTR, CN by FTR, and FTR by FBI combinations within each size-class and for the size-classes combined. Each of those combinations contained the FTR variable, which was expected to increase with increasing catchment size. As a result, the correlations were stronger with increasing size-class for each of the pair combinations.

Table 2. Catchment measures summary. Catchment assessment variables included runoff curve number (CN), family taxa richness (FTR), family biotic index (FBI), and habitat rating (HR). Each catchment was also assigned a water quality (WQ) rating.

Name	Area (acres)	CN	FTR	FBI	HR	WQ Rating
WBU_02	76	56	27	3.04	72	a - Excellent
WBU_01	28	56	15	3.64	72	a - Excellent
WBU_03	286	59	33	3.67	72	a - Excellent
LW_11	121	61	30	4.01	70	b - Very Good
CC_01	42	60	23	4.04	72	b - Very Good
CC_04	112	61	17	4.07	68	b - Very Good
SF_01	14	58	16	4.16	72	b - Very Good
LW_10	681	63	20	4.21	65	b - Very Good
WC_02	188	62	17	4.31	64	c -Good
SF_02	142	61	18	4.4	68	c -Good
WC_01	37	64	14	4.48	49	c -Good
WC_04	81	62	20	4.83	68	c -Good
LW_09	816	66	20	4.87	45	c -Good
CC_03	495	65	11	4.98	46	c -Good
CC_02	702	69	13	5.12	47	d - Fair
CSC_01)	40	70	9	5.24	46	d - Fair
WC_05	81	67	14	5.29	68	d - Fair
LW_06	24	68	15	5.35	68	d - Fair
LW_01	82	69	13	5.36	50	d - Fair
WC_03	148	71	15	5.37	54	d - Fair
WC_08	91	72	9	5.39	34	d - Fair
LW_05	53	72	14	5.58	44	d - Fair
FGR_01	102	73	4	5.7	32	d - Fair
LW_03	98	70	19	5.75	28	d - Fair
BC_01	366	76	9	6.04	16	e - Fairly Poor
LW_08	60	73	15	6.1	38	e - Fairly Poor
WC_07	661	74	8	6.16	28	e - Fairly Poor
LW_02	32	72	16	6.25	28	e - Fairly Poor
LW_07	33	75	18	6.35	36	e - Fairly Poor
WC_06	25	77	10	6.36	12	e - Fairly Poor
LW_04	66	78	9	6.57	12	f - Poor
PH_01	160	80	9	6.63	14	f - Poor
DC_01	124	88	4	7.98	14	g - Very Poor

Table 3. Matched pair combinations. Below are the matched pair combinations and linear regression results for the three catchment size-classes and for the catchments combined.

Combinations	Size-class	r^2	Slope	Intercept
HR (x) by FTR (y):	Small	0.22	0.07	10.75
	Medium	0.56	0.27	2.38
	Large	0.61	0.28	2.67
	Combined	0.47	0.22	4.91
HR (x) by FBI (y):	Small	0.75	- 0.04	7.33
	Medium	0.75	- 0.05	7.56
	Large	0.90	- 0.04	7.09
	Combined	0.77	- 0.05	7.34
CN (x) by FTR (y):	Small	0.16	- 0.21	28.96
	Medium	0.70	- 0.79	69.45
	Large	0.61	- 0.83	72.12
	Combined	0.51	- 0.63	58.25
CN (x) by FBI (y):	Small	0.95	0.14	- 4.01
	Medium	0.96	0.14	- 4.61
	Large	0.96	0.13	- 3.94
	Combined	0.95	0.14	- 4.26
CN (x) by HR (y):	Small	0.78	- 2.49	217.35
	Medium	0.82	- 2.36	209.03
	Large	0.88	- 2.83	238.89
	Combined	0.82	- 2.51	218.50
FTR (x) by FBI (y):	Small	0.10	- 0.08	6.48
	Medium	0.65	- 0.12	7.16
	Large	0.73	- 0.11	6.77
	Combined	0.51	- 0.11	6.95

HR = Habitat Rating, FTR = Family Taxa Richness, FBI = Family Biotic Index, and CN = Curve Number. Catchment size ranges were Small = 14 to 60, Medium = 66 t0 124, and Large = 142 to 816 acres.

The results of the matched pair regression correlations were strongest for the HR by FBI, CN by HR, and CN by FBI combinations. For each of those combinations, the results were similar for each of the three size-classes. The correlation for the CN by FBI combination was the strongest and most consistent within size-classes.

The strong negative correlation for the CN by HR regression combination suggested that higher runoff/rainfall condition is related to lower near-stream habitat quality. The strong negative correlation for the HR by FBI regression combination suggested that lower habitat quality is related to lower water quality. The very strong positive correlation for the CN by FBI regression combination suggested that higher runoff/rainfall condition is related to lower overall water quality.

An examination of the results from the three reference catchments showed progressive higher FTR (15, 27, and 33) with larger catchment area (28, 76, and 286 acres), while maintaining low FBI values (3.64, 3.04, and 3.67) and excellent water quality (WQ) ratings. Those results suggested that higher FTR was found in larger catchments, which was expected. However, the higher FTR in impacted catchments was due to the presence of higher numbers of tolerant macroinvertebrate families, which reflects the value of using biotic indices. The overall results of this study suggested that CNs may be a good predictor of expected FBI values in perennial headwater streams within the range of catchment sizes examined.

Figure 1 shows graphically the relationship between CNs and FBI scores for the 33 catchments by size-class. Figure 2 shows graphically the relationship between CNs and FBI scores for the 33 catchments combined.

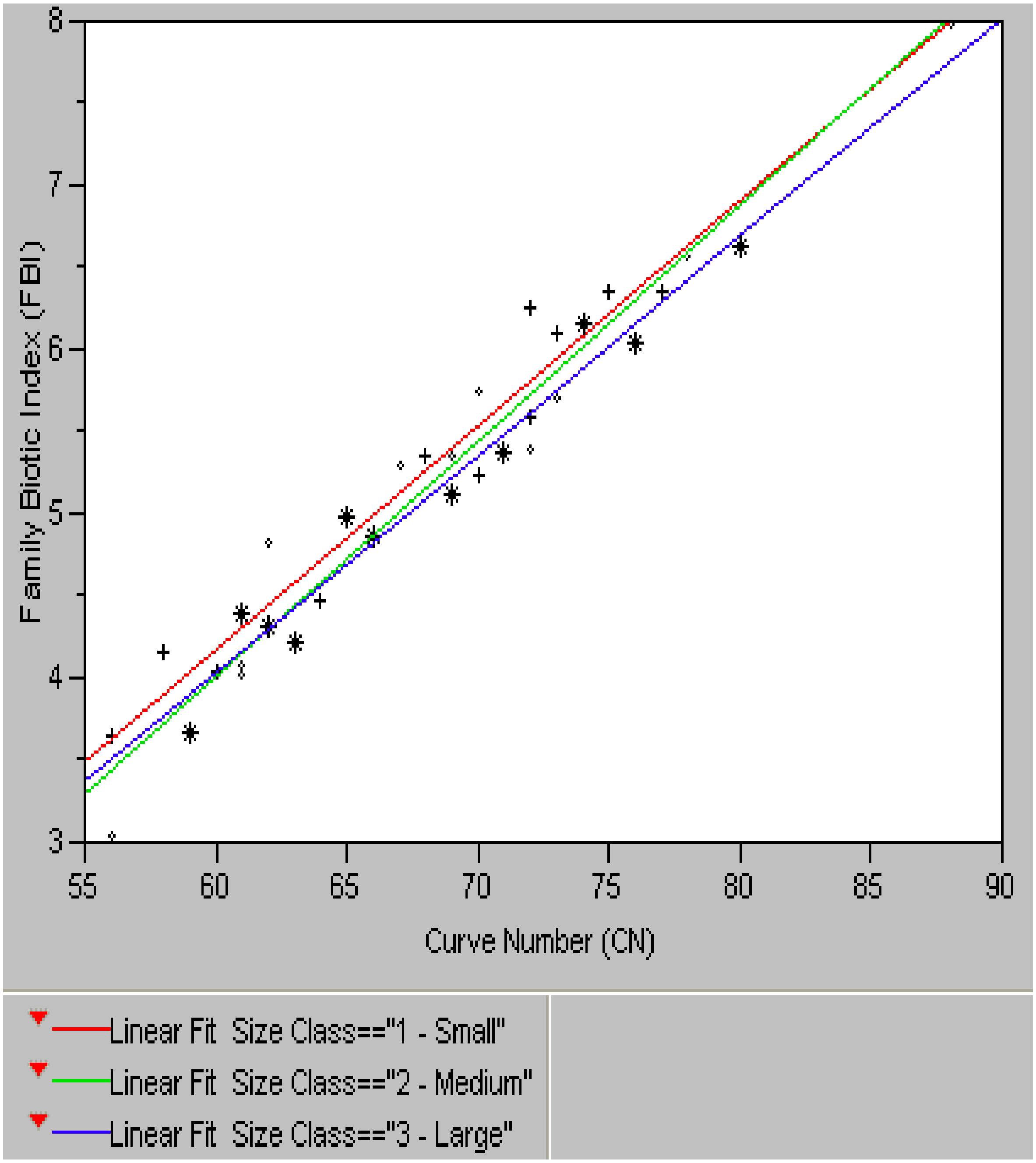

Figure 1. Relationship between runoff curve numbers (CNs) and family biotic index (FBI) scores for the 33 catchments by size-class.

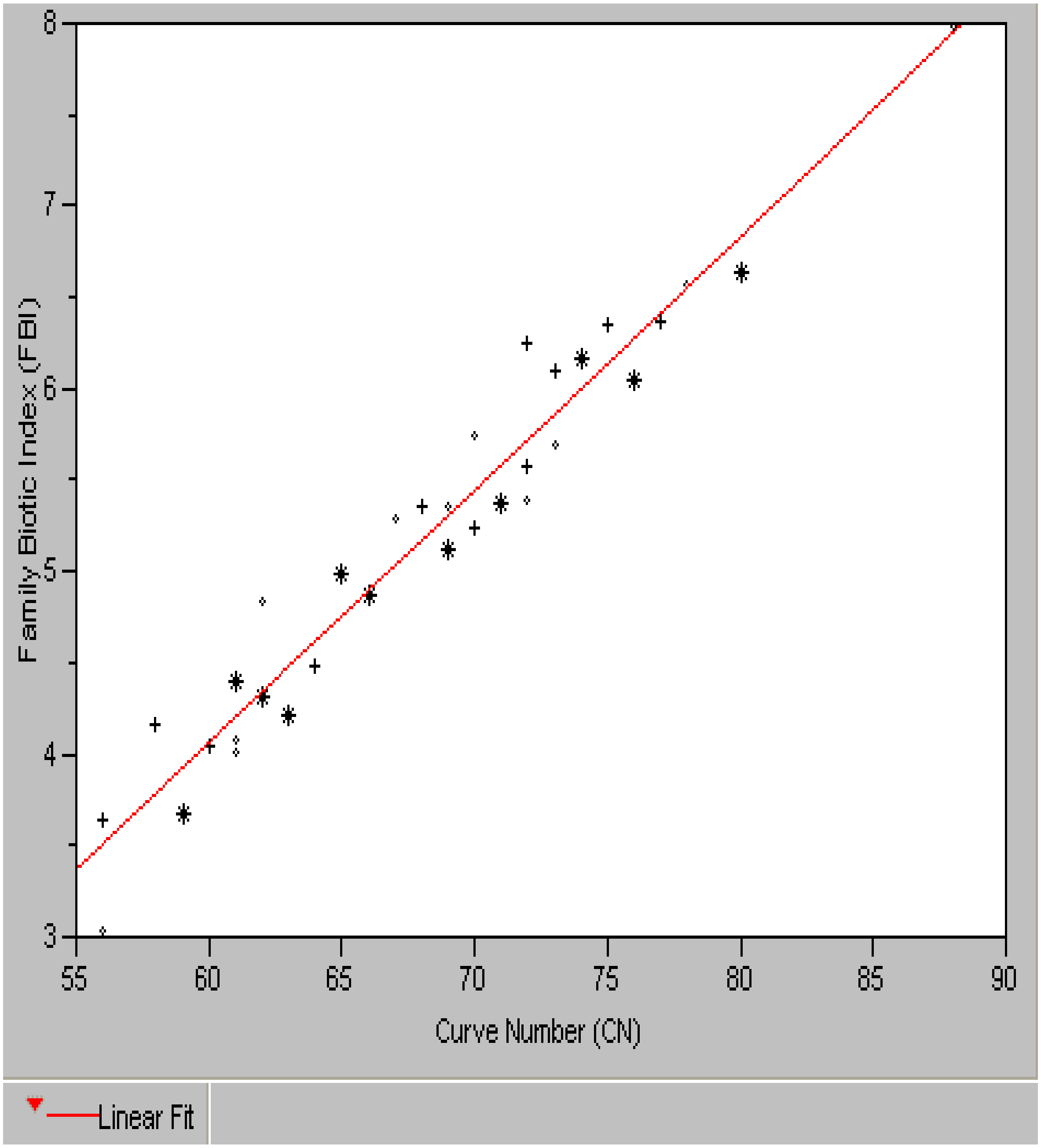

Figure 2. Relationship between runoff curve numbers (CNs) and family biotic index (FBI) scores for the 33 catchments combined.

The following linear regression equations correspond with the Figures 1 and 2. They were developed to predict FBI scores using CNs for the three catchment size-classes and for the 33 catchments combined:

Small	FBI = -4.0103 + 0.1364 (CN); (r^2 = 0.95)	RMSE = 0.2455
Medium	FBI = -4.6148 + 0.1437 (CN); (r^2 = 0.96)	RMSE = 0.2965
Large	FBI = -3.9392 + 0.1328 (CN); (r^2 = 0.96)	RMSE = 0.1985
Combined	FBI = -4.2556 + 0.1387 (CN); (r^2 = 0.95)	RMSE = 0.2476

FBI = Family Biotic Index and CN = Curve Number

Conclusion

The rehabilitation of aquatic habitats for improving water quality is a typical stream restoration objective even though the transformation of the upland landscape may be the critical force affecting the health of streams and rivers. Recent studies have used imperviousness as an indicator of the water quality of streams and rivers, particularly in urbanizing watersheds, and it has become a very useful measure. However, variously managed pervious surfaces dominate most of the North Carolina landscape and their impacts on water quality should not be ignored.

This study used a method that combined both pervious and impervious surfaces into a measure of their weighted cumulative runoff effects, or catchment runoff condition. Even though imperviousness may represent the single most dramatic impact on stream quality, catchment runoff condition may better elucidate the contributing factors leading to systemic water quality problems than the use of imperviousness alone, especially under less urbanized conditions. The results of the study suggested that catchment runoff condition was strongly related to near-stream habitat and in-stream water quality measures.

Granting agencies that provide funding for stream restoration activities often require that projects improve water quality. Furthermore, project proposals are evaluated, in part, by their ability to achieve measurable water quality results. Water quality measures can include information on near- and in-stream habitat condition as well as information about the macroinvertebrate community, such as taxa richness and biological index scores. This study used near-stream habitat ratings (HRs) and the average runoff condition (CNs) of 33 Piedmont headwater catchments to predict macroinvertebrate water quality indicator values. Results of the study suggested that the use of both methods could serve as a starting point for restoration activities with CNs being used to predict achievable restoration outcomes.

This study was limited to Wake County in the Eastern Piedmont of NC and should be expanded to include other regions of the state to further validate the usefulness of runoff CN's for catchment-wide purposes. Additional analysis comparing the use of CN or impervious extent should be performed.

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CHAPTER TWO

BLUE-LINE HYDROGRAPHY IN NORTH CAROLINA

Abstract

The ArcView geographic information system (GIS) was used to summarize the drainage lengths of the US Geological Survey (USGS) 1:24,000 scale digital blue-line hydrography for North Carolina (NC) by the following areas; physiographic regions (5), major river basins (17), region-basin units (35), and 107 randomly selected USGS 7.5-minute quadrangle units. The length of stream and river miles in the region-basin and quadrangle units were used to evaluate the variability of within region drainage densities (Dds) and to compare Dds between regions across the state.

Dd distributions were evaluated using the Shapiro-Wilk W test for normality. The test indicated that the 35 region-basin units had a normal distribution; however, the 107 quadrangle unit sample contained 9 extreme values. Regional Dd comparisons subsequently used 35 region-basin units and 98 quadrangle units and were made by ANOVA and Tukey-Kramer HSD procedures.

The two statistical methods produced similar results with differences confined to the Coastal Plain regions. The regional blue-line Dds were generally related to topography and progressively increased across the state by region as follows: Tidewater (TW) – Inner Coastal Plain (ICP) – Sandhill (SH) - Piedmont (P) - Mountain (M).

Four of the quadrangle unit sample extreme values were located in the TW (3) and ICP (1) regions and had relatively low Dds. Low Dds for portions of those regions were not

unexpected and their elimination from the analysis resulted in mean Dds being greater than those of respective region-basin units. The other five extreme values were located in the P (2) and M (3) regions and had relatively high Dds. Based on a visual examination of their hydrography they were eliminated prior to statistical analysis. Their elimination from the analysis also resulted in lower Dds, however, the Dds were still higher than those of respective region-basin units.

A visual examination of the hydrography for the three M region extreme values along with their respective river basin hydrography revealed uncharacteristic patterns in the blue-line portrayal. The patterns conformed to the outlines of the 7.5-minute quadrangles and they had Dds 2 to 3 times greater than adjacent quadrangle units as well as river basin averages. An expanded visual examination of the hydrography showed that variability among quadrangles in the blue-line portrayal was widespread. Until irregularities in the blue-line hydrography are reconciled, its usefulness in summarizing drainage lengths is limited. Water resources programs that rely on the 1:24,000 scale hydrography for resource allocations and regulatory purposes should use it with caution.

Since a summary of the blue-line hydrography for NC had previously not been compiled, the percentage of the blue-line stream and river miles by major river basin that have been catalogued by the Division of Water Quality (DWQ) based on their use-support ratings were determined.

Introduction

The blue-line hydrography portrayed on the US Geological Survey (USGS) 7.5-minute, 1:24,000 scale topographic map series is a valuable source of information for state agencies involved in water resources management. Although its use in identifying headwater streams may be limited (Leopold 1994), the blue-line drainage network of medium to large streams and rivers is currently used in North Carolina (NC) for a variety of purposes. For example, the NC Department of Environment and Natural Resources (DENR), Division of Water Quality (DWQ), Basinwide Planning Program uses the blue-lines to catalogue the use-support ratings of stream and river reaches across the state (NC DENR 2002a). The NC DENR DWQ Wetlands/Water Quality Certification Unit uses the blue-lines in conjunction with stream-lines shown on county soil surveys to manage riparian buffers in the Neuse River and Tar-Pamlico River basins (NC DENR 2002b). The NC DENR Ecosystem Enhancement Program requires that potential stream restoration projects be located along a USGS designated perennial blue-line drainage to be eligible to receive stream restoration resources (NC DENR 2002c).

Used as a basis for regulatory and resource allocation purposes, the hydrography should represent actual drainage features and be portrayed in a consistent manner across the state. However, according to Leopold (1994), the USGS mapping guidelines allowed considerable subjectivity in how headwater drainages were portrayed on the maps including upstream extent and flow permanence. For example, in developing the 1:24,000 scale topographic map series, the blue-line hydrography was not intended to show smaller channels in finely dissected terrain (Mark 1983). In those areas, only the more prominent channels were to be plotted using the blue-line symbol. Perennial drainages were to be published with a solid blue line symbol regardless of their length and intermittent streams were to be published with an interrupted blue line if they were longer than 2,000 feet.

Drainages at the source and upper part of the drainage system were to terminate no higher than about 1,000 to 2,000 feet from the basin divide (Mark 1983, Leopold 1994). The choice of symbols actually shown on a map, if any, however, was based on consistent portrayal (Leopold 1994). Since the blue-line symbols were drawn for individual quadrangles, following the guidelines could produce a consistently portrayed network for individual quadrangles (Mark 1983) but that were different from adjacent quadrangles, thereby resulting in substantially different drainage densities (Dds).

In mid-2001, the NC Center for Geographic Information and Analysis (CGIA) completed the process of digitizing all of the hydrologic features shown on the 971 quadrangle topographic maps for NC, however, no attempt was made to summarize the various features. The purpose of this study was to summarize the length of stream and river miles for the state. Lengths were summarized by physiographic region, major river basin, and region-basin subunits. Lengths by basin were contrasted to those reported by the DWQ. The hydrography was also sub-sampled by 7.5-minute quadrangle units to examine the variability in Dds within physiographic regions and for between region comparisons.

Methods

North Carolina recognizes 17 major river basins across the state (Figure 1) and typically three physiographic regions, Mountain (M), Piedmont (P), and the Coastal Plain. In this study, the Coastal Plain was divided into three distinct regions, Sandhill (SH), Inner Coastal Plain (ICP), and Tidewater (TW), giving a total of five physiographic regions (Figure 2). An additional physiographic region, the Outer Banks, represents only 0.61% (300 of 49,286 square miles) of the state's upland surface area and was not included in this study.

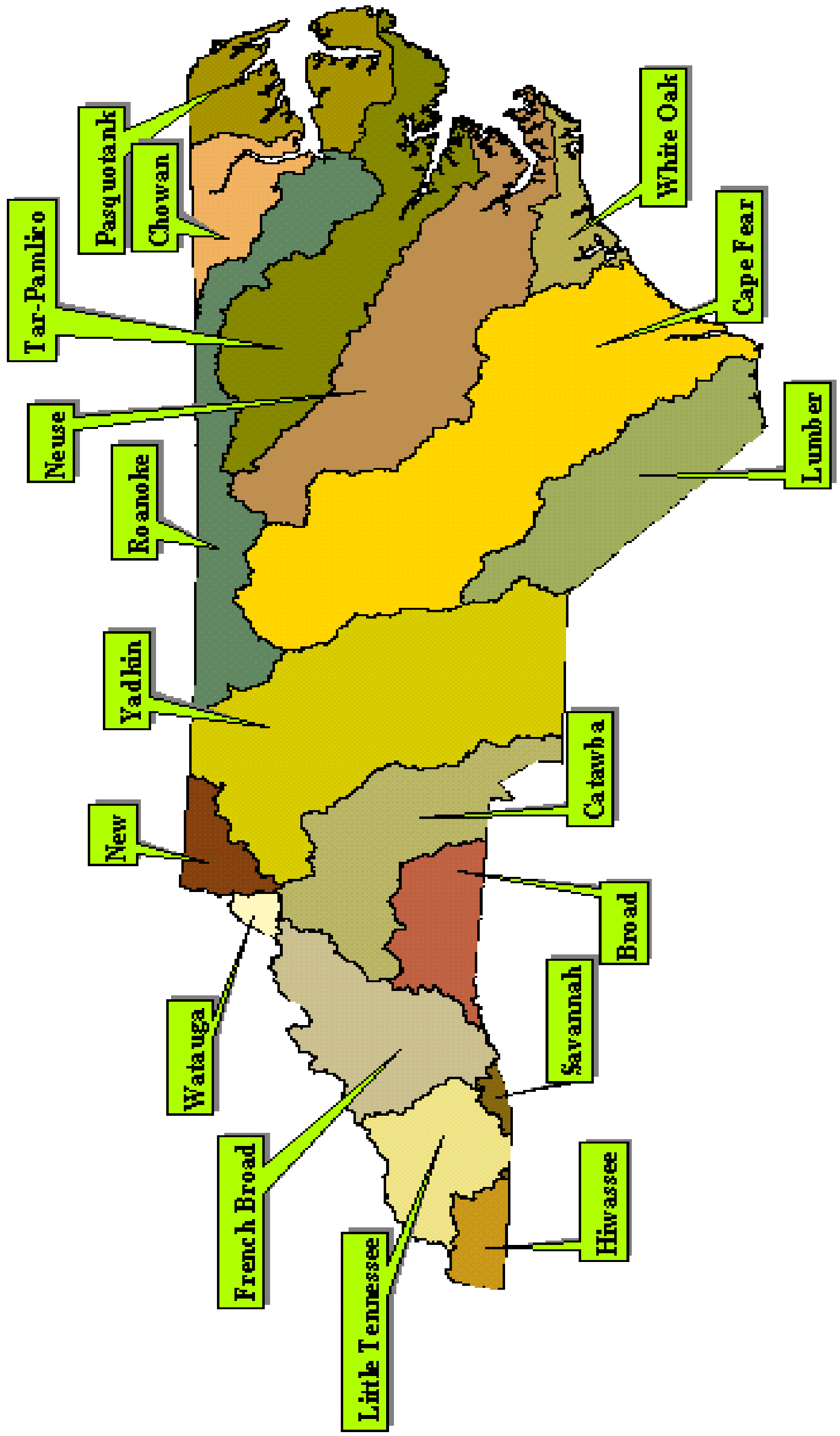

Figure 1. Major river basins (17) in North Carolina.

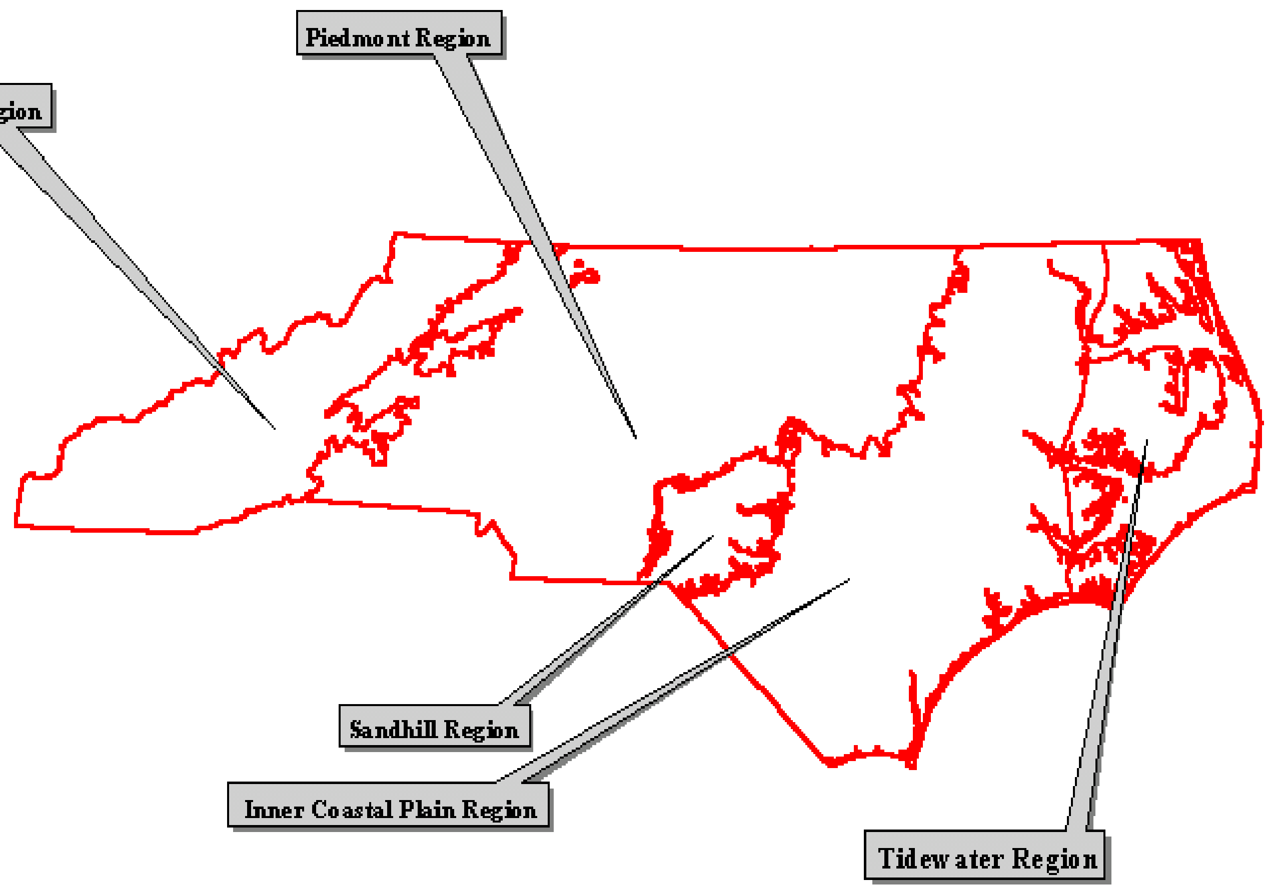

Figure 2. Major physiographic regions (5) in North Carolina.

According to Daniels et al. (1999), the M region ranges in elevation from 1,495 to 6,680 feet above mean sea level (MSL) with maximum slope gradients ranging from 60 to 95 percent.

The P region ranges in elevation from 295 to 1,495 feet above MSL with maximum slope gradients ranging from 25 to 60 percent. The Coastal Plain ranges in elevation from 0 to 650 feet above MSL, however, elevations in the TW region (Pamlico soil system) are 20 feet or less, elevations in the ICP region are up to 295 feet, and elevations in the SH region range as high as 650 feet. Maximum slope gradients in the TW region are 2 percent, 12 percent in the ICP region, and 25 percent in the SH region.

Digitizing of the USGS blue-line hydrography portrayed on the 971 USGS 7.5-minute quadrangle maps for NC was completed by CGIA in mid-2001. This study used ArcView GIS (ESRI, v. 3.1) to extract the stream and river segments from the hydrography database to determine length estimates for the five physiographic regions and 17 major river basins. To assess the variability of Dds within physiographic regions, regions were sub-divided by their respective major river basin components that produced 35 region-basin units (Figure 3). For example, the Broad River basin begins in the M region of NC and flows in a southeast direction into the P region before entering South Carolina. Therefore, the Broad River basin had M and P region-basin units. Stream and river lengths were extracted from the database as follows: natural drainages were portrayed as single blue-lines on the topographic maps, coded 412 in the database, and the lengths for each area were summed. Large streams and rivers were portrayed with right- and left-bank blue lines on the topographic maps, coded 605 and 606 in the database. The lengths for both banks were summed for each area and divided by two, then added to their respective summed single

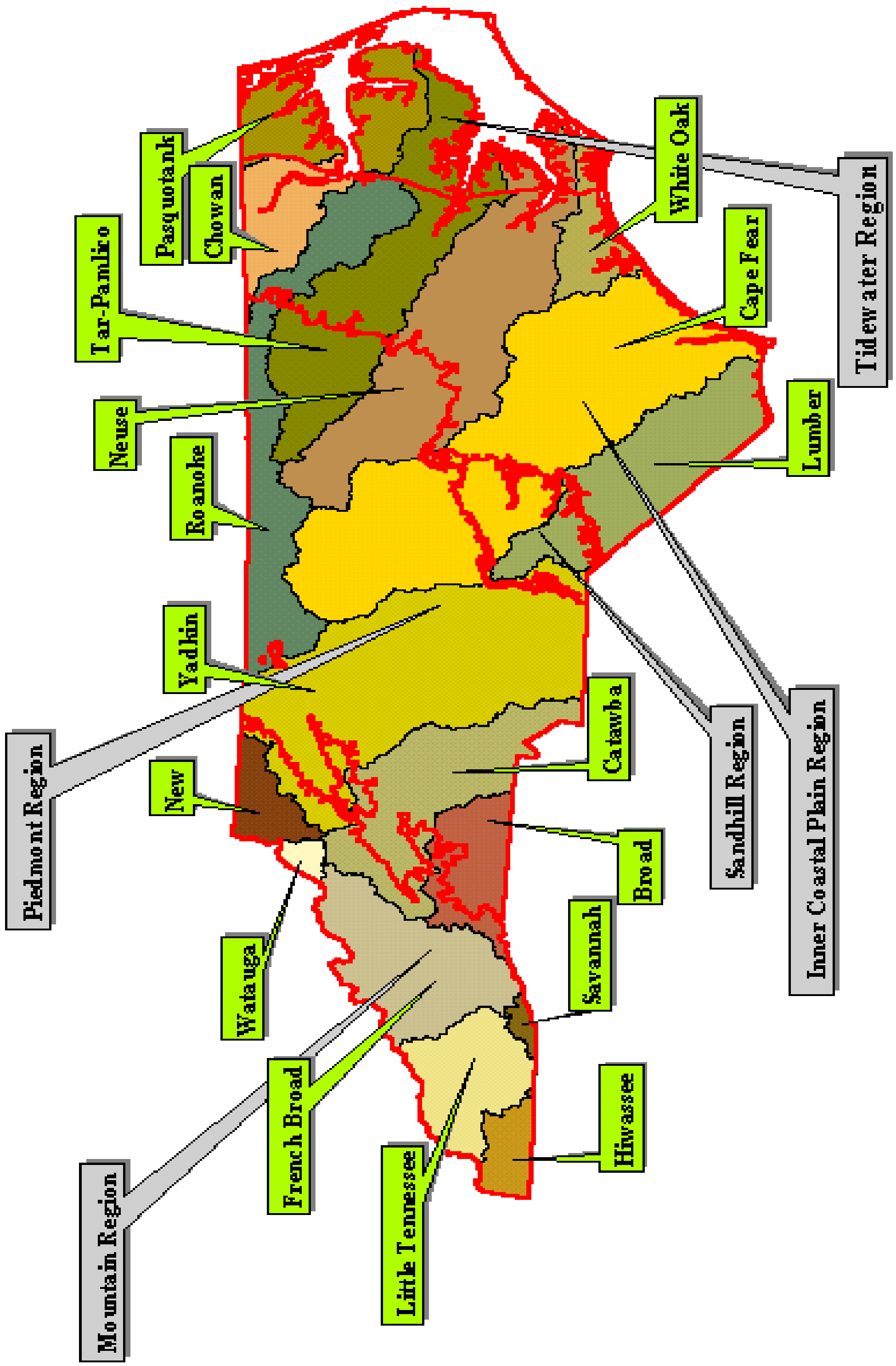

Figure 3. Thirty-five region-basin units in North Carolina.

blue-line value. The summed length values were divided by their corresponding upland areas to determine Dds. Upland areas were determined by subtracting the area of surface water bodies from each of the region, basin, and region-basin unit areas.

To further assess Dd variability within and between regions, a random sample of 107 7.5-minute quadrangle units was selected from across the state. Stream and river lengths for each quadrangle unit were determined as above. Quadrangle unit Dds were determined by dividing the stream and river lengths by the upland area of the quadrangles. Upland area was determined by subtracting the area of large water bodies from the quadrangle area.

Dds for both the 35 region-basin units and the 107 quadrangle units were tested for normality using the Shapiro-Wilk W Test (JMP Version 4.10). The Dds were then compared by region for both methods using ANOVA.   Subsequent regional all pairs comparisons were made using Tukey-Kramer HSD procedures (JMP Version 4.10). Comparisons were also made between the stream miles catalogued by the NC Division of Water Quality and the total blue-line miles.

Results

A summary of the blue-line lengths (miles), areas (square miles), and drainage densities (mi/mi^2) for each of the 17 major river basins across NC are shown in Table 1. Included in Table 1 are the drainage lengths catalogued by the DWQ that have use- support ratings and their percentage of the basin totals. The percentage of the blue-line lengths catalogued by NC DWQ ranged from 27% for the Tar-Pamlico River basin to 68% for the Savannah River basin. For the entire state, approximately 36% of the blue-line streams and rivers across the state have been evaluated and catalogued.

Table 1. Summary of blue-line (BL) miles for the 17 major river basins in North Carolina. Also shown are the area (square miles) and mean drainage density (Dd, miles per square mile) of each river basin. Division of Water Quality (DWQ) miles are those catalogued based on their use-support ratings. DWQ/B-L (%) represents the percent of the total B-L miles catalogued by DWQ. B-L miles were from USGS 1:24,000 scale hydrography.

River Basin	B-L Miles	Area	Dd	DWQ Miles	DWQ/B-L (%)
Broad	3,496	1,513	2.31	1,473	42%
Cape Fear	19,874	9,322	2.13	6,049	30%
Catawba	7,086	3,285	2.16	3,004	42%
Chowan	2,032	1,378	1.47	788	39%
French Broad	8,149	2,830	2.88	4,136	51%
Hiwassee	1,981	644	3.08	989	50%
Little Tennessee	4,423	1,797	2.46	2,703	61%
Lumber	5,597	3,335	1.68	2,283	41%
Neuse	11,585	6,234	1.86	3,440	30%
New	1,907	753	2.53	801	42%
Pasquatank	1,224	1,948	0.63	478	39%
Roanoke	7,714	3,503	2.20	2,389	31%
Savannah	309	171	1.81	210	68%
Tar-Pamlico	8,612	3,916	2.20	2,335	27%
Watauga	647	205	3.16	303	47%
White-Oak	1,298	931	1.39	446	34%
Yadkin	18,230	7,221	2.52	5,989	33%
Totals =	**104,164**	**48,986**		**37,816**	

Using total blue-line miles and total upland area values shown in Table 1, NC had a mean Dd of 2.13. Six basins had mean Dds lower than the state average, while 10 were greater. The Dd for the Cape Fear River basin was the same as the state average.

Six of the 17 river basins were located within a single physiographic region, the M region. Five of those six basins also had Dds greater than the state average. The M region basin with the lowest Dd was the Savannah (1.81), while the adjacent Hiwassee River basin

Dd (3.08) was 1.7 times greater. The Watauga River basin, another M region basin, had the greatest Dd (3.16), which was 1.25 times greater than the adjacent New River basin (Dd = 2.53). The two smallest of the M region basins had similar sizes, the Savannah 171 square miles and the Watauga 205 square miles, yet the Dd for the Watauga was 1.75 times greater than the Savannah.

The blue-line hydrography for the Hiwassee, New, Savannah, and Watauga River basins were visually inspected for irregularities or unusual variability in stream network portrayal. No irregularities were apparent in the New or Savannah River basins. However, both the Hiwassee and Watauga basins had areas with an uncharacteristic "blocky" appearance with higher concentrations of blue-lines than adjacent areas. The blue-line hydrography for the Watauga River basin is shown in Figure 2. The "blocky" appearance conformed to the shape of respective 7.5-minute quadrangle maps suggesting inconsistent portrayal of stream networks among quads within the Hiwassee and Watauga River basins.

A visual examination of adjacent quadrangle raster images in the Watauga basin, the Boone, Sherwood, Valle Crucis, and Zionville quadrangles, indicated that first-order streams were better represented in the Sherwood quadrangle area. For example, the Dd within the Sherwood quadrangle is approximately 6.35 mi/mi^2, while the Dds for areas within the adjacent Boone, Valle Crucis and Zionville quadrangles were 2.35, 2.21 and 1.98 mi/mi^2, respectively.

While it was not the intent of this study to distinguish between intermittent and perennial blue-line designations, the blue-line symbols used for the Watagua River basin did

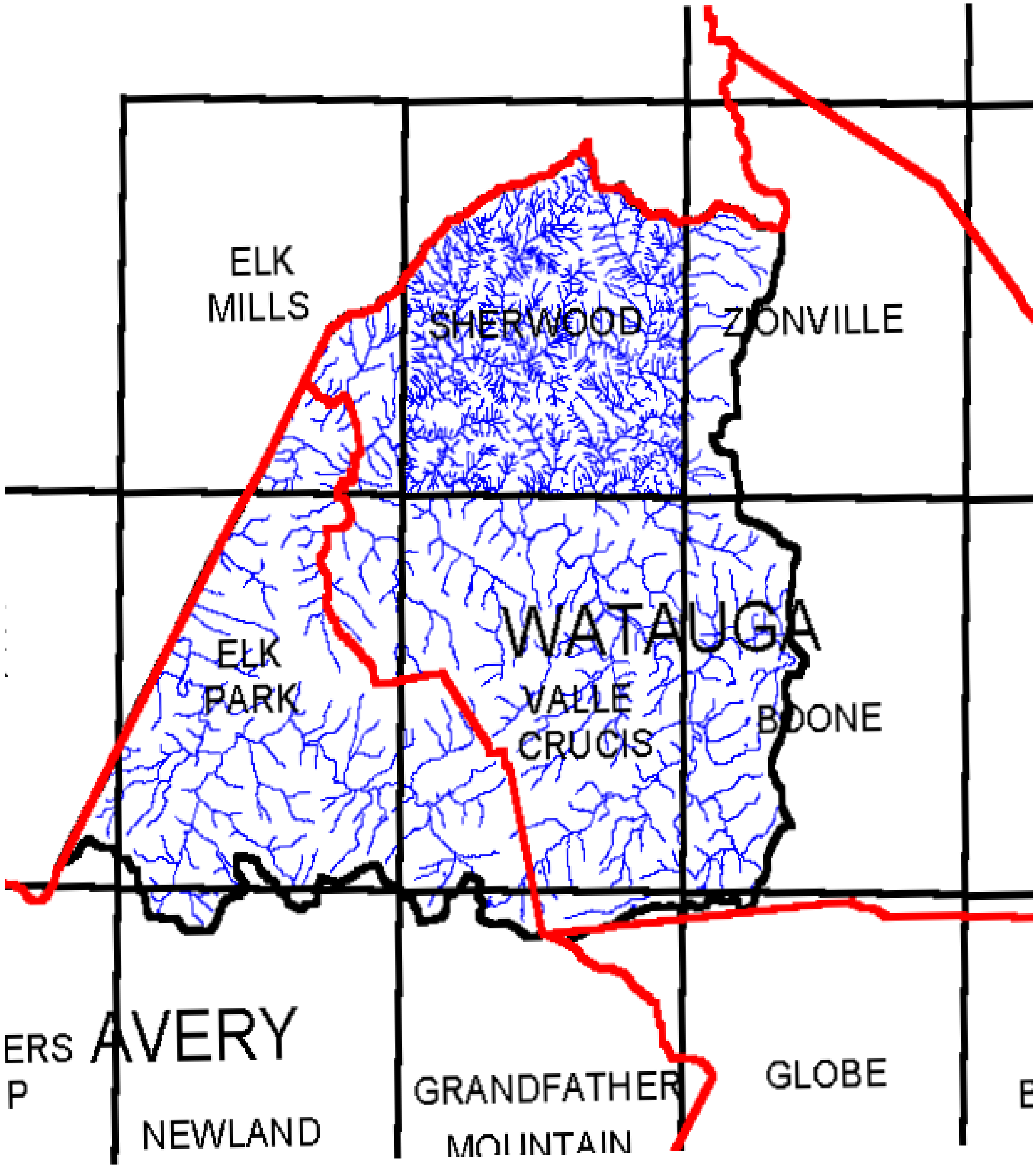

Figure 4. Blue-line hydrography for the Watauga River Basin, Avery and Watauga Counties, North Carolina. Also shown are the names and outlines of the 7.5-minute quadrangle units encompassing the area. The hydrography was digitized from the US Geological Survey 1:24,000 scale topographic map series by the North Carolina, Center for Geographic Information and Analysis.

not appear to be portrayed consistently either. For example, all of the stream and river hydrography shown on the Sherwood, Valle Crucis, and Zionville quadrangles carried the perennial designation, while all of the smaller streams shown on the Elk Mills and Elk Park quadrangles carried the intermittent designation. Small streams shown on the Boone quadrangle carried both blue-line symbols.

Table 2 summarizes the stream lengths, areas, and Dds for the 35 region-basin units by physiographic region. Regional Dds used summed regional length and area totals, which resulted in slightly different Dds than those shown in Table 3, where sample means were used.

Results of a Shapiro-Wilk W Test for normality indicated that 9 of the original 107 quadrangle units had extreme values. Based on a visual examination of the blue-line hydrography for those quadrangles, they were not included in the subsequent analysis. For comparison purposes, the number of extreme values for each region and the mean Dd by region that includes the values were as follows: Mountain (M, 3, Dd = 2.88), Piedmont (P, 2, Dd = 2.76), Sandhill (SH, 0, Dd = 2.35), Inner Coastal Plain (ICP, 1, Dd = 1.76) and Tidewater (TW, 3, Dd = 0.80).

Results of the ANOVA and Tukey-Kramer HSD procedures are shown in Table 3 and indicated that Dds were significantly different (alpha = 0.05, $p < 0.001$) between regions for both statistical methods. All pairs comparisons made for region-basin units indicated that Dds for the M and P region were significantly greater than the ICP and TW region Dds. SH and ICP region Dds were significantly greater than the TW Dd. No differences between M,

Table 2. Summary of blue-line (BL) miles for the 35 region-basins units by physiographic region. Total drainage densities (Dd, miles/area, square miles) by region were as follows: Mountain (M, Dd = 2.61), Piedmont (P, Dd = 2.50), Sandhill (SH, Dd = 2.04), Inner Coastal Plain (ICP, Dd = 1.78) and Tidewater (TW, Dd = 0.68).

Region	River Basin	B-L Miles	Area	Dd
M	Broad River	1,123	481	2.33
M	Catawba River	1,811	850	2.13
M	French Broad River	8,149	2,830	2.88
M	Hiwassee River	1,981	644	3.08
M	Little Tennessee River	4,423	1,797	2.46
M	New River	1,907	753	2.53
M	Roanoke River	46	22	2.09
M	Savannah River	309	171	1.81
M	Watauga River	647	205	3.16
M	Yadkin River	1,578	654	2.41
	Region total =	**21,974**	**8,407**	
P	Broad River	2,373	1,032	2.30
P	Cape Fear River	8,916	3,410	2.61
P	Catawba River	5,275	2,435	2.17
P	Chowan River	40	21	1.90
P	Neuse River	4,839	2,129	2.27
P	Roanoke River	5,673	2,215	2.56
P	Tar-Pamlico River	4,204	1,503	2.80
P	Yadkin River	16,210	6,305	2.57
	Region total =	**47,530**	**19,050**	
SH	Cape Fear River	2,191	988	2.22
SH	Lumber River	1,354	701	1.93
SH	Yadkin River	442	262	1.69
	Region total =	**3,987**	**1,951**	
ICP	Cape Fear River	8,767	4,924	1.78
ICP	Chowan River	1,942	1,309	1.48
ICP	Lumber River	4,243	2,634	1.61
ICP	Neuse River	6,331	3,455	1.83
ICP	Pasquatank River	39	58	0.67
ICP	Roanoke River	1,991	1,225	1.63
ICP	Tar-Pamlico River	3,720	1,486	2.50
ICP	White-Oak River	1,106	746	1.48
	Region total =	**28,139**	**15,837**	
TW	Chowan River	1,942	48	1.04
TW	Neuse River	6,331	650	0.64
TW	Pasquatank River	39	1,890	0.63
TW	Roanoke River	1,991	41	0.10
TW	Tar-Pamlico River	3,720	927	0.74
TW	White-Oak River	192	185	1.04
	Region total =	**2,534**	**3,741**	

Table 3. ANOVA and Tukey-Kramer HSD summary statistics. Mean drainage densities (Dds, mi/mi^2) were compared by region using 35 region-basin units and 98 USGS 7.5 minute quadrangle-units. CV is the coefficient of variation and is expressed as percent. An X in the region matrix indicates significant differences. Alpha = 0.05.

35 Region-basin Units

Region	n	Mean Dd	SD	CV	TW	ICP	SH	P	M
TW	6	0.70	0.35	50%		X	X	X	X
ICP	8	1.62	0.51	31%	X			X	X
SH	3	1.95	0.27	14%	X				
P	8	2.40	0.29	12%	X	X			
M	10	2.49	0.44	18%	X	X			

98 USGS 7.5 Minute Quadrangle Units

Region	n	Mean Dd	SD	CV	TW	ICP	SH	P	M
TW	4	1.29	0.13	10%			X	X	X
ICP	21	1.82	0.71	39%				X	X
SH	12	2.35	0.52	22%	X				
P	38	2.63	0.47	18%	X	X			
M	23	2.60	0.52	20%	X	X			

P, and SH regions were detected and no differences between SH and ICP Dds were detected. Results of the all pairs comparisons made for the 98 quadrangle units were similar to those for the region-basin units except for the Coastal Plain regions where no significant difference in Dds between the ICP and TW regions was found.

Conclusion

This study examined the USGS 1:24,000 scale blue-line hydrography for NC and estimated a stream and river length of 104,164 miles. Of that length, 37,816 miles (36%) have been classified and catalogued by the NC DENR DWQ. The blue-line hydrography provides a broad-scale perspective of how streams and rivers are portrayed across physiographic regions of the state with regard to ranges in elevation and maximum slope gradients. That result was expected since Dds typically increase with mean landscape gradient (Montgomery and Dietrich 1988) and steep hillslopes (Dunne and Leopold 1978). Significant differences in Dds between physiographic regions were observed, however, only for regions within the larger Coastal Plain, a result that was not expected.

The most confounding result of the study was that the blue-lines on individual 7.5-minute quadrangles were not consistently portrayed, which produced large variation in Dds within river basins and regions. An examination of the hydrography for adjacent quadrangles in the Watauga River basin indicated that the differences in Dds were due to the level of detail at which first order blue-line drainages were portrayed on the maps, which suggested irregularities in cartographic representation. The irregularities appeared broad-scale. Other examples where Dds were substantially greater than adjacent quadrangles included the Greens Creek quadrangle located in the Little Tennessee River basin (Mountain region), the Fuquay-Varina quadrangle located in the Cape Fear River basin (Piedmont region), the Troy quadrangle located in the Yadkin River basin (Piedmont region), and the Laurinburg quadrangle located in the Lumber River basin (Inner Coastal Plain and Sandhills regions).

The USGS 1:24,000 scale blue-line hydrography is a valuable tool in managing water resources in North Carolina. However, this study suggests that the blue-line hydrography should be used with caution, especially when used in the allocation of public resources or when its use may affect the regulated community. What appears to be irregularities in the blue-line portrayal may have unintentional but inequitable consequences for the citizens of the state and should be further investigated. The irregularities found in this study suggests that a closer examination of the blue-line drainage network for the state is warranted.

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NC DENR 2002a. North Carolina Department of Environment and Natural Resources, Division of Water Quality, Basinwide Planning Program. http://h2o.enr.state.nc.us/basinwide/basinwide_stats.htm

NC DENR 2002b. North Carolina Department of Environment and Natural Resources, Division of Water Quality, Wetlands/Water Quality Certification Unit. http://h2o.enr.state.nc.us/nps/neuse.htm

NC DENR 2002c. North Carolina Department of Environment and Natural Resources, Ecosystem Enhancement Program. http://h2o.enr.state.nc.us/wrp/criteria/criteria4.htm

CHAPTER THREE

ACCOUNTING OF HEADWATER DRAINAGES IN THE UPPER NEUSE RIVER BASIN OF NORTH CAROLINA

Abstract

The stream lengths in seven US Geological Survey (USGS) 1:24,000 scale first-order blue-line (FO-BL) headwater catchments located in the upper Neuse River basin, Piedmont physiographic region of North Carolina (NC) were field-measured. In each catchment, map measurements were made of first-order blue-line streams and the lengths of additional channels were determined by the traditional contour crenulation (T-CC) method. Catchment areas ranged from 0.08 to 0.45 square miles (53 to 286 acres, respectively) and were normally distributed using the Shapiro-Wilk W test. Catchment drainage densities (Dds) were determined for each stream length measurement method, which were tested and found normally distributed. Dds for the three methods were compared using ANOVA and Tukey-Kramer HSD procedures. The mean Dd for the field-measured method was 8.77 miles per square mile (mi/mi^2). The mean Dd for the T-CC method was 7.35 mi/mi^2, however, no significant difference between the T-CC and field-measured Dds was detected. Both field-measured and T-CC mean Dds were significantly greater than the mean FO-BL Dd (2.80 mi/mi^2).

Pearson product-moment correlations produced strong coefficients for field-measured and T-CC stream lengths (R = 0.98), and for length and area measurements for both the field-measured length and area (R = 0.99) and T-CC length and area (R = 0.97) methods. A

regression equation was developed to predict T-CC stream length (P_1T-CC) using drainage area.

An additional 15 catchments located in the upper Neuse River basin, also within the Piedmont physiographic region, were randomly selected, bringing the total number of catchments to 22. The fifteen catchments had drainage areas within the range of the initial seven catchments (0.09 to 0.24 square miles or 59 to 155 acres). Catchment areas were normally distributed. T-CC Dds were determined for each of the catchments and they were normally distributed. The prediction equation for P_1T-CC lengths that was developed from the initial seven drainage areas was used to predict lengths (P_2T-CC) for the 15 randomly selected catchments. Subsequent P_2T-CC Dds were normally distributed. T-CC and P_2T-CC Dds were compared using ANOVA and a paired t-test. The mean T-CC Dd (8.15 mi/mi^2) was greater than the P_2T-CC Dd (7.63 mi/mi^2), however, no significant difference between the two means was detected.

This study found that the total length of streams within Piedmont NC headwater catchments could be predicted using catchment area. No significant difference was found between map-measured and field-measured Dds. Field-measured and map-measured Dds were significantly greater than Dd estimates based on the USGS 1:24,000 scale blue-line hydrography.

Introduction

Headwater streams are an important part of larger river networks because they are tightly linked to their surrounding landscape (Hynes 1970, Hynes 1975, Vannote et al. 1980, Webster et al. 1992, Allan and Flecker 1993, Bonell 1993, Allan et al. 1997, Bolstad and

Swank 1997, Likens et al. 1997, Pringle 1997). For example, it has been estimated that first through third order streams represent 95% of the number of drainage channels, about 75% of the total drainage length, and carry as much as 90% of the excess flow in the United States (Leopold et al. 1964, Dunne and Leopold 1978, Leopold 1994). Therefore, runoff from headwater areas determines both the quantity and quality of water received downstream and may impose important constraints on hazard control as well as resource development on the main river (Leopold et al. 1964, Dunne and Leopold 1978, Naiman 1983, Clinnick 1985, Cooper et al. 1987, Burt 1992, Webster et al. 1992, Kusler and Larson 1993, Gilliam 1994, Leopold 1994, Daniels and Gilliam 1996, Gilliam et al. 1997, Wenger 1999, Alexander et al 2000, Peterson et al. 2001). Headwater streams, however, are largely overlooked and are being lost from the landscape at an alarming rate by human activities (Meyer and Wallace 2001). One reason that they are being overlooked is due to the reliance on the blue-line hydrography shown on USGS 1:24,000 scale maps by water resource managers. For example, the NC Department of Environment and Natural Resources (DENR), Division of Water Quality (DWQ), Basinwide Planning Program uses the blue-lines to catalogue the use-support ratings of stream reaches across the state (NC DENR 2002a). The NC DENR DWQ Wetlands/Water Quality Certification Unit uses the blue-lines in conjunction with stream lines shown on county soil surveys to manage riparian buffers in the Neuse River and Tar-Pamlico River basins (NC DENR 2002b). The NC DENR Ecosystem Enhancement Program requires that potential stream restoration projects be located along a USGS designated perennial blue-line stream to be eligible to receive stream restoration resources (NC DENR 2002c).

In developing the USGS 1:24,000 scale topographic map series, however, the blue-line hydrography was not intended to show smaller channels in finely dissected terrain (Mark 1983). In those areas, only the more prominent channels were to be plotted using the blue-line symbol. For example, perennial streams were to be published with solid blue lines regardless of their length and intermittent streams were to be published with an interrupted blue line if they were longer than 2,000 feet. Streams at the source and upper part of the network were to terminate no higher than about 1,000 feet from the basin divide (Leopold 1994). The choice of what symbol is actually shown, if any, however, is based on consistent portrayal (Leopold 1994). Therefore, the use of the blue-line network in headwater areas may not provide realistic estimates of the actual presence and lengths of headwater streams.

Appropriate size-based generalizations of actual channel networks, however, can be determined from the USGS 1:24,000 scale topographic maps (Morisawa 1957, Mark 1983, Leopold 1994). Strahler (1957) for example, developed a commonly used procedure that involved extending a blue-line drainage network to include valleys and swales judged prominent enough to yield channel flow during storms. The valleys were indicated by inflections or crenulations in the topographic contour patterns shown on the maps and drainage lines were continued as far upstream as cusps in the contours indicated their presence. The practice has been used for many years in North American drainage network studies and is referred to as the traditional contour crenulation method, or T-CC method. According to Krumbein and Shreve (1970), experienced operators generally produce consistent and similar delimitations of the drainage network.

The purpose of this study was to evaluate the T-CC method for estimating stream lengths in Piedmont headwater catchments by comparing results to field-measured lengths and the lengths of streams portrayed by the blue lines on the maps.

Methods

The Neuse River basin is the third largest river basin in North Carolina having an upland surface area of 6,234 square miles; it occupies approximately 12.7 percent of the upland surface area of the state. The river flows in a southeasterly direction as it crosses the state and spans two physiographic regions - the Coastal Plain (66 percent) and the lower Piedmont (34 percent). In this study, the Upper Neuse basin was defined as the portion of the basin located within the Piedmont physiographic region (see Figure 1, Chapter 2).

The Piedmont physiographic region overlies crystalline rock geology where Ultisol soils predominate. Annual rainfall averages approximately 45 inches per year. According to Daniels et al. (1999), elevations in the Piedmont range from 295 to 1,495 feet above sea level. Based on the major soils of the region, the Upper Neuse Basin had maximum soil slope gradients that ranged from 25 to 40 percent. Since terrain length measurements with slope gradients within the 25 to 40 percent range could be 3 to 8 percent greater than planimetric lengths, catchment slope gradients were first evaluated to determine if planimetric lengths required a terrain slope correction factor. All slope gradients for the 26 catchments examined were less than 5 percent and therefore, terrain length slope corrections were not made.

Twenty-two catchments were evaluated. Seven catchments were initially selected based on their having FO-BL streams shown on USGS 1:24,000 scale topographic maps and being located on large tracts of accessible and mostly undeveloped public lands. The remaining fifteen catchments were randomly selected from nine USGS quadrangles located entirely within the Upper Neuse area. Quadrangles were assigned a number and then the numbers were shuffled. Nine numbers were drawn and the corresponding topographic maps were used. Each of the quadrangles was divided into four quadrants, which were further subdivided for a total of 16 sub-quadrants per quadrangle. Two headwater catchments were then randomly selected from the quadrangles by two rolls of a die, which indicated the quadrant and sub-quadrant area to be sampled. All catchments were required to be mostly undeveloped.

In all 22 catchments, the FO-BL stream lengths and the drainage areas of the catchments were measured on the digital version of the 1:24,000 scale quadrangles using ArcView (3.1, ESRI). Additional streams in the 22 catchments not portrayed by blue lines were determined by the T-CC method on the digital quadrangles following procedures used by Strahler (1957). Drainage lines extended the blue-line stream network to include valleys or swales judged prominent enough to yield channel flow during storms. Valleys on the maps were indicated by inflections or crenulations in the topographic contour patterns. Drainage lines were continued as far upstream as cusps in the contours indicate their presence. The drainage lines stopped at the upper most contour line having a cusp. The expanded stream network was denoted as the T-CC stream network. The lengths of the added streams were measured on the digital maps to produce total T-CC stream lengths.

Total stream lengths in the initially selected seven catchments were measured in the field using a tape. Drainage lengths of ephemeral streams were measured as far up stream as indicated by channel processes and required the presence of channel banks (Montgomery and Dietrich 1988, Dietrich and Dunne 1993). The upstream extent of the channels typically had a distinct nick-point at the channel head.

The drainage areas of the initial seven catchments ranged from 0.08 to 0.57 mi^2 in size and established the size range requirement for the fifteen randomly selected catchments. Dds for each method were determined by dividing the respective total stream lengths for each catchment by its catchment area.

Two groups of catchments were analyzed to compare Dds among the three methods of measuring stream lengths. The first group consisted of the initial seven catchments and the second group included the 15 randomly selected catchments. All statistical analyses were performed using JMP, version 4.0.2 (SAS Institute, Cary, NC) with an alpha level of 0.05. Data within the groups were tested for normality using the Shapiro-Wilk W test prior to analysis. Mean Dd comparisons by stream length measurement method were made using ANOVA and Tukey-Kramer HSD procedures. Correlation coefficients for field-measured and T-CC stream lengths, field-measured stream length and watershed area, and T-CC stream length and watershed area were determined using Pearson product-moment procedures. Prediction equations to predict total T-CC stream lengths from catchment area were developed using linear regression. The equation developed from the Group 1 catchments (y = P_1T-CC length) was tested by using it to predict the total T-CC stream length for the Group 2 catchments (P_2T-CC length) and comparing the predicted drainage density to that measured on the maps for each catchment. The P_2T-CC Dds and the T-CC Dds were compared using ANOVA and a paired t-test.

Results

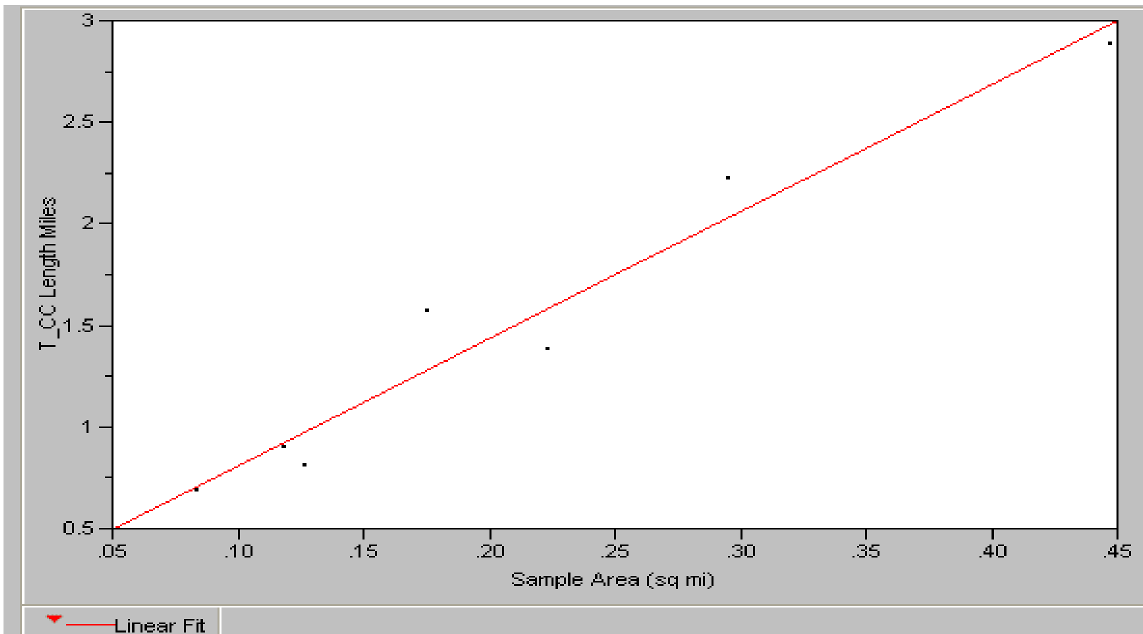
Drainage areas of the initial seven catchments (Group 1) ranged from 0.08 to 0.45 mi^2 (53 to 286 acres, respectively) and were normally distributed. The mean field-measured (8.77 mi/mi^2) and T-CC (7.35 mi/mi^2) Dds were not significantly different from one another (Table 1, Analysis Group 1), but both were significantly greater than the mean FO-BL Dd (2.80 mi/mi^2).

Table 1. Methods comparisons using drainage densities (Dds). Below are the average sample area (mi^2 and acres), number of samples (n), average Dds (mi/mi^2), standard deviations (SD) and coefficient of variation (CV) for the field-measured, first-order blue-line (FO-BL), and traditional contour crenulation (T-CC) methods used in the study. The analyses were grouped sequentially as described in the text. The letter adjacent to the average Dd value denotes if the means were significantly different within each group using Tukey-Kramer HSD procedures in group 1 and a paired t-test in group 2.

Analysis Group	Method	Mean Area mi^2 (acres)	n	Dd mi/mi^2		SD	CV
1	FO-BL	0.21 (134)	7	2.80	A	1.21	43%
	T-CC	0.21 (134)	7	7.35	B	1.05	14%
	Field-Measured	0.21 (134)	7	8.77	B	0.84	10%
2	T-CC	0.14 (92)	15	8.15	A	1.89	23%
	P_2T-CC	0.14 (92)	15	7.63	A	0.39	5%

Field-measured and T-CC stream lengths were strongly correlated with one another ($R = 0.98$), and both were strongly correlated with drainage area (field-measured length and area, $R = 0.99$ and T-CC length and area, $R = 0.97$). The T-CC stream length by catchment drainage area correlation relationship is shown in Figure 1. The following linear regression equation was developed to predict T-CC length (P_1T-CC) using drainage area:

P_1T-CC Length = 0.1838 + 6.25 (Area)	Length = miles Area = square miles
n = 7, r2 = 0.95	



Linear Fit

T_CC Length Miles = 0.1837827 + 6.2508851 Sample Area (sq mi)

Summary of Fit

RSquare	0.949749
RSquare Adj	0.939699
Root Mean Square Error	0.199622
Mean of Response	1.493173
Observations (or Sum Wgts)	7

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	3.7657604	3.76576	94.5005
Error	5	0.1992456	0.03985	Prob > F
C. Total	6	3.9650060		0.0002

Figure 1. Catchment drainage area by T-CC stream length correlation.

The areas of the Group 2 catchments and Dds determined from predicted (P_2T-CC) stream lengths were both normally distributed using the Shapiro-Wilk W test. Six of the 15 catchments did not have FO-BL streams portrayed on the maps. The mean T-CC Dd (8.15 mi/mi^2) was greater than the P_2T-CC Dd (7.63 mi/mi^2), however, the difference between the two means was not significant.

Conclusion

The results of this study suggested that Dds in the upper Neuse River basin of NC computed from map measurements (T-CC) of total stream length were similar to Dds computed from field measurements of stream length. More importantly, however, was that stream lengths were reliably predicted using catchment area alone, eliminating the very time intensive map measuring T-CC step. Additional field measurements are recommended to further validate the procedure.

Drainage density estimates for the FO-BL and T-CC methods for measuring total catchment stream length in this study were consistent with those of other NC studies. For example, the average T-CC Dd for watersheds ranging from 15.48 to 306 mi^2 in size was estimated to be 7.71 mi/mi^2 (Calvo-Alvarado and Gregory 1997). The average T-CC Dd in this study for catchments ranging from 0.08 to 0.57 mi^2 in size was estimated to be 7.82 mi/mi^2 (n = 26). The results of the FO-BL analysis in this study also indicated Dds (2.85 mi/mi^2, n = 17) consistent with other findings. For example, in Chapter 2, the blue-line Dd for the Piedmont region was 2.50 mi/mi^2 and the average blue-line Dd for the 31 watersheds evaluated by Calvo-Alvarado and Gregory (1997) was 2.57 mi/mi^2 (Bruton, unpublished data). Unlike the Calvo-Alvarado and Gregory (1997) study, which used a sampling unit to estimate average watershed T-CC Dds, this study used entire headwater catchments. The average T-CC catchment area of 0.21 mi^2 in this study (n = 26), however, was similar to the sample unit area of 0.25 mi^2 used by Calvo-Alvarado and Gregory (1997). When compared to the Dds from field-measured stream lengths in this study (8.77 mi/mi^2), the blue-line Dds under estimated field-measured Dds by a factor of 3.

Based on the more conservative T-CC Dd estimate found in this study (7.82 mi/mi^2, n = 26), approximately 64 percent of the headwater drainages in the upper Neuse River basin are largely overlooked by state water quality regulators. With increasing attention being given to the impacts of activities within headwater catchments (Doppelt et al. 1993, Bolstad and Swank 1997, Alexander 2000, Meyer and Wallace 2001, Peterson et al. 2001), where blue-lines are particularly deficient (Leopold 1994), attention should be given to standardizing a method for the accounting of headwater drainages in North Carolina. Protection and rehabilitation efforts in the upper Neuse River basin should not be limited to approximately 36 percent of the drainages that carry the blue-line symbol.

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CHAPTER FOUR

A FRAMEWORK FOR ESTIMATING HEADWATER SOURCE AREA DRAINAGE DENSITIES FROM USGS 7.5 MINUTE TOPOGRAPHIC MAPS IN NORTH CAROLINA

Abstract

Supplementing the blue-line streams portrayed on USGS 1:24,000 scale topographic maps by inserting drainage lines that correspond to crenulations in topographic contours is a common practice in developing headwater drainage networks. The drainage lines approximate the extent of primary stormwater runoff and sediment source areas in a catchment. This study used two such methods to estimate stream lengths and drainage densities (Dds) for 122 randomly selected first-order blue-line (FO-BL) headwater catchments across five physiographic regions of North Carolina (NC). The LV-90 method incorporated guidelines related to topography for the placement of drainage lines and was used as a topographic control against which the FO-BL and the traditional contour crenulation (T-CC) methods were compared. Catchments in two regions, the Tidewater (TW) and Inner Coastal Plain (ICP), had very low relief and many did not have FO-BL drainages. Total stream lengths of the 108 catchments that did have FO-BL streams were log transformed and had normal distributions using the Shapiro-Wilk W test. Pearson product-moment procedures indicated a very strong correlation ($R = 0.97$) between LV-90 and T-CC drainage lengths. The FO-BL lengths were less strongly related to topography ($R = 0.75$). The mean T-CC Dd was significantly greater than the mean FO-BL Dd in four of the five regions. The mean T-CC Dd was also significantly greater than the mean LV-90 Dd

in the Piedmont (P) and Mountain (M) regions. These results suggested that the T-CC method was used consistently across the state with regard to topography. Other studies have demonstrated that Dds based on T-CC stream lengths were not significantly different than those based on field-measured lengths.

Unlike other studies, however, this study compared Dds across physiographic regions having significant differences in elevations with multiple contour intervals (CIs) ranging from 1 to 40 feet. This study also differed from other studies in that it used the FO-BL catchment area as the basic sampling unit.

FO-BL catchment areas were significantly different between regions but not as expected. For example, mean catchment area for the M region, which had significantly greater relief than the other four regions, was greater than those for the SH and P regions, another indication of topographic unconformity within the FO-BL drainage network.

While catchment relief was initially thought to be an important factor in predicting T-CC Dds, the ICP was the only region where there was a significant increasing trend in Dds with increasing catchment relief. Excluding the TW region due to normality requirements, the ICP region had the least mean relief, which was significantly less than that for the SH and P regions where it was not significantly different. Mean relief for the M region was significantly greater than mean relief for the SH and P regions.

Linear regression was used to predict drainage lengths from catchment areas in the ICP, SH, P, and M regions. The regression fits ranged from moderate for the ICP region to very strong for the SH region (ICP $r^2 = 0.70$, SH $r^2 = 0.94$, P $r^2 = 0.83$, M $r^2 = 0.90$). The P and M region regression equations were used to predict T-CC stream lengths for an additional 10 P and 10 M randomly selected catchments. The T-CC method was used to estimate stream lengths in each of the catchments and Dds were determined. Predicted (P_1) T-CC Dds were then compared to the map-measured T-CC Dds by ANOVA and paired t-test for each region. In the P region, the mean P_1 Dd was significantly greater than the map-measured T-CC Dd (P_1 = 9.57 and T-CC = 8.28), while in the M region the mean P_1 Dd was less (not significantly) than the map-measured T-CC Dd (P_1 = 9.69 and T-CC = 10.59).

A second regression equation was determined using the regional stream lengths, however, the second prediction equation (P_2) used only those catchments from the original data set within the same CI. P_2 T-CC Dds were then compared to the map-measured T-CC Dds by ANOVA and paired t-test. In the second analysis, the mean P_2 Dd was not significantly different than the map-measured T-CC Dds for the P region (P_2 = 9.47 and T-CC = 8.28) and in the M region the differences lessened (P_2 = 10.00 and T-CC = 10.59).

The results of the study found that catchment size and map CI were important factors in predicting T-CC stream lengths from drainage areas within physiographic regions across NC. By region, the stream lengths originating from headwater primary source areas for USGS FO-BL catchments were 2 to 4 time greater than the lengths indicated by the blue-line symbol, thus demonstrating the need for an alternative method for primary source identification. This study provided a framework for developing an index for estimating the density of primary runoff source drainages in headwater catchments, however additional validation is recommended.

Introduction

Headwater catchments are made up of two interrelated drainage systems: the channel network and the hillslopes. The hillslopes control the production of stormwater runoff, which in turn, is transported through the channel network towards the catchment outlet. On hillslopes in humid areas such as NC, Horton (1945) overland flow is typically confined to impervious surfaces, areas where the vegetation has been removed, and areas where the infiltration of the soil has been reduced (Dunne 1975, Dunne, Moore, and Taylor 1975). Where permeable and well-drained soils exist, however, runoff flows are less variable in magnitude and delayed when compared to less pervious surfaces (Harris et al. 2000). The primary sources of runoff from these areas are subsurface stormflow and saturation overland flow, both of which tend to emerge from relatively narrow runoff-producing zones confined to low-lying parts of a catchment (Dunne 1975). The source that predominates in a given catchment is primarily dependent upon hillslope gradient and underlying geology. For example, in areas where steep hillslopes border a narrow valley floor, subsurface stormflow dominates and in areas where valley bottoms are wider and foot slopes are gentler, when the valley soil becomes saturated, saturation overland flow may dominate. The effects of hillslope hollows or convergent headwater areas encourage lateral soil-water movement that may produce both subsurface and saturation overland flow resulting in the development of a channel head and subsequent drainage channel (Anderson and Burt 1978, Beven and Kirkby 1979, O'Loughlin 1986). Channel head development is primarily dependent on the area and slope gradient of the unchannelled contributing drainage area (Montgomery and Dietrich 1988). However, because side slopes usually cover a larger area of a catchment, they produce more runoff per unit area than hollows, especially if the slopes are steep (Beven et al. 1988). Therefore, the runoff producing areas of a catchment are primarily driven by topographic gradients (Bonell 1993), and one of the most useful basin characteristics for mapping runoff areas is topography (Dunne 1975).

Primary source areas are an important part of larger river networks because of their linkage to the surrounding landscape (Hynes 1970, Hynes 1975, Vannote et al. 1980, Webster et al. 1992, Allan and Flecker 1993, Bonell 1993, Allan et al. 1997, Bolstad and Swank 1997, Likens et al. 1997, Pringle 1997). That linkage produces runoff from headwater areas that can impact both the quantity and quality of downstream receiving waters and may impose important constraints on hazard control (i.e. flooding) as well as water resource development on the main river (Leopold et al. 1964, Dunne and Leopold 1978, Naiman 1983, Clinnick 1985, Cooper et al. 1987, Burt 1992, Webster et al. 1992, Kusler and Larson 1993, Gilliam 1994, Leopold 1994, Daniels and Gilliam 1996, Gilliam et al. 1997, Wenger 1999, Alexander et al 2000, Peterson et al. 2001). Approximately half of the total length of a drainage network is composed of first order channels (Strahler 1957, Kirkby 1993). First through third order streams typically represent 95% of the number of channels, about 75% of the total channel length, and carry as much as 90% of the excess flow in the United States (Leopold et al. 1964, Dunne and Leopold 1978, Leopold 1994). During storm events it is the low-order, often ephemeral drainages that act as the primary source of surface flow to perennial streams (Hewlett and Hilbert 1967). Maintaining stream hydrology and the prevention of sediment accession to higher-order streams, therefore, relies on the protection of headwater source areas (Clinnick 1985, Cooper et al. 1987, Gilliam 1994, Hubbard and Lowrance 1994, Wenger 1999).

Primary source areas are largely overlooked, however, and are being lost from the landscape at a high rate by human activities (Meyer and Wallace 2001). One reason that they are ignored is due to the difficulty of measuring the sources over broad geographic areas. As a consequence, water resource managers in North Carolina (NC) often rely on the blue-line symbols shown on US Geological Survey (USGS) 1:24,000 scale topographic maps for accounting, regulatory, and other purposes (NC DENR 2002a, b, and c). As excellent as they are, the USGS maps were not intended to show headwater source areas in finely dissected terrain and the blue-line symbols that they carry are not believed to represent a viable data source for predicting source area extent (Mark 1983, Leopold 1994).

The ability to predict source area extent in NC would facilitate the development of a primary source Dd index for the state, which could be used as a measure of the efficiency with which water and sediment are discharged from a catchment (Dunne and Leopold 1978, Schumm 1997, Knighton 1998). Such an index should provide a useful starting point for comparing the potential effectiveness of source area protection zones among watersheds (Lowrance et al. 1997). For example, the higher the proportion of streamflow originating from relatively short flow paths to small streams (higher Dd), the higher the potential importance of source area zones in non-point source (NPS) pollution control (Lowrance et al. 1997).

Drainage density is defined as the total channel length divided by catchment area (Horton 1945) and reflects the interaction between incisive channelization processes, ground surface resistance, and diffusive infilling processes (Knighton 1998). Drainage density affords one of the best available quantitative expressions of drainage texture, an expression of the relative spacing of channels in fluvially dissected terrain (Leopold and Bull 1979, Easterbrook 1999). Because of its wide variation, Dd is a number of primary importance in landform scale analysis (Strahler 1957). In relation to drainage basin processes, Dd is perhaps the most useful single index of a stream network in that it reflects climate patterns, geology, soils and vegetation cover of a basin (Gregory and Walling 1973). Drainage density typically increases with mean landscape gradient (Montgomery and Dietrich 1988), and areas with high Dds are associated with high flood peaks, high sediment production, and steep hillslopes (Dunne and Leopold 1978). Drainage density is also an important predictor of nutrient removal in modeling watersheds where natural stream channels are eliminated (Smith et al 1997, Meyer and Wallace 2001).

Previous studies have demonstrated that appropriate size-based generalizations of actual channel networks can be determined from the USGS maps using crenulations in topographic contours (Morisawa 1957, Mark 1983, Leopold 1994, Bruton 2003). Strahler (1957), for example, used a contour crenulation procedure that involved extending the blue-line drainage network on topographic maps to include valleys or swales that were judged prominent enough to yield channel flow during storms. Individual stream-lines were continued as far upstream as cusps in the contours indicated their presence. The practice is commonly referred to as the traditional contour crenulation (T-CC) method and has been used for many years in North American drainage network studies (Morrisawa 1957, Leopold 1994, Calvo-Alvarado and Gregory 1997). According to Schumm (1997), the method may over-estimate the length of actual channel networks, however, in Chapter 3, the T-CC method was used in the upper portion of the Neuse River Basin of NC and Dds using the T-CC method were not significantly different than Dds determined using stream lengths that were field-measured. Because judgement is required by operators in the stream network delimitation process, rules governing the placement of stream lines on maps have been proposed (Mino 1942, Yatsu 1950, Melton 1957, Lubowe 1964). However, according to Krumbein and Shreve (1970), experienced operators generally produce consistent and similar delimitations of the drainage network using the T-CC method.

The usefulness of the T-CC method for determining size-based generalizations of drainage networks has been demonstrated, however, its implementation over a broad geographical and topographically diverse area such as NC would require a substantial input of resources. Alternative methods for predicting drainage lengths by using catchment areas would facilitate the development of mathematical equations for predicting the generalized extent of drainages in headwater areas and thereby substantially reduce the amount of effort otherwise required for measuring actual stream lengths.

The purpose of this study was to develop the framework for a primary source area Dd index for NC. To do so included the following procedures: Develop a method (LV-90) with topographic rules governing the placement of stream-lines to be used as a control for which USGS first-order blue-line (FO-BL) and T-CC drainage lengths could be compared. Develop a method for predicting headwater catchment drainage lengths across the state that considers catchment relief and drainage area, contour interval (CI), as well as physiographic region.

Methods

North Carolina typically recognizes three physiographic regions, Mountain (M), Piedmont (P), and the Coastal Plain. In this study, the Coastal Plain was divided into three distinct regions, Sandhill (SH), Inner Coastal Plain (ICP), and Tidewater (TW), giving a total of five physiographic regions. An additional physiographic region, the Outer Banks, represents only 0.61% (300 of 49,286 square miles) of the state's upland surface area and was not included in this study. According to Daniels et al. (1999), the M region ranges in elevation from 1,495 to 6,680 feet with maximum slope gradients ranging from 60 to 95 percent. The P region ranges in elevation from 295 to 1,495 feet with maximum slope gradients ranging from 25 to 60 percent. The Coastal Plain ranges in elevation from 0 to 650 feet, however, elevations of the TW region (Pamlico soil system) are less than 20 feet, elevations of the ICP region are less than 295 feet and elevations of the SH region range as high as 650 feet. Maximum slope gradients in the TW region are 2 percent, 12 percent in the ICP region, and 25 percent in the SH region.

Physiographic region boundaries and the index for the 971 USGS 7.5-minute quadrangles were obtained from the NC Center for Geographic Information and Analysis (Basin Pro 2.1). The quad index and the physiographic region areas were overlain using ArcView GIS 3.1 (ESRI). Map quads located entirely within each region were initially selected for possible inclusion in the study. A total of 122 quads were then randomly selected from across the state. The number of quads selected from each region was generally based on the region's proportional area of the state with a minimum of six quads. Each quadrangle was subdivided into 16 quadrants, one of which was randomly selected and sampled. A rural catchment with a first-order (Strahler 1957) blue-line stream within each quadrant area was selected and catchment area was measured on the digital 1:24,000 scale map using ArcView. Relief was determined by subtracting the elevation at the catchment's mouth from its maximum elevation. The lengths of first-order blue-line (FO-BL) streams were measured on the maps using ArcView and Dds were calculated by dividing the total blue-line length for each catchment by its respective catchment area (Horton 1945).

Using the T-CC method, additional stream-lines were added to the FO-BL stream network using the Strahler (1957) method, which involved tracing an extended drainage network to include valleys or swales that were judged prominent enough to yield channel flow during storms. The swales were indicated by inflections, or crenulations, in the topographic contours and individual stream-lines were continued as far upstream as cusps in the contours indicated their presence. The T-CC lengths were measured on the maps using ArcView and Dds were calculated by dividing the total T-CC stream length for each catchment by its respective catchment area.

The name LV for the LV-90 method was selected because 90-degree "Ls" and "Vs" in contour lines were easily used on the computer screen to determine whether a contour crenulation angle was 90-degrees or less. (See Figure 1 for an example of the LV-90 method.) The 90-degree criterion was selected after a preliminary examination of contour crenulation angles across the state. An angle greater than 90-degrees tended to exaggerate drainage lengths in the TW and portions of the ICP region where the topography is very difficult to interpret from maps (Calvo-Alvarado and Gregory 1996). The 90-degree

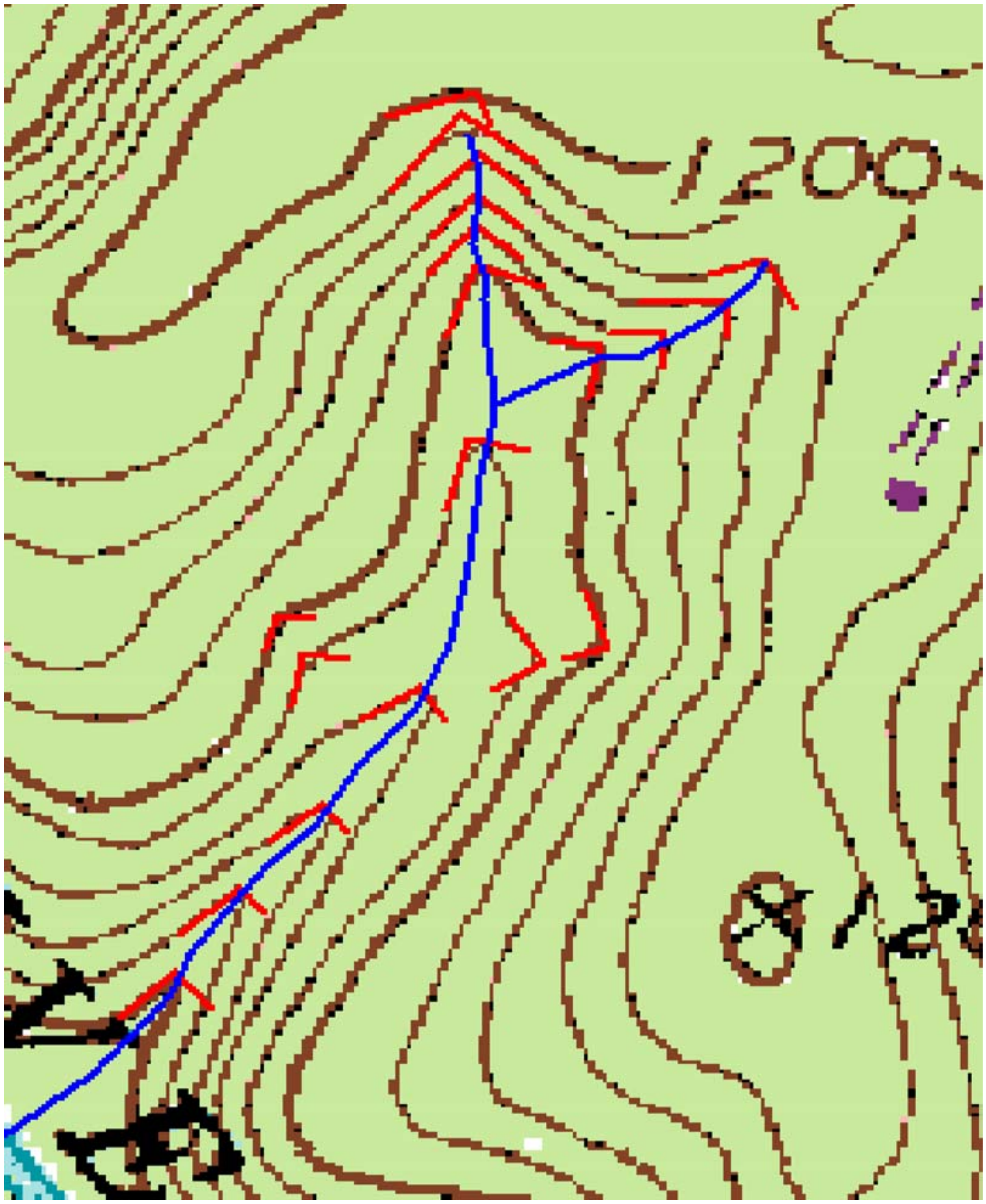


Figure 1. An example of the LV-90 method. Crenulations in map contours were used to identify the extent of potential headwater source areas from USGS 1:24,000 scale topographic maps across North Carolina. The LV-90 method was used as a topographic control and was based primarily on a maximum inflection angle of 90 degrees. Drainage lines were stopped at the upper most crenulation having an angle estimated to be 90 degrees or less. The T-CC method also used contour crenulations as a guide for the placement of drainage lines; however, a maximum inflection angle was not used. For this example, total LV-90 and T-CC drainage length estimates were the same.

criterion tended to underestimate drainage lengths in the P and M regions. Future studies may consider using different angles for each region.

LV 90 CC stream-lines were added to the FO-BL stream network as follows: category 1 stream-lines were reaches with more than one crenulation of 90-degrees or less. The lines were stopped at the upper most 90-degree or less contour line. For the last 90-degree or less contour line to be included, the distance between the previous contour line (no inflection criterion) did not exceed the distance of the previous 90-degree or less segment length. Category 2 stream-lines were reaches with a single crenulation of 90-degrees or less. Those LV-90 tributaries were adjacent to the main stem of the blue-line stream and were included if they occurred within the first or second contour line. Extensions to the main stem of the blue-line stream were included only if they occurred within the first, second, or third contour line. (Blue-lines often ended between contours.) Portions of blue-line lengths that did not conform to the rules were not included, thus a LV-90 CC length could be less than FO-BL length.

Category 1 criterion minimized the inclusion of discontinuous channels. The Category 2 criterion allowed the inclusion of short continuous side tributaries. LV 90 lengths were measured on the digital maps using ArcView and Dds were calculated by dividing the total LV 90 length for each catchment by its respective catchment area.

LV-90 drainage lengths were used as a topographic control against which FO-BL and T-CC drainage lengths were compared using Pearson product-moment correlation procedures (JMP Version 4.10, SAS). Drainage length distributions were analyzed by Shapiro-Wilk W procedures (JMP Version 4.10, SAS). Lengths were subsequently log transformed prior to analysis.

The distributions of Dds by stream length measurement method, catchment areas, and relief values were analyzed by using Shapiro-Wilk W procedures. Subsequent method and regional comparisons were made using ANOVA and all pairs comparisons using Tukey-Kramer HSD procedures (JMP Version 4.10, SAS). Area and relief values were log transformed prior to analysis.

Mathematical equations were developed using linear regression to predict T-CC stream lengths from drainage areas for each region. The equations were used to predict T-CC lengths for an additional 10 P and 10 M region randomly selected catchments having CIs similar to the catchments from which the equations were developed. The 10 P catchments were located in the upper Neuse River basin and the 10 M catchments were located in Burke County. Predicted T-CC Dds were determined by dividing the predicted lengths by their respective drainage areas. Predicted T-CC Dds were compared to map-measured T-CC Dds by ANOVA and subsequent paired t-test (JMP Version 4.10, SAS).

Results

Table 1 summarizes mean catchment area (mi^2) and mean relief (feet) by CI and by physiographic region for the 122 randomly selected FO-BL headwater drainages included in the study. Table 1 also shows the mean T-CC Dd for the 122 catchments. Within region Dds generally increased with decreasing CI in the ICP region, however, the opposite occurred for the P and M regions. The changes in Dds within the P region were not as dramatic as the changes within the M region and may have been the result of a small sample size within the

Table 1. Summary statistics for the 122 first-order blue-line (FO-BL) catchments by contour interval (CI) and T-CC Dd values. Dd values are means and are not transformed. Regions are Tidewater (TW), Inner Coastal Plain (ICP), Sandhill (SH), Piedmont (P), and Mountain (M)

Region	(n)	CI (feet)	Relief (feet)	mi^2	T-CC Dd
TW	1	1	5	3.88	0.00
TW	8	5	7	3.01	0.62
ICP	12	2	32	0.81	4.53
ICP	19	5	28	1.32	4.05
ICP	1	10	14	0.74	3.07
SH	6	10	112	0.26	8.51
P	43	10	110	0.24	9.39
P	6	20	130	0.23	9.97
M	1	10	552	0.59	6.87
M	5	20	862	0.42	8.84
M	20	40	1,090	0.34	10.03

20-foot CI. The larger change in Dds within the M region was probably due to the small sample size within the 10-foot CI, a decreasing trend in catchment area size with increasing CI, and a substantially greater increase in relief.

Table 2 summarizes the catchment area by region comparisons. Catchment areas used in the analysis were normally distributed by region and included 117 catchments. Mean catchment areas significantly decreased from the TW to the SH regions. The mean ICP region area was not significantly different than the mean SH region area and the mean SH region area was not significantly different from the mean P and M region areas, however,

Table 2. Mean area (square miles, mi^2) by region comparisons for the 117 normally distributed first-order blue-line (FO-BL) catchments in the study. Comparisons were made on log transformed data using ANOVA and Tukey-Kramer HSD procedures. Values shown are not transformed. Regions are Tidewater (TW), Inner Coastal Plain (ICP), Sandhill (SH), Piedmont (P), and Mountain (M).

Region	(n)	mi^2	TW	ICP	SH	P	M
TW	4	2.24			X	X	X
ICP	32	1.11				X	X
SH	6	0.26	X				
P	49	0.24	X	X			
M	26	0.37	X	X			

both the P and M region mean areas were significantly less than the mean TW and ICP region areas.

Table 3 summarizes the Dds by method, method by region, and region by method analyses. Dds using all 122 catchments were not normally distributed and thus the number of catchments was reduced by eliminating extreme values before statistical comparison were made. Shapiro-Wilk W test indicated that the lack of a normal distribution for Dds using the LV-90 and T-CC methods was due to the number of zero Dd values for the TW and ICP regions. As a result, the number of catchments was reduced from 122 to 113 for the LV-90 and T-CC methods. The number of FO-BL catchments was reduced from 122 to 103. Extreme values for the FO-BL method include a number of high Dd values, primarily in the M region, as well as the zero values for the TW and ICP regions.

Table 3 Mean drainage density (Dd) values and comparisons for all pairs tests using Tukey-Kramer HSD procedures. Group A contains the mean drainage density (Dd) for each of the three methods. To satisfy normality requirements, the number of catchments was reduced from the original 122 to the number indicated. In Group B, regional Dds were compared by method. The number of catchments in each sub-group is equal to the method total in Group A. In Group C, Dds for each region were compared by method. Also shown are standard deviations (SD) and coeffecients of variation (CV). An X indicates significant differences between mean Dd values. The three methods were first-order blue-line (FO-BL), LV-90, and traditional contour crenulation (T-CC).

Group A

Method	n	Dds	SD	CV	FO-BL	LV 90	T-CC
FO-BL	103	2.42	1.15	48%		X	X
LV 90	113	6.78	2.86	42%	X		X
T-CC	113	8.02	3.37	42%	X	X	

Group B

1. **First Order-Blue Line (FO-BL) Method**

n	Dds	SD	CV		TW	ICP	SH	P	M
4	0.69	0.87	126%	TW			X	X	X
27	2.01	1.39	69%	ICP			X		
6	3.55	1.35	38%	SH	X	X			
41	2.72	0.82	30%	P	X				
25	2.36	0.87	37%	M	X				

2. **LV 90 Method**

n	Dds	SD	CV		TW	ICP	SH	P	M
4	1.25	1.53	122%	TW		X	X	X	X
28	4.69	2.96	63%	ICP	X			X	X
6	7.25	1.81	25%	SH	X				
49	8.29	2.11	25%	P	X	X			
26	6.93	1.81	26%	M	X	X			

3. **Traditional-Contour Crenulation (T-CC) Method**

n	Dds	SD	CV		TW	ICP	SH	P	M
4	1.25	1.53	122%	TW		X	X	X	X
28	4.80	3.11	65%	ICP	X			X	X
6	8.51	2.02	24%	SH	X				
49	9.46	2.16	23%	P	X	X			
26	9.68	2.05	21%	M	X	X			

Group C

1. **Tidewater (TW) Region**

n	Dds	SD	CV	Method	FO-BL	LV 90	T-CC
4	0.69	0.87	126%	FO-BL			
4	1.25	1.53	122%	LV 90			
4	1.25	1.53	122%	T-CC			

2. **Inner Coastal Plain (ICP) Region**

n	Dds	SD	CV	Method	FO-BL	LV 90	T-CC
27	2.01	1.39	69%	FO-BL		X	X
28	4.69	2.96	63%	LV 90	X		
28	4.80	3.11	65%	T-CC	X		

3. **Sandhill (SH) Region**

n	Dds	SD	CV	Method	FO-BL	LV 90	T-CC
6	3.55	1.35	38%	FO-BL		X	X
6	7.25	1.81	25%	LV 90	X		
6	8.51	2.02	24%	T-CC	X		

4. **Piedmont (P) Region**

n	Dds	SD	CV		FO-BL	LV 90	T-CC
41	2.72	0.82	30%	FO-BL		X	X
49	8.29	2.11	25%	LV 90	X		X
49	9.46	2.16	23%	T-CC	X	X	

5. **Mountain (M) Region**

n	Dds	SD	CV		FO-BL	LV 90	T-CC
25	2.36	0.89	38%	FO-BL		X	X
26	6.93	1.81	26%	LV 90	X		X
26	9.68	2.05	21%	T-CC	X	X	

Table 3 also summarized the results of ANOVA and Tukey-Kramer HSD procedures. As indicated in Group A, there were significant differences in overall mean Dds between methods, between regions by method (Group B), and between methods by region (Group C).

Dds for the FO-BL method were variable. FO-BL mean Dds increased from the TW to the ICP to the SH regions where they peaked and then decreased to the P and to the M regions. Mean SH, P, and M region Dds were not significantly different from one another but were significantly greater than the mean TW Dd. The mean SH Dd was significantly greater than the mean ICP Dd, but the P and M regions were not. The mean ICP Dd was not significantly different than TW, P, or M region Dds.

Mean Dds for the LV-90 method were also variable, however, they showed a significant increasing trend from the TW to the P regions. Although the differences were not significant, the mean Dd for the M region was less than the mean P and SH Dds. Tukey –Kramer HSD results were similar for the LV-90 and T-CC methods.

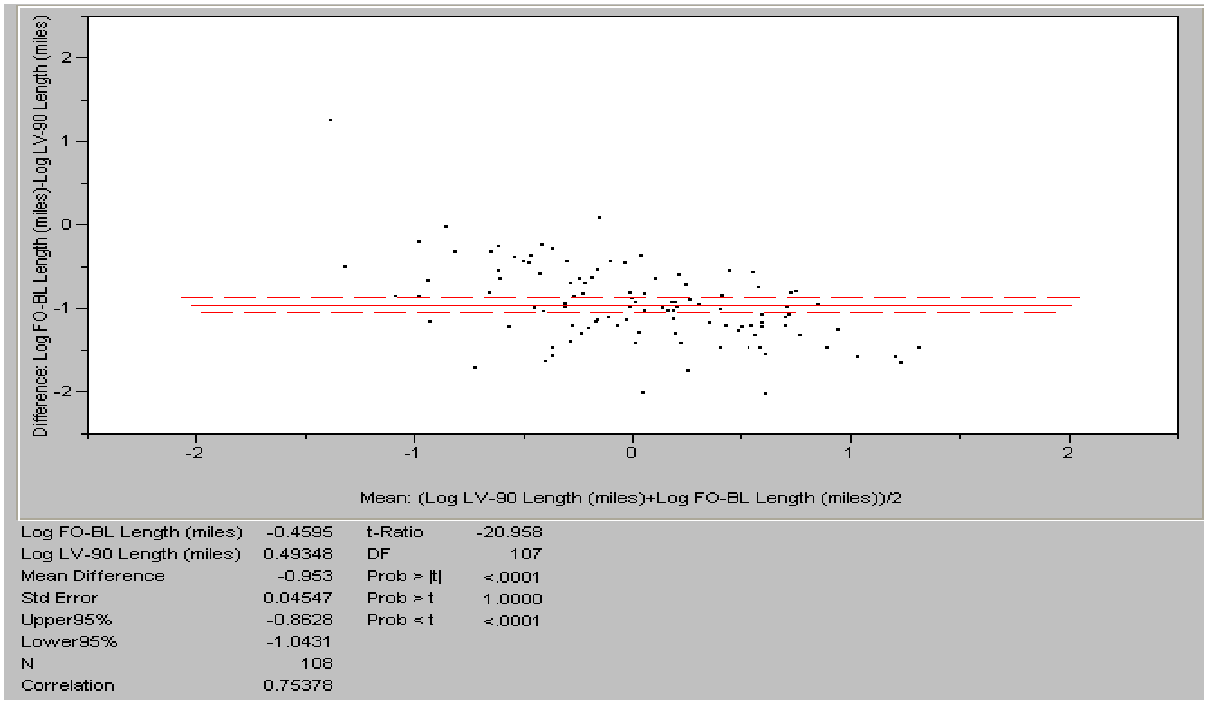
Mean Dds for the T-CC Dd method increased across the state progressing from the TW to the M regions. Mean T-CC Dds were not significantly different in the SH, P, and M regions, but all three were significantly greater than the mean TW Dd. Mean P and M Dds were significantly greater than the mean ICP Dd, however, the mean SH Dd was not.

In the regional analyses (Table 2, Group C), there were no significant differences in mean Dds by method for the TW region. For the ICP and SH regions, there were no significant differences in mean Dds between the LV-90 and T-CC methods, however, in both regions mean LV-90 and T-CC Dds were significantly greater than mean FO-BL Dds. In the P and M regions, there were significant differences in mean Dds between all three methods.

LV-90 drainage lengths had topographic rules governing their placement and were used as a standard for comparing the FO-BL and T-CC drainage lengths. The results of the length comparisons are shown in Figure 2. Drainage lengths for all three methods were log transformed prior to analysis. The FO-BL lengths showed a modest correlation ($R = 0.75$) with LV-90 drainage lengths, while LV-90 and T-CC drainage lengths showed a much stronger correlation ($R = 0.97$). That result suggested that the T-CC method was used consistently across the state with regard to topography.

For the T-CC length by catchment area predictions, the initial equations were developed using all of the catchments within the P and M regions (P $n = 49$, M $n = 26$) without consideration of map CI. The equations were used to predict T-CC drainage lengths for an additional 10 P region and 10 M region randomly selected catchments. The results indicated that the mean predicted (P_1) Dd for the P region was significantly greater than the mean map-measured T-CC Dd ($P_1 = 9.57$ and T-CC = 8.28) and that the mean P_1 Dd for the M region was less (not significantly) than the map-measured T-CC Dd ($P_1 = 9.69$ and T-CC = 10.59).

A second equation was determined using the initial regional drainage lengths, however, the second prediction equation (P_2) used only those catchments within the same CIs. For the P region catchments only those within the 10-foot CI were used to develop the P_2 equation ($n = 43$). For the M region only catchments within the 40-foot CI were used to develop the P_2 equation ($n = 20$). The results of the second analysis found no significant difference between the mean P_2 (9.47) and map-measured T-CC (8.28) Dds for the P region. For the M region the difference between the mean P_2 (10.00) and T-CC (10.59) Dds lessened.



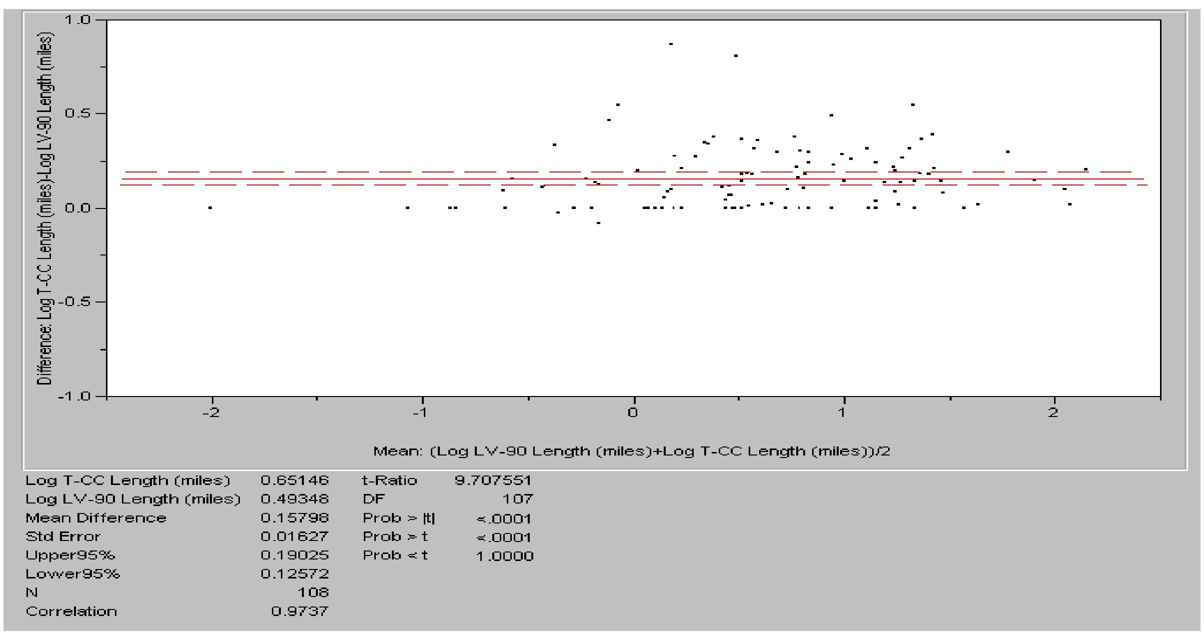


Figure 2. Drainage length correlations. FO-BL (top) and T-CC (bottom) lengths were matched with LV-90 drainage lengths using Pearson product-moment correlation procedures. T-CC drainage lengths had a much stronger correlation with LV-90 lengths (R = 0.97) than the FO-BL lengths (R = 0.75) suggesting that the T-CC method was used consistently across the state with regard to topography.

The P_2 T-CC length by catchment area prediction equations were as follows:

Piedmont (P) Region:

$$\text{Log } P_2 \text{ T-CC Length} = 1.9466228 + 0.838209 \text{ (Log Area in square miles)}, r^2 = 0.84$$

Mountain (M) Region:

$$\text{Log } P_2 \text{ T-CC Length} = 2.1655462 + 0.9018464 \text{ (Log Area in square miles)}, r^2 = 0.88$$

Conclusion

The purpose of this study was to develop the framework for a primary source area Dd index for NC. It is recognized that the stormwater runoff and sediment source areas of a catchment are driven by topographic gradients (Bonell 1993), and that one of the most useful basin characteristics for mapping source areas is topography (Dunne 1975). This study began by looking at one of the most readily available and commonly used sources of hydrography, the blue-lines portrayed on the USGS 1:24,000 scale topographic map series. The reliability of the blue-line hydrography for mapping the extent of primary source areas has been questioned over the years, which has led to the development of alternative methods for mapping headwater drainage networks (Strahler 1957, Mark 1983, Leopold 1994).

The most commonly used approach for identifying headwater source areas is the T-CC method. According to Krumbein and Shreve (1970), experienced operators generally produce consistent and similar delimitations of the drainage network using the T-CC method and few past studies have incorporated contour inflection angles as a means of standardization. This study developed a method (LV-90) appropriate for NC's topography, which was used as a control to evaluate the topographic relationships of the T-CC and FO-BL methods. This study found that the strength of the FO-BL by LV-90 drainage length relationship was not sufficient to warrant further analysis using blue-line lengths. The results of the T-CC by LV-90 length analysis, however, indicated a very strong topographic relationship ($R = 0.97$) and suggested that the T-CC method was used consistently across the state with regard to topography. Another NC study found no significant differences between T-CC and field-measured Dds in the P region (Chapter 3). Additional validation of the results of this study is recommended. On a regional basis, this study found that the drainage lengths originating from headwater primary source areas for USGS FO-BL catchments were 2 to 4 times greater than the lengths indicated by the blue-line symbol, thus demonstrating the need for an alternative method for primary source identification.

Considerable progress has been made in explaining and predicting systematic downstream changes in river networks and the importance of headwater source areas (Meyer and Wallace 2001, see review in Power and Dietrich 2002). Since downstream receiving waters are so dependent upon headwater areas with regard to its quality, species diversity, and hydrology, benefits to water resources could be maximized by including the full extent of headwater drainages in management decisions (Doppelt et al. 1993, Otto et al. 2002, Saunders et al. 2002). This study has provided a framework for developing a Dd index for headwater drainages in NC that uses existing USGS 1:24,000 scale topographic maps.

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