STREAMS DO WORK: MEASURING THE WORK OF LOW-ORDER STREAMS ON THE LANDSCAPE USING POINT CLOUDS

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ABSTRACT:

The mutable nature of low-order streams makes regular updating of surface water maps necessary for accurate representation. Low-order streams make up roughly half the streams in the conterminous United States by length, and small inaccuracies in stream head location can result in significant error in stream reach, order, and density. Reliable maps of stream features are vital for hydrologic modeling, ecosystem research, and boundary monitoring. High resolution digital elevation models derived from lidar data have shown promise in low order stream modeling yet forested high relief landscapes and low relief agricultural areas remain challenging. Here we present early results from research analyzing lidar point clouds to identify features and patterns that may be used in low-order stream identification and classification in challenging geographic conditions. This work has identified characteristics derived from point clouds that correlate with the presence of streams and stream heads and show promise for mapping small streams. In low topographic relief agricultural areas, cross sections collected at regular intervals along drainage channels extracted as 3D lines show a significant jump in value and variance of profile curvature standard deviation at stream heads. In high relief areas, observations show potential for stream mapping by identifying trends in riparian zone structure. Lidar return point density from riparian vegetation under 30 feet tall dips in the vicinity of intermittent stream heads. Also seen is an increase in point density above 60 feet downstream of stream heads. The trends found here likely reflect a change in vegetation structure relative to the presence of streams.

1. INTRODUCTION

Low-order streams refer to headwater streams that represent the initiation of flow accumulation in channels that lead to the formation of rivers. Here we focus on first-order streams as defined by the Strahler stream order (Strahler, 1952). The first-order designation indicates that no other streams flow into the stream in question. Low –order streams make up a large part of the streams in the conterminous United States (Nadeau and Rains, 2007) and thus make up a large portion of both riparian zones and ecosystem boundary regions, which are important for biodiversity, ecosystem resilience, and natural resource health (Naiman et al., 1993). The high proportion of headwater streams to overall streams also renders them important for hydrologic modeling and management.

The National Hydrography Dataset (NHD) is a component of the U.S. Geological Survey's (USGS) National Map that represents surface water features of the United States. The NHD is used widely by researchers and governments yet historic collection methods and changes in the landscape and hydrologic conditions have led to inaccuracies in the NHD. The inaccuracies are pronounced among low-order features, especially in low topographic relief agricultural and high relief forested areas (Stanislawski et al., 2015). Given the importance of low-order features and the need for regular update of the NHD, this research seeks to identify techniques for automated validation of stream features using remotely sensed data. The USGS 3D Elevation Program (3DEP) is systematically collecting light detection and ranging (lidar) data over the conterminous United States, Hawaii, and the U.S. territories. The quality specifications mandated by 3DEP (Heidemann, 2018) and potential for broad coverage make lidar products ideal datasets for this work.

Flow accumulation modeling, typically used for stream mapping, is difficult in agricultural areas, because of small variations in surface topography and anthropogenic effects on surface water. Similar challenges exist in high topographic relief forested areas where the topographic drainage pattern is less confounding but vegetation complicates modelling more than it does in low relief agricultural areas.

In recent years, many studies have employed remote sensing methods in the mapping of streams (Biron et al., 2013; Cavalli et al., 2008; Perroy et al., 2010). James et al. (2007) looked at headwater stream detection and geomorphic feature measurement in vegetated areas using 4 m DEMs generated from lidar data and determined that the spatial resolution was inadequate for reliable geomorphic measurement at the gully scale. James and Hunt (2010) used 4 m digital elevation models (DEM) and a 0.6 m contour map with flow accumulation modeling to show that the resultant headwater mapping is possible in areas of moderate-to-steep topographic relief using automated methods and looks at classification of relative drainage area but encountered significant errors suggesting additional data are required for accurate mapping. Lang et al. (2012) studied wetland connectivity and found significant improvements over the NHD using lidar but did not address headwater mapping and validation of derived maps. Maceyka and Hansen (2015) showed great improvement in stream mapping in low relief vegetated environments over the NHD using lidar derived DEMs and National Agricultural Imagery Program (NAIP) 2013 images, yet the process was not automated and required hand digitizing of some channels.

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While studies have broached the use of remote sensing data to map stream attributes, an automated process that will validate the NHD and classify headwater streams in low and high topographic relief humid regions is yet to be developed.

This paper describes ongoing work investigating the use of lidar point cloud data for the validation of stream features in the NHD and preliminary findings. Remote identification of a small stream in a channel, a variably-sized valley in the terrain that may or may not contain surface water, is challenging spatially, spectrally, and hydrologically given that the absence of water at any given point in time does not necessarily exclude a channel from a river classification. In this paper we investigate detection of the erosive and generative work done on the landscape which often has a larger footprint and is not temporally constrained to wet periods. Channel and bank structure is investigated using point generated surface cross sections. Analyses of the cross sections of first-order NHD features in low topographic relief areas reveals a significant jump in value and variance of the standard deviation of profile curvature (Ps) at stream heads. Analysis of above ground point return density in high topographic relief forested areas reveals trends in return density at differing elevations above ground that appear to correlate with the presence of first-order streams. The changes in channel and vegetation structure as indicated by these findings, may be useful in automated low order stream mapping and NHD validation.

2. METHODS

2.1 Data

The selection of study areas for this work was guided by several factors. Firstly, there must be lidar data available of sufficient resolution and in humid regions with low topographic relief or high topographic relief and dense vegetation. Secondly, some means of validation is required to test detection methods. Ideal training data include expert field validated stream head points marking the initiation of an intermittent or perennial feature in a channel. Such data are expensive and time consuming to collect and therefore difficult to obtain. Other, less accurate means of validating the likely presence of a stream is supervised analysis of high resolution optical and elevation data. Optical data used here includes NAIP ortho-rectified airborne collections and Worldview-2 (DigitalGlobe) satellite images.

Approximate locations of the selected study areas in the conterminous United States are shown in the top panel of Figure 1. The two low topographic relief study areas are within the Eastern Great Plains Ecological Division (Comer et al., 2003). The topographic data used for this study in the low relief areas are airborne lidar from NHD Hydrologic Unit Code (HUC) 10 watersheds in central Iowa, the Panther Creek watershed (PC), and northern Illinois, the Forked Creek (FC) watershed. These areas were selected because they likely include inaccurate NHD stream features as identified by Coefficient of Line Correspondence (CLC) analysis (Stanislawski et al., 2015). CLC analysis performs an automated conflation process to identify likely matching and mismatching linear features, in this case between NHD stream lines and lines derived from a weighted flow accumulation model (Stanislawski et al., 2015).

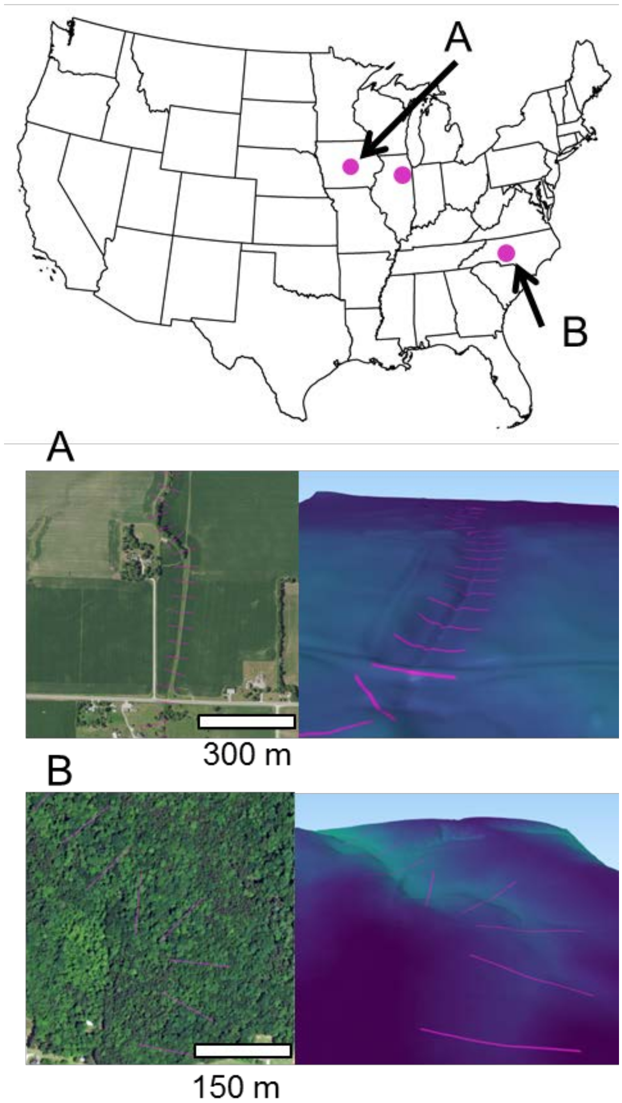

Figure 1. Locations of study areas and examples of first-order streams in respective regions. RGB images are generated from NAIP data, 3D images are generated from lidar-derived 1 m DEM, vertical exaggeration applied for A. A- low topographic region with NHD designated first-order stream over lain with 75 m cross sections, B- High relief area with 100 m cross sections overlying a field validated first-order stream

The lidar data for central Iowa is Quality Level 3 (QL3) (> 0.5 aggregate nominal pulse density, pls/m^2) collected in 2008. Using a DEM with nominal cell size of 3 m, elevation for the PC watershed ranges between 266.6 and 330.3 m, with a mean and standard deviation of slope of 3.7 and 5.5 percent rise, respectively. The Illinois lidar data is QL2 (> 2 pls/m^2) collected in 2014. The elevation for the FC watershed ranges between 157.9 and 213.6 m, with a mean and standard deviation of slope of 2.6 and 3.3 percent rise, respectively All USGS 3DEP lidar data are collected during leaf-off conditions. Stream head locations are validated in these areas using NHD flowlines, NHD Plus flow volume estimates, a weighted flow accumulation model, and satellite and airborne optical images.

Data for the high relief study area are aerial lidar point clouds from a 6 square kilometer (km^2) catchment in Rowan County (RC), North Carolina, referred to as study area RC. This watershed is in the Central Interior and Appalachian Ecological Division (Comer et al., 2003). The elevation for the RC watershed ranges between 194.1 and 256.8 m, with a mean and standard deviation of slope of 11.8 and 8.9percent rise, respectively. The North Carolina Department of Environment and Natural Resource provided field collected estimates of stream head locations and stream permanence.

2.2 Low Topographic Relief Analysis

In order to test methods for channel structure measurement of first-order streams, 75 meter (m) cross sections are extracted as 3D lines. The channel framework used to extract the cross sections is the NHD stream data set. The cross section lines are extracted from a 1 m resolution DEM generated from lidar last returns which represent the bare earth. The cross sections are spaced 50 m apart and lines that intersect road features are excluded. The NHD flowlines are used to orient cross sections over valley channels. The extracted cross-section lines are tested for range in z value (height), mean z value, line curvature, and standard deviation of curvature.

The 3D lines for each of the cross-section lines, possessing xyz values, are pulled from a triangulated irregular network (TIN) built from the point cloud using LP360 software (GeoCue Group Inc.). Vertices represent the intersection of the 2D cross-section line and the TIN edges. These values are interpolated into regularly spaced points using a shape-preserving piecewise cubic interpolation method in MATLAB® (The MathWorks Inc.).

Riparian zone analysis was considered in the low topographic regions, but comparing a digital surface model (DSM), generated from first returns (possible vegetation surface), to a DEM shows that there are many areas along streams where there is no difference between the two surfaces. This indicates that the resolution of the lidar data is insufficient to discern much of the vegetation variation in these areas.

2.3 High Topographic Relief Analysis

For the high topographic relief region, analysis thus far has focussed on riparian structure trends as a potential indicator of the presence of streams in channels. Cross sections are drawn upon valley channels and used to sample vegetation pulse return at varying heights above the surface. Cross-section width for this study area is 100 m. The U.S. Forest Service (Merritt et al., 2017) give a minimum cross-section width of 6 m for headwater streams while others (Clinton et al., 2010) find vegetation variation pattern relative to Appalachian headwaters that indicate a riparian zone extending up to 20 m perpendicular to stream channels. Considering the potential for a 40 m wide riparian zone and deviation between flow lines and actual stream channels, 100 m was chosen. Cross section spacing is 25 m here.

The NHD stream lines for the high relief area represent less than half of the length of the network identified by the field validated data. Therefore, drainage lines were extracted from the elevation using the open source GeoNet tools (Passalacqua et al., 2010; Sangireddy et al., 2016) with the flow accumulation threshold set to 500 cells, which extends drainage lines near the edge of the catchment. Cross-section analysis was limited to extracted drainage lines with identified stream heads falling on them, as well as three headwater drainage lines without stream heads as control samples.

For cross-section analysis, the above ground lidar point cloud was sampled by generating density maps summing the return point density at 10 ft height intervals with 8 intervals over all, the lowest being 0- 10 ft and the highest being greater than 70 ft above ground elevation. Vertices are generated at regular intervals along cross-section lines. The vertices are assigned values from the point density intervals. The result is eight points generated for each cross-section vertex, with each point populated with associated 3D coordinate and point density attributes (Figure 2). Density aggregation for each vertex point was completed through the natural neighbor interpolation method within ArcMap® (Esri) using a 2.5 m sampling distance (Sibson, 1981).

Initial tests for correlation between vegetation structure and stream presence are range, mean, and sum of point densities along cross sections. The values are generated for eight elevation ranges and tested for vertical trends as well as along stream trends.

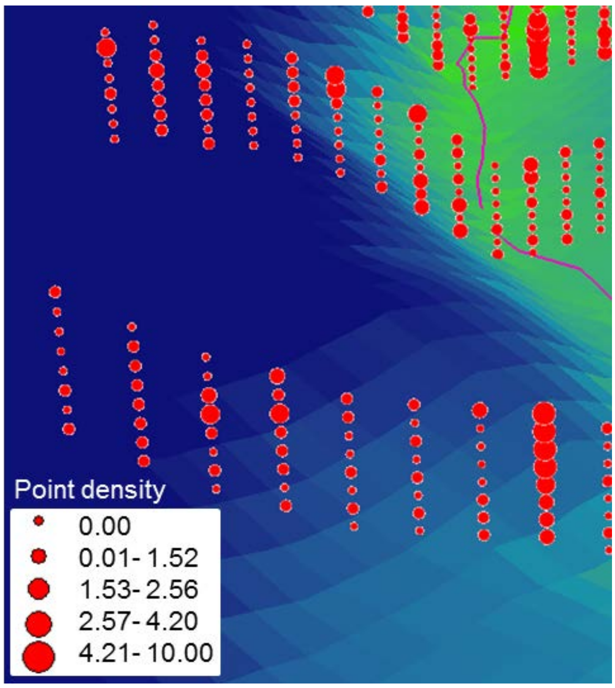

Figure 2. An illustration of how density of return points is aggregated along cross sections to estimate vegetation conditions.

3. RESULTS

This work has identified characteristics derived from lidar point clouds that correlate with stream presence and show promise for mapping and validating stream lines. Cross sections collected at regular intervals along drainage channels extracted as 3D lines show a significant jump in profile curvature standard deviation (Ps) at stream heads in low topographic relief regions. In the North Carolina high relief forested study area, canopy structure shows evidence of thinning in the sub canopy and greater overall tree height correlating with the presence of streams in channels. At the time of this writing, channel structure cross section analysis was not complete for the North Carolina study area.

3.1 Low Topographic Relief Results

Roughly 1600 cross sections were extracted from the Illinois and Iowa point clouds using 30 NHD High Resolution (HR) first-order stream lines in PC area and 19 first-order stream lines in the FC area. The cross sections are 75 m in width and are collected at 50 m intervals. Analysis of the standard deviation of the profile curvature of each line shows a pronounced jump in value at stream heads with higher values and variance in the presence of streams. The threshold that generally differentiates cross sections above and below stream heads is Ps= ~0.1 (Figure 3). For cross sections over existing NHD streams classified as either intermittent or perennial, 77% (n= 1082) of the Ps values are above the threshold while miss-classified or ephemeral features have 91% (n= 566) of the Ps values below 0.1.

As can be seen in Figure 3, variance is a factor that distinguishes the Ps values between the cross section populations. The range for stream cross sections is 0.67 Ps and 0.20 for non-streams. A moving variance of 5 cross-sections was passed over the Ps results for individual streams in the FC area to test whether a jump in variance alone could identify stream heads. The results were mixed. Anomalous values create spurious jumps and the short first order stream lines do not return enough cross sections to make a reliable test. Placing cross sections closer together and testing for outliers may resolve some of the issues.

3.2 High Topographic Relief Results

Analysis of above ground return point density trends and their correlation with the presence of streams in channels is ongoing. In the North Carolina RC area, ten valley channels with intermittent stream heads in various locations and three channels without streams (Figure 4) have been analyzed. The analysis indicates a pattern of decreasing return point density as elevation decreases in all of the valleys (i.e., moving downstream). Trends related to the presence of streams or stream heads are present, but the limited sample size and noise in the data make the discernment challenging. There appears to be a slump in understory return point density for points below 30 ft that correlates with the presence of intermittent stream heads. The dip roughly spans 75m along the channel and is present in all stream bearing channels analyzed in varying amounts. The > 60 ft return point density generally increases with decreasing channel elevation while overall above ground return point density decreases.

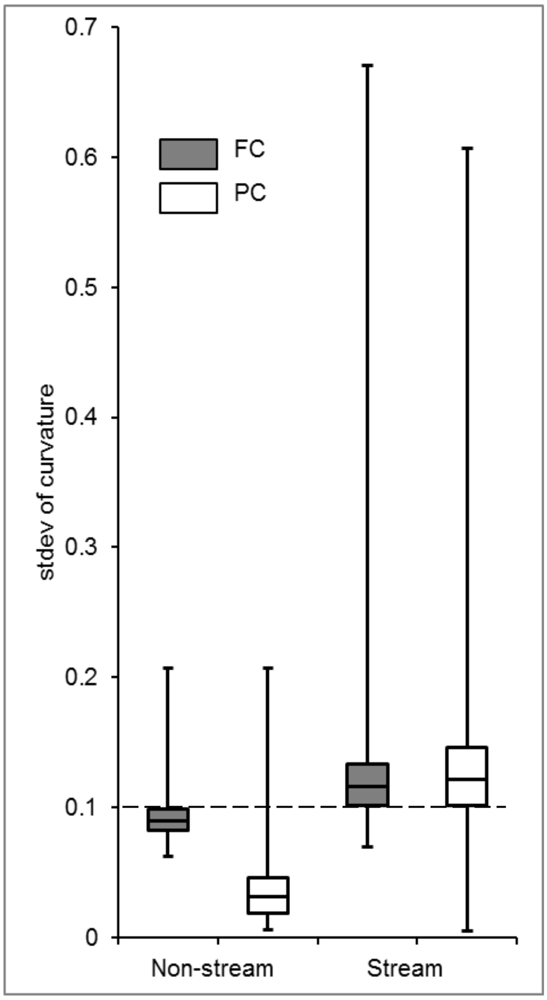

Figure 3. Standard deviation of cross section profile curvature from PC and FC study areas. Dotted line shows approximate between stream and non-stream cross-sections.

4. DISCUSSION

The findings discussed here offer promising potential strategies for identifying low order streams and the location of stream heads. This work focusses on a limited subset of landscapes yet these are common landscapes in the United States and they are some of the most problematic for remote mapping of low order streams.

The identification of streams in low relief landscapes using the Ps value of cross sections could be automated using a ratio of cross sections below the 0.1 threshold to cross sections above the threshold, where too few cross sections above the threshold suggests a channel is not a stream. The location of stream heads may be detectable using the same method or perhaps using a moving variance window over a more dense set of cross sections. Range and magnitude of curvature as components for stream head detection have been used by others (Passalacqua et al., 2010; Sangireddy et al., 2016) yet supervision is generally required and results are mixed. Accurate identification of roads and other built features in the landscape will be necessary as these are the most common source of anomalously high Ps values found here. Another complicating feature regarding Ps values is the occurrence of ephemeral features that result in similar Ps values. Discernment of ephemeral features from intermittent and perennial streams likely will require other data sources such as optical imagery and temporal flow volume estimates.

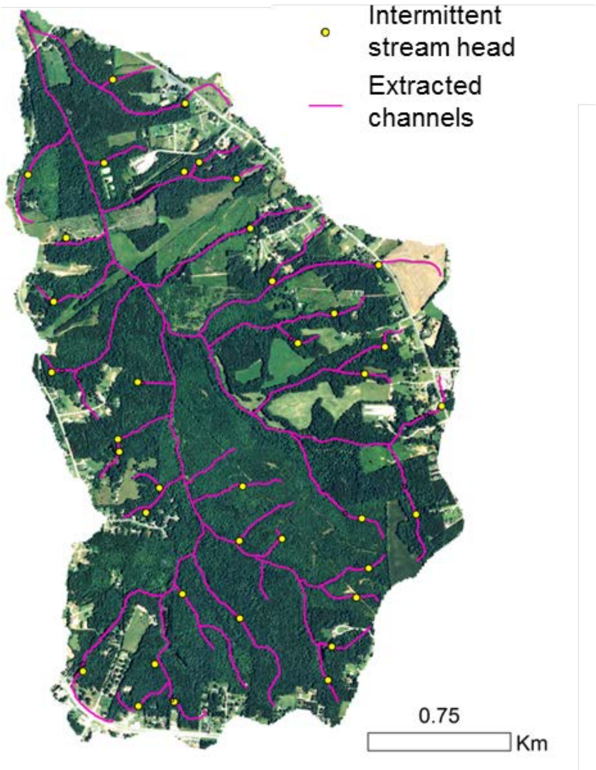

Figure 4. The Rowan County North Carolina study area. Channels analyzed for this work are located in the southern forested region.

Canopy composition complexity, density, and height can all vary with proximity to stream banks and with stream permanence (Ring et al., 2018). As applied here, the 3D analysis of return point density from vegetation is a test to determine whether unique riparian structure can be differentiated from surrounding forest remotely. The goal is to develop an automated process for low-order stream validation/detection in high relief forested areas. Variation and density of point returns below the canopy, excluding ground returns, is a measure of canopy complexity. Remote sensing methods have been applied to identify the presence of unique riparian zone structure and vegetation (Johansen et al., 2010) in arid regions. Here we investigate the use of lidar point cloud data for detection in humid regions.

Several trends in vegetation return point density relative to the presence of streams in channels are seen in this analysis. The reduction in lower vegetation point density with distance downstream may be the result of channel widening displacing vegetation and/or increased development of the upper canopy. Increased point density above 60 ft nearer to valley bottoms is another trend that appears to correlate with the presence of streams in channels. Increased tree height may be a function of species variation that can be expected in the presence of surface water (Gregory et al., 1991).

A trend identified here that is not as easily explained is the presence of a dip in point density below ~30 ft in the vicinity of stream heads with values rebounding downstream of the dip. Drop in vegetation density near stream heads may be the result of variable hydrologic conditions leading to inconsistent vegetation habitat. The dip in point density may be a feature unique to intermittent streams yet this cannot be determined with the data discussed here due to the lack of identified perennial stream heads in the watershed.

5. SUMMARY

This paper applies cross-sectional analysis of lidar point cloud data to measure the 3-dimensional structure of surface-water drainage channels and the vegetation canopy around the riparian zone. The goal is to develop automated techniques to validate lower order drainage lines for updating the NHD HR. This on-going research has focused on two small study areas in low relief agricultural conditions and one area in higher relief semi-mountainous forested conditions. Automated derivation of surface drainage networks using flow accumulation modeling with HR DEM data is a challenge in these conditions, which requires imprecise image interpretation and manual editing techniques. Preliminary results of the 3D structure analysis of drainage channels using lidar data indicate some relations may exist for automated validation of streams in channels or enhancement of drainage network extraction techniques.

3D channel structure analysis indicates a possible relation between standard deviation of cross section curvature and the headwater location of first-order drainage lines in the low relief agricultural watersheds. A similar relation has not yet been identified for the high relief forested conditions. However, some trends in vegetation density with relation to channel location are evident in 3D point return densities for channel cross sections in the high-relief forested conditions. Further testing is needed to refine these preliminary findings and identify limitations. Nevertheless, the 3D channel structure analysis of drainage lines appears to be a promising technique for validating drainage line features and possibly deriving stream permanence estimates. Automating the cross-sectional analysis technique will enhance implementation for rapid testing of larger datasets over a broad range of conditions.

DISCLAIMER

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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