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COMPARISON OF STREAM EXTRACTION MODELS USING LIDAR DEMS

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ABSTRACT: Headwater stream networks serve as a critical hydrologic link between the surrounding landscape and the larger, connecting stream outflows within a watershed. For application of various riparian buffer rules that address transport of nonpoint source pollutants to headwaters streams, the State of North Carolina relies on two types of stream maps: United States Geological Survey (USGS) 1:24,000 scale topographic maps and Natural Resources Conservation Service (NRCS) county soil survey maps. State agencies also rely on these outdated map products to conduct planning and operations with regard to the locations of streams and the potential impact of infrastructure improvements in the state on water quality. Beginning in 2000, the North Carolina Flood Plain Mapping Program (NCFPMP) has acquired Light Detection and Ranging (LIDAR) data and created Digital Elevation Models (DEMs) and subsequent stream break lines and flood hazard zones (NCFPMP 2006). However, the ability of NCFPMP products to model the location of headwater streams is unknown. In this research, several methods and tools used to interpolate a DEM from LIDAR elevation points were compared for accuracy in stream extraction. The DEM produced by the most appropriate interpolation method was used with various stream extraction techniques to determine the most accurate method of modeling first and second order stream networks. Multiple watersheds of 1000 acres or more, representing a cross-section of Soil Systems (Daniels et al. 1999) and Level IV Ecoregions (Griffith et al. 2002) across the state are being surveyed by GPS to provide horizontal stream location data to select and validate extraction methods. Several readily available DEMs were compared to interpolated DEMs for each of the study sites to determine the DEM source data that produces the best horizontal accuracy of modeled stream channels. This paper reports on methods development and preliminary results from four of the planned 12+ ground truth study watersheds.

INTRODUCTION

Administrative rules in the State of North Carolina require protection of vegetated riparian buffers along intermittent and perennial streams in selected river basins that appear on a NRCS soil survey map or a USGS 1:24,000 scale topographic map (State of NC 2000). However the blue lines depicted on USGS maps consistently under-represent stream length and drainage area, often depicting third-order channels as first order (Heine et al. 2004). Surveys of headwaters stream networks in catchments up to about 1 mi^2 by the NC Division of Water Quality (NCDWQ) illustrates the magnitude of the map errors in NC (Table 1). The USGS maps under-represented the presence of headwaters streams and opposite errors commonly occurred in soils maps.

Table 1. Percent error in total stream length of headwaters streams within the study watersheds as depicted on NCRS and USGS maps compared to onsite determinations. Unpublished data – NC Division of Water Quality, Wetlands and Stormwater Unit.

Region	NRCS Maps	USGS Maps
Coastal Plain	+29	+31
Piedmont	+3	-25
Mountains	+28	-44

The amount of labor involved in verifying the accuracy of blue lines on current cartographic publications has led to intensive research into the development of automated methods to extract stream networks from digital terrain data. Digital elevation models (DEMs) have long been used to model topographic characteristics of the earth's surface. Traditional applications of terrain analysis using DEMs included neighborhood functions that calculate slope, aspect, and shaded relief,

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and non-neighborhood functions such as flow direction and filling of artificial depressions (Jenson and Domingue 1988). Grid based DEMs are also used for the purpose of extracting stream networks. From a grid data set representing points of elevation, a flow direction grid is calculated, representing the direction of steepest slope from one cell to the next. Then a flow accumulation grid is generated from the flow direction grid, representing the sum of upslope cells that flow into any one cell within the grid (Tarboton et al. 1991). By establishing a threshold of flow accumulation above a certain value, representing the sum of upslope cells, it is possible to classify cells downslope of that point (i.e. the channel origin) in the grid as channels (O'Callaghan and Mark 1984). The use of DEMs in this manner has been widely used, for example in 1) the generation of stream networks for Hortonian analysis (Helmlinger et al. 1993); 2) modeling of catchment characteristics for the purpose of runoff modeling (Wharton 1994); and 3) combination of channel locations and wetness indices to locate riparian buffers (Burkart et al. 2004).

Much research has focused on the effects of DEM resolution and quality on the accuracy of extracted stream networks. (Zhang and Montgomery 1994) found that terrain features are more accurately represented as grid size decreases. They concluded, however, that attempting to use a DEM resolution less than that of the original survey data introduced interpolation errors and that a grid resolution of 98.4 ft (30 m) was inappropriate for use in hydrologic modeling. When applied to small catchment modeling, determination of catchment parameters such as cumulative area distribution has been shown to be extremely sensitive to inconsistencies in elevation data (Willgoose and Walker 1999). Hydrologic models using stream lengths derived from a USGS 98.4 ft (30 m) DEM produced less reliable outputs than when the stream lengths were derived from a higher resolution DEM obtained from more accurate local sources of elevation data (Kenward et al. 2000). When creating DEMs from point elevation data, interpolation techniques also have a significant effect on the accuracy of morphological features depicted in the digital surface (Aguilar et al. 2005).

Recently, DEMs produced from Light Detection and Ranging (LIDAR) elevation point data have been replacing older types of DEMs produced from stereo photography or the Shuttle Radar Topography Mission. LIDAR DEMs with RMSE of 48 in were found to be significantly more accurate than Level I and II USGS DEMs (Hodgson et al. 2003). Slope and land cover were factors that had the greatest influence on local DEM accuracy of LIDAR DEMs. Due to the high resolution at which LIDAR DEMs can be produced and their superior accuracy in representing elevation, LIDAR DEMs are frequently used to delineate possible flood inundation areas for disaster management planning (Raber 2003). When applied to the automated generation of stream networks, LIDAR DEMs have proven to be significantly more reliable than traditional datasets such as the USGS 98.4 ft (30 m) DEMs (Miller et al. 2004). LIDAR DEMs are capable of representing small changes in topography that influence the accuracy of flood inundation models (Marks and Bates 2000). Many functions of hydrologic modeling depend on accurate calculation of watershed slope gradient. USGS DEMs were found to systematically under estimate slope gradient when compared to LIDAR DEMs (Hill and Neary 2005).

This paper describes the horizontal comparison of accuracy for: 1) currently available “blue line” streams from USGS and NRCS products; 2) stream networks extracted from currently available DEMs; and 3) stream networks extracted from DEMs interpolated from bare earth LIDAR data. We review methods development and discuss preliminary results from four of the planned 12+ ground truth study watersheds.

METHODS

Field Surveys

To determine the accuracy of horizontal stream locations produced by different resolution DEMs coupled with different stream extraction models, headwaters stream networks were mapped in the field with GPS. The GPS hardware used was a Leica System 500 with a real time beacon connected to a hand held computer running ArcPad (Colson et al. In Press). Multiple watersheds of 1000 acres or more, representing a cross-section of Soil Systems (Daniels et al. 1999) and Level IV Ecoregions (Griffith et al. 2002) across NC have been selected. We selected rural watersheds with low percentages of impervious surface. Data from four of the study watersheds where field surveys have been completed are included in this paper. These include 1 in the Eastern Blue Ridge Foothills Ecoregion (Low and Intermediate Mountain Soil System), 2 in the Northern Outer Piedmont Ecoregion (Felsic Crystalline Soil System), and 1 in the Rolling Coastal Plain Ecoregion (Upper Coastal Plain and Piedmont Soil System). Names given the study watersheds and the NC county in which they are located are respectively: White Mountain, Caldwell County; Timberlake, Person County; Falls Lake, Wake County; and Johnston, Johnston County.

For each of the study sites, preliminary watersheds were delineated from 20 ft LIDAR DEMs using watershed mouths determined from USGS topographic maps. Land owners within the study watersheds were contacted and permission was obtained to enter properties for the purpose of the GPS surveys. For each watershed the stream survey began at the mouth of the delineated watershed and stream channels were “walked” with the GPS. At intervals a coordinate of stream channel location was determined at the center of the stream channel cross-section and obtaining a GPS coordinate point accurate to about 7-10 ft (2-3) meters. Higher accuracy of the GPS coordinates was not possible due to deep valleys in the Piedmont and

Mountain watersheds and dense forest canopy cover in all watersheds. The spacing of the stream channel coordinate points was dictated by canopy cover, satellite geometry, and water depth but generally a point was logged every 50 to 150 feet of channel length. A point was also taken at each confluence and at hydraulic controls in the stream such as beaver dams, culverts, and pond outlets. Stream origins were determined using the NC Division of Water Quality methodology for field identification of intermittent and perennial stream origins (NCDWQ 2005) and stream origin locations were recorded with the GPS to an accuracy of 3.3 ft (1 m). During the course of the surveys, 4 water moccasins were encountered under less than comfortable conditions, 6 costly GPS antenna cables and 1 digital camera were destroyed, and the principal surveyor required 3 treatment programs for allergic insect and plant reactions.

DEM Creation and Stream Extraction

Bare earth LIDAR data were obtained from the NCFPM website (NCFPMP 2006) to create DEMs at a resolution of 5ft. Interpolation of the DEMs was accomplished with TOPOGRID, the standard Topo to Raster tool available in ArcGIS 9.1. TOPOGRID is an ArcGIS implementation of the Australian National University Digital Elevation Model (ANUDEM) software created to derive elevation and stream data from raw elevation data (Hutchinson 1989). TOPOGRID allows for a number of input parameters that significantly influence the morphologic accuracy of the output DEM including accounting for vertical error of the source data and how much smoothing of the surface is desired. DEMs from the USGS and NCFPM were compared with respect to the horizontal accuracy of stream networks extracted from them. USGS DEMs were downloaded from (http://seamless.usgs.gov) at 98.4 ft (30 m) and 32.8 ft (10m) resolutions and NCFPM 20ft DEMs were also acquired from the NCFPM website. DEMs were clipped to the minimum size necessary to encompass the entire study site at each location and the USGS DEMs were reprojected to the NC State Plane (Feet) coordinate system and elevation values were converted to feet. The NCFPM 20 ft resolution LIDAR derived DEM was obtained from the NCFPM website.

A Python script was written to batch process the interpolation of LIDAR point elevation data for each of the study sites. The script iterated through a range of values for: 1) roughness penalty, 2) discretisation error, 3) vertical standard error, 4) and tolerance. TOPOGRID interpolation was performed using predefined ranges for the variable parameters then several geoprocessing functions were called to extract a stream line shapefile. The entire process was looped until a DEM and shapefile had been generated using all of the possible variables. Another script created a multi-ring buffer around the blue lines and created a table indicating how many survey points occurred within each buffer ring corresponding to what user defined variables were used during the TOPOGRID step. It was discovered that a roughness penalty of .5 produced the best DEM and stream extraction results.

Extraction of stream networks from the LIDAR derived DEMs was accomplished using 2 extensions to ArcGIS, The Arc Hydro Toolset (Arc Hydro) (ESRI 2005) and Terrain Analysis Using Digital Elevation Models (TauDEM) (Tarboton 2005). Arc Hydro uses built in geoprocessing functions to perform watershed and stream line delineation steps, while TauDEM uses custom developed libraries. The main differences between the two tools are that:

- Arc Hydro uses the D8 flow direction method and allows for further post processing steps such as time series analysis of watershed data and construction of geometric flow networks using the Arc Hydro output.
- TauDEM utilizes the D-∞ flow direction method and allows for the determination of channel initiation using several criteria (Tarboton 1997).

For this study the comparison of the two stream extraction tools was limited to the influence that flow direction method had on horizontal accuracy of stream network extraction. Both tools allow for the determination of channel origin using a contributing area threshold which is the minimum drainage area or number of grid cells that represent the point of transition from divergent flow to convergent flow. This study focused on the origins of first order intermittent or perennial streams as the origin of the stream network and ephemeral channel characteristics were not addressed. Contributing area thresholds for all sites were set to values that insured modeled stream lines extended well past surveyed first order intermittent or perennial stream origins to guarantee that a stream line passed through every first order stream origin.

The purpose of this portion of the research was to assess the horizontal accuracy of stream extraction models and their source data. Developing and testing channel initiation determination techniques and comparing accuracies of stream network maps in terms of number of headwaters stream segments, total stream miles, and drainage density will be addressed in continuing research.

Testing of Horizontal Accuracy of Various Stream Maps

The method of testing the horizontal accuracy of the headwaters stream segments mapped by the GIS stream extraction methodology was also utilized to test the horizontal accuracy of streams depicted on currently available map products: 1) National Hydrography Dataset (NHD) high and medium resolution stream lines (http://nhd.usgs.gov/); 2) NRCS soil survey maps; 3) North Carolina Floodplain Mapping Program (NCFPM) stream break lines (http://www.ncfloodmaps.com/); and 4) county GIS stream layers. NHD high resolution stream lines were not available for all study sites. Stream lines from NRCS

soil maps were obtained by scanning and rectifying paper soil maps from county soil survey publications and "heads up digitizing" the intermittent and perennial stream lines drawn on the maps. County GIS data containing stream lines (when available) were obtained from county GIS websites and included in the reference stream data. The horizontal accuracy of mapped stream centerlines was assessed by determining the number and percent of field surveyed GPS coordinate points of stream channel centerlines that were located within parallel buffers created by the ArcGIS buffer tool along the mapped stream centerlines. Buffer lines were created at distances of 10, 25, 50, and 1000 feet from the mapped stream centerline.

RESULTS

The horizontal accuracy of stream lines from available maps and those extracted by Arch Hydro (AH) and TauDEM (TD) from different resolution LIDAR DEMs are shown in Table 2. For each comparison the total number of surveyed points varies due to removal of points that skew the accuracy of the results because the point cannot be matched to the correct stream segment. The accuracy comparison used below is the percent of field surveyed GPS stream centerline points that fell within 10 ft of the mapped stream line (percent accuracy).

Of the currently available stream maps, GIS stream line data from Wake and Person Counties were the most accurate at 64 % and 41 % respectively. Metadata for the Wake County Hydro lines indicate that the blue lines were derived from break line analysis, but the source of the elevation data was not clear. No county data were available from Caldwell County, NC for the White Mountain site. The Person County blue lines are not continuous (split at roads and other obstructions) and are not useable for any computer modeling purpose. Stream lines digitized from the soil maps were of relatively low horizontal accuracy, with only 1-17 % accuracy. The NCFPM break lines were of lowest horizontal accuracy of all currently available stream maps with only 0-8 % of field surveyed GPS points within 10 ft of the respective break lines. The NHD blue lines were the most consistent dataset, albeit of relatively low accuracy, with accuracies ranging from 5% to 17% . Overall, blue lines depicted on current cartographic and digital products exhibit a high degree of unreliability for any purpose other than reference use. Overall mean accuracy of field surveyed stream centerline points within 10 feet of a mapped stream line for these datasets were: 1) County- 38%, 2) NCFPM – 8 %, 3) NHD – 10%, and 4) soil maps – 8%. Note that this comparison is only for horizontal location of stream segments; accuracy of numbers of network segments and overall stream network accuracy per watershed will be addressed in a future paper.

Streams extracted from USGS and NCFPM DEMs by Arc Hydro and TauDEM methods showed significantly higher overall location accuracy than the blue lines on available maps. However, when compared amongst each other, the GIS extracted streams exhibited some inconsistencies that will be addressed in the continuing research. For example, stream lines extracted from the USGS 32.8 ft (10 m) and 98.4 ft (30 m) DEMs showed little difference in location accuracy and streams extracted from the NCFPM 20 ft DEM showed no difference between the two extraction tools (Arc Hydro and TAUDEM), both returning 19% accuracy. Extracted stream lines for Falls Lake showed the best accuracy at all scales and tools, and White Mountain had the worst results using the USGS DEMs at both scales. Due to undetermined reasons, it was not possible to extract streams from the USGS 98.4 ft (30 m) DEMs using TAUDEM. Overall mean accuracy of field surveyed stream centerline points within 10 feet of respective mapped stream lines for these datasets were; 1) AH 98.4 ft (30 m) – 15%, 2) AH 20 ft – 32 %, 3) TD 20 ft – 40%, 4) AH 32.8 ft (10 m) – 21%, and 5) TD 32.8 ft (10 m) – 20%.

Overall accuracy of stream lines extracted from DEMs was significantly better than that of available products, including NCFPM break lines. This suggests that for any modeling effort requiring accurate determination of channel length, it would be worthwhile to utilize stream extraction tools such as Arc Hydro and TAUDEM to generate input instead of relying on current data that does not truly represent ground truth. The 32.8 ft (10 m) and 98.4 ft (30 m) USGS DEMs for the Johnston, Falls Lake, and Timberlake sites are resampled DEMs from the NCFPM LIDAR derived 20 ft DEM but the White Mountain USGS DEMs are the old type, explaining the poor performance of those DEMs for the White Mountain site.

The poor accuracy of extracted stream lines for Johnston site (mean of 16%) confirms the belief that stream extraction from DEMs in low relief of the Coastal Plain presents some difficulties. Little or lack of topographic relief in the Coastal Plain, combined with extensive alteration of the stream networks due drainage ditches and stream channelization require the investigation of sink filling and flow direction algorithms more appropriate for flat terrain. For all other sites, the accuracy of the stream lines extracted from the NCFPM 20 ft DEMs is comparable to those extracted from the USGS DEMs. The difference in results between output from Arc Hydro and TauDEM does not suggest errors in the models themselves but illustrates the differences in flow routing algorithms used by each. Arc Hydro is limited to the use of the D8 flow direction method built into the ArcGIS software while TauDEM, with its custom libraries which do not rely upon built in ArcGIS functions, can generate D-∞ flow direction grids.

Up to 16 more field study sites will be included in the final analysis phase of this project. Further research will investigate the range of parameters that can be used in TOPOGRID, DEMs produced using spline with regularized tension in GRASS (Mitasova and Hofierka 1993), and several channel initiation threshold determination methods. It is anticipated that a range of parameters specific for each ecoregion in North Carolina will be developed to be applied to interpolation of LIDAR data and extraction of stream networks.

Table 2: Relative accuracies of stream centerlines on available digital maps and the modeled stream centerlines measured by number of field survey points within 10, 25, 50, and 1000 feet wide buffers along the stream centerlines.

Study Site	Stream Map Data Set	Number of field survey points within each buffer				Number of field survey points	Percent of Field Survey Points Within 10 ft of Mapped Stream
		10	25	50	>50		
Falls Lake	Wake County	60	29	2	3	94	64%
	NCFPM	0	0	0	92	92	0%
	NHD	16	5	5	66	92	17%
	Soil Map	1	12	26	53	92	1%
	(AH) 98.4 ft DEM	21	39	22	11	93	23%
	(AH) 20 ft DEM	21	39	22	11	93	23%
	(TD) 20 ft DEM	43	28	7	15	93	46%
	(AH) 32.8 ft DEM	39	29	19	1	88	44%
	(TD) 32.8 ft DEM	38	32	18	2	90	42%
	(AH) 5 ft DEM	66	22	4		92	72%
	(TD) 5 ft DEM	68	22	2		92	74%
Johnston	Johnston County	13	14	26	53	106	12%
	NCFPM	9	11	11	74	105	9%
	NHD	13	14	25	54	106	12%
	Soil Map	18	18	21	48	105	17%
	(AH) 98.4 ft DEM	11	24	27	38	100	11%
	(AH) 20 ft DEM	19	22	24	35	100	19%
	(TD) 20 ft DEM	19	24	23	33	99	19%
	(AH) 32.8 ft DEM	10	20	35	35	100	10%
	(TD) 32.8 ft DEM	10	21	33	36	100	10%
	(AH) 5 ft DEM	21	26	23	35	105	20%
	(TD) 5 ft DEM	23	30	14	27	94	24%
White Mountain	Caldwell County						
	NCFPM	29	26	27	225	307	9%
	NHD	20	24	34	229	307	7%
	Soil Map	22	22	45	199	288	8%
	(AH) 98.4 ft DEM	18	28	55	196	297	6%
	(AH) 20 ft DEM	134	100	49	20	303	44%
	(TD) 20 ft DEM	134	100	47	24	305	44%
	(AH) 32.8 ft DEM	16	20	48	197	281	6%
	(TD) 32.8 ft DEM	25	36	55	165	281	9%
	(AH) 5 ft DEM	144	101	42	18	305	47%
	(TD) 5 ft DEM	152	97	42	14	305	50%
Timberlake	Person County	35	28	10	13	86	41%
	NCFPM	13	9	3	61	86	15%
	NHD	4	9	6	67	86	5%
	Soil Map	7	17	13	49	86	8%
	(AH) 98.4 ft DEM	20	22	20	25	87	23%
	(AH) 20 ft DEM	39	18	10	20	87	45%
	(TD) 20 ft DEM	44	29	4	7	84	52%
	(AH) 32.8 ft DEM	23	25	30	9	87	26%
	(TD) 32.8 ft DEM	18	25	30	11	84	21%
	(AH) 5 ft DEM	39	18	10	20	87	45%
	(TD) 5 ft DEM	50	23	6	7	86	58%

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REFERENCES

Aguilar, F. J., F. Aguera, M. A. Aguilar and F. Carvajal. 2005. Effects of Terrain Morphology, Sampling Density, and Interpolation Methods on Grid DEM Accuracy. Photogrammetric Engineering and Remote Sensing **71**(7): 805-816.

Burkart, M. R., D. E. James and M. D. Tomer. 2004. Hydrologic and Terrain Variables to Aid Strategic Location of Riparian Buffers. Journal of Soil and Water Conservation **59**(5): 216-223.

Colson, T. P., J. D. Gregory, S. A. C. Nelson, and E. G. Shipman. In Press. A Mobile Geographic Information System to Support Stream Identification. Paper in this Proceedings.

Daniels, R. B., S. W. Buol, H. J. Kleiss, and C. A. Ditzler. 1999. Soil Systems in North Carolina. Tech. Bull. 314. Department of Soil Science, North Carolina State University, Raleigh.

ESRI. (2005). Hydro Data Model. Retrieved January, 2006, from http://support.esri.com/index.cfm?fa=downloads.dataModels.filteredGateway&dmid=15.

Griffith, G. E., J. M. Omernik, J. A. Comstock, M. P. Schafale, W. H. McNab, D. R. Lenat, T. F. MacPherson, J. B. Glover, and V. B. Shelburne. 2002. Ecoregions of North Carolina and South Carolina. Color poster with map, descriptive texts, summary tables, and photographs; map scale 1:1,500,000. U.S. Geological Survey, Reston, VA.

Heine, R. A., C. L. Lant and R. R. Sengupta. 2004. Development and Comparison of Approaches for Automated Mapping of Stream Channel Networks. Annals of the Association of American Geographers **94**(3): 477-490.

Helmlinger, K. R., P. Kumar and E. Foufoula-Georgiou. 1993. On the Use of Digital Elevation Model Data for Hortonian and Fractal Analyses of Channel Networks. Water Resources Research: 2599.

Hill, A. J. and V. S. Neary. 2005. Factors affecting estimates of average watershed slope. Journal of Hydrologic Engineering **10**(2): 133-140.

Hodgson, M. E., J. R. Jensen, L. Schmidt, S. Schill and B. Davis. 2003. An evaluation of LIDAR- and IFSAR-derived digital elevation models in leaf-on conditions with USGS Level 1 and Level 2 DEMs. Remote Sensing of Environment **84**(2): 295-308.

Hutchinson, M. F. 1989. A new procedure for gridding elevation and stream line data with automatic removal of spurious pits. Journal of Hydrology **106**(3-4): 211.

Jenson, S. K. and J. O. Domingue. 1988. Extracting topographic structure from digital elevation data for geographic information system analysis. Photogrammetric Engineering and Remote Sensing **54**(11): 1593.

Kenward, T., D. P. Lettenmaier, E. F. Wood and E. Fielding. 2000. Effects of Digital Elevation Model Accuracy on Hydrologic Predictions. Remote Sensing of Environment **74**(3): 432.

Marks, K. and P. Bates. 2000. Integration of high-resolution topographic data with floodplain flow models. Hydrological Processes **14**(11-12): 2109-2122.

Miller, S. N., S. R. Shrestha and D. Semmens. 2004. Semi-automated Extraction and Validation of Channel Morphology from LIDAR and IFSAR Terrain Data. *In* Proceedings of the ASPRS Annual Conference, Denver, CO.

Mitosova, H. and Hofierka. 1993. Interpolation by Regularized Spline with Tension: 2. Application to Terrain Modeling and Surface Geometry

NCDWQ. 2005. Identification Methods for the Origins of Intermittent and Perennial streams. Version 3.1. NC Division of Water Quality, Stormwater and Wetlands Branch, Raleigh, NC. http://h2o.enr.state.nc.us/ncwetlands/regcert.html

NCFPMP. 2006. http://www.ncfloodmaps.com/default_swf.asp

O'Callaghan, J. F. and D. M. Mark. 1984). The extraction of drainage networks from digital elevation data. Computer Vision, Graphics, and Image Processing **28**(3/4): 323-344.

Raber, G. 2003. The Effect of Lidar Posting Density on DEM Accuracy and Flood Extent Delineation. *In* Proceedings of the UCGIS Summer Assembly 2003, Pacific Grove, California.

State of NC. 2000. Neuse River Basin: Nutrient Sensitive Waters Management Strategy: Protection and Maintenance of Existing Riparian Buffers. North Carolina Administrative Code, Title 15A, Chapter 02B, Section .0233. Available at http://reports.oah.state.nc.us/ncac.asp.

Tarboton, D. 1997). A new method for the determination of flow directions and upslope areas in grid digital elevation models. Water Resources Research **33**(2): 309-320.

Tarboton, D. 2005. Terrain Analysis Using Digital Elevation Models (TauDEM). Retrieved January, 2006, from http://hydrology.neng.usu.edu/taudem/.

Tarboton, D. G., R. L. Bras and I. Rodriquez-Iturbe. 1991). On the extraction of channel networks from digital elevation data. Hydrological Processes: 81.

Wharton, G. 1994. Progress in the use of drainage network indices for rainfall-runoff modeling and runoff prediction. Progress in Physical Geography **18**(4): 539-557.

Willgoose, G. and J. Walker (1999). On the Effect of Digital Elevation Model Accuracy on Hydrology and Geomorphology. Water Resources Research **35**(7): 2259-2268.

Zhang, W. and D. R. Montgomery. 1994. Digital elevation model grid size, landscape representation, and hydrologic simulations. Water Resources Research **30**(4): 1019-1028.