Identifying Temporary Headwater Streams and Channel Heads in the North Carolina Piedmont

By

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Executive Summary

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Headwater streams begin upstream at the channel head and extend downstream to the confluence of second or third order streams. They may exhibit ephemeral, intermittent, or perennial flow regimes and often comprise a disproportionate share of the drainage network. Recent studies estimate that intermittent and ephemeral streams comprise 59% (3,200,000 km) of total stream length in the United States. Dense, dendritic and fractal networks exponentially expand the extent of stream reaches. These vast networks are squeezed into the landscape and thus unsurprisingly have a substantial impact on downstream water quality, biodiversity, water supply, nutrient cycling, and water treatment costs. However, despite the importance and predominance of headwater streams in the landscape, their extent remains poorly mapped and understood.

The National Hydrography Dataset (NHD) is the digitized version of USGS 1:24,000 scale topographic maps, which are typically used to locate streams for a variety of planning and regulatory purposes. Numerous studies have found the NHD to be inadequate for determining the extent of stream networks, with underestimations of 56 percent in North Carolina and up to 300 percent in urban areas reported. Moreover, the Piedmont eco-region is expected to urbanize by 165 percent over the next 50 years. Since these small streams thoroughly perfuse the landscape and serve as the most proximate intersection of the lotic and terrestrial environments, they are especially sensitive to development pressure. Thus any attempt to protect the integrity of the Piedmont's environmental services and water resources will be extraordinarily difficult, and prohibitively costly, if this urban growth cannot be managed to avoid the maximum amount of harm. This study presents a reliable method for locating these streams, including intermittent and ephemeral streams that were recently held to be jurisdictional waters by the EPA.

Fieldwork was undertaken from June to October of 2014 in the Edeburn and Korstian Divisions of the Duke Forest. Drainage lines were walked from the downstream position of perennial flow to the upstream channel head position with a high-resolution satellite Global Positioning System (GPS). Four types of channel segments used to categorize stream reaches: (1) presence of water, (2) channelized, (3) presence of pools & riffles, and (4) well-defined concentrated flow. Dietrich and Dunne's (1993) definition of the channel head, the upstream limit of concentrated flow, was used to classify the four simple types of channel heads recorded in this study: (1) headcuts, (2) spring saps, (3) headwater ponds, & (4) first-order stream heads. Ultimately a total of 117 channel heads and 67 km of streams were mapped in this study. The NHD only displayed 24 km of streams over the same area. This means that the NHD only captured ~35 percent of the actual stream network, a significant underestimation.
GIS analysis was completed to see if a better estimation of the stream network could be achieved. Three flow routing algorithms (D8, D∞, MD∞) and grid resolutions (3-meter, 6-meter, 10-meter) were used for sensitivity analysis (9 combinations total) to test flow accumulation thresholds. Two flow accumulation thresholds were selected: (1) Upslope-accumulated area (UAA) \( A = \left( \sum_{i=1}^{\text{# of cells}} \text{cell}_{i} \right) \times \text{(Cell Area)} \), and (2) Slope-area (A<sub>S</sub>) \( A_{S} = A \times S^{1} \) where \( S \) is local slope (m/m). UAA and A<sub>S</sub> values were extracted from mapped channel head locations to compute probability density functions (PDFs) and cumulative distribution functions (CDFs). Median UAA values were found to range from 0.075 – 1.122 hectares and median A<sub>S</sub> values ranged from 43.98 – 1731.39 (where A is in m<sup>2</sup>.

Grid resolution was found to be the dominant control on flow accumulation threshold values with the 3-meter and 10-meter DEM providing the smallest values. Flow algorithm choice only appeared to be pertinent for the coarsest DEM, 10-meter, where the MD∞ algorithm produced half the predicted flow accumulation value of D8. 50<sup>th</sup> (median) and 75<sup>th</sup> quantile CDF channel head values were then used to create stream networks for the 3-meter DEM with the MD∞ algorithm, which had the smallest flow accumulation values. These predicted streams were compared to mapped streams and channel heads. The 75<sup>th</sup> quantile channel head values provided the best approximation of the stream network, with minimal overprediction. There was a negligible difference between the two flow accumulation threshold methods, although A<sub>S</sub> did tend to outperform UAA using the 75<sup>th</sup> quantile channel head values. Median channel head values produced a stream network with significant overprediction and feathering, particularly for the A<sub>S</sub> threshold.

A hypsometric curve was also created for the study site, which determined that it is generally dominated by fluvial erosion, but also influenced diffusive processes. A scaling relationship between local slope (m/m) and UAA (ha) was then created with a slope-area curve. The curve gives every grid cell in the DEM (~7 million) a set of x, y coordinates that can be plotted in two-dimensional coordinate space. The slope of this curve, or “rollover” point, transitions from \( \frac{dS}{dA} > 0 \) at low contributing areas (positive) to \( \frac{dS}{dA} < 0 \) at large contributing areas (negative). This transition is associated with a change from diffusive, transport-limited hillslopes to fluvial erosion processes. The curve was fit with a piecewise regression with breakpoints at the median and 75<sup>th</sup> quantile channel head values. The transition from positive to negative slope in the regression occurred at the median channel head value. The finding that half the channel heads occur before this transition point suggests that groundwater and subsurface water contributions may be significant, as channel initiation begins before critical hillslope length is reached.

The 75<sup>th</sup> quantile channel head CDF value was found to accurately delineate the extent of the stream network, while minimizing overprediction. This method for stream network prediction greatly enhances the accuracy of the hydrography data when compared to the NHD, especially for temporary headwater streams. While field mapping channel heads is time and labor intensive, it can be used to better inform and test predictive methods that can quickly and more accurately determine the extent of the stream network.

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Introduction

Headwater Streams

Headwater streams begin upstream at the channel head and extend downstream to the confluence of second or third order streams. They may exhibit ephemeral, intermittent, or perennial flow regimes and often comprise a disproportionate share of the drainage network\(^1\). The Environmental Protection Agency (EPA) defines streams as, “connected to downstream waters via channels that convey water and subsurface water either year-round (i.e. perennial flow), weekly to seasonally (i.e. intermittent flow), or only in direct response to precipitation (i.e. ephemeral flow).”\(^2\) Recent studies estimate that intermittent and ephemeral streams comprise 59% (3,200,000 km) of total stream length in the United States\(^3\), which is roughly equivalent to the distance travelled by four expeditions to the moon or half of the entire road network of the United States\(^4\). Dense, dendritic and fractal networks exponentially expand the extent of stream reaches. These vast networks are squeezed into the landscape and thus unsurprisingly have a substantial impact on downstream water quality\(^5\), biodiversity\(^6\), water supply\(^7\), nutrient cycling\(^8\), and water treatment costs\(^9\). However, despite the importance and predominance of headwater streams in the landscape, their extent remains poorly mapped and understood.

\(^{1}\) Nadeau & Rains (2007)
\(^{3}\) Nadeau & Rains (2007)
\(^{4}\) Federal Highway Administration
\(^{5}\) Boggs et al. (2012)
\(^{6}\) Meyer et al. (2007)
\(^{7}\) EPA Connectivity US Waters Final Rule (2015) pp. 3-1
\(^{8}\) Bernhardt et al. (2002)
\(^{9}\) Gartner et al. (2014)
Jurisdictional Waters?

Federal protection for streams and rivers is covered under the 1972 Clean Water Act (CWA), which represented a comprehensive effort to curb water pollution. The CWA passed with bipartisan support and is lauded as a landmark in environmental legislative history. However, the scope of waters protected under the CWA, so-called “waters of the United States”, remains a controversial issue to this day.

Prior to 2001, the Army Corps of Engineers (USACE) exerted jurisdiction over non-navigable, isolated, and intrastate waters on the basis of habitat for migratory birds\(^\text{10}\). The SWANCC decision by the Supreme Court invalidated this determination\(^\text{11}\) and instead suggested “navigable waters must possess a significant nexus to waters that are or were navigable in fact or that could reasonably be so made.”\(^\text{12}\) Further confusion arose in 2004 when the Supreme Court split on a case regarding the jurisdictional reach of the USACE\(^\text{13}\).

The two cases became known colloquially as the *Rapanos* case, which referenced a case in Michigan where a wetland located 20 miles from the closest navigable water was filled, even though the state and the plaintiff’s own environmental consultant warned against it. The Supreme Court reached two pluralities for and against the plaintiffs, with Justice Kennedy ultimately deciding the case. Justice Kennedy relied on language from SWANCC and determined that a “significant-nexus” must exist for a water feature to be jurisdictional under the CWA. The definition of a significant nexus depended on whether the features, “either alone or in combination with similarly situated lands in the region, significantly affect the chemical, physical, and biological integrity of other covered waters more readily

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\(^{10}\) Christie & Haussmann (2003)
\(^{11}\) Solid Waste Agency of Northern Cook County v. U.S. Army Corps of Engineers Jan. 9, 2001
\(^{12}\) Frankel (2001)
\(^{13}\) Carabell v. U.S. Army Corps of Engineers, 2004; United States v. Rapanos, 2004
understood as *navigable.*"\(^{14}\) In essence, this made the determination of jurisdictional waters reliant upon EPA and USACE “significant-nexus” determinations. Since untold heterogeneity exists in the landscape, let alone across the entire nation, it would be burdensome for landowners, businesses, and federal regulatory authorities to make determinations on an ad-hoc basis. Thus the EPA and USACE collaborated to create a “final rule” to determine what should be considered a jurisdictional water of the United States on the basis of connectivity.

The EPA and USACE released their final rule in January of 2015, which found, “substantial evidence [that] physical, chemical, and biological connections from headwater streams- including those with ephemeral, intermittent, and perennial flows- [connect] to waters immediately downstream.”\(^{15}\) This ruling effectively makes headwater streams, including intermittent and ephemeral streams, jurisdictional waters subject to CWA protection. Since temporary streams compose 59% of stream networks in the United States, it is unsurprising that, in combination, they “affect the chemical, physical, and biological integrity” of downstream waters. While this determination makes eminently good scientific sense, it poses significant management challenges. Most notably, the extent and location of headwater streams is not well known. This study attempts to present a method for determining the extent of headwater streams in the Piedmont region of North Carolina that can be readily applied elsewhere to remedy this troublesome issue.

\(^{14}\) United States v. Rapanos, 376 F.3d 629 (6th Cir. 2004).
\(^{15}\) EPA Connectivity US Waters Final Rule (2015) pp. 3-1
Problems with the NHD

The National Hydrography Dataset (NHD) contains vector datasets, or flowlines, for streams in the United States and is maintained by the United States Geological Survey (USGS). The NHD is the digitized version of USGS 1:24,000 scale topographic maps, which are typically used to locate headwater streams for a variety of planning and regulatory purposes. Blue lines in the NHD represent surface water features. The original USGS mapping procedures allowed for significant subjectivity in depicting headwater streams however\textsuperscript{16}. In particular, the blue lines used in the NHD were not intended to display small channels in finely dissected terrain\textsuperscript{17}, such as in the Piedmont of North Carolina. Temporary streams were not included as blue lines unless they were longer than 2,000 feet\textsuperscript{18}. Therefore, a substantial portion of the drainage density was omitted from the original USGS quadrangles and subsequently the NHD as well.

Numerous studies have found these blue lines to be inadequate for determining the extent of stream networks. In North Carolina, the NHD may underestimate total stream length by at least 56\%, with most of the underestimation resulting from missing 1\textsuperscript{st} and 2\textsuperscript{nd} order headwater streams\textsuperscript{19}. Similar studies found that the NHD may underestimate drainage densities by as much as 250\% in Mid-Atlantic urban areas\textsuperscript{20} and 300\% in the Upper Little Tennessee River catchment\textsuperscript{21}.

\textsuperscript{16} Leopold (1994)  
\textsuperscript{17} Mark et al. (1993)  
\textsuperscript{18} Bruton (2004)  
\textsuperscript{19} Colson et al. (2008)  
\textsuperscript{20} Elmore et al. (2013)  
\textsuperscript{21} Benstead & Leigh (2012)
Small-scale variability in local topography can confound efforts to identify channel heads, which are defined as “the upstream boundary of concentrated water flow.”\textsuperscript{22} Moreover, mapping techniques typically rely on aerial photography or satellite imagery to detect streams. Small, headwater streams are often shrouded in vegetation\textsuperscript{23}, making identification through such methods highly problematic. A better approach would involve delineation through a Digital Elevation Model (DEM), which is a 3-D representation of the Earth’s surface. DEMs have been used successfully to extract stream networks for a variety of applications. The main constraints are adequate DEM resolutions, algorithm choices for filling depressions or pits, and realistic depictions of hillslope-valley flow routing. DEM resolution and flow routing algorithms are addressed in the study.

\textit{Study Site}

The Eastern Piedmont region of North Carolina overlays three major physiographic regions: the Raleigh belt, the Carolina slate belt, and the Triassic basin. The two divisions of the Duke Research Forest surveyed for this study, the Edeburn Division (formerly known as the Eno) and the Korstian Division, are located in Orange County. The Carolina slate belt basin dominates this area and features slate bedrock composed of fine-grained felsic, metamorphic rocks with deep silt loam and clay soils. Basalt intrusions are also common\textsuperscript{24}. Elevation across the two sites is similar; however, the Korstian features unusually steep topography for the region with frequent protrusions from the underlying bedrock.

The two divisions in the study are part of separate 12-digit hydrologic unit codes (HUCs). New Hope Creek bisects the Korstian Division and flows into the Jordan Lake

\begin{footnotesize}
\begin{itemize}
\item \textsuperscript{22} Dietrich & Dunne (1993)
\item \textsuperscript{23} Vannote et al. (1980)
\item \textsuperscript{24} Daniels et al. (1999)
\end{itemize}
\end{footnotesize}
reservoir, which is a major water supply source for the region, and then ultimately into the Cape Fear River. The Edeburn Division serves as the headwaters for Stony Creek, which eventually enters the Eno River. The Eno empties into the Falls Lake Reservoir, before continuing downstream as the Neuse River. Both drinking water reservoirs, Jordan Lake and Falls Lake, are subject to nutrient management rules that will require significant nutrient reductions in the coming years.

The study sites are bound by the City of Durham to the east, the City of Chapel Hill to the north, and the town of Hillsborough to the southwest. Intensive industrial and agricultural land use practices greatly influence the landscape to this day. The channel network extent is sensitive to these previous alterations and may change over time as land uses continue to change\textsuperscript{25}. In particular, intensive agricultural use from the 18\textsuperscript{th} to early 20\textsuperscript{th} century contributed to widespread soil loss through erosion. Numerous gullies developed as a result. Today many of these lands have been reforested, including the two divisions of the Duke Forest evaluated in this study. It is unclear what role this legacy from the agricultural era may play in channel network extent, although some studies suggest it may increase the extent of the ephemeral channel network\textsuperscript{26}. Recovery to a pre-agricultural extent may also be possible given the climate, soils, and slope of the area.

\textsuperscript{25} Elmore & Kaushal (2008)
\textsuperscript{26} Jefferson & McGee (2012)
Development Pressure

Today much of the Piedmont is reforested and the most intensive agricultural practices have generally been halted. There is a new threat to the region’s stream network however. The USGS projects the urban footprint of the Piedmont to increase rapidly over the next 50 years. In fact, it projects the Piedmont to experience the largest absolute change in urban extent of any ecoregion in the Southeast, a 165% increase from 17,800 km² in 2009 to 47,500 km² by 2060\textsuperscript{27}. This will accompany a significant increase in the coverage and extent of impervious surfaces. Watersheds with greater than 10% impervious cover experience dramatic alterations in the hydrologic flow regime and face numerous problems

\textsuperscript{27} Terando et al. (2014)
related to water quality and aquatic habitat\textsuperscript{28}. Since relatively little research has been done on similar low-relief streams\textsuperscript{29}, it is imperative that a reliable method for determining the extent of streams be established for the region, especially given the area’s intense development pressure.

These small streams thoroughly perfuse the landscape and serve as the most proximate intersection of the lotic and terrestrial environments. Research indicates that 85\% of the catchment area drains to streams with a contributing area of less than 20 hectares\textsuperscript{30} and that small streams play a disproportionate role in regulating water quality in large drainage basins due to their large surface-to-volume ratios, especially for nutrient spiraling\textsuperscript{31}. Thus any attempt to protect the integrity of the Piedmont’s environmental services and water resources will be extraordinarily difficult, and prohibitively costly, if this urban growth cannot be managed to avoid the maximum amount of harm. The NHD has clearly proven insufficient for this endeavor, especially since the streams at greatest risk of development are generally small first or second-order streams that remain unknown or unmapped. This study presents a reliable method for locating these streams, including intermittent and ephemeral streams that were recently found to be jurisdictional waters by the EPA.

\textit{Justification for the Use of Channel Initiation Thresholds}

Horton first proposed the idea that overland flow initiates channelization where hillslope length reaches a \textit{critical distance}, $x_c$, where, “the available eroding force exceeds the resistance $R_i$ of the soil to erosion. [This] eroding force increases downslope of the

\textsuperscript{28} Schueler (2009)  
\textsuperscript{29} Doyle & Bernhardt (2011)  
\textsuperscript{30} Seibert & McGlynn (2003)  
\textsuperscript{31} Peterson et al. (2001)
watershed line.” He recognized this made x susceptible to rainfall intensity and frequency (in part relating drainage density to the Budyko Curve’s water-limited and energy-limited systems), Manning roughness n, infiltration capacity, and the slope angle (which Horton even verified with field data). Eroded particles could only be transported in fluvial-dominated areas and Horton noted, “there is a limiting volume of eroded material which can be transported in suspension by a unit volume of overland flow at a given velocity,” before being re-deposited as sediment in diffusive-dominated areas. This understanding of a critical distance still underpins efforts today to delineate channel networks through the application of upslope accumulated area (UAA) and area-slope (AS) thresholds in GIS, despite being published 70 years ago. Both of these measures are used in the study.

Montgomery & Dietrich (1992) used Horton’s critical distance to show that ridges and valleys of a certain finite size dissect the landscape and correspond to topographic thresholds for fluvial channelization, especially the lower bound. They defined the drainage area as the area upslope of their measurement location in convergent topography and found a basic geometric similarity between drainage area and mainstream length in watersheds spanning 11 orders of magnitude. This suggests that there is both a fractal nature to watersheds and that at the finest scale of landscape dissection, there are empirically determinable thresholds for channelization in the landscape. Moreover, recent work indicates that flow path distance and flow path gradient along a stream network are highly correlated to water’s residence time in the landscape \((r^2 = 0.91)\). Thus, some form of a Hortonian critical distance, that includes some measure of upslope area or distance to

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33 Chorley (1995)
34 McGuire et al. (2005)
the ridge and/or the local slope of the hillslope, should exist in most watersheds, since channel initiation generally begins at the finest scale. This may justify the use of channel initiation thresholds to determine the extent of temporary headwater streams.

**Methods**

*Mapping Procedures*

A number of studies have attempted to accurately predict the extent of stream networks; however, several more recent studies have actually incorporated field mapping and verification\(^{35}\). A generally accepted method for measuring channel positions was used for this study that involved determining the location of channel heads. Fieldwork was undertaken from June to October of 2014 in the Edeburn and Korstian Divisions of the Duke Forest (Map 1). Dietrich and Dunne’s (1993) definition of the channel head, the upstream limit of concentrated flow, was used to classify the four simple types of channel heads recorded in this study: (1) headcuts, (2) spring saps, (3) headwater ponds, & (4) first-order stream heads. The categories 1, 2, and 3 were selected primarily based on geomorphological indicators.

Headcuts, category 1, represented a significant topographic break from the upstream valley to a channel and would have been classified by Dietrich & Dunne (1993) as Horton overland flow generated large steps (0.1 - 1.0 meter) or small headcuts (1 - 10 meter), which matches well with the Jefferson & McGee (2012) described bowl-shaped depression headcuts. Category 2, spring saps, demonstrated the intersection of subsurface flow with the land surface, typically along fractures in bedrock, and slow flowing water was observed in these locations. Category 3, headwater ponds, channel heads were recorded

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\(^{35}\) Russell et al. (2014); Clubb et al. (2014); Julian et al (2012); Elmore et al. (2013); Jefferson & McGee (2012); Hancock & Evans (2006)
where tree throws were observed to have created a depressional pond at the head of a stream, similar to the findings of Clubb et al. (2014). Dietrich and Dunne (1993) would have described these locations as subsurface flow large steps and small headcuts or as mass failures. Taken together, these three categories represent the three runoff processes suggested to control channel head location: Hortonian overland flow, mass failure, and subsurface flow intersecting with the landscape. 

Alternatively, the first-order stream head (category 4) was based on several Group B primary hydrology indicators from the USACE Wetlands Delineation Manual: drift lines, sediment deposits, watermarks, and sediment on plants or debris. These indicators generally demarcated ephemeral streams, which only carry stormwater in direct response to precipitation events. This criteria was chosen based on the NC Division of Water Quality (NCDWQ) Methodology Stream Identification Method, which defined ephemeral streams as streams that, “may or may not have a well-defined channel, the aquatic bed is always above the water table, and stormwater runoff is the primary source of water.” Hancock & Evans (2006) used a similar definition to define a point where divergent hillslope flows converged to a single drainage line with a well-defined flow path. Likewise, Clubb et al. (2014) and Jefferson & McGee...
(2012) used leaf and stick debris jams oriented downstream as indication of ephemeral streams. Downstream locations of incision with definable banks were also noted.

Drainage lines were walked from the downstream position of perennial flow (New Hope Creek or Stony Creek) to the upstream channel head position with a satellite Global Positioning System (GPS). Four types of channel segments used to categorize stream reaches: (1) presence of water, (2) channelized, (3) presence of pools & riffles, and (4) well-defined concentrated flow. The first category, presence of water, varies seasonally and temporally; however, the period of fieldwork coincided with the driest time of the year and measurements were not made directly after storm events, so it may be assumed that these segments generally held water during most typical hydrologic years and seasons. Category 2 relied on the presence of definable banks, outlined by Dietrich & Dunne (1993), which frequently were significantly incised and often included evidence of fluvial bedrock incision. Category 3 included evidence of sorted bedload, breaks in slope, and plunge-riffle sequences. Category 4 relied on criteria similar to category 4 channel heads above and represented drainage lines with a well-defined flow path. The presence of water received hierarchical importance (category 1) and was absent in category 2, 3, and 4 channels. Streams frequently alternated between the four categories over the course of 20-30 meters, likely reflecting changes in slope, convergence, and subsurface soil properties. Categories were only changed if a
segment exhibited a different category for at least 15 meters. Large breaks in slope, or knickpoints, were also recorded.

In the Carolina slate belt, it is common for temporary streams to alternate above and below the surface. Therefore, temporary stream channel heads were only recorded when a stream was observable for at least 10 meters downstream, similar to Russell et al. (2014). Additionally, notes and annotations were taken along stream segments documenting evidence of disturbance from agricultural archeological sites and forest road influence (stone walls, culverts, etc.) as well as the presence of significant headcutting processes. Channel heads were omitted in areas with significant disturbance, such as below a forest road culvert, or in areas where access was restricted due to dense vegetative cover (southeast sections of the Edeburn and Korstian). Likewise, a section of the Korstian was not mapped due to time restrictions.

A Trimble XT unit was used to record stream and channel head locations. This unit was capable of submeter accuracy, which met the requirements of the NCDWQ and the North Carolina Geodetic Survey (NCDWQ, 2008). Channel head positions were averaged for at least 100 recordings (resulting in submeter accuracy <1m) and stream channels were mapped to an accuracy of less than three meters. Accuracy was improved using Pathfinder software to post-process differentially correct field data using three nearby (<25km) CORS base stations. 41 channel heads were mapped in the Edeburn Division, while 78 were mapped in the visited sections of the Korstian Division. Ultimately a total of 117 channel heads and 67 km of streams were mapped in this study.

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39 Russell et al. (2014)
Flow Algorithms

O’Callaghan & Mark (1983) first proposed a flow algorithm, D8, for extracting drainage networks from DEM data. Until then, geomorphological studies relied on curvature-based methods for determining places where surface runoff would tend to be concentrated or from contours on topographic maps. The D8 algorithm routes flow from each pixel, or grid, to the steepest downslope neighbor\(^\text{40}\). This is based on the assumption that for overland flow, water will travel downhill in the direction of the greatest slope or aspect. Effectively, there is a relationship between topography and water. Water erodes the land creating channels, which then influence and convey water downstream along preferential channel pathways. The single flow direction (SFD) nature of the D8 algorithm encapsulates this idea.

Unfortunately while the D8 method is widely used, it has several notable disadvantages. Namely, it may provide an unrealistic depiction of flow pathways. Cells often have multiple downhill neighbors and D8 only allows flow to occur in one of eight directions, at 45°, which results in exaggeratedly straight lines\(^\text{41}\). This is particularly problematic when the steepest gradient falls between two of the eight directions and essentially introduces randomness into what should be deterministic process that is repeatable\(^\text{42}\).

Tarboton (1997) proposed the use of triangular facets to address the limitation of SFD algorithms and to allow for flow to more than one downslope cells. In this SFD algorithm, D∞, when “the direction does not follow one of the cardinal directions, upslope area is calculated by apportioning the flow from a pixel between the two downslope pixels

\(^{40}\) O’Callaghan & Mark (1983)  
\(^{41}\) Quinn et al. (1991)  
\(^{42}\) Tarboton (1997)
according to how close the flow angle is to the direct angle of the pixel center." Essentially this allows area to flow into one or two cells downslope depending on the flow direction in the 3 x 3 cell window centered on a particular cell. This algorithm is a significant improvement upon the D8 algorithm and has been widely used in a number of applications.

While the D∞ algorithm undoubtedly provides advantages over D8, it still struggles to allow for adequate dispersion, particularly on divergent hillslopes. Multiple flow direction algorithms (MFD) proportion flow to downslope cells according to weighted slopes, which is a more realistic depiction of flow routing processes. This dispersion occurs even in convergent hillslopes however, resulting in over dispersion that is problematic for determining the UAA and specific catchment area. Seibert & McGlynn (2007) developed the MD∞ algorithm to combine the advantages of MFD algorithms with the use of triangular facets used to compute local slope directions and gradients from D∞. Principally, MD∞ was designed to provide a better depiction of overland flow dispersion and allows downslope flow in up to eight downslope cells where appropriate. It has been found to be relatively unaffected by grid orientation and generally produces results similar to D∞, except on convex slopes where it produces more realistic flow dispersion.

Grid Resolution

When O’Callaghan and Mark (1983) first developed their D8 algorithm, 90 and 60-meter grids were the most commonly available DEMs. Since then, grid resolution has

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43 Tarboton (1997)
44 Alexander et al. (2007), Beven (2011), Turcotte et al. (2001), etc.
45 Seibert & McGlynn (2007)
46 Quinn et al. (1991, 1995)
47 Id at 43
48 Orlandini et al. (2012)
49 Seibert & McGlynn (2007)
greatly improved and the USGS maintained National Elevation Dataset (NED) now offers 30 and 10-meter grids over the conterminous 48 states\textsuperscript{50}. Light Detection and Ranging (LIDAR) remote sensing technology offers even finer resolution data. For instance, the state of North Carolina began a statewide floodplain-mapping program in response to damages from Hurricane Floyd (1999). The North Carolina Floodplain Mapping Program (NCFMP) resulted in statewide 20-foot (~6-meter) DEMs. Due to the nominal spacing of the initial LIDAR collection points, a 3-meter DEM was also later produced in certain locations throughout the state and integrated with the NED. Orange County, the location of this study, was one of those locations. The USGS plans to expand coverage of the 3-meter NED nationwide in the coming years and is also developing an even higher resolution 1-meter dataset.

Grid, or raster, resolution significantly affects the downstream routing of UAA and slope scaling. It also influences runoff generation from physically based models such as TOPMODEL (Beven & Kirkby, 1979)\textsuperscript{51}. Coarse-scale DEMs (30-meters or greater) make identifying channel networks challenging and may be more appropriate for identifying the hillslope-valley transition\textsuperscript{52}. Finer DEMs (5-meters or less) better depict hillslope morphology, leading to more consistent agreement between field data and local slope versus upslope accumulated area thresholds\textsuperscript{53}. Alternatively very fine-scale DEMs (< 50cm) may be distorted by microtopography and are computationally intensive; therefore, a 10-meter grid size has been suggested as a reasonable compromise (Zhang & Montgomery, 1994) for accurately depicting hillslope morphology, while still recognizing that high

\textsuperscript{50} Gesch, D.B. (2007)  
\textsuperscript{51} Zhang & Montgomery (1994)  
\textsuperscript{52} Montgomery, Foufoula-Georgio (1993)  
\textsuperscript{53} Tarolli & Fontana (2009)
resolution data availability is limited, large DEM data volumes are prohibitive, and that microtopography may be prone to distortion. However, this is still an open question and other studies indicate that 0.2-1-meter grids are optimal for overland flow dispersion\(^{54}\). This study seeks to examine a range of moderate to fine-scale DEMs (3, 6, and 10-meters).

**GIS Datasets**

Following post-processing, field data was imported into ESRI’s ArcGIS 10.2 and Whitebox GAT ‘Iguazu’ v. 3.2.1, an open-source GIS program provided by the University of Guelph\(^{55}\), for terrain analysis and hydrologic flow routing. Three flow direction algorithms were used: D8, D\(\infty\), and MD\(\infty\). The D8 method is only flow routing algorithm available in the standard ArcGIS 10.2 toolbox, so Whitebox GAT (which contains all three) was used for all flow direction and accumulation processes. NED 10 and 3-meter DEMs, NHD flowlines, 12-digit HUC boundaries, and SSURGO 2.2 soil data were all obtained from the Geospatial Data Gateway, which provides natural resources data through a partnership between three Service Center Agencies (SCA): Natural Resources Conservation Service (NRCS), the Farm Service Agency (FSA), and Rural Development (RA)\(^ {56}\). 6-meter DEM data was downloaded from North Carolina State’s online Library Data Services\(^ {57}\) and Duke Forest boundaries, contours, and forest roads were provided by the Duke Forest Office in a geodatabase format.

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\(^{54}\) Orlandini et al. (2012)  
\(^{55}\) John Lindsay, Department of Geography, University of Guelph  
\(^{56}\) Geospatial Data Gateway  
\(^{57}\) North Carolina State GIS Library
**Upslope Accumulated Area & Slope-Area Relationships**

Hydrologic pre-processing of DEMs was required to appropriately route flow. First, spurious depressions were filled using a flat increment of 0.001 in the algorithm proposed by Wang & Liu (2006) over the HUC 12 catchment for both study sites. This pre-processing step ensured continuous flow from each grid cell to a downstream outlet cell at the edge of the raster. A flow direction raster was then created from the “filled-DEM” to direct flow to downslope cell(s) as appropriate for each of the three flow-direction algorithms. After creating a new flow direction raster, the upslope area, $A$, was calculated at each pixel as:

$$A = \left( \sum_{i=1}^{\# \text{of cells}} cell_i \right) \times (\text{Cell Area})$$

The upslope-accumulated area (UAA), or contributing area, refers to the catchment area draining to a particular cell on the landscape. A UAA value can then be selected to demarcate grid cells that are part of the channel network if their upslope area is larger than a defined threshold value\(^{58}\). Several methods for selecting an appropriate UAA threshold are examined in this study.

Another relationship threshold for channel initiation relates local slope (m/m) to contributing area (m\(^2\)), where $A_S = A \times S(\frac{S}{\chi})$. The slope-area method predicts channels to form where changes in sediment transport processes occur\(^{59}\) and critical shear stress is exceeded\(^{60}\). Montgomery & Dietrich (1994) suggested a slope-area threshold criterion based on critical shear stress, $C \leq A \tan^2 \theta$, where a slope exponent $\left( \frac{S}{\chi} \right)$ of 2 represented overland flow. Alternatively, recent work in the Piedmont suggests a slope exponent value closer to 1 may be more appropriate for the region given its legacy of erosion and gullyng.

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\(^{58}\) Tarolli & Fontana (2009)

\(^{59}\) Ijjasv-Vasquez & Bras (1994)

\(^{60}\) Horton (1945)
from intensive agricultural use\textsuperscript{61}. This simplifies the slope-area relationship to $A_S = A*S$, where the UAA (m$^2$) grid can simply be multiplied by the local slope (m/m) grid. A threshold $A_S$ value can then selected from the $A_S$ grid to delineate the channel network.

**Channel Head Windows**

117 channel heads were located in the field with a horizontal accuracy of less than 2 meters following post-processing in Pathfinder. These features were represented as points in ArcGIS 10.2 and were converted to grid cells (using either the UAA or $A_S$ grids as snap rasters) for subsequent analysis. A 3 x 3 grid window (9 cells total) was then created for the channel heads at each grid scale (3m, 6m, 10m) using the Extend Tool to minimize the effect of grid orientation and field measurement error (see Table for 1 window sizes). Maximum UAA and $A_S$ values were then extracted at every channel head window for each of the nine flow algorithm and grid scale combinations using the Zonal Statistics as Table Tool. A tool was created to iterate the extraction process, which prevented channel head window grids from overlapping and being incomplete (< 9 cells). The same tool was used to extract local slope (m/m) at each channel head window for the three DEM grid resolutions.

<table>
<thead>
<tr>
<th>Table 1: Channel Head Window Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEM Resolution</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>3-meter</td>
</tr>
<tr>
<td>6-meter</td>
</tr>
<tr>
<td>10-meter</td>
</tr>
</tbody>
</table>

\textsuperscript{61} Jefferson & McGee (2012)
Results & Discussion

*Mapped Streams vs. NHD Blue Lines*

NHD blue lines have been shown to underestimate the extent and sinuosity of the stream network, particularly for low-order headwater streams. Work in the North Carolina Piedmont found that NHD lines were within 15.24 meters, which is the minimum recommended buffer distance for the Piedmont\(^\text{62}\), of mapped streams for only 60 percent of the NHD lines in the region\(^\text{63}\). This indicates that the NHD lines have poor horizontal accuracy and miss a large degree of sinuosity in the stream network. Likewise, field mapping of the study site found 67 kilometers of streams, while the NHD indicated there were only 24 kilometers of stream in the same area. This means that the NHD only captured ~35 percent of actual streams, representing a significant underestimation of both

\(^{62}\) Osmond et al. (2002)

\(^{63}\) Colson (2006)
extent and sinuosity (Map 2 & 3). Moreover, the actual accuracy of the NHD is likely even worse, since a number of headwater streams in both divisions could not be mapped due to dense vegetative cover, lack of access in wetland areas, and time restrictions. The southeast corner of the Edeburn Division in particular was a difficult to accurately map due to lack of access (Map 3).

**UAA Threshold**

After extracting the maximum UAA values for each channel head, the median value was calculated for each flow algorithm and grid resolution combination (9 total). Median

<table>
<thead>
<tr>
<th>Flow Algorithm</th>
<th>3-meter</th>
<th>6-meter</th>
<th>10-meter</th>
</tr>
</thead>
<tbody>
<tr>
<td>D8</td>
<td>0.089</td>
<td>1.122</td>
<td>0.475</td>
</tr>
<tr>
<td>D∞</td>
<td>0.075</td>
<td>1.067</td>
<td>0.558</td>
</tr>
<tr>
<td>MD∞</td>
<td>0.078</td>
<td>1.229</td>
<td>0.485</td>
</tr>
</tbody>
</table>
contributing areas were found to range from 0.075 - 1.122 hectares, indicating a finely dissected landscape (Table 1). There was also greater variation between grid resolutions than between flow algorithms (Table 3). The 3-meter and 10-meter DEMs produced the smallest contributing areas, while the 6-meter DEM resulted in significantly larger values. There was no trend in contributing area relative to flow algorithm however. For example while $D_{\infty}$ produced the smallest median contributing area using a 3-meter DEM, it produced the largest median contributing area with a 10-meter DEM.

Probability density functions (PDF) were computed to describe the likelihood of channel heads initiating at an UAA value for each of the flow algorithm and grid scale combinations (Figure 1). Essentially the area under the PDFs is $\int_{UAA_{MIN}}^{UAA_{MAX}} f_X(x)dx$. PDF plots were created in R using the ggplot2 package, which used a kernel density plot and assumed a lognormal Gaussian distribution. A Kolmogorov-Smirnov test was used to test the probability distribution of the UAA values and a p-value of <0.05 was found, which verified the use of a log-normal distribution.

<table>
<thead>
<tr>
<th>Grid Resolution</th>
<th>Flow Algorithm</th>
<th>3-meter</th>
<th>6-meter</th>
<th>10-meter</th>
</tr>
</thead>
<tbody>
<tr>
<td>D8</td>
<td>10.60</td>
<td>31.67</td>
<td>109.01</td>
<td></td>
</tr>
<tr>
<td>D∞</td>
<td>11.74</td>
<td>31.66</td>
<td>112.48</td>
<td></td>
</tr>
<tr>
<td>MD∞</td>
<td>6.60</td>
<td>31.61</td>
<td>109.46</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: STDV of UAA (ha)

**Figure 1. Probability Density Functions for Upslope Accumulated Area**
Likelihood of Channel Head Initiation

- **Flow Algorithms**
  - D8
  - D−Infinity
  - MD−Infinity

- **DEM Resolution**
  - 10-meter
  - 3-meter
  - 6-meter

**Upslope Accumulated Area (ha)**
Cumulative distribution functions (CDF) were also created in R using ggplot2 and the function ecdf(x) was used to compute the empirical CDF (Figure 2). The ecdf(x) function is a step function that jumps at the number of tied observations of a value, \( i \), divided by the total observations, \( n \), or \( i/n \). It can be described as \( F_n(t) = \frac{\sum_{i} i}{n} = \frac{1}{n} \sum_{i=1}^{n} i \). Effectively, the CDFs show the fraction of channel heads (y-axis) with a UAA value less than or equal to a particular UAA value (x-axis). Likewise, subtracting the fraction of channel heads from 1 returns the fraction of channel heads with a greater UAA.

When considering the 3-meter DEM with the MD\( \infty \) flow algorithm, it appears that 75 percent of channel heads have a UAA of less than 1 hectare and 25 percent have a UAA greater than 1 hectare. Moreover, half of channel heads have a UAA of less than 0.1 hectares. Given such small contributing areas, it is reasonable to conclude that there may be another important control besides UAA on channel initiation in the region.

The importance of grid scale is also readily apparent in the CDFs. While 75 percent of channel heads have a UAA of less than 0.645 hectares for the 3-meter DEM, 75 percent of channel heads have a UAA of less than 5.343 hectares for the 6-meter DEM and 6.011 hectares for the 10-meter DEM (Table 4). Differences in flow algorithm choice appear to be minimal at low UAA channel heads and more important at higher UAA channel heads. CDFs are depicted below in Figure 2.

<table>
<thead>
<tr>
<th>Quantiles</th>
<th>3-Meter D8</th>
<th>D( \infty )</th>
<th>MD( \infty )</th>
<th>6-Meter D8</th>
<th>D( \infty )</th>
<th>MD( \infty )</th>
<th>10-Meter D8</th>
<th>D( \infty )</th>
<th>MD( \infty )</th>
</tr>
</thead>
<tbody>
<tr>
<td>25%</td>
<td>0.021</td>
<td>0.021</td>
<td>0.024</td>
<td>0.145</td>
<td>0.164</td>
<td>0.171</td>
<td>0.081</td>
<td>0.080</td>
<td>0.078</td>
</tr>
<tr>
<td>50%</td>
<td>0.089</td>
<td>0.076</td>
<td>0.078</td>
<td>1.122</td>
<td>1.067</td>
<td>1.229</td>
<td>0.475</td>
<td>0.558</td>
<td>0.485</td>
</tr>
<tr>
<td>75%</td>
<td>0.697</td>
<td>0.624</td>
<td>0.645</td>
<td>4.615</td>
<td>5.067</td>
<td>5.343</td>
<td>6.000</td>
<td>6.510</td>
<td>6.011</td>
</tr>
</tbody>
</table>
Figure 2. Cumulative Distribution Functions for Upslope Accumulated Area

**Flow Algorithms**
- D8
- D-\(\infty\)
- MD-\(\infty\)

**Resolutions**
- 3-meter
- 6-meter
- 10-meter

<table>
<thead>
<tr>
<th>Flow Algorithms</th>
<th>3-meter</th>
<th>6-meter</th>
<th>10-meter</th>
</tr>
</thead>
<tbody>
<tr>
<td>D8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D-(\infty)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MD-(\infty)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The median (50th quantile) and 75th quantile CDF values were used as UAA thresholds, using a 3-meter DEM and the MD∞ algorithm, to predict the stream network in Maps 4 – 7 for the Korstian and Edeburn divisions. The median CDF value significantly overpredicts the extent of the stream network in Maps 4 & 6, while the 75th quantile CDF value does a reasonable job of approximating the mapped stream network (Maps 5 & 7). Many of the predicted, unmapped streams that do not match the mapped stream network may in fact exist, and are not an overprediction of the stream network extent. As was previously noted, some streams were not mapped due to time restrictions or lack of access. In the Korstian division, steep cliffs along New Hope Creek prevented a few small, isolated streams from being mapped. Additionally, wetlands in both divisions (southeast region for both) made mapping almost impossible. When considering these limitations, the 75th quantile stream network roughly mirrors the mapped stream network.
Map 4: Median UAA Threshold Edeburn Division

Channel Heads
Category
- ▲ Headcut
- ▲ Headwater Pond
- ▲ Litter Scatter
- △ Spring Sap

Mapped Streams
Predicted Streams: UAA threshold 0.078 (ha)

0 0.25 0.5 Kilometers
Map 5: 75th Quantile UAA Threshold Edeburn Division
Map 6: Median UAA Threshold Korstian Division

Hydrologic Features
- Mapped Streams
- New Hope Creek
- Predicted Streams: UAA threshold 0.078 (ha)
- Wetlands

Channel Heads
Category
- Red: Headcut
- Green: Headwater Pond
- Purple: Litter Scatter
- Yellow: Spring Sap

Author: JP Miller
Datum: NAD 1983
Projection: UTM Zone 17N
**Area-Slope Threshold**

The low contributing area values for channel initiation suggest that slope, and thus energy grade, plays an important role in channel initiation. Horton first used Du Boys (1879) sediment discharge per unit width formula to show that the force to erode soil by overland flow relied upon both a critical distance, $x_c$ (UAA), and slope. Du Boys' formula explained bedload transport as a function of excess shear, $\tau_o - \tau_e$, where the boundary between motion and no motion is exceeded (incipient motion). Since channel heads represent the upstream extent of channels, they cannot receive sediment from upstream *ex vi termini* (in the form of either the suspended load or bedload). Channel heads must instead carve their own channel via excess shear, which must be initiated via bedload transport during overland flow or from subsurface-flow and mass wasting. Meyer-Peter & Müller (1948) later adopted a position similar to Du Boys, but noted that total stress, $\tau_o$, only relates to the stress that flow exerts on the boundary of the channel. Only a portion of this actually interacts with sediment grains producing transport. This is known as the skin fraction, $\tau'$, and varies locally due to both slope and particle size. Since bed grain size is extremely difficult to estimate in channels, let alone across an entire watershed, it seems more reasonable to work with a readily discernable terrain surface derivative such as slope.

After multiplying the UAA grid by local slope (m/m), maximum Area-Slope values were extracted for each channel head. The median value ranged from 43.98 - 1731.39 (Table 5).

<table>
<thead>
<tr>
<th>Flow Algorithm</th>
<th>Grid Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>MD~D</td>
<td>3-meter 6-meter 10-meter</td>
</tr>
<tr>
<td>D8</td>
<td>60.08 1731.39 262.79</td>
</tr>
<tr>
<td></td>
<td>43.98 1436.97 214.57</td>
</tr>
<tr>
<td></td>
<td>45.69 1532.50 166.17</td>
</tr>
</tbody>
</table>

Table 5: Median Area-Slope

---

65 Chorley (1995)

for the nine flow algorithm and grid resolution combinations. Grid resolution exerted a strong influence on the Area-Slope grids, with the 3-meter DEM generating the smallest values and the 6-meter DEM producing $A_S$ values an order of magnitude larger. This effect was noted when determining the UAA threshold, but became even more pronounced in the Area-Slope grid due to the addition of local slope (m/m).

Probability density functions (PDF) were computed to describe the likelihood of channel heads initiating at an $A_S$ value for each of the flow algorithm and grid scale combinations (Figure 2). The area under the PDF curve is defined as $\int_{A_{S_{MIN}}}^{A_{S_{MAX}}} f(x) dx$. The probability that a channel head initiates at an exact $A_S$ value is actually zero percent, but the probability for ranges of likely channel head initiation can be found by integrating the area under the PDF curve (ex. 50% probability that a channel head initiates at an $A_S$ value of less than 45.7 for a 3-meter grid using the MD$\infty$ algorithm).

**Figure 3. Probability Density Functions for Area-Slope Relationship**
Cumulative distribution functions were also created for every flow algorithm and grid resolution combination. CDFs show the fraction of channel heads (y-axis) with an $A_S$ value less than or equal to a particular $A_S$ value (x-axis). Likewise, subtracting the fraction of channel heads from 1 returns the fraction of channel heads with a greater $A_S$.

There are several notable trends when comparing $A_S$ values between algorithms and grid resolutions. The 3-meter grid produces substantially lower $A_S$ values and seems to be less affected by flow algorithm choice (Table 6). The 10-meter DEM appears to track the 3-meter fairly close; however, the $MD_\infty$ algorithm produces less than half the $A_S$ value that $D_8$ would predict at these channel head locations for the 50th and 75th percent quantiles$^{67}$. This difference is significant for two reasons: (1) 10-meter DEMs from the NED are the finest grid resolution widely available, and (2) $D_8$ is the only available flow algorithm in ArcGIS 10.2, which is the most commonly used GIS software program. Likewise, $MD_\infty$ and $D_\infty$ produce substantially smaller $A_S$ values on the 6-meter DEM. The differences in algorithm choice become less pronounced on the 3-meter DEM, indicating that flow algorithm choice is more important for coarser, and generally more widely available, DEMs.

The largest difference in $A_S$ values is seen in the 6-meter DEM however, which is an order of magnitude higher than the 3-meter and 10-meter DEMs. This may be an artifact of actual DEM creation (this was the only grid not obtained from the NED), the calculation of local slope for each grid cell, or flow routing and accumulation. The 6-meter DEM also produced the highest UAA values (Table 4), which likely accounts for the subsequently high $A_S$ values.

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$^{67}$ Quantiles represent the values at regular intervals of the inverse of the CDFs. They mark the boundary of equal-sized data subsets.
Table 6: Channel Head Area-Slope Values by Quantile

<table>
<thead>
<tr>
<th>Quantiles</th>
<th>3-Meter</th>
<th>6-Meter</th>
<th>10-Meter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D8</td>
<td>D∞</td>
<td>MD∞</td>
</tr>
<tr>
<td>25%</td>
<td>9.81</td>
<td>9.74</td>
<td>11.73</td>
</tr>
<tr>
<td>50%</td>
<td>60.08</td>
<td>43.98</td>
<td>45.69</td>
</tr>
<tr>
<td>75%</td>
<td>308.29</td>
<td>269.37</td>
<td>272.65</td>
</tr>
</tbody>
</table>

Figure 4. Cumulative Distribution Functions for Area-Slope Relationship
Median and 75th quantile CDF values, for the 3-meter DEM with the MD∞ algorithm, were used to establish an $A_S$ threshold for stream prediction (Maps 8 – 11) for the Korstian and Edeburn divisions. The median $A_S$ threshold overpredicted the extent of the stream network (Maps 8 & 10) relative to the UAA median threshold (Maps 4 & 6), with significant feathering along headwater streams. Alternatively, the 75th quantile $A_S$ threshold provides a slightly better approximation of the mapped stream network (Maps 9 & 11) than the 75th quantile UAA threshold. This suggests that slope may be a contributing factor to channel initiation in the region. The influence of slope is further supported by the work of Julian et al. (2012) and Jefferson & McGee (2012). Julian et al. (2012) found a correlation between local slope and log contributing area ($r^2$=-0.55) for 78 channel heads in the Virginia Piedmont, while Jefferson & McGee found an $A_S$ relationship of $380 = A_S^{1.27}$ ($r^2$=0.62) for 100 channels in the western North Carolina Piedmont.
Map 9: 75th Quantile AS Threshold Edeburn Division

Channel Heads

Category

- Headcut
- Headwater Pond
- Litter Scatter
- Spring Sap

Predicted Streams: AS threshold 272.65

Mapped Streams

Scale: 0 0.25 0.5 Kilometers

Author: John P. Miller
Datum: NAD 1983
Projection: UTM 17N
Hypsometry Index & Curve

Hypsometry, or the study of distribution of ground surface area with respect to elevation in a catchment\textsuperscript{68}, was also evaluated for the study site. The Hypsometric Index (HI) generalizes the relief of a catchment based on erosional development and can be calculated as: $(Z_{\text{mean}} - Z_{\text{min}})/(Z_{\text{max}} - Z_{\text{min}})$ for a DEM, where $Z$ is elevation. Willgoose & Hancock (1998) used the ratio to partition catchments into those dominated by diffusive processes (>0.5) and those dominated by fluvial erosion (<0.5). Simple analysis in ArcGIS on the 3-meter DEM determined the ratio to be 0.45 for the study site, indicating a balanced, but generally fluvial sediment transport driven landscape.

Likewise, a hypsometric curve could be developed for the study site. In ArcGIS, the 3-meter DEM was divided into 100 elevation bins. Then, the Hypsometric Toolbox\textsuperscript{69} was used to determine the cumulative frequency and area (ha) in each bin (Figure 5). The elevation bins indicate that a little less than half of the watershed’s total area (2,300 ha) is

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{hypsometric_curve}
\caption{Elevation Bins and Hypsometric Curve}
\end{figure}

\textsuperscript{68} Strahler (1952)
\textsuperscript{69} Jerry Davis, Director, Institute for GIScience, SFSU
stored relatively high in the watershed, where diffusive processes dominate (hillslopes). The majority of the watershed’s area is held at relatively low elevations and has been transported from higher areas by channelized fluvial and alluvial processes. This indicates that fluvial processes likely play the most important role in the watershed, but diffusive processes are still play a role as well.

*Slope-Area Curve Scaling*

Another common approach to determine the scaling relationship between local slope (m/m) and UAA (ha) is to create a slope-area curve, with local slope on the y-axis and UAA on the x-axis. This gives every grid cell in the DEM a set of x, y coordinates that can be plotted in two-dimensional coordinate space. Axes are logged to allow for proper visualization. The slope of this curve, or “rollover” point, transitions from \( \frac{ds}{dA} > 0 \) at low contributing areas (positive) to \( \frac{ds}{dA} < 0 \) at large contributing areas (negative)\(^{70}\). This transition is associated with a change from diffusive, transport-limited hillslopes to fluvial erosion processes\(^{71}\) and generally cannot be observed in coarser resolution DEMs\(^{72}\).

Dietrich and Dunne (1993) followed Horton’s (1945) pioneering work on channel networks and found these curves to be applicable in areas where overland flow is responsible for channel maintenance, which was first suggested by Horton’s critical hillslope length \( x_c \) (although Dietrich and Dunne do account for overland saturation flow, which was not included by Horton). Channel initiation occurs in these locations when the basal shear stress of runoff exceeds the critical shear stress of the landscape’s surface. Given the relative lack of groundwater springs and subsurface seeps in the study site

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\(^{70}\) Ijjasv-Vasquez & Bras (1994)

\(^{71}\) Cohen et al. (2008)

\(^{72}\) Montgomery & Foufoula-Georgiou (1993)
combined with the low saturated hydraulic conductivity of the thick clay soils, it seems possible that overland flow acts as a significant runoff mechanism in the area.

Local slope and UAA grids (3-meter grid with the MD∞ algorithm) for the entire study site and the channel head windows (4 grids total) were imported from ArcGIS 10.2 into R using the “raster” package. Each grid cell (~7 million total) was converted to a point, which could then be plotted in the two dimensional space of the slope-area plot. The resulting plot showed significant noise, so the transparency for each point was set to 0.01. Dashed lines were drawn at the median (0.078 ha) and 75th quantile (0.645 ha) UAA values (as determined by the CDF). Two curves were fit to the data, a second-order polynomial regression (Figure 6) and a piecewise regression with breaks at the median and 75th quantile values (Figure 7).
Dietrich & Dunne (1993) first hypothesized that the critical channel initiation threshold was $c = AS^2$, thus a second-order polynomial was first chosen as a fit for the data. The slope of the regression line can be measured in units of $\Delta Y/\Delta X$, which describes the change in local slope (m/m) for each unit change in UAA (ha). Thus the positive slope of the polynomial regression can be thought to describe the diffusive hillslope areas ($\frac{dS}{dA} > 0$), while the negative slope indicates areas dominated by fluvial sediment transport ($\frac{dS}{dA} < 0$). It is interesting to note that the polynomial regression appears to have a positive slope until the median UAA CDF value is reached (0.078) and then transitions to a negative slope that gets steeper for the remainder of the plot. The slope is clearly negative by the time it passes through the 75th quantile UAA CDF value, indicating fluvial processes at work. This likely explains the significantly better fit of the 75th quantile values as a UAA threshold relative to the median value (Maps 4 and 6 vs. 5 and 7).
The “segmented” package\textsuperscript{73} was used to create the piecewise regression at two break points where there was a suspected change in the direction of the relationship between local slope (m/m) and UAA (ha). This required “a priori” knowledge of where the breakpoints exist and necessitates iteration to provide adequate results. The median and 75\textsuperscript{th} quantile CDF values were selected as breakpoints based on: (1) the slope of the 2\textsuperscript{nd}-order polynomial regression (Figure 5), (2) the peak y-axis value in the PDF, and (3) the change in slope of the CDF. Together these measures suggested the median and 75\textsuperscript{th} quantile values as logical breakpoints.

The package requires an initial least squares regression model to be run before estimating a new model with segments based on breakpoints. The initial linear regression model was formulated as \(Y_i = \beta_0 + \beta_1 X_1 + \epsilon_i\) where \(Y_i\) was the local slope (m/m), \(\beta_0\) was the intercept, \(\beta_1\) was the slope of the best fit, \(X_1\) was the UAA (ha) value, and \(\epsilon_i\) is the error term. The piecewise regression model can then be run as \(y \sim \beta_1 x + \beta_2 (x - c)\)\textsuperscript{74}, where \(c\) is the breakpoint. The model returned a p-value of <0.01 for all three least squares regressions and the best fit is depicted in Figure 6. The segment from 0 to 0.078 (median UAA) had a positive slope, while the subsequent two segments produced a negative slope (Table 7). The slope of the regression, \(\beta_1\), is \(\Delta Y/\Delta X\), which is the same as \(\frac{\text{d} s}{\text{d} A}\). The initial positive slope in the first segment of the piecewise regression represents likely hillslopes, the

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
          & Slope & St.Err. & t value & CI(95%).l & CI(95%).u \\
\hline
Segment 1 & 2.71E-02 & 2.30E-03 & 11.8 & 2.26E-02 & 3.16E-02 \\
Segment 2 & -5.71E-02 & 9.82E-04 & -58.11 & -5.90E-02 & -5.51E-02 \\
Segment 3 & -1.06E-05 & 1.11E-06 & -9.612 & -1.28E-05 & -8.45E-06 \\
\hline
\end{tabular}
\caption{Piecewise Regression Slopes}
\end{table}

\textsuperscript{73} Muggeo, V.M.R. (2008)
\textsuperscript{74} Lemoine, Nathan. (2012)
second segment is roughly the transition from diffusive to fluvial processes, and the third segment represents fluvial channels.

Thus, the 75\textsuperscript{th} quantile CDF value likely approximates the stream network more closely because the HI and hypsometric curve indicate that fluvial erosion plays a larger role in the study site and the firm transition to a negative slope (i.e. where fluvial channels begin) in Figure 6 occurs around the 75\textsuperscript{th} quantile value. The noise in channel head data is likely attributable to the nature of the four types of channel heads that were mapped, which included 1\textsuperscript{st}-order stream heads, headwater ponds, spring saps, and headcuts. 1\textsuperscript{st}-order stream heads and headcuts are initiated by overland flow, whereas spring saps and headwater ponds are likely a product of subsurface flow. Slope-area plots were explicitly developed to be effective in areas where channel maintenance is dominated by overland flow. Overland flow appears to play an important role in runoff processes; however, channel heads that are initiated by processes other than overland flow account for 16 percent of total channel heads (Table 8). Differences in runoff mechanisms, heterogeneity in the soil subsurface, and perturbation of the landscape through prior intensive land use practices all help explain why it is so difficult to fully approximate the stream network without predicting false positives.

<table>
<thead>
<tr>
<th></th>
<th># Channel Heads</th>
<th>Percent of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Headcuts</td>
<td>40</td>
<td>34.19%</td>
</tr>
<tr>
<td>1\textsuperscript{st}-Order Stream Heads</td>
<td>58</td>
<td>49.57%</td>
</tr>
<tr>
<td>Spring Saps</td>
<td>10</td>
<td>8.55%</td>
</tr>
<tr>
<td>Headwater Ponds</td>
<td>9</td>
<td>7.69%</td>
</tr>
</tbody>
</table>
Conclusions

Temporary headwater streams makeup a significant share of the stream network and provide numerous ecosystem services. These small, sensitive streams represent the intersection of lotic and terrestrial ecosystems and thoroughly perfuse the landscape. Their close connection to hillslopes makes them particularly susceptible to degradation through changes to land use or land cover. Since the Piedmont eco-region is expected to urbanize rapidly over the next 50 years, essentially creating a new megalopolis from Raleigh to Atlanta reminiscent of the urban northeast corridor of the United States\textsuperscript{75}, it is imperative that the location of these fragile freshwater systems be identified and protected. Recent “jurisdictional waters” rulemaking by the US EPA and USACE recognizes this and clarified that these temporary headwater streams are federally protected waters. However, despite the overwhelming body of scientific evidence that demonstrates temporary headwater streams are physically, chemically, and biologically connected to downstream waters\textsuperscript{76}, their extent and location remains largely unmapped or unknown.

67 kilometers of streams were mapped in this study and only 35 percent of them were captured by the most comprehensive existing hydrography dataset, the NHD. Moreover, the NHD performed especially poorly in predicting both sinuosity and temporary stream locations. Stream prediction was greatly enhanced through field mapping of 117 channel heads. Maximum UAA and A\textsubscript{s} values were extracted from 3 x 3 grid windows at these locations and were used to predict thresholds for channel initiation. These threshold values were sensitive to grid scale for all flow algorithms, while algorithm choice appeared to be more pertinent at coarser resolutions. This is noteworthy because

\textsuperscript{75} Terando et al. (2014)
\textsuperscript{76} EPA Connectivity US Waters Final Rule (2015)
the coarsest DEM used in this study, the 10-meter NED DEM, is the most widely available DEM for GIS analysis. Moreover, the D8 algorithm is the only algorithm available in ArcGIS 10.2, which is the predominant GIS software. This flow algorithm and grid resolution combination consistently produced the largest threshold channel initiation values (more than double of any other). These large threshold values mean that the most commonly used method for predicting stream network extent will struggle to delineate most temporary headwater streams. Differences between UAA and $A_S$ thresholds appeared to be minor; however, $A_S$ values tended to perform worse than UAA values at low CDF values and better at higher CDF thresholds. Thus, the inclusion of local slope can provide improved stream prediction performance, but a UAA threshold can generally give a rough estimate of stream extent.

A hypsometric index and curve can easily be developed to get a first estimate of whether a catchment is dominated by diffusive processes, fluvial erosion, or a combination of both. This first estimate, along with CDF and PDF channel head UAA values, can then help inform breakpoint choice for a piecewise regression of a slope-area plot. The change in slope magnitude of the slope-area plot indicates where diffusive processes end and where fluvial erosion begins. Channel initiation thresholds for stream network prediction should be chosen on the basis of the dominant erosion process predicted by the hypsometric index and be reflected in the change in slope magnitude from the piecewise regression of the slope-area plot. The 75th quantile channel head CDF value can also be used to accurately delineate the extent of the stream network, while minimizing overprediction. These methods for stream network prediction greatly enhance the accuracy of hydrography data when compared to the NHD, especially for temporary headwater streams.
While the methods discussed in this study present a more reliable stream network, there is still room for additional study and analysis. Slope-area plots assume that both overland flow and local slope influence channel initiation. Studies attempting to find a relationship between area and slope for channel initiation have achieved mixed results\textsuperscript{77}, which likely reflects heterogeneity in area, slope, subsurface composition, and runoff mechanisms across the landscape. This relationship is unlikely to hold in areas dominated by diffusive processes, low relief areas (i.e. Coastal Plain of North Carolina), or in locations where subsurface flow is the dominant process for channel maintenance. In areas where subsurface flow is important, channel initiation will occur before Horton’s critical distance \(x_c\) due to groundwater and subsurface flow contributions. The finding that half the channel heads occur before this transition point suggests that ground and subsurface water contributions may be significant, as channel initiation begins before critical hillslope length is reached. Additionally, consideration should be given to the number of field mapped channel heads needed to accurately predict the extent of the stream network. If the number proved sufficiently low, field mapping could be used to regionally calibrate the stream network. While field mapping channel heads is time and labor intensive, it can be used to better inform and test predictive methods that can quickly and more accurately determine the extent of the stream network.

References


39. Quinn, P. F., K. J. Beven, and R. Lamb (1995), The In (a/tanb) index: How to calculate it and how to use it within the TOPMODEL framework, Hydrol. Processes, 9, 161–182.


51. United States v. Rapanos, 376 F.3d 629 (6th Cir. 2004).


