ACCURACY ASSESSMENTS FOR HEADWATER STREAM MAPS IN WESTERN NORTH CAROLINA

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ABSTRACT

Headwater streams are essential to downstream water quality, therefore it is important they are properly represented on maps used for stream regulation. Current maps used for stream regulation, such as the United States Geological Survey (USGS) topographic maps and Natural Resources Conservation Service (NRCS) soil survey maps, are outdated and do not accurately nor consistently depict headwater streams. In order for new stream maps to be used for regulatory purposes, the accuracy must be known and the maps must show streams with a consistent level of accuracy. This study assessed the valley valley presence/absence and stream length accuracy of the new stream maps created by the North Carolina Center for Geographic Analysis (CGIA) for western North Carolina. The CGIA stream map does not depict headwater streams with a consistent level of accuracy. This study also compared the accuracy of stream networks modeled using the computer software program, Terrain Analysis using Digital Elevation Models (TauDEM), to the CGIA stream map. The stream networks modeled in TauDEM,also do not consistently predict the location of headwater streams across the mountain region of the state. The location of headwater streams could not be accurately nor consistently predicted by solely using aerial photography or elevation data. Other factors such as climate, soils, geology, land use, and vegetation cover should be considered to accurately and consistently model headwater stream networks.

INTRODUCTION

Purpose

Federal, state, and local agencies rely on maps, such as the USGS 1:24,000 topographic, NHD digital USGS topographic, and NRCS 1:100,000 soil survey maps, to regulate streams or plan for restoration. These maps were not constructed with sufficient detail to be used as stream maps and are outdated (Drummond, 1974). Topographic and soil survey maps poorly depict true stream networks because they often do not show first order streams, in addition to many second and third order streams (Morisawa, 1957; Coffman et al., 1972; Benda et al. 2005).[1] The first, second, and third order streams in a watershed are the headwater streams of a stream network (Strahler 1957). USGS maps are known to have inconsistent drainage densities among quadrangles, which affects the number and location of streamlines (lines on a map that represent streams) depicted on a map (Colson et al. 2008). Because of this, regulating headwater streams in areas where two quadrangles meet can be difficult. A study showed NRCS soil maps overpredicted total headwater stream length by an average of 54% in nine watersheds across the state of North Carolina (Colson et al. 2008). The same study showed USGS topo maps underpredicted total headwater stream length by an average of 34% (Colson et al. 2008). Headwater streams have a significant impact on downstream water quality, and therefore it is important that they are accurately depicted on the maps used by agencies in order to ensure proper regulation (Brooks and Colburn 2011). The inconsistency and inaccuracies are due to the fact that USGS topo and NRCS soil surveys were not intended to be used for stream regulation (Russell 2008).

North Carolina officials saw the need for a state-wide stream map that more accurately depicts the position of streams on the landscape. A new stream map was created by CGIA, but funding only allowed for a stream map to be developed for the mountain region of the state (Appendix 1). Concurrently, a separate stream mapping study by the North Carolina Division of Water Quality

1. A stream network includes all of the streams, of any order, that are within a defined drainage basin or watershed.

(DWQ) was in progress to “develop a stream map for the state that more accurately depicts first and second order streams” (Russell 2008). Based on field data, DWQ has been able to use different variables to model headwater streams for areas in the coastal plain and piedmont regions of the state. Although nine mountain watersheds have been field-mapped by DWQ, models for headwater streams have not been developed for any areas in the western portion of the state. It may be possible to combine the stream mapping efforts in North Carolina between the two agencies by using the streamlines created by CGIA and mountain field data from DWQ. The two agencies have already agreed “to integrate the headwater stream mapping products with CGIA to produce one North Carolina stream map that meets multiple use requirements” (Russell 2008). The first step to this integration is determining how well the CGIA stream map depict headwater streams.

The two most important attributes of a stream map are known accuracy and consistent accuracy. If the accuracy of the CGIA stream map is known and is shown to be consistent, it is possible to use the map as a tool for regulatory purposes. In order to determine the accuracy of the CGIA stream map, I performed accuracy assessments using the nine mountain watersheds that were field-mapped by DWQ. The accuracy assessments for the CGIA streamlines for each of the nine watershed is the first part of this study. There are two components to the accuracy assessment. The first component includes an evaluation of a map's correct depiction of the presence or absence of streams within the valleys of a watershed, called the valley presence/absence accuracy. The second component of an accuracy assessment determines the difference between the total stream length of a map compared from the field-verified total stream length in a watershed, called the stream length accuracy.

For the second part of this study, I chose two different methods to model stream networks using a computer software program called Terrain Analysis Using Digital Elevation Models (TauDEM) (Tarboton 2009). I also performed accuracy assessments for the stream networks that were created using TauDEM. This study compares the headwater stream accuracies of TauDEM stream networks to the CGIA streamlines. TauDEM is a computer program that is fast, simple and free to use, whereas CGIA was an effort that took substantial amounts of time and money to complete. The first purpose of this study was to determine the accuracies and consistencies of headwater streams on the CGIA stream map. The second purpose of the study was to compare the CGIA stream map accuracies to other methods used to model stream networks that were less costly and time-consuming than the CGIA effort.

Importance of Headwater Streams

Headwater streams constitute 60 to 85% of the total stream length of a network, and drain 70 to 90% of the drainage basin area (Benda et al. 2005, MacDonald and Coe, 2007). In a watershed, “headwater streams represent the maximum interface with the landscape and therefore are predominantly accumulators, processors, and transporters of materials from the terrestrial system" to the larger order streams (Vannote et al., 1980; Kyshakevych 2009). They perform essential functions that benefit water quality such as retention of organic debris, cycling of nutrients and sedimentation, flood control, and dissipation of energy from runoff that lessens downstream erosion (MacDonald and Coe 2007). Headwater streams host a myriad of macroinvertebrate species, many of which are essential to nutrient cycling and transport to the entire stream network (Meyer and Wallace 2001; Gomi et al. 2002, Adams and Spotila 2005). They are able support macroinvertebrates and other small species by providing suitable breeding and rearing sites and allowing for species migration across the landscape (Zale 1989). Because headwater streams provide so many important functions and include so much of the total stream length in a watershed, it is imperative that they are properly regulated.

Headwater Stream Formation

Headwater streams in mountainous regions begin from three possible channel-initiation processes: overland flow, landsliding, and seepage erosion (Montgomery and Dietrich 1989). The starting point of a first order stream within a valley is the stream origin, or channel head. The first process that can form channel head is overland flow. Overland flow occurs when the precipitation rate exceeds the infiltration rate (Jaegar et al. 2007). The rate at which water can infiltrate the soil depends on porosity and permeability of the soil, meaning less permeable soils with lower porosity will have slower infiltration rates (Kyshakevych 2009). Saturation excess is a process that occurs when more precipitation falls onto soil that is already saturated. The precipitation will then become runoff. Other watershed characteristics, such as the amount and type of vegetation cover, potential evapotranspiration, climate, geology, drainage area, and slope will also affect the infiltration rate and overland flow in a watershed (Adams and Spotila, 2005). Overland flow is responsible for most channel heads in watersheds with lower-gradient slopes (Montgomery and Dietrich 1989). The channel-initiation points from overland flow are often considered gradual (Montgomery and Dietrich 1989). Channel heads caused by overland flow "are characterized by signs of concentrated flow upslope of the channel head as evidence by the presence of debris such as leaves and small twigs piled behind rooted vegetation and plants trained down slope" (Jaegar et al. 2007).

The second channel-initiation process in mountainous areas is landsliding and is more common in areas with steeper slopes (Montgomery and Dietrich 1989). Landslides are caused by subsurface water flow in areas with a steep gradient (Adams and Spotila, 2005). In watersheds with steeper slopes, the water moves into the top soil layer and then horizontally towards deep valleys. The subsurface water flow increases the pore pressure within the soil layer, which reduces the ability of the soil to stay in place (Montgomery and Dietrich 1989). When precipitation falls in watersheds with steeper slopes, the water moving across the land will have a higher velocity, causing channel-initiation points to often times be concave and abrupt (Montgomery and Dietrich 1989). Channel heads caused by landslides can be "identified by the presence of recent mass wasting scars" (Jaeagar et al. 2007). The same watershed characteristics that affect overland flow can also affect landsliding processes.

The third channel-initiation process is seepage erosion, which occurs on both gentle and steep slopes. (Montgomery and Dietrich 1988; Montgomery and Dietrich 1989). The seepage erosion process occurs from convergent subsurface flow, similar to landsliding. However, the channel heads formed by seepage erosion are not as abrupt or severe as those formed by landsliding. Channels formed from seepage erosion often "begin as discontinuous channel segments with evidence of headcut undermining," and are difficult to identify without field-based evidence (Montgomery and Dietrich 1988).

CGIA Streamlines

In the summer of 2004, the Studies Act (SL2004.161) called for a plan from the NC Geographic Information Coordinating Council (GICC) and NC Department of Environmental and Natural Resources (NCDENR) to create new maps of surface waters (NC Stream Mapping Program).The Stream Mapping Study Working Group, a group composed of consultants, academic advisers, and government employees from federal, state, and local levels, drafted an implementation plan that studied different methodologies that could be used to produce maps, potential cost, an estimated time-frame, and the key benefits of the project (NC Stream Mapping Program).

Also during 2004, Hurricanes Ivan and Frances caused massive flooding and millions of dollars worth of damage in western North Carolina. In 2005, the Hurricane Recovery Act (SL2005-1) was passed, declaring 19 North Carolina mountain counties disaster areas and in need of assistance. The act also appropriated funds for the NC Stream Mapping Project to develop new stream maps for western North Carolina (NC Stream Mapping Program). It was decided that CGIA, a part of NCDENR, would be the lead agency that would manage the development of the new streamlines. CGIA created the new streamlines using methodologies discussed in the "Implementation Plan to Improve the Mapping and Digital Representations of Surface Waters in North Carolina" (Implementation Plan), written in 2004 by the original Stream Mapping Study Working Group (NC Stream Mapping Program). CGIA created the new streamlines using recent aerial photography, Light Detection and Ranging (LIDAR) data, and ArcGIS. ArcGIS is a geographic information systems (GIS) computer software program that allows the user to view, create, edit, and maps and analysis spatial data. All streamlines were drawn in using aerial photography, as this method was shown to be most accurate in the Implementation Plan (NC Stream Mapping Program). When streams could not be determined with aerial photography, ArcHydro, a collection of stream network delineation tools in ArcGIS, was used (NC Stream Mapping Program). A 6-acre (0.024281 km^2) drainage area threshold was used for the stream network delineation tool in ArcGIS, based on a single study of urban streams in Greensboro, NC (NC Stream Mapping Program). When modeling stream networks using computer software programs such as ArcGIS, the chosen drainage area threshold is important. In nature, streams in watersheds with different slopes and will have different drainage areas (Montgomery and Dietrich 1992). The slope-drainage area relationship is further explained in the Methods section. To capture headwater streams, streamlines were extended 200 feet (69.6 m) beyond the modeled stream origin in order to ensure penetration of the 6-acre (2.4281 ha or 0.024281 km^2) drainage area (NC Stream Mapping Program). The main focus for the CGIA stream map was to improve the horizontal accuracy of streams on maps, not to accurately show headwater streams (NC Stream Mapping Program).

Headwater Stream Spatial Dataset

In a separate project from the NC Stream Mapping Project, DWQ began work on the Headwater Stream Spatial Dataset (HSSD) in 2004. The HSSD aims to improve the representation of headwater streams on maps that can be used by agencies such as DWQ, United States Army Corps of Engineers (USACE), and the Environmental Protection Agency (EPA) for research and regulatory purposes for North Carolina (Russell 2008). For the HSSD, DWQ collects field data of intermittent and perennial stream origins in selected watersheds and uses these data to create a field-based stream network in TauDEM.[2] Once a field-based stream network is created, GIS analysis of watershed characteristics such as slope, drainage area, soils, and precipitation can be used to create a predictive model of streams for a different location with similar characteristics (Russell 2008).

The selected watersheds are chosen to represent the Omernik and EPA Level IV ecoregions that occur in North Carolina (Omernik 1987; Environmental Protection Agency 2011). Level IV ecoregions are the finest level of organization for ecological regions based on "geology, physiography, vegetation, climate, soils, land use, wildlife, and hydrology" (Environmental Protection Agency 2011). Because the Level IV ecoregions represent landscapes with similar characteristics, the sites chosen for the HSSD "were stratified by ecoregion, given the assumption that ecoregions will control for landscape variability" (Russell 2008). The data that are derived from GIS analysis of the selected watersheds act as a sample of the characteristics of the ecoregion. Using statistical analysis and logistic regression, predictive models are created for each ecoregion by DWQ using the field-mapped watersheds (Russell 2008).[3]

METHODS

Study Areas

There are 5 different ecoregions that are represented by the nine watersheds (Table 1). Out of

2 Intermittent streams flow seasonally and perennial streams flow throughout the year.

3 "Logistic regression is a statistical method for analyzing a dataset in which there are one or more independent variables that determine an outcome. The outcome is measured with a dichotomous variable (in which there are only two possible outcomes)" (medcalc.org). For the HSSD, the two possible outcomes are 0 "not a stream" or 1 "stream" for each cell of a DEM. The cells with a value of 1 will make up a stream network.

the field-mapped watersheds, four are within the Eastern Blue Ridge Foothills ecoregion, two are within the Southern Metasedimentary Mountains, and there is one watershed in each of the Southern Crystalline Ridges and Mountains, High Mountains, and Broad Basin ecoregions (Figure 1). The watersheds where stream origins were mapped by DWQ are mostly forested and occur on public lands to minimize the effects of land use disturbance (Table 2) (Russell 2008). The size of the watersheds range from 1.09 to 6.43 km^2 (269 to 1,588 acres) with an average of 45 stream origins mapped per watershed (Table 2). The slopes and contributing upstream drainage areas were extracted from GIS analysis at the stream origins for each watershed (Table 3). The watersheds with the highest slopes also have the lowest drainage areas. These data demonstrate the inverse slope-drainage area relationship discussed by Montgomery and Dietrich (1989).

Table 1. Level IV Ecregion Descriptions. A brief description of the five Level IV ecoregions used in this study, arranged from the most western ecoregion to the most eastern in the mountains.

Level IV Ecoregion	Description
High Mountains (HM)	• Boreal-like climate than surrounding regions • Frigid soils rather than mesic soils • Several disjunct high-elevation areas generally above 1,375 meters
Southern Metasedimentary Mountains (SMM)	• Contains rocks that are not as strongly metamorphosed as seen in Southern Crystalline Ridge and Mountains • Steep, dissected, and densely forested mountains • Mostly forested
Broad Basin (BB)	• Drier, lower elevations, and less relief than Southern Crystalline Ridge and Mountains and Southern Metasedimentary Mountains • Mostly forested, but overall has more pasture, cropland, industrial land uses, and human settlement than other Blue Ridge ecoregions
Southern Crystalline Ridges and Mountains (SCRM)	• Greater relief and higher elevations than Broad Basin and Eastern Blue Ridge Foothills • Elevation ranges 400 to 1500 meters
Eastern Blue Ridge Foothills (EBRF)	• Warmer and drier than most other Blue Ridge ecoregions • Lower elevations (300 to 850 meters) • More Piedmont influences

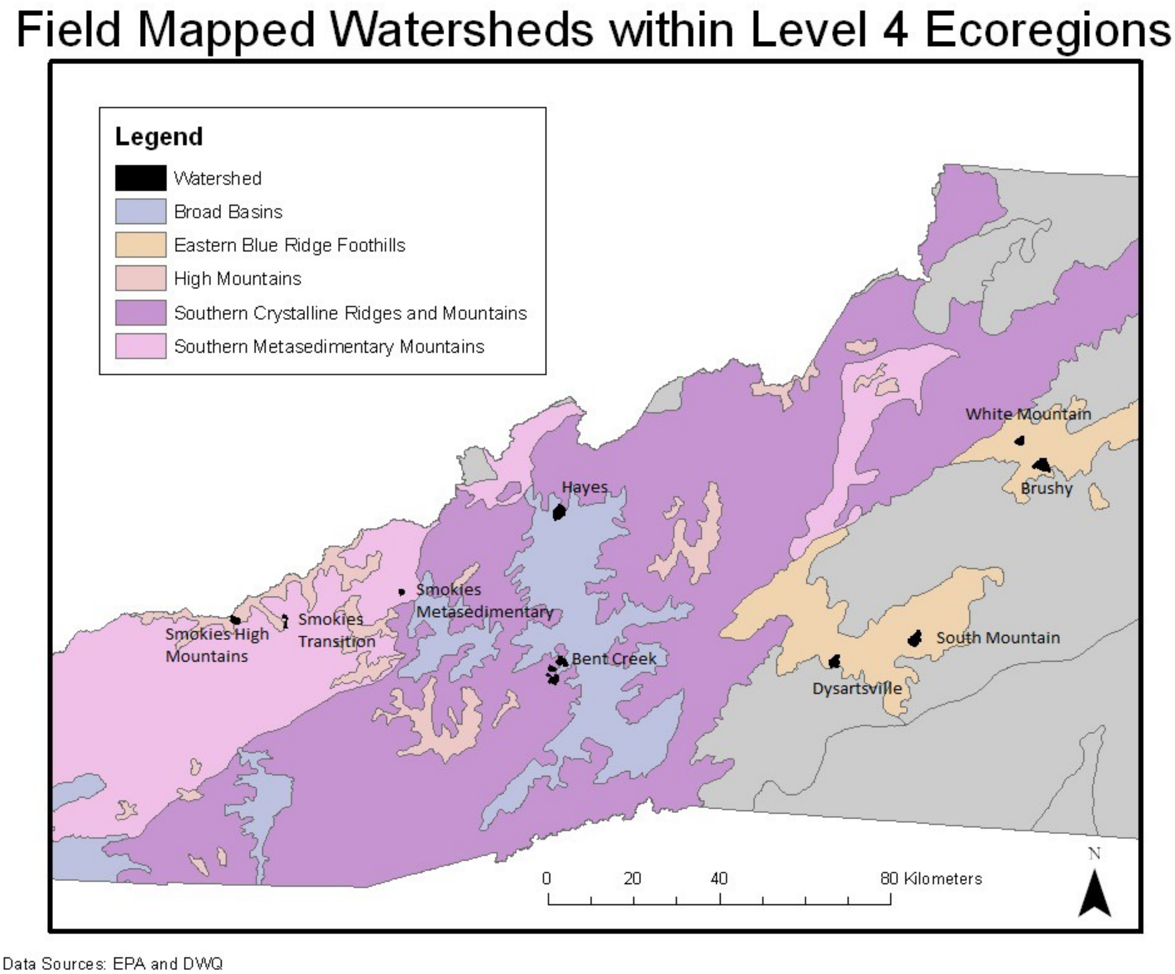

Figure 1. A map of the locations of each watershed used in this study.

Table 2. Watershed Characteristics. Characteristics of each of the nine watersheds used in this study. The table is arranged from smallest to largest watershed area. The percentage of open areas in each watershed includes any land cover that is not considered shrub land or forested. This means cropland, pasture, and developed areas are considered open area (NLCD 2006).

Ecoregion	Watershed	Area (km^2)	Drainage Density (km^2/km)	% of Open Area
EBRF	White	2.80	4.61	0
	Dysartsville	4.64	4.26	6
	South	6.03	2.91	10
	Brushy	7.24	3.60	7
SMM	Smokies Trans	1.09	4.13	0
	Smokies Meta	1.18	4.23	4
HM	Smokies High	2.93	1.72	3
BB	Hayes	6.62	4.12	55
SCRM	Bent	8.47	2.52	2
	Mean	4.56	3.57	9.67

Table 3. Drainage Areas and Slopes at Stream Origins. The contributing upstream drainage area and slope taken at the field-verified stream origins.

Watershed	Drainage Area Mean (acres)	Drainage Area Range (acres)	Watershed	Slope Mean	Slope Range
Smokies Trans	0.11	0.51	Smokies Trans	0.47	0.71
Smokies High	0.26	0.48	South	0.39	0.64
South	1.38	5.52	Smokies Meta	0.38	0.71
Smokies Meta	2.15	21.94	Smokies High	0.31	0.31
White	2.23	11.55	White	0.23	0.43
Bent	2.56	22.15	Bent	0.20	0.47
Brushy	3.20	24.08	Dysartsville	0.19	0.40
Hayes	3.34	19.30	Brushy	0.16	0.42
Dysartsville	3.63	18.97	Hayes	0.13	0.25

Collecting Field Data

The flow regimes of the stream origins were identified using the *Methodology for Identification of Intermittent and Perennial Streams and Their Origins Version 4.11*. This is a method that evaluates the morphology, hydrology, and biology as indicators of duration of flow at a stream origin (NCDWQ 2010). Only intermittent and perennial stream origins were mapped for this study because USACE and

DWQ do not typically regulate ephemeral streams.[4] To map stream origins, DWQ began at the most downstream point of the watershed to be studied. Using aerial photographs and USGS topographic maps as guidance, they walked up the stream until a tributary was observed (Russell 2008). The tributary was then followed until they encountered another tributary or reached the stream origin (Russell 2008). This process was repeated until the entire stream network was mapped. The stream origin points were taken with a mapping-grade GPS unit. In instances where the mapping-grade GPS unit could not acquire enough satellites, a less accurate recreational-grade GPS unit was used.

Creating Digital Elevation Models

In order to create the field-verified stream networks, a base DEM was created from LIDAR bare earth points (Appendix 2). The bare earth data were downloaded from the North Carolina Floodplain Mapping Program (ncfloodmaps.org). The bare earth points are given as a text file with values for x (latitude), y (longitude), and z (elevation). The x, y, and z values were converted into a point shapefile using ArcCatalog (a part of ArcGIS) Version 9.3.1. In ArcMap (a part of ArcGIS) Version 9.3.1, the point shapefile was converted into a raster with a 5 meter by 5 meter resolution. Each cell, or pixel, of the raster represents 25 m^2 of the earth's surface. There are approximately four bare earth points of data for each cell of the raster. This raster is the base DEM that will be used in TauDEM (Tarboton 2009).

Creating Field-verified Stream Networks

To create the field-verified stream networks, I used TauDEM Version 4.0 and ArcMap Version 9.3.1 (Appendix 2) (Tarboton 2009). Using the base DEM, a stream network can be modeled using TauDEM as a toolbox in ArcMap (Appendix 3). The initial stream networks created by TauDEM were

4 Ephemeral streams carry stormwater from precipitation, but do not experience continuous flow and lack the stream origins features that indicate some sort of continuous flow.

edited to fit the field-mapped stream origins. The edited streamlines are the field-verified stream networks that are used for the accuracy assessments.

Modeling Stream Networks in TauDEM

I used two different methods in TauDEM to create stream networks for this study. The first was the DEM curvature based method (Appendix 2). This method uses the Peucker-Douglas algorithm to determine which cells of the DEM are considered to be either convex or concave (Peucker and Douglas 1975, Band 1986). The cells are grouped in a 2 by 2 matrix across the extent of the DEM. The elevation data for each cell is extracted from the DEM and cells are evaluated in the matrix.The convex cells have the highest elevation values of the matrices and are marked as ridges (or not streams) with a value of 0 (Tarboton 2004). The concave cells have the lowest elevation values of the matrices and marked as streams with a value of 1. The stream cells will make up the streamlines within the watershed (Tarboton 2004). When using the Peucker-Douglas algorithm alone, the stream cells often times lack connectivity and do not form continuous streamlines. For the DEM curvature based method, the idea of thinning, discussed in length by Band (1986), is used to produce connected streamlines (Tarboton 2004). In order to connect the stream cells, the contributing area of the stream cells is calculated and a contributing area threshold is determined. The cells that exceed the threshold have the most contributing area and are the lowest points on the landscape. The lowest elevations are most likely where water will flow to on the landscape and support stream flow. The cells that exceed the contributing area threshold are marked as streams and are used to connect the gaps in the streamlines (Tarboton 2004).

The second method I used to delineate stream networks was the area and slope threshold method (Appendix 2). The area and slope threshold is determined by the following inequality:

$$AS^y > T \qquad (1)$$

where A is the drainage area and S is slope. For the area and slope threshold method in TauDEM, the values for y and T are chosen by the user (Tarboton 2004). Based on empirical data of mountainous terrain in the western region of the country, Montgomery and Dietrich (1992) found that a value of 2 for y and a threshold (T) of 200 adequately determined the location of streams. They determined "that an inverse relationship between the drainage area contributing to a channel head (source area) and the local valley slope defines a topographic threshold between channeled and unchanneled regions of the landscape" (Montgomery and Dietrich 1992). In areas with steeper slopes, less drainage area is required to for channel initiation. Conversely, areas with gentler slopes require a larger area to supply enough water to form streams in a watershed.

Each cell in the DEM has drainage area and slope values. Drainage area is calculated from all of the number of cells in the DEM that are upslope, and slope is calculated from the elevation data. Using these data and the equation (1) above, a value is calculated for each cell. If the value exceeds the threshold (T) chosen by the user, it is given a value of 1 and is considered a stream. If the value is less than the threshold chosen by the user, it is given a value of 0 and is not a stream. The collective cells make up streamlines, and the streamlines in a watershed make up the stream network. I felt the threshold where T = 200, as determined by Montgomery and Dietrich (1992), would be a starting point for this study, since the watersheds I used are also located across mountainous terrain. I tested three different threshold values to determine how the level of accuracy for each watershed changed by increasing the threshold for the area and slope method. I used the threshold values of 150, 200, and 300.

Performing Accuracy Assessments

For this study, I performed accuracy assessments for CGIA and modeled streamlines from the different methods in TauDEM. The accuracy assessments for each watershed include an evaluation of the model's ability to correctly predict the valley presence/absence of streams and total stream network length. The true skill statistic (TSS) was used to evaluate the ability of a method to correctly predict the location of streams by the use of omission and commission errors (Figure 2; Table 3) (Allouche et. al., 2006; Russell 2008). The TSS values range from 0 to 1. The highest possible value for a TSS is 1, meaning a model accurately predicted the location of every field-verified stream and did not predict any streams in valleys that do not have field-verified streams.

The possible outcomes using the TSS are:

a) True positive – the number of valleys correctly predicted to have streams

b) False positive – the number of valleys predicted to have streams that do not actually have streams

c) False negative – the number of valleys that have streams, but were not predicted by the model

d) True negative- the number of valleys correctly predicted to not have streams

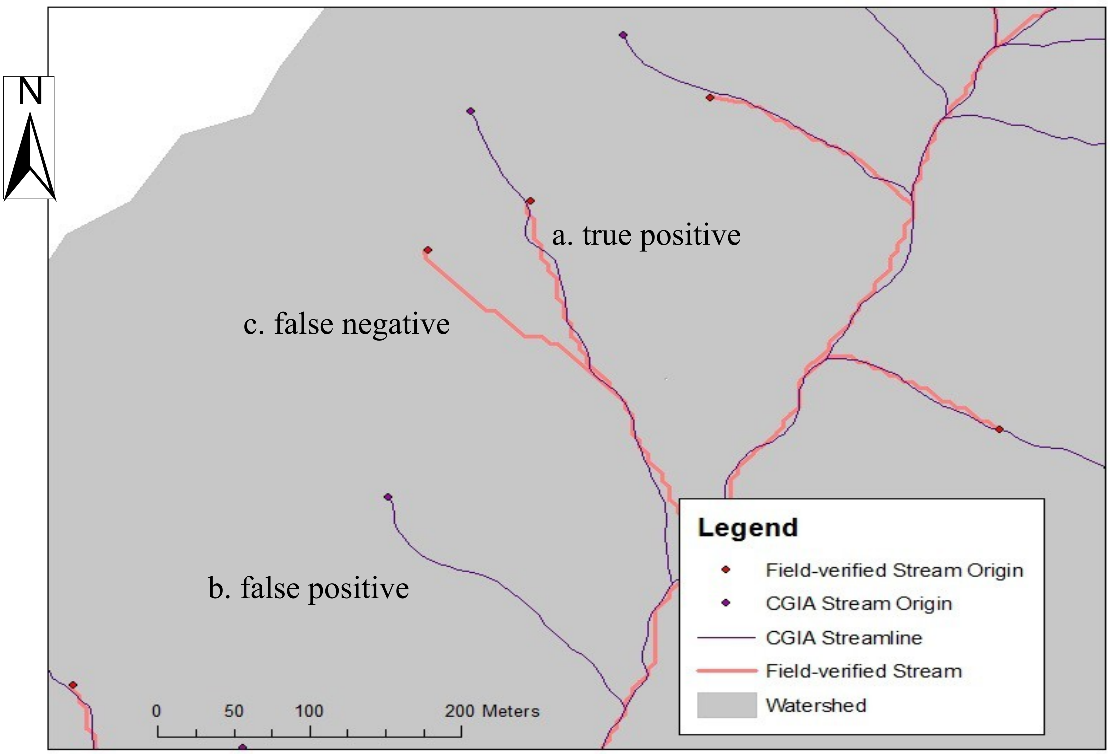

Figure 2. Possible Outcomes for the TSS. An example of true positive, true negative, and false negative streamline segments in a watershed using field-based data and CGIA streamlines.

Table 4. TSS Formulas. Source : Allouche et al., 2006.

Measure	Formula	Notes
Sensitivity	a / (a + c)	"n" is determined by counting the number of valleys in a watershed using the gord grid created in TauDEM. For this study, all the valleys with a gord value of 3 or higher were counted. "d" can be calculated by the following: n – (a + b + c)
Specificity	d / (b + d)	
TSS	(sensitivity + specificity) -1	
n	a + b + c + d	

RESULTS

CGIA Streamlines

With a few exceptions, the CGIA stream map produced the highest TSS values (Figure 3). The second best method was DEM curvature based, with the average of TSS values only 9% different from the CGIA streamlines (Table 4). On average, the DEM curvature based method performed better than all of the thresholds used for the area and slope method. The average TSS for T = 200 shows only a 3% difference from the average TSS of the curvature based method. The South Mountain watershed has the largest range of TSS values between all of the methods, with values ranging from 0.38 from the T = 150 to 0.67 from the curvature based method.

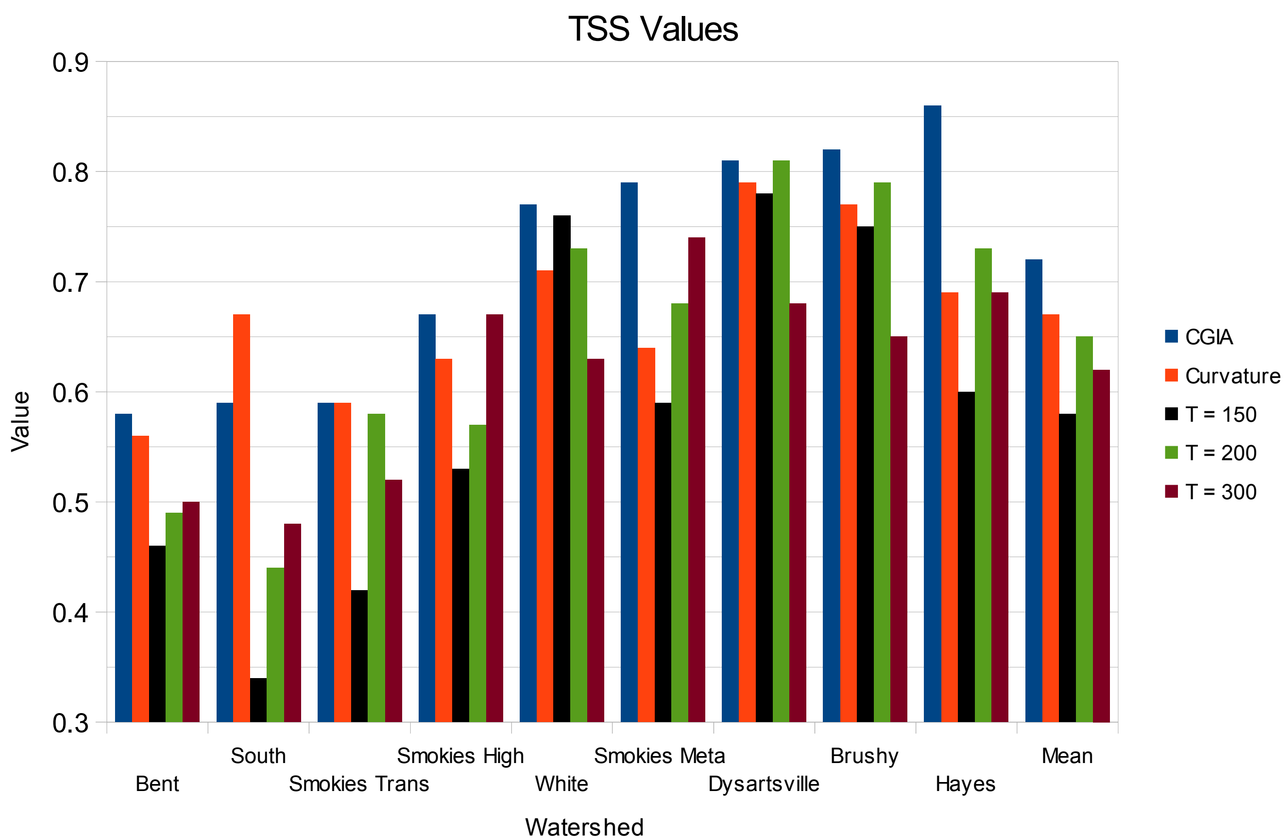

Figure 3. A graph showing the TSS values for each method. The watersheds are arranged from the lowest to the highest TSS value of the CGIA streamlines.

Table 5. The percent differences from CGIA. Percentages with (-) means the TSS for that method was higher than the TSS for the CGIA streamlines.

% Difference from CGIA TSS Values				
Watershed	**Curvature**	**T = 150**	**T = 200**	**T = 300**
South	(-) 14	49	39	25
Smokies Trans	0	29	2	12
Dysartsville	2	4	0	16
Bent	3	21	16	14
Smokies High	6	21	15	(-) 25
Brushy	6	9	4	21
White	8	1	5	18
Smokies Meta	19	25	14	6
Hayes	20	30	15	20
Mean	**9**	**21**	**12**	**18**

The three watersheds with the highest TSS values are the Hayes, Brushy, and Dysartsville (Figure 4). These three watersheds also had the highest upstream drainage area average and 3 out of the 4 lowest slope averages measured at the field-mapped stream origins (Table 3). The location of headwater streams may be easier to determine with aerial photography in areas with lower slopes, hence the higher TSS values. The Hayes watershed had the highest TSS value at 0.86, and the substantially highest percentage of open land cover with over 50% of open area in the watershed (Table 2). The open areas on the aerial photograph that were used to delineate the Hayes watershed most likely attributed to the high TSS value.

The South Mountain watershed had the second highest open area land cover with approximately 10% of open land, but was tied for the lowest TSS value of 0.58. The low specificity and high percentage of percent error of total stream length for South Mountain shows that the number and the length of the headwater streams in the watershed were overpredicted (Table 5). The CGIA streamlines that are in the open area of the watershed are somewhat accurately depicted and the stream lengths are similar to actual stream lengths (Appendix 4). However, in the forested areas of the watershed, the stream lengths greatly exceed the true stream origins and the number of false positives increases as well.

The CGIA stream map overpredicted the total length of the stream network for all of the nine watersheds (Table 5). CGIA overpredicted the number of streams for two-thirds of the watersheds. In the Smokies High watershed, CGIA overpredicted the number of streams by over 200%. The White Mountain and Smokies Transition watersheds were the only two watersheds that CGIA underpredicted the total number of streams, but both have overpredicted stream lengths. The CGIA stream map correctly predicted the number of streams for Smokies Metasedimentary watershed, but overpredicted the total stream length as well, by 38%. It is evident that, in most cases, the CGIA streamlines inaccurately depict the actual length of the headwater streams.

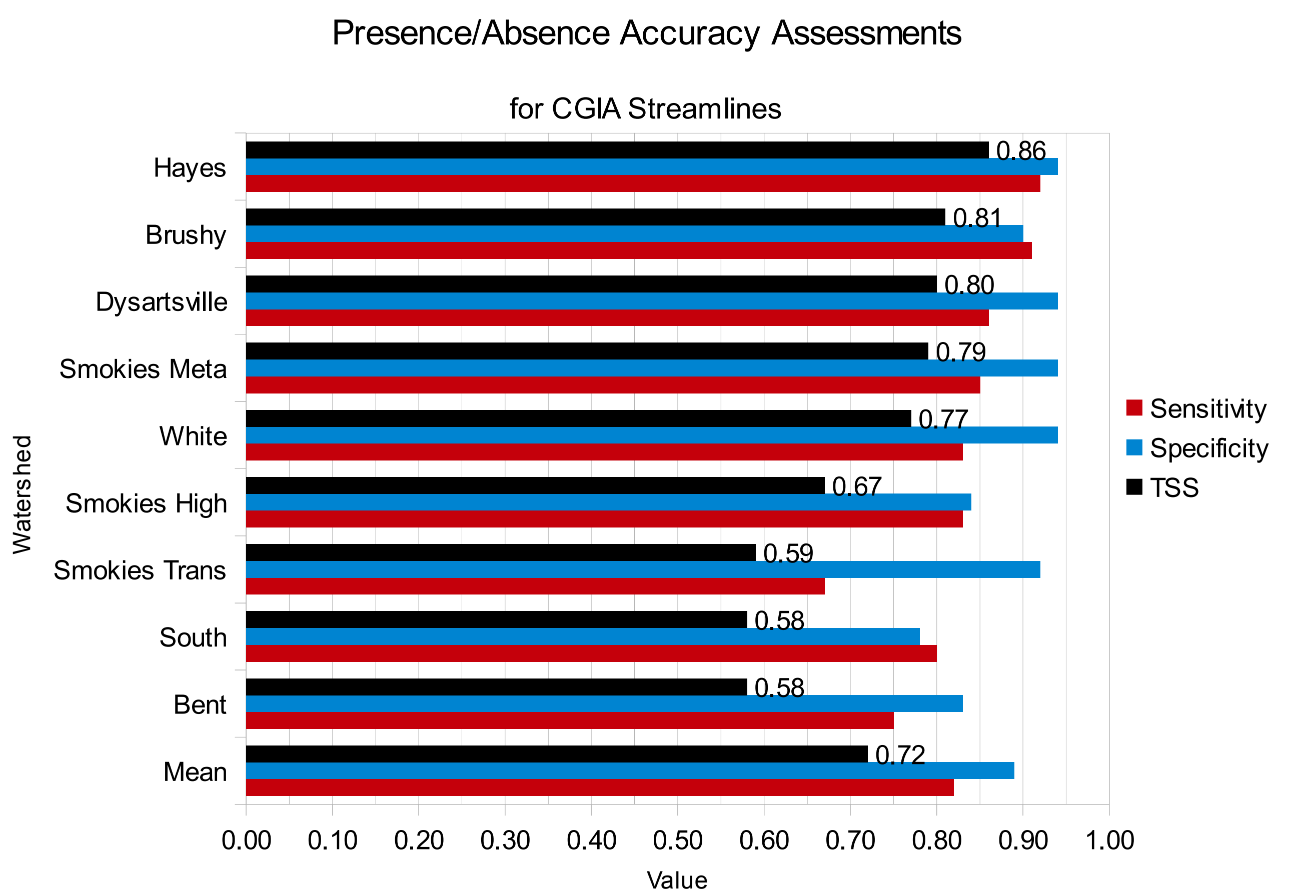

Figure 4. A bar chart showing the sensitivity, specificity, and TSS values for the CGIA streamlines in each watershed. The numbers shown within the chart are the TSS values.

Table 6. Number of Stream Origins and Stream Length Accuracies for CGIA Streamlines. The the number of stream origins and the total stream length accuracy assessment for the CGIA streamlines. The stream lengths for all watersheds were overpredicted.

Watershed	Field-Verified # of Stream Origins	CGIA # of Stream Origins	Difference	Field-verified Length (km)	Model Length (km)	Model Length Error % Over Predicted
Dysartsville	48	49	1	19.76	23.01	16
White	42	39	-3	12.92	15.39	19
Hayes	63	75	12	27.26	34.48	26
Smokies Meta	13	13	0	4.98	6.87	38
Brushy	64	93	29	26.07	35.99	38
Smokies Trans	14	13	-1	4.49	6.25	39
Bent	77	93	16	21.34	30.72	44
South	46	75	29	18	31.12	73
Smokies High	9	29	20	5.03	11.49	128
Mean	**42**	**53**	**11**	**15.54**	**21.70**	**47**

DEM Curvature Based Method

The watersheds that had the higher TSS values for CGIA (Hayes, Brushy, Dysartsville, and White Mountain) also had the highest TSS values for the DEM curvature based method (Table 8). The same is true for the watersheds with the lower TSS values (Smokies Transition, Bent Creek, and Smokies High), with the exception of South Mountain. The South Mountain watershed had the highest TSS value when using the curvature method than all other methods. However, even though the curvature method produced a higher TSS value for South Mountain, a TSS value of 0.67 is still fairly low.

The DEM curvature based method had a highest average specificity of all the other methods, including the CGIA streamlines method. A high specificity means there was a low number of false positives for each watershed, so the number of streams were not overpredicted. However, the DEM curvature method has an average low sensitivity. This suggests the method is has a high number of false negatives, so the method is predicting less streams than actually exist. This is also reflected in the low model stream length error percentage (Table 8). On average, the curvature method has a tendency to underpredict the number of headwater streams in a watershed.

Table 7. The table shows valley presence/absence and stream length accuracy assessments for the DEM curvature based method.

DEM-based Curvature Method						
Presence/Absence Accuracy Assessment				Stream Length Accuracy Assessment		
Watershed	Sensitivity	Specificity	TSS	Field-verified Length (km)	Model Length (km)	Model Length Error % Over/Under Predicted
Smokies Trans	0.62	0.93	**0.55**	4.49	4.58	**2**
Bent	0.65	0.91	**0.56**	21.34	27.46	**29**
Smokies High	0.67	0.96	**0.63**	5.03	6.58	**31**
Smokies Meta	0.69	0.95	**0.64**	4.98	5.26	**6**
South	0.76	0.91	**0.67**	18.00	20.09	**12**
Hayes	0.73	0.96	**0.69**	27.26	26.73	**(-) 2**
White	0.77	0.94	**0.71**	12.92	12.77	**(-) 2**
Brushy	0.85	0.92	**0.77**	26.07	30.44	**17**
Dysartsville	0.82	0.98	**0.79**	19.76	17.37	**(-) 12**
Mean	0.73	0.94	**0.67**	-	-	**13**

Area and Slope Method, T = 150

Even though the area and slope method with T = 150 produced the lowest average TSS values of all the methods, a similar pattern of TSS values for the watersheds can be seen. The same watersheds have high TSS values and low TSS values using the area and slope method with a 150 threshold as the previous methods. The Dysartsville, Brushy, and Hayes watersheds have the lowest slopes, highest average drainage area, and the highest TSS values (Table 5, Table 6). The Dysartsville watershed had a reasonably high TSS value, an extremely high sensitivity value, and high specificity (Table 9). This means a majority of streams were correctly predicted, and a very low number of actual streams were missed by the method. In watersheds that have high slope means and ranges and low average drainage areas, such as South Mountain and Smokies Transition, had very low specificity values when the area and slope method with a threshold of 150 was used. This means the method was overpredicting the number of headwater streams in the watershed, which can also be seen by the percent error of overpredicted stream length (Table 9).

A low threshold works best in watersheds with lower-gradient slopes and larger drainage areas. For watersheds that have higher-gradient slopes, there will be a higher number of cells in the DEM that exceed the threshold. The method will determine more cells as streams when modeling a stream network in valleys that do not actually contain headwater streams. When a threshold is too low, the method will overpredict the number and length of streams in watersheds with steep slopes. The area and slope method with a threshold of 150 works well for lower-gradient areas, but performs poorly in mountainous areas with steep slopes.

Table 8. The table shows valley presence/absence and stream length accuracy assessments for the area and slope method when T = 150.

Area/Slope T = 150						
Presence/Absence Accuracy Assessment				Stream Length Accuracy Assessment		
Watershed	Sensitivity	Specificity	TSS	Field-verified Length (km)	Model Length (km)	Model Length Error % Over/Under Predicted
South	0.86	0.52	**0.38**	18.00	37.15	**106**
Smokies Trans	0.92	0.49	**0.42**	4.49	13.73	**206**
Bent	0.77	0.69	**0.46**	21.34	45.94	**115**
Smokies High	0.83	0.70	**0.53**	5.03	15.58	**210**
Smokies Meta	0.77	0.82	**0.59**	4.98	11.71	**135**
Hayes	0.68	0.91	**0.60**	27.26	27.14	**-0.4**
Brushy	0.89	0.86	**0.75**	26.07	34.59	**33**
White	0.91	0.86	**0.76**	12.92	17.74	**37**
Dysartsville	0.98	0.80	**0.78**	19.76	25.17	**27**
Mean	0.85	0.74	**0.59**	-	-	**97**

Area and Slope Method, T = 200

The same pattern from the area and slope method when T = 150 can be seen for T = 200, with the exception of the White Mountain watershed. The South Mountain, Bent, and Smokies watersheds still have lowest TSS values and the Brushy, Dysartsville, White, and Hayes watershed have the highest (Table 10). The average specificity and TSS values increased when the threshold for the area and slope method increased. The increase in average specificity and the decrease in the average % error of stream length from the 150 threshold indicate that the increased threshold is not overpredicting as many streams. Fewer cells of the DEMs for the watersheds are exceeding the 200 threshold. The average sensitivity is the same for the 150 and 200 area and slope thresholds, meaning the 200 threshold is still missing the about the same number of streams. However, since the models have less overpredicted streams than the 150 threshold, the 200 threshold is considered a more accurate representation of headwater streams. The threshold of 200 produced, on average, more accurate stream networks than the 150 and 300 thresholds for the area and slope method.

Table 9. The table shows valley presence/absence and stream length accuracy assessments for the area and slope method when T = 200.

Area/Slope T = 200						
Presence/Absence Accuracy Assessment				Stream Length Accuracy Assessment		
Watershed	Sensitivity	Specificity	TSS	Field-verified Length (km)	Model Length (km)	Model Length Error % Over/Under Predicted
South	0.87	0.57	**0.44**	18.00	34.10	**89**
Bent	0.72	0.77	**0.49**	21.34	38.08	**78**
Smokies High	0.83	0.74	**0.57**	5.03	11.30	**125**
Smokies Trans	0.92	0.66	**0.58**	4.49	11.48	**156**
Smokies Meta	0.77	0.91	**0.68**	4.98	9.81	**97**
Hayes	0.84	0.89	**0.73**	27.26	20.15	**(-) 26**
White	0.83	0.90	**0.73**	12.92	15.67	**21**
Brushy	0.88	0.91	**0.79**	26.07	27.83	**7**
Dysartsville	0.96	0.85	**0.81**	19.76	21.97	**11**
Mean	0.85	0.80	**0.65**	-	-	**68**

Area and Slope Method, T = 300

The area slope method with a threshold of 300 produced different results than the previous methods. When the threshold increased from 200 to 300, the TSS values increased for the watersheds with steeper slopes (South Mountain, Bent Creek, Smokies Meta, and Smokies High) and decreased for watersheds with lower slopes (Dysartsville, Brushy, Hayes, and White) (Table 11). The stream length percent error further explains this. The lower-gradient watersheds have underpredicted stream lengths and low sensitivity. This indicates a threshold of 300 for lower-gradient areas may be too high, and therefore it will underpredict the number of headwater streams. The TSS values for the watersheds with higher-gradient slopes are still extremely low, not the method did not produce accurate representations of stream networks for these watersheds. The threshold of 300 produced the best stream network for the Smokies Metasedimentary watershed than any other method. An increase of the threshold for the area and slope method may produce higher TSS values for these watersheds. A higher threshold better predicts headwater streams in areas with higher slopes than lower thresholds.

Table 10. The table shows valley presence/absence and stream length accuracy assessments for the area and slope method when T = 300.

Area/Slope T = 300						
Presence/Absence Accuracy Assessment				Stream Length Accuracy Assessment		
Watershed	Sensitivty	Specificity	TSS	Field-verified Length (km)	Model Length (km)	Model Length Error % Over/Under Predicted
South	0.71	0.77	**0.49**	18.00	27.71	**54**
Bent	0.62	0.89	**0.50**	21.34	30.90	**45**
Smokies Trans	0.77	0.75	**0.52**	4.49	9.11	**103**
White	0.67	0.96	**0.63**	12.92	12.22	**(-) 5**
Brushy	0.68	0.96	**0.65**	26.07	22.38	**(-) 14**
Smokies High	0.83	0.84	**0.67**	5.03	7.88	**57**
Dysartsville	0.75	0.93	**0.68**	19.76	17.18	**(-) 13**
Hayes	0.83	0.85	**0.69**	27.26	12.84	**(-) 53**
Smokies Meta	0.77	0.96	**0.74**	4.98	7.25	**46**
Mean	0.74	0.88	**0.62**	-	-	**43**

DISCUSSION

The CGIA stream map worked better in open areas and watersheds that have lower slopes. The open areas make it easier to view the location of stream channels on aerial photography, hence the high TSS value for the Hayes watershed. In areas with lower gradients, it may be possible the stream channels are also easier to determine than watersheds with higher gradients. It may also be possible the reason the CGIA streamlines have different accuracies among watersheds is due to the relationship between the number of streams across a landscape and slope. It has been shown the number of streams is inversely related to the slope of a watershed (Tucker and Bras 1998). Watersheds with steeper slopes with have more concentrated flow with higher velocities than flows in watersheds with lower slopes. This will cause deeper, more incised valleys and a lower number of streams. The valleys may only support ephemeral flow, but in most cases, the flow regime of a channel cannot be determined by simply using aerial photography. It is possible that these ephemeral channels are being drawn in as intermittent or perennial stream channels on the CGIA stream map. Since CGIA tends to overpredict streams, the watersheds with higher gradients tend to have lower TSS values than watersheds with lower slopes. Since the accuracy of the CGIA streamlines seems to depend on the percent of open areas and slope, the TSS values are not consistent among watersheds within the same ecoregion. This is evident with the Eastern Blue Ridge Foothills ecoregion.

The average TSS values of stream networks generated by the DEM curvature based method in TauDEM differ from the CGIA stream map by only 9%, but are also inconsistent among watersheds in the same ecoregion. The area and slope method with a threshold of 200 differed by only 12% from CGIA, but still had low and inconsistent accuracies. This is because only elevation and drainage area data are considered. In state with similar mountainous terrain, it may be possible to use elevation data to model stream networks in lieu of extensive stream mapping programs. Many states may lack the funding and infrastructure to support such programs, but TauDEM may provide another way to make stream maps. While the stream networks created with TauDEM do not provide sufficient nor consistent accuracy to be used for regulatory purposes, they may be used in along with regulatory stream maps to provide a better idea of headwater stream locations.

CONCLUSION

The CGIA stream map does not depict headwater streams with a consistent level of accuracy among ecoregions, and therefore is not recommended to be used for stream regulation. However, the CGIA streamlines do provide accurate representations of streams in open areas, and therefore may work well for other purposes, such as planning for urban streams or restoring streams in open areas. The goal of the CGIA stream map was to upgrade the horizontal accuracy of stream maps, not to accurately depict the location of headwater streams. Based on the findings of this study, the CGIA stream map do not consistently show headwater streams within ecoregions, and for this reason, the HSSD will now begin working on logistic regression models for the five ecoregions for the nine watersheds.

The main focus of the HSSD is to improve headwater stream representation on maps used for research and regulatory purposes. Because other factors such as topography, climate, soils, geology, and vegetation contribute to the formation of headwater streams, simply using aerial photography or elevation data will not sufficiently nor consistently model stream networks (Tucker and Bras 1998). By using the field-mapped stream origins and GIS-derived data of watershed characteristic, the HSSD has the ability to model headwater streams at a more accurate and consistent level among ecoregions (Russell 2008).

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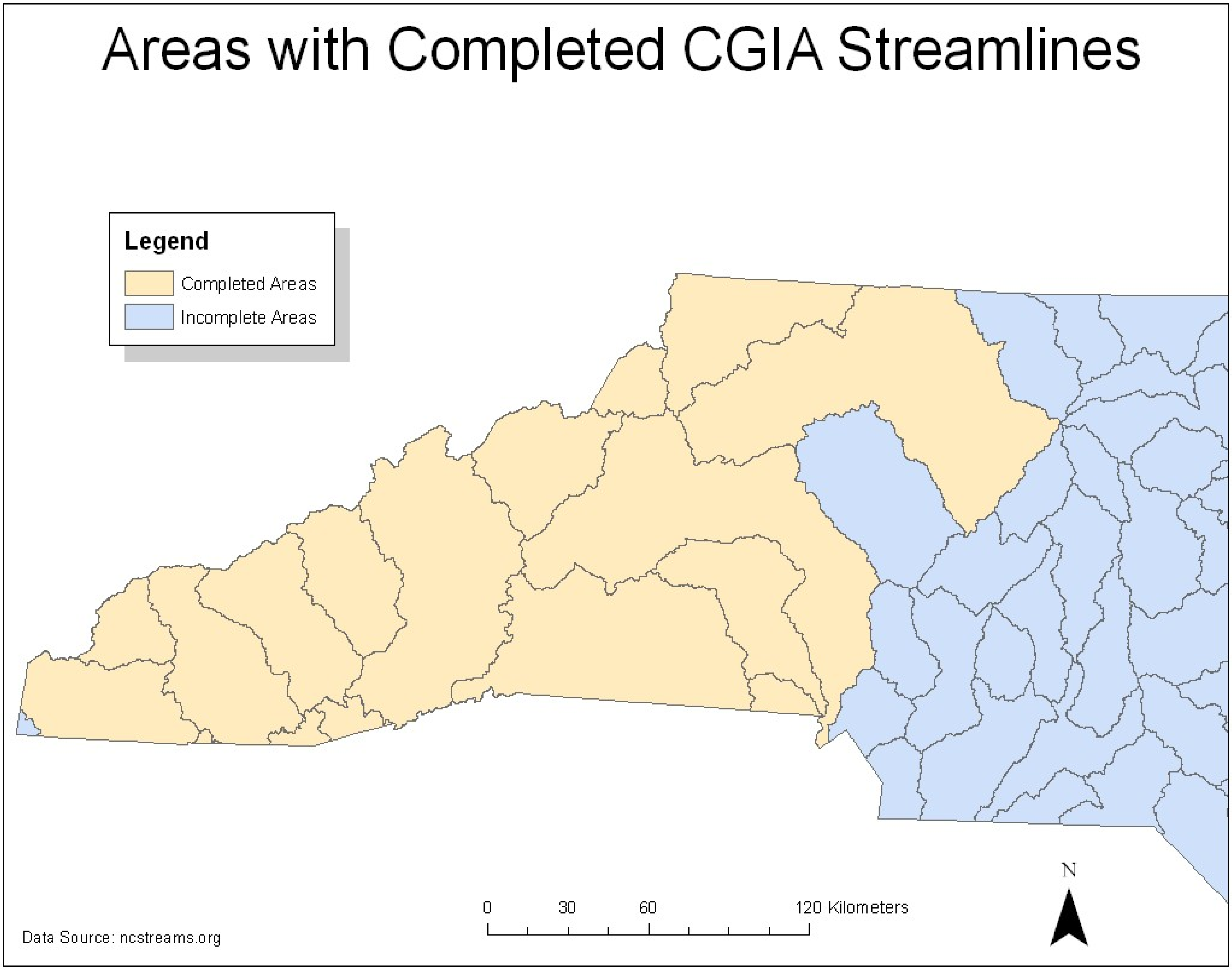
Appendix 1. A map of areas with completed CGIA streamlines.



Appendix 2. Procedure logs that explain each section from the METHODS in detail.

Creating DEMs

1. Go to ncfloodmaps.com > Data Download > County Data > LIDAR Bare Earth
2. Using the Elevation grid shapefile provided by the website and ArcGIS, determine which tiles to download
3. Download file > The text file downloaded shows x, y, and z coordinates that represent the location and elevation of the bare earth points in feet
4. Convert x, y, and z coordinates into meters
5. ArcCatalog > New > Shapefile > Edit > Select XY Coordinate System > Projected Coordinate Systems > State Plane > NAD 1983 > NAD StatePlane North Carolina FIPS 3200.prj
6. ArcMap > Spatial Analyst > Topo to Rater > Cellsize (X, Y) 5, 5 for 25 meter resolution

Creating Field-verified Stream Networks

1. Go to hydrology.usu.edu/taudem/taudem4.0/index.html#intall > Download and install TAUDEM Version 4.0.6
2. Arc Map > Add Toolbox > Taudem
3. View > Toolbars > Customize > Terrain analysis using Digital Elevation Models (TauDEM)
4. Basic Grid Analysis > Select Base DEM Grid > use DEM created from LIDAR bare earth points
5. Basic Grid Analysis > Do All > Uncheck Check for Edge Contamination > Compute
6. Now, need to create an outlet shapefile:

- ArcCatalog > New > Shapefile > Edit > Select XY Coordinate System > Projected Coordinate Systems > State Plane > NAD 1983 > NAD StatePlane North Carolina FIPS 3200.prj
- ArcMap > Add Data > add outlet shapefile
- Editor > Start Editing > select outlet shapefile > Task: Create New Feature > place a point at the most downstream point of the stream network that includes the streams with mapped origins > use the ad8 raster created from TauDEM as guidance, the white lines are deep valleys and most likely stream locations > Save Edits > Stop Editing

7. Network Delineation > Select Outlets Shapefile > select the outlet shapefile that was created > Do All Network and Watershed Delineation Steps
8. Editor > Start Editing > select the new stream network shapfile > delete and add streamlines to mapped stream origins using the guidance of the ad8 and sd8 to place streamlines in line with the valleys > Save Edits > Stop Editing

Modeling Stream Networks in TauDEM

1. ArcMap > add all raster that were created using Basic Grid Analysis if they are not already > Select Base DEM > use DEM created from LIDAR bare earth points
2. Network Delineation > Select Outlets Shapefile > select the outlet shapefile that was created
3. DEM curvature based:

- Network Delineation > River Network Raster Upstream Outlets > Stream delineation method > DEM curvature based > Check Use the range below to automatically select threshold by drop analysis > Check Upstream of outlets only > Uncheck Check for Edge Contamination >

Compute

4. Area and slope threshold for 150, 200, and 300

- Network Delineation > River Network Raster Upstream Outlets > Stream delineation method > Area and slope threshold > Uncheck Use the range below to automatically select threshold by drop analysis > Stream delineation parameters and settings: Threshold T: 150 > Exponent y: 2 > Check Upstream of outlets only > Uncheck Check for Edge Contamination > Compute
- Network Delineation > River Network Raster Upstream Outlets > Stream delineation method > Area and slope threshold > Uncheck Use the range below to automatically select threshold by drop analysis > Stream delineation parameters and settings: Threshold T: 200 > Exponent y: 2 > Check Upstream of outlets only > Uncheck Check for Edge Contamination > Compute
- Network Delineation > River Network Raster Upstream Outlets > Stream delineation method > Area and slope threshold > Uncheck Use the range below to automatically select threshold by drop analysis > Stream delineation parameters and settings: Threshold T: 300 > Exponent y: 2 > Check Upstream of outlets only > Uncheck Check for Edge Contamination > Compute
- Note: Some streamlines will need to be edited when they are thicker than 1 cell wide

Appendix 3. A list of grids that are created in TauDEM using the Basic Grid Analysis function (Tarboton 2004).

Name	Suffix	Input to	Output from	Description
Base Elevation grid	dem	Fill Pits		Digital elevation model (DEM) grid to serve as the base input for the terrain analysis and stream delineation.
Pit Filled Elevation Grid	fel	D8 Flow Directions, Dinf Flow Directions, River Network Raster	Fill Pits	Grid of elevation values with pits filled. This is usually the output of the "Fill pits" function in which case it is elevations with pits removed.
Flow Path Grid	fdr	Fill Pits		A grid giving flow directions used to impose existing streams into the system. This uses the D8 direction encoding, i.e. 1 - East, 2 - North East, 3 - North, 4 - North West, 5 - West, 6 - South West, 7 - South, 8 - South East. No data values should indicate off stream locations.
Verified Flow Path Grid	fdrn	D8 Flow Directions, Dinf Flow Directions, River Network Raster	Fill Pits	A grid giving flow directions used to impose existing streams into the system. This uses the D8 flow direction encoding, i.e. 1 - east, 2 - North east, 3 - North, 4 - North west, 5 - West, 6 - South West, 7 - South, 8 - South east. No data values indicate off stream locations.
D8 Flow Direction Grid	p	D8 Contributing Area, Flow Distance to Streams, Grid Network Order and Flow Path Lengths, Stream Order Grid and Network Files, River Network Raster, Stream Shapefile and Watershed Grid, Watershed Grid to Shapefile	D8 Flow Direction	A grid giving flow direction by the D8 method. The encoding is 1 - east, 2 - North east, 3 - North, 4 - North west, 5 - West, 6 - South West, 7 - South, 8 - South east.
D8 Slope Grid	sd8		D8 Flow Directions	A grid giving slope in the D8 flow direction. This is measured as drop/distance.
D-Inf Flow direction Grid	ang	Dinf Contributing Area, Decaying Accumulation, Upslope Depencence, Downslope Influence, Reverse Accumulation, Concentration Limited Accumulation, Transport Limited Accumulation	Dinf Flow Directions	A grid giving flow direction by the Dinfinity method. Flow direction is measured in radians, counter clockwise from east. This is created by the function "Dinf flow directions".
D-Inf Slope Grid	slp	Slope/Area (Wetness Indicator), River Network Raster	Dinf Flow Directions	A grid of slope evaluated using the Dinfinity method.
D8 Contributing Area Grid	ad8	Stream Order Grid and Network Files, River Network Raster	D8 Contributing Area	A grid giving the contributing area evaluated by accumulating the area or weight loading upslope of each location, measured as a number of pixels or sum of weight loadings. This is created by the function "D8 contributing area"
D-inf Specific Catchment Area Grid	sca	Slope/Area (Wetness indicator), River Network Raster	Dinf Contributing Area	A grid giving the contributing area evaluated by accumulating the area or weight loading upslope of each location, using the Dinf algorithm. If weights are not specified this is measured in specific catchment area units, i.e. area per unit contour width, using grid cell as the unit width and grid cell size squared as grid cell area. Created by the function "Dinf contributing area"
Strahler Network Order Grid	gord	River Network Raster	Grid Network Order and Flow Path Lengths	A grid giving the Strahler stream order for each flow path. Strahler order is defined as follows. Source streams (or flow paths) are first order. When two or more flow paths of the same order join the outgoing path has order one higher. When high order paths flow in to low order paths the order remains the same.
Total Upslope Length Grid	tlen		Grid Network order and Flow Path Lengths	A grid that gives the total length of upslope flow paths terminating at each grid cell.
Longest Upslope length Grid	plen	River Network Raster	Grid Network order and Flow Path Lengths	A grid that gives the length of the longest upslope flow path terminating at each grid cell.
Stream Raster Grid	src	Stream Order Grid and Network Files, Flow Distance to Streams	River Network Raster	A grid indicating streams, by the grid cell value 1 on streams and 0 off streams. This is created by the function "Full river network raster" or "River network raster upstream of outlets"
Network Order Grid	ord		Stream Order Grid and Network Files	A grid giving the Strahler stream order for each delineated stream grid cell.
Watershed Grid	w	Watershed Grid to Shapefile	Stream Shapefile and Watershed Grid	A grid demarcating each reach watershed. This is created by the function "Stream Shapefile and Watershed Grid"

Appendix 4. A map of the South Mountain watershed that shows the location CGIA streamlines in comparison with field-mapped data and land cover.