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A Method for Quantifying Stream Network Topology over Large Geographic Extents

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Abstract

An understanding of stream network topology is necessary for a landscape-level perspective of stream hydrology and ecology. We present a method for quantifying stream network topology that overcomes computational constraints of DEM-based analysis over large geographic extents. This method converts vector stream flow paths to raster flow paths to predict spatially-explicit stream properties from a network-constrained upstream cell count (UCC) to flow origins. UCC data enable calculations of stream network structure at designated grain sizes and spatial extents. UCC values were strongly related to empirical measures of upstream basin area ($R^2 = 0.94$) and stream width ($R^2 = 0.65$) within the mid-Atlantic highlands, USA, suggesting that UCC data provide a reasonable surrogate for empirical measures of stream size within the stream network. By reducing raster grids to the flow path, the UCC method reduced file sizes by 99% compared to digital elevation models. The UCC method can improve our understanding of fluvial landscape hydrology and ecology by enabling spatial analysis of stream networks over large geographic extents.

Keywords: stream network topology, upstream cell count, landscape ecology, digital elevation models

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Introduction

A goal of stream hydrology and ecology is to understand how the spatial structure of stream networks affects the movement of water, energy, and organisms (Wiens, 2002). Spatial analysis of stream network topology (i.e., size and proximity of connected streams) therefore is necessary to quantify the effects of stream networks and to compare these effects across large watersheds or regions (Fausch et al., 2002). However, current DEM methods for stream network analysis are impractical across large geographic extents due to computational limitations associated with grid file size. Moreover, simple averaging of DEMs across scales is unlikely to provide the spatial resolution necessary for analysis of stream network topology (Martz et al., 2007). In this paper, we develop and validate a method to quantify stream network topology that overcomes prior analytical limitations for spatial analysis across large geographic extents.

Stream networks exhibit a hierarchically-branched structure wherein conditions at one point in the network may be influenced by conditions in connected streams (Frissell et al., 1986; Ward et al., 2002). Spatial patterns of precipitation and landform features in upstream areas affect flow travel-time and volume at downstream pour-points (Beven and Hornberger, 1982). Basin shape and morphometric patterns have an influence on hydrologic response shown through unit-hydrograph models (Moussa, 2003). Non-point source pollution models are also sensitive to the spatial aggregation of input data in upstream areas (FitzHugh and Mackay, 2000). For these reasons, the spatial structure of stream networks in upstream areas is a fundamental attribute of many spatially-explicit hydrological models (e.g., HEC-HMS, SWAT; see review in Arnold et al., 1998).

Ecological research has revealed complex patterns of connectivity within stream networks. Long-distance dispersal of stream fishes (i.e., >1 fluvial kilometer [fkm], distance along the stream centerline) has been observed from upstream to downstream locations, as well as from downstream to upstream locations (Albanese et al., 2004; Roghair and Dolloff, 2005; Gresswell and Hendricks, 2007). As a result, the size and proximity of downstream conditions may affect stream fish communities by regulating the species available for dispersal into connected streams (Gorman, 1986; Osborne and Wiley, 1992; Hitt and Angermeier, 2006, 2008a, 2008b). An understanding of stream ecology therefore requires the analysis of stream network topology over large geographic extents (Fausch et al., 2002; Ganio et al., 2005).

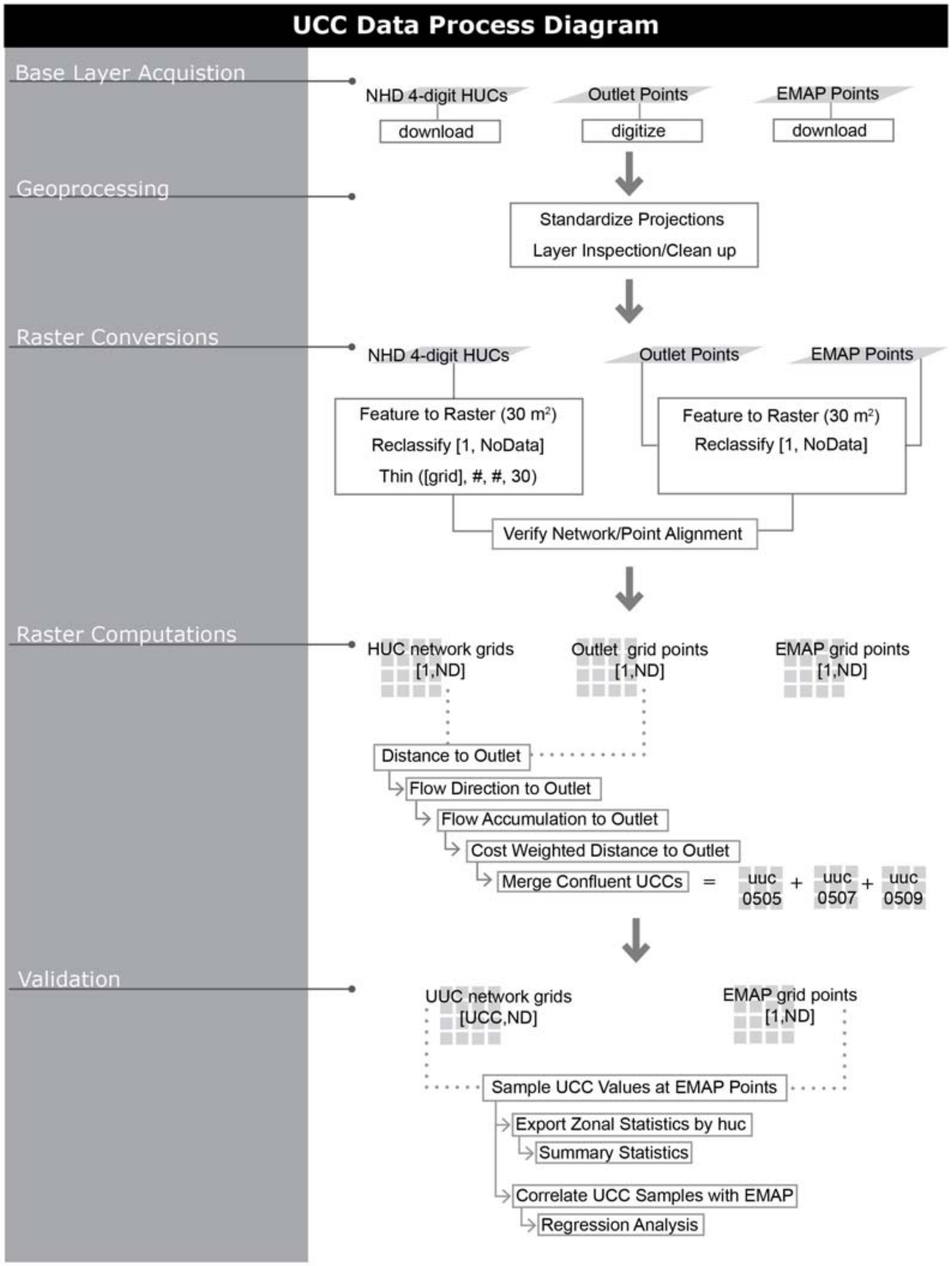
The first studies of stream network topology developed stream-order methods to investigate geomorphic causes of erosion and watershed evolution (Horton, 1945; Strahler, 1952; Shreve, 1966). Such stream-order methods have been widely used to characterize flow volume and physical habitat at locations within stream networks (Wiens, 2002). However, stream-order calculations have a limited capacity to characterize stream network topology. First, stream-order lacks information on spatial proximity (i.e., distance to connecting streams). Second, wide variation in stream volume among stream-orders may confound interpretation of stream sizes (e.g., large 2nd order streams may be very similar to small 3rd order streams) (Hughes and Omernik, 1981). Third, stream-orders lack information on downstream conditions (i.e., stream connections to large or small streams) that may affect biological communities. In contrast, studies in network topology are investigating how basin shape descriptors such as upstream basin area, perimeter length, and channel connectivity affect hydrological and ecological responses (Moussa, 2003).

Digital elevation models (DEMs) have been widely used to derive spatially-explicit stream networks. DEMs are raster data wherein grid cells represent an elevation that is averaged or interpolated to the cell size (e.g., 30 m^2). Relative changes in elevation among adjacent grid cells are used to calculate flow direction and accumulation, and to delineate flow networks. DEM-based flow paths have performed well in comparisons to aerial photograph-based flow paths (Jenson and Domingue, 1988) and have been widely applied in geomorphological studies (see Jenson, 1991). However, DEMs are impractical for analysis of large geographic extents due to computational limitations for processing large file sizes.

Vector data provide an alternative approach for quantifying stream network topology over large geographic extents. Vector data can delineate a line in any direction, and in a stream network is only limited by the direction of the upstream line segment. In contrast, raster data are limited in representing linear connectivity in only 8 orthogonal/diagonal directions. This property limits raster stream network data from scaling appropriately at large extents because averaging raster cells to a coarser resolution for studying large extents will significantly impact the basin size, boundary, and channel structure (Martz et al., 2007). Unlike raster data, high-resolution vector data can rescale a stream network to any equal or finer scale appropriately.

The National Hydrological Dataset (NHD, http://nhd.usgs.gov/) provides a continuous coverage of stream flow paths in the United States. The NHD was derived from U.S. Geological Survey maps of perennial streams at various spatial scales (USGS, 1999). The NHD are organized by a hierarchical Hydrologic Unit Code (HUC), which provides the cataloguing of data by basin size and shape rather than by rectangular DEM grid extents. The HUC is a widely recognized and powerful cataloguing unit. For example, the Pfafstetter methodology uses a combination of the 8-digit HUC cataloguing units and stream order enumeration to describe stream networks across continental scales (Verdin and Verdin, 1999). Although vector data will have much smaller file sizes than the DEM data for a given area, vector data in their raw form cannot quantify continuous variation in stream network topology because vector features are typically delineated as segments of various lengths, thus confounding distance-based calculations.

We propose a method for quantifying stream network topology that integrates elements of raster- and vector-based analyses. Our approach uses stream vector data as the base layer (i.e., NHD), develops a rasterized representation of distance from points in the stream network to the flow origin, and provides an approach for the spatial analysis of the network. The Upstream Cell Count (UCC) method utilizes the relationship between stream length and basin area (Hack, 1957) to develop a spatially-explicit representation of stream network topology. In this paper, we (1) present a method for UCC calculations, (2) validate UCC results against empirical data for stream size in the mid-Atlantic highlands region, and (3) discuss the potential applications of this method for stream ecology and fluvial geomorphology.



We visually inspected the stream vector data and replaced “double channels” with single channels. This was necessary because the UCC represents all streams as single lines, whereas large rivers are often represented by two lines corresponding to each bank of the river. We used editing tools in ArcGIS to manually correct for double-channels. We did not evaluate reservoirs in this analysis and therefore chose to map flow paths without reservoir boundaries (i.e., as the pre-impoundment river corridor). We also visually inspected the stream vector data for topological errors (i.e., missed confluences) within all watersheds and added connecting links where necessary.

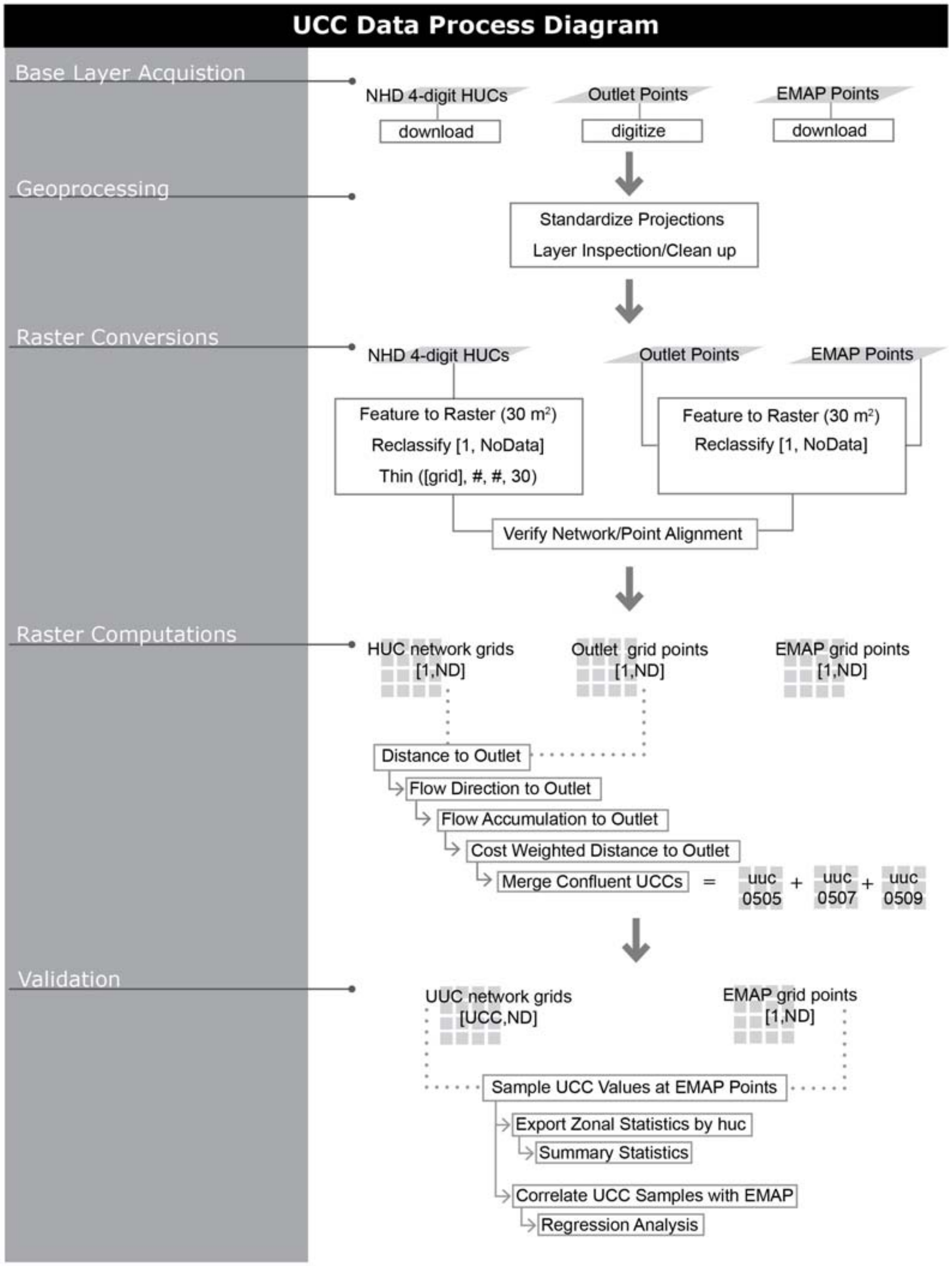


Figure 2. Process flowchart for calculating and validating Upstream Cell Counts (UCCs).

Next, we converted the stream vector data in each 4th-code HUC to raster grids of 30m^2 cells. We use 30m^2 cell sizes to enable overlay calculations for run-off models using readily available raster datasets such as the National Land Cover Dataset (NLCD), and digital elevation (DEM) data and derivatives such as slope and aspect. We reclassified the grids as [1, NoData] to separate river channels from non-river channel areas, a step that greatly reduces raster file sizes and thus reduces processing times in subsequent steps. The linear raster is thinned to one cell width using the raster function “Thin ([grid], #, #, 30).” This step ensures uniformity of the stream grids across the study area and avoids “lateral” counts in UCC calculations.

The UCC value for each cell of the thinned raster stream network is the count of the number of stream cells in the network upstream of the target cell (Figure 3a). This is analogous to the output of the FlowAccumulation function with the ‘catchment’ constrained to the linear flow network. However, to use the FlowAccumulation function, a flow direction grid is required, and the flow direction grid derived from the DEM will not correctly represent the thinned linear network. A simple solution is to calculate for the raster linear network a cost-weighted distance from the outlet point, then to calculate the flow direction using this cost-weighted distance as the surface (i.e., as a surrogate elevation grid). The UCC sums cell values by increments of 1 cell in a downstream direction throughout the network with the target cell evaluated as the sum of upstream cell values plus the number of contributing cells (Figure 3a). With this approach, UCCs can be calculated using the vector stream network as the sole data source and it is not necessary to evaluate a DEM for the basin. For the application presented here, UCCs were calculated for each of the 4th code HUCs (Figure 3b), and these were then merged together by adding appropriate offset values for downstream basins.

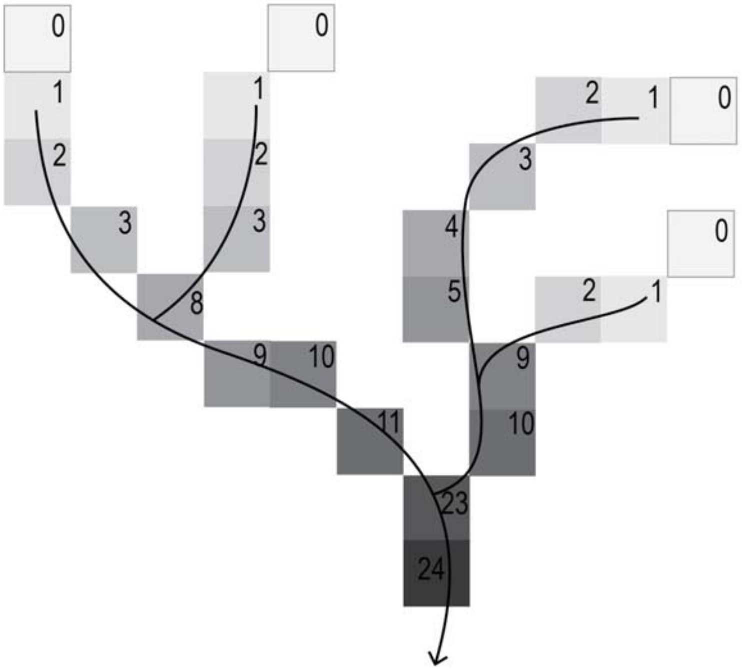


Figure 3(a). Conceptual diagram of the additive function for Upstream Cell Count (UCC) calculations, where the target cell is evaluated as the sum of upstream cell values plus the number of contributing cells.

To evaluate the suitability of UCCs as a representative of stream dimension, we compared UCC data to empirical measures of stream size within the study area. We used data from the U.S. Environmental Protection Agency’s Environmental Monitoring and Assessment Program (EMAP) (Lazorchak et al., 1998). EMAP sites were selected using a stratified random sampling methodology (Herlihy et al., 2000), and detailed site characteristics include measures of stream width and depth, and upstream basin size (see http://www.epa.gov/emap/). Stream widths were averaged from 11 cross-sectional measurements; stream depths were averaged from 100 measures of the stream thalweg, evenly spaced along a stream length measuring 40-times the mean stream width (Lazorchak et al., 1998). Upstream basin size from each sampling site was calculated from GIS data by US EPA personnel (Lazorchak et al., 1998). We conducted simple linear regressions between UCCs and stream data from 198 randomly-selected EMAP sites in the mid-Atlantic highlands, USA.

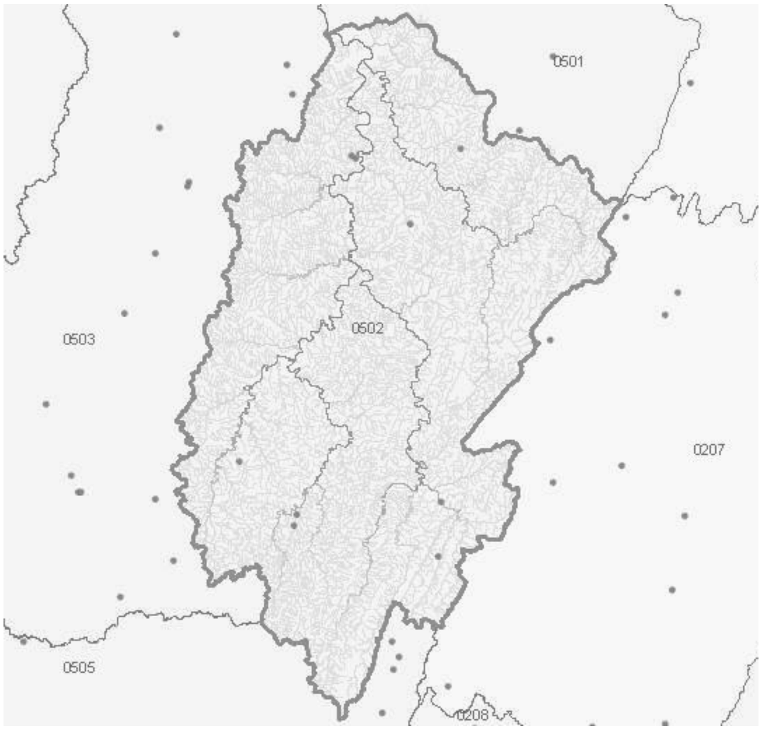


Figure 3(b). Example of HUC cataloguing and UCCs calculated for a watershed in the mid-Atlantic highlands, USA (lower Monongahela basin, West Virginia).

Results and Discussion

UCC data ranged from 1 to 4.55 x 10^6 cells in the mid-Atlantic highlands study area (Table 1). As expected, the presence of large river mainstems (e.g., Ohio River) within 4th-code HUCs influenced the range of UCC values (Table 1). UCC data were strongly related to upstream basin areas in EMAP data (R^2=0.94, Table 2; Figure 4a). However, mean stream width and depth showed weaker relationships with UCCs (R^2=0.65 and 0.29, respectively, Table 2; Figures 4b-c). UCCs were not related to EMAP site elevation (Table 2; Figure 4d). Stream network delineations with UCC data reduced file sizes from DEM data an average of 99% per unit area in the mid-Atlantic highlands (Table 3).

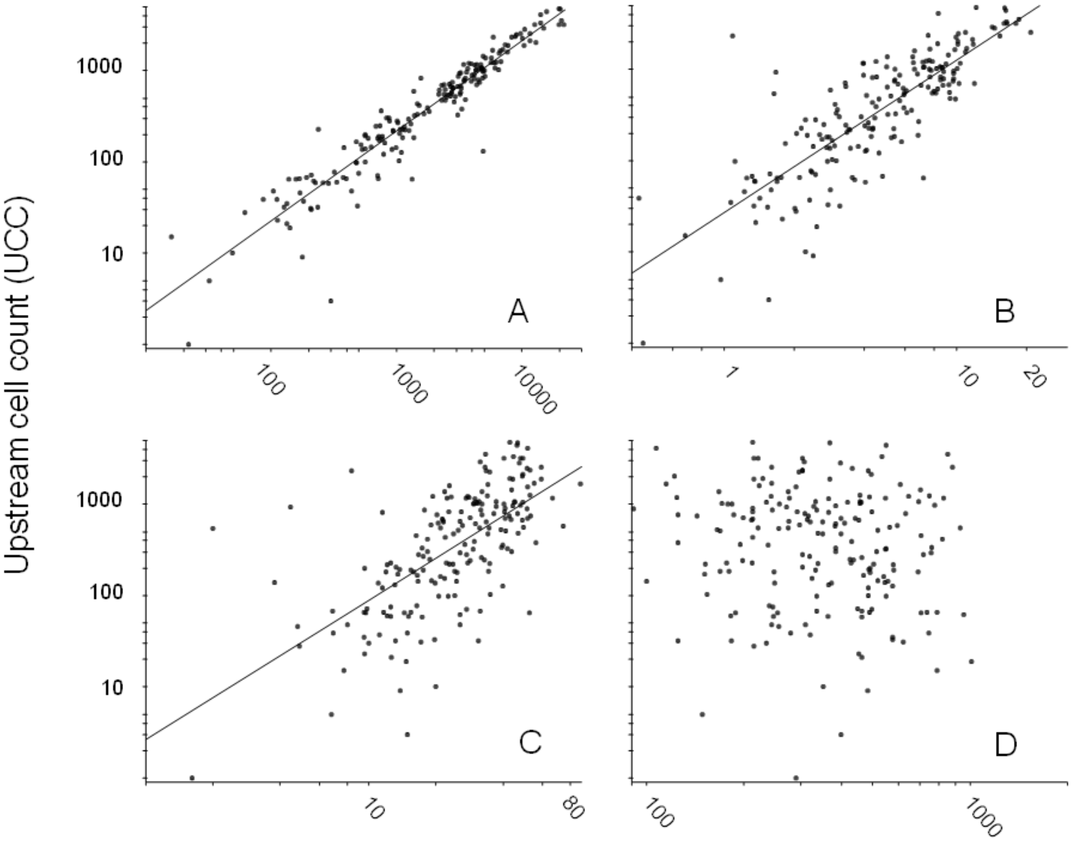


Figure 4. Correlation of Upstream Cell Counts (UCCs) and empirical measures of stream condition in the mid-Atlantic highlands, USA: (A) basin size, (B) stream width, (C) stream depth, and (D) elevation.

The UCC analysis provides a reasonable surrogate of stream volume and provides new opportunities for stream network analysis across large geographic extents. UCC data were closely related to upstream basin areas (Table 2; Figure 4), a known correlate of stream volume (e.g., Hughes and Omernik, 1983). This result supports Hack’s (1957) observation of the fundamental relationship between stream length and basin area. Moreover, our results provided information on stream size throughout the stream network at a grain size of 30m^2 cells. The UCC is limited by the accuracy of the vectorized stream network, but NHD are digitized at three scales specified as “local”, “high”, and “medium” resolution with seamless coverage over a large geographic region. Our approach integrated elements of vector and raster data to utilize the benefits of each (i.e., small file sizes and spatially-explicit analyses, respectively).

UCCs offer several important benefits from DEM-based analyses of stream network topology. First, derivation of the UCC does not require a DEM, and the greatly reduced file sizes (Table 2) enable spatial analyses across larger geographic extents. Second, the use of NHD as a base layer provides a logical cataloging unit to organize spatial analyses as well as other data relevant for hydrological analyses (see http://nhd.usgs.gov/) see Figure 3(B) Example of HUC cataloguing and UCCs calculated for a watershed in the mid-Atlantic highlands, USA (lower Monongahela basin, West Virginia). Third, NHD data use a consistent flow accumulation threshold (i.e., determined by U.S. Geological Survey where a perennial stream forms at the 1: 100,000 map scale) instead of an arbitrarily defined flow accumulation threshold determined by the user. Fourth, UCCs revealed stronger relationships to upstream basin area than 30 m^2 DEMs (Walker and Willgoose, 1999). Smaller DEM cell sizes may increase the precision of stream network delineation (e.g., 2.5 m^2; Miller, 1999) but such data requirements would limit spatial analyses across large geographic extents. Future research may investigate the sensitivity of UCC grid cell size to network topology parameters.

Table 1. Upstream Cell Count (UCC) summary statistics for the mid-Atlantic highland study area

Basin	Minimum	Maximum	Mean
Delaware	1	739,490	7895
Susquehanna	1	1,505,344	11592
Potomac	1	872,042	11629
Lower Chesapeake	1	689,463	8603
Chowan-Roanoke	1	872,340	51128
Allegheny	1	699,026	37900
Monongahela	1	463,958	50758
Upper Ohio	1	2,578,600	35536
Muskingum	1	512,980	222565
Kanawha	1	744,205	46083
Big Sandy-Guyandotte	1	264,155	58798
Middle Ohio	1	4,553,860	22810
Upper Tennessee	1	1,176,670	643787

Table 2. Coefficients of determination (R^2) for linear regression between Upstream Cell Counts (UCC) and environmental variables for random sample sites from EPA EMAP data

Variable	**Transformation**	**R^2**
Upstream basin area (ha)	None	0.898
	Log_{10}	0.915
Mean stream width (m)	None	0.665
	Log_{10}	0.647
Mean stream depth (cm)	None	0.423
	Log_{10}	0.290
Site elevation (m)	None	0.010
	Log_{10}	0.005

UCC data should not be used to evaluate stream widths or elevations of rivers and streams. The relatively poor relationship between UCCs and elevation may be explained by the fact that EMAP sites encompassed multiple physiographic provinces of different elevations (i.e., blue ridge, ridge and valley, Appalachian plateau). In addition, stream widths are influenced by riparian condition, geology, and land use (Leopold et al., 1964) but these factors were not considered in this analysis. Because EMAP sites are randomly distributed throughout the study area (Herlilhy et al., 2000), we assumed that these factors were randomly distributed across stream sizes.

For the data used in this study, UCC values less than 100 show relatively poor fits with upstream basin size (Figure 4). This is probably due to the fact that streams in our base layer were derived from 1:100,000 scale maps (i.e., medium-resolution NHD) and the location of stream initiation may be more precise in finer-scale maps. For example, Vance-Borland et al. (2009) showed that 1:100,000 scale maps in the Pacific Northwest contained approximately one half of the total stream length shown on 1:24,000 scale maps. As a result, UCC data may be not be appropriate for analyzing individual small streams (e.g., 1st-order [Strahler, 1952]). Instead, UCC data should be used to quantify the spatial properties of stream networks. Because length-to-area relationships are strong, the UCC could also be used to estimate watershed elongation ratios and fractal dimensions in channel structure (De Bartolo et al., 2006).

Hitt and Angermeier (2008a) evaluated UCC data to assess fish dispersal dynamics and found that fish communities were influenced by the size and proximity of connected streams within 20 fkm. In a separate analysis of UCC data, Hitt and Angermeier (2008b) showed that fish communities in streams flowing into rivers within 10 fkm were less responsive to stressors than in streams that lacked riverine confluences. In these studies, UCCs enabled analyses across multiple physiographic regions and spatial grains simultaneously, thus providing an important perspective of stream network dynamics.

Table 3. Data file size comparisons between digital elevation models (DEM) and upstream cell counts (UCC) in the mid-Atlantic highlands study area

Basin	Area (10^3 km^2)	DEM (MB)	UCC (MB)
Delaware	48.1	474.5	3.5
Susquehanna	71.3	703.8	7.1
Potomac	38.1	375.6	4.1
Lower Chesapeake	56.4	557.1	4.9
Chowan-Roanoke	55.4	546.9	4.1
Allegheny	30.3	299.1	3.3
Monongahela	19.1	188.6	2.2
Upper Ohio	34.7	342.2	4.4
Muskingum	20.9	205.8	2.3
Kanawha	31.7	313.1	3.5
Big Sandy – Guyandotte	15.5	152.8	1.7
Middle Ohio	23.0	227.1	2.7
Upper Tennessee	44.8	442.2	5.4
Mean	**34.8**	**371.4**	**3.8**

Conclusions

A method has been presented for quantifying stream network topology that overcomes computational constraints of DEM-based analysis over large geographic extents. The proposed method uses stream vector data as the base layer, develops a rasterized representation of distance from points in the stream network to the flow origin, and provides an approach for the spatial analysis of the network. It was found that the UCC data are appropriate for the analysis of stream network structure across large geographic extents. Future research should attempt to link UCC data with spatial measures of stream network connectivity. Combining this measure of stream network connectivity with UCC data would enable new analyses of organismal dispersal based on the size and configuration of stream networks (Campbell-Grant et al., 2007). Such stream network-scale analyses are necessary for conservation and restoration planning (Fausch et al., 2002). Moreover, analysis of UCCs across watershed shapes could reveal the effects of confluence-mediated stream geomorphology (Benda et al., 2004).

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Appendix

ArcGIS Script Codes

The following script codes show how each step in the process was calculated using parametric functions from ArcToolbox and Raster Calculator.

Convert NHD vector to raster stream grid

Spatial Analyst → Convert → Features to raster: grid size (30 m), extent (same as stream grid)

Calculate a cost-weighted distance grid

```
(out_float_grid) COSTDISTANCE (<source_grid>,<cost_grid>,{out_backlink_grid},
                         {out_allocate_grid},{max_distance},{value_grid})
```

Calculate flow direction grid

```
 (out_int_grid) FLOWDIRECTION (<surface_grid>,  {out_drop_grid}, {NORMAL | FORCE})
```

Calculate flow accumulation grid

```
 (out_float_grid) FLOWACCUMULATION (<dir_grid>, {weight_grid}, {FLOAT | INT})
```

Merge converging UCCs

```
(out_int_grid) Con( <ucc_grid> >= 0, <ucc_grid> + # of contributing cells, <ucc_grid>)
```