Effects of Stream Order and Data Resolution on Sinuosity Using GIS

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ABSTRACT

This research focuses on estimation and analysis of stream sinuosity using GIS. Fifty-five streams including 13 streams of order 0, 17 streams of order 1, 15 streams of order 2 and 10 streams of order 3 in Virginia were considered. Several GIS datasets from various sources, including the Virginia Base Mapping Program (VBMP) and United States Geological Survey (USGS), were used to generate stream networks using GIS.

Sinuosity was computed using GIS based on a technique comparable to the approach used in an Environmental Monitoring and Assessment Program’s (EMAP’s) field survey report. Field sinuosity data from EMAP report were used as reference data for analyzing the accuracy of sinuosity values from different GIS data sources and resolutions. The GIS technique was implemented for computing sinuosity for 55 streams in Virginia using vector data including the VBMP Hydro44 and National Hydrography Data (NHD).

Insufficient statistical evidence was found to support the hypothesis that the computed sinuosity values using Hydro44 and NHD data are different from EMAP field data for all 55 streams. Sinuosity values computed using Hydro44 and NHD were found to increase with the increase in EMAP sinuosity (positive correlation) for all 55 streams. EMAP data on sinuosity, however, did not predict sinuosity values computed using Hydro44 ($R^2 = 27\%$) and NHD ($R^2 = 10\%$) sources well. It was found that the GIS technique of computing sinuosity using digital data such as Hydro44 (VBMP source) and NHD (USGS source 1:24,000) is better suited for stream orders 2 and 3. Insufficient statistical evidence was found that computed sinuosity values for streams derived using various resolutions (i.e., DTM 3m, DTM 10m, DTM 30m, DEM 10m and DEM 30m) are different from EMAP field data. Positive correlation was observed between sinuosity values for streams derived in all resolutions with EMAP field data. DTM 10m resolution data yielded best correlation value (75\%) with EMAP field data.
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1. INTRODUCTION

The Geographic Information System (GIS) has become a very important tool in processing and analyzing spatial data in hydrology and water resources modeling. Digital Elevation Models (DEMs) provide very important data that is used in GIS to derive the physical characteristics of a watershed such as land slope, channel length and channel sinuosity.

In order to define sinuosity, consider stream segment AB shown in Figure 1.1. Sinuosity of stream segment AB is defined as the ratio of actual stream length (or reach length), shown using a solid curved line, to straight-line distance (or valley length) shown using a dotted line, in Figure 1.1. This is a measurement of the degree to which a stream meanders down its valley. A stream is straight when the sinuosity value is 1. It is considered a sinuous stream if sinuosity ranges from 1 to 1.5 and finally a stream is considered meandering if sinuosity is greater than 1.5 (Kunze, 2004).

![Figure 1.1 Definition of sinuosity: Ratio of Reach Length and Valley Length](image)

There is a strong relationship between sinuosity of a stream and its slope. Generally, the more gentle the slope the greater the sinuosity. Sinuosity has also been used in classifying the streams into perennial, intermittent or ephemeral. For example, on Upper Neuse River basin in North Carolina, streams in soft sediment change from ephemeral to intermittent at a point where it increases its meandering significantly (Restrepo and Waisanen, 2004).
Sinuosity of streams is typically determined using field measurements (Kaufmann et al., 1999). In this research, GIS techniques have been used to assess stream sinuosity values for a variety of stream orders. Since resolution of data plays an important role in GIS, the effect of data resolution on sinuosity assessment has been examined. The author is not aware of any studies that have examined relationship between stream order and stream sinuosity using GIS technique. Also, the effects of data resolution on sinuosity using GIS have not been examined extensively and this is the major focus of this research.

1.1 OBJECTIVES

The objectives of the study are to:

1. Develop and implement a method of computing stream sinuosity using GIS.

2. Evaluate and analyze the effects of stream order on stream sinuosity using vector data in GIS.

3. Evaluate and analyze the effects of data resolutions on stream sinuosity using raster data in GIS.
2. LITERATURE REVIEW

A number of studies have been conducted to analyze the effects of data resolution on hydrologic parameters. Studies have also been conducted on the relationship between sinuosity and physical habitat. These studies are reviewed briefly below.

2.1 Data Resolution Effect on Hydrologic Parameters / Modeling

Investigators at the USGS (USGS, 2008) studied the effects of data resolution on the outputs of various water quality models. Characteristics of digital elevation models and their impacts on hydrological and water quality models were examined using two 16 ha watershed sites in Atchison County, Missouri. In this study, standard 30 m USGS DEMs were compared with field data. Results indicate that the DEMs correctly predicted slope at only 21 and 30 percent of the field sampling locations. It has also been argued (USGS, 2008) that DEMs with spatial resolutions of 2-10 m are required to represent important hydrologic processes and patterns in many agricultural landscapes. Effects of data structure and cell size on Agricultural Non-Point Source (AGNPS) pollution model inputs were examined and it was demonstrated that computed flow path lengths and upslope contributing areas vary with element size. In a study in Oklahoma, the impact of DEM resolution on extracted drainage properties for an 84-km² watershed was examined using hypothetical drainage network configurations and DEMs of increasing size. Various quantitative relationships were derived and one major conclusion is that the grid spacing must be selected relative to the size of the smallest drainage features.

Helmlinger et al. (1993) studied the channel network extraction from DEM data with the specified threshold area using Horton’s Ratios and Fractal dimension methods. This study was performed on three watersheds: South Fork Smith River in California, Schoharie Creek in New York, and Big Creek in Idaho. It was concluded that there was a relationship between DEM data resolution and the threshold area in defining the channel network.
Wolock and Price (1994) used TOPMODEL to show that the map scale source of the DEM has an effect on model prediction of the depth to the water table, the ratio of overland flow to total flow, peak flow, and variance and skew of predicted stream flow. The authors further reported that the mean depth to the water table decreased with increasing coarseness of the data resolution and the maximum daily flow increased with increasing coarseness of the resolution.

Costanza and Thomas (1994) established a strong relationship in resolution and predictability on hydrologic models. The authors resampled the map data sets at several different spatial resolutions and measured the predictability at each resolution. The results indicated that the increasing resolution provided more descriptive information about the patterns in data. However, it also increased the difficulty of accurately modeling those patterns. The model predictability can be increased by lowering the resolution by averaging out some of the chaotic behavior at the expense of losing detail about the phenomenon. The authors concluded that “the aim is to choose the resolution that maximizes the effectiveness of the model in balancing the conflicting trends of data and model predictability with changing resolution”.

Thieken et al. (1998) studied the sensitivity of surface runoff simulations in a variety of watershed configurations with synthetic storms using infiltration excess runoff model. The study revealed that elevation data with different resolutions diverge enormously in landscape representation and in the derived parameters such as slopes, flow directions and channel networks. It was reported that coarse DEMs show a smoother terrain and shorter flow paths than highly resolved data.

The effect of vertical accuracy of DEMs on hydrologic prediction accuracy was evaluated by Kenward et al. (2000). The authors evaluated three DEMs and associated streamflow simulations for a 7.2 sq km USDA-ARS watershed at Mahantango Creek, PA. They used the standard 30-m USGS 7.5-minute DEM, a 5-m product derived from low altitude aerial photography, and a 30-m product derived from interferometric processing of Spaceborne Imaging Radar-C (SIR-C). Comparisons of runoff predicted
using a hydrologic model based on the three DEMs showed that mean annual predicted runoff volumes were 0.3 and 7.0 percent larger for the USGS and SIR-C DEMs, respectively, as compared to the reference DEM (30 m resampled from 5 m DEM produced by Photo Science Co.). The larger differences were observed in individual hydrographs, the USGS and SIR-C DEMs predicted lower peaks, and higher base flows, than did the reference.

Glenn and Ginger (2001) examined the DEM grid size on hydrologic modeling. The authors used a GIS to evaluate the hydrologic parameters such as drainage area, flow length, relief, slope, curve number, time of concentration, and peak discharge in DEMs with cell sizes of 12, 36, 60, and 96 ft, and 30 and 90 m respectively. The results indicated that the data resolution resulted in systematic errors or biases in parameter estimates for flow length, relief, slope, time of concentration, and ultimately peak discharge. As resolution grew coarser, the estimated flow length, relief, and time of concentration decreased consistently. As a result, a tendency for overestimation in peak discharge was observed in coarser resolution.

Usery et al. (2004) analyzed the effects of data resolution on watershed modeling. The data was re-sampled from 30-m to 60-, 120-, 210-, 240-, 480-, 960-, and 1920-m pixels using GIS. In this study, the authors developed databases of elevation, land cover, and soils at various resolutions in four watersheds. These were used as an input in Agricultural Non-Point Source (AGNPS) pollution model. Results indicate that elevation values at specific points compare favorably between 3- and 30-m raster datasets. Analysis of data re-sampled from 30-m to 60-, 120-, 210-, 240-, 480-, 960-, and 1920-m pixels indicated a general degradation of both elevation and land cover correlations as resolution decreases.

Chaubey et al. (2005) studied the effect of DEM data resolution on predictions from the Soil and Water Assessment Tool (SWAT) model. Observed hydrologic, meteorological, watershed characteristics and water quality data were used in the simulation. The effect of input data resolution was evaluated by running seven scenarios at increasing DEM grid sizes (30 m, 100 m, 150 m, 200 m, 300 m, 500 m, 1000 m). Results showed that
DEM resolution affects the watershed delineation, stream network and sub-basin classification in the SWAT model. A decrease in DEM resolution resulted in decreased stream flow. However, the model predicted that total phosphorus did not always decrease with DEM resolution. Results of this study indicate that the choice of input DEM resolution depends on the watershed response of interest. Minimum DEM data resolution ranged from 100 to 200 m to achieve less than 10% error in SWAT output for flow predictions. The authors’ study also indicates that the SWAT model output was most affected by input DEM data resolution. A coarser DEM data resolution resulted in decreased representation of watershed area and slope and increased slope length.

Hill et al. (2005) compared the effects of resolution of data obtained from two sources (i.e., Light Detection and Ranging (LiDAR) and USGS DEM) in estimating the watershed slope. The results indicate that watershed slope estimates based on the USGS DEMs are systematically under-estimated. The data were further analyzed using the contour based method. The results derived from this method are comparable to the DEM-based estimates. However, both estimates of watershed slope differ considerably from the main channel slope.

Wang and Zheng (2005) compared the USGS national elevation dataset (NED), DEM data and four sets of LIDAR DEMs for Pitt County, North Carolina to determine the effects of resolution on extent of floodplains in the region of interest. The two sets of the LIDAR DEMs have a spatial resolution of 6.1 m and 15.2 m, respectively. The LIDAR DEMs were resampled to 30 m resolution to compare with NED data. Results indicated that the overall accuracy for selected flooded and non-flooded sites ranged from 92.5–96.1%.

2.2 Sinuosity and Habitat

In a study conducted by Fukuoka et al. (1999), the authors analyzed the relationship between flood flows in meandering channels and the relative depth and sinuosity. It was reported that sinuosity greatly impacts the flow direction of the main channel and flood
channel. The authors further reported that active exchange flow occurs between the main channel and flood channel for highly sinuous streams.

Kaufmann et al. (1999) describe methods for evaluating physical habitat in wadeable streams in the U.S. and provided guidance for computing sinuosity and a variety of other measures of stream size in a report of the USEPA under its Environmental Monitoring and Assessment Program (EMAP). The method described to compute sinuosity and the sinuosity field data have been adopted in this study.

Fukushima (2001) analyzed the relationship between channel sinuosity and locations of a nest of fish eggs that is covered with gravel. The author found that salmonid species preferred to spawn at sites above which stream reaches have higher than average sinuosity. This connection between channel planform and salmonid spawning habitat selection accounts for previous observations that salmonids typically construct a nest of eggs at similar locations along streams from year to year.

Bilkovic et al. (2002) considered sinuosity as one of the stream parameters in designing and testing the habitat suitability index (HBI) data. This study was conducted in Mattaponi and Pamunkey rivers in Virginia. The authors have evaluated several morphological and instream habitat factors that influence fishery production. The results also include the presence of fish eggs and larvae in the sinuous sites of streams.

The physical habitat and fish community biotic integrity data was analyzed by Hood (2004) in the estuarine marshes of the Skagit River delta in Washington state. The sinuosity of low gradient streams was one of the variables used to compute the Index of Biotic Integrity (IBI). One of the outcomes of this study suggests that the loss of channel sinuosity has an impact on decreasing the channel habitat diversity such as salmon, trout, and sturgeon.
2.3 Sinuosity Estimation

McCleary et al. (2002) computed slope and sinuosity for small streams in the west central part of Alberta using GIS derived values. In comparison with field measurements, the GIS results underestimated stream sinuosity for streams within a watershed area of 20 sq. km.

Heatwole and Lohani (2004) evaluated effects of data resolution on sinuosity in a study conducted in Troubles Creek watershed in Virginia. It was found that sinuosity for the derived stream networks decreased as data grid size increased.

Sinuosity is a common parameter in stream characterization studies (Arya, 2002) and restoration design (Rosgen, 1994). The best estimate of site-specific stream parameters is through field surveying, but this process is very time consuming. Analysis using a GIS and digital data sources can be a much simpler approach that may provide reasonable estimates of sinuosity at desired locations.

2.4 SUMMARY OF LITERATURE REVIEW

Based on the above studies, it can be assumed that the spatial resolution of data does affect the estimation of hydrologic parameters. However, there have been few studies on the effects of data resolution on sinuosity estimation. In addition, few studies have been done to assess the role of sinuosity on stream habitat. Studies have also indicated that there is a relationship between habitat and stream sinuosity. However, the author is not aware of any comprehensive studies that were conducted to see the sinuosity as a function of spatial resolution. Also, effects of stream order on sinuosity have not been analyzed. In this study, GIS analysis is used to estimate sinuosity using different data sources including streams of various orders and resolutions of data.
3. STUDY AREA AND DATA SOURCES

The study area for this research includes watersheds of a number of rivers including Big Sandy River, Clinch-Powell River, Holston River, James River, New River, Potomac River, Rappahannock River and Roanoke River in the state of Virginia (see Figure 3.1). The selection of watersheds is based on availability of all data listed below:

- Field data including sinuosity, reach length and valley length from Environmental Monitoring and Assessment Program (EMAP) in the state of Virginia.

- Raster data from Virginia Base Mapping Program (VBMP) for those locations where EMAP data, as above, are available.

- Digital Elevation Model (DEM) 10-meter data from US Geological Survey (USGS) for locations where EMAP and VBMP data, as above, are available.

- National Hydrography Data (NHD) from USGS for locations where EMAP, VBMP and DEM data, as above, are available.

Altogether, 55 EMAP points on stream reaches satisfied the criteria and supporting data sets were identified, collected, and processed. These streams were further classified into their stream orders. The data set includes 13 streams of order zero, 17 streams of order one, 15 streams of order two and 10 streams of order three. The locations of EMAP field data on these streams in Virginia and stream orders are shown in Figure 3.1.
Figure 3.1 Location of 55 EMAP field sample points on various Streams in Watersheds of Virginia. The watershed boundary map is adapted from Center for Geospatial Information Technology at Virginia Tech.
3.1 DATA SOURCES AND DESCRIPTION

Acronyms used to refer various data and the sources of these data are listed in Table 3.1.

Table 3.1: Data Acronyms and Sources

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Data Sources*</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMAP</td>
<td>Physical habitat field data from Environmental Monitoring and Assessment Program (EMAP) of the EPA. <a href="http://www.epa.gov/emap">http://www.epa.gov/emap</a></td>
</tr>
<tr>
<td>Hydro44</td>
<td>Hydrography is vector data from Virginia Base Mapping Program (VBMP). <a href="http://www.vgin.vipnet.org">http://www.vgin.vipnet.org</a></td>
</tr>
<tr>
<td>NHD</td>
<td>National Hydrography Dataset (NHD) is vector data from USGS. <a href="http://nhd.usgs.gov">http://nhd.usgs.gov</a></td>
</tr>
<tr>
<td>DTM 3m</td>
<td>Raster data sets from Virginia Base Mapping Program (VBMP). <a href="http://www.vgin.vipnet.org">http://www.vgin.vipnet.org</a></td>
</tr>
<tr>
<td>DTM 10m</td>
<td>Raster data sets from Virginia Base Mapping Program (VBMP). <a href="http://www.vgin.vipnet.org">http://www.vgin.vipnet.org</a></td>
</tr>
<tr>
<td>DTM 30m</td>
<td>Raster data sets from Virginia Base Mapping Program (VBMP). <a href="http://www.vgin.vipnet.org">http://www.vgin.vipnet.org</a></td>
</tr>
<tr>
<td>DEM 10m</td>
<td>Digital Elevation Model (DEM) is a raster data set. <a href="http://www.gisdatadepot.com">http://www.gisdatadepot.com</a></td>
</tr>
<tr>
<td>DEM 30m</td>
<td>Digital Elevation Model (DEM) is a raster data set. <a href="http://www.gisdatadepot.com">http://www.gisdatadepot.com</a></td>
</tr>
<tr>
<td>DRG</td>
<td>Digital Raster Graphic (DRG) from USGS. Also, known as a digital topographic map <a href="http://fisher.lib.virginia.edu/collections/gis/vagaz/">http://fisher.lib.virginia.edu/collections/gis/vagaz/</a></td>
</tr>
<tr>
<td>DOQ</td>
<td>Digital Orthophoto Quadrangle from USGS. These are aerial photographs. <a href="http://fisher.lib.virginia.edu/">http://fisher.lib.virginia.edu/</a></td>
</tr>
</tbody>
</table>

* All sources accessed February 2008.

The following sections briefly describe various data presented in Table 3.1.

3.1.1 EMAP data

The physical habitat of streams was characterized in the Environmental Monitoring and Assessment Program (EMAP) of EPA. EMAP is a research program of the EPA that
has an objective to develop the tools necessary to monitor and assess the status and trends of natural ecological resources. EMAP data includes various habitat parameters including reach length, valley length, reach sinuosity, fish cover, vegetation types, etc. These habitat parameters are available at each sample point and are considered in this study. Location of EMAP field sample points on various streams in the Mid-Atlantic region are shown in Figure 3.2. In this study, sample points that are located in Virginia are considered.

3.1.2 Hydro44 data

This hydrography vector data was digitized by the Virginia Base Mapping Program (VBMP) agency from the VBMP 2002 imagery. Hydro44 data represents the rivers, streams, ponds, lakes, and other bodies of water. Figure 3.3 shows an example of digital hydrography layer from an aerial photograph.
3.1.3 NHD

The National Hydrography Dataset (NHD) from USGS contains detailed geospatial information about surface waters. This high-resolution data is developed from digital line graph (DLG) files. The DLG data are primarily derived from USGS 7.5-minute topographic quadrangle maps at 1:24,000 and 1:25,000 scales (1:25,000 and 1:63,360 scales for Alaska). Figure 3.4 shows examples of stream networks in two scales using NHD (West Virginia GIS Technical Center, 2005). In this study, the 1:24,000 scale is used.
3.1.4 DTM data

DTM data is a product of the Virginia Base Mapping Program (VBMP) and is available in .dgn file format. This data includes mass points and break lines. A mass point has x (easting), y (northing) and z (elevation) coordinates. The line data features are represented by breaklines. These breaklines represent the sudden changes in terrains associated with linear ground features such as road edges and ridgelines. Breaklines are also consist of vertices. These vertices also have x (easting), y (northing), and z (elevation) coordinates. An example of mass points and breaklines is shown in Figure 3.5.

![Example of DTM data](image)

*Figure 3.5 Example of DTM data: Points represent easting, northing and elevation data. Lines represent features such as rivers, roads, and breaklines represent the sudden changes in terrains* 

3.1.5 DEM data

The USGS DEM data are cell-based digital representations of the continuous surface of the earth in a raster form. The accuracy of this data is determined by the resolution. In this study, DEM 10m resolution data, 1:24,000 scale was used and downloaded in an quadrangle format (Figure 3.6).
3.1.6 DRG data

The digital raster graphic (DRG) is also called a digital topographic map. This is a USGS product. In this study, the DRG data was used as a source of topographic information of the stream network.

3.1.7 DOQ data

Digital Orthophoto Quadrangles (DOQ) data is produced by USGS and is based on either grayscale or color-infrared (CIR) images with a 1-meter ground resolution. This data is used as a source for identifying actual streams on aerial photographs.
4. DATA PROCESSING AND METHODS

The purpose of data processing was to identify and create stream networks from various vector and raster data sources at the chosen EMAP field sample locations. In the case of vector data, 55 EMAP sample locations were identified. In the case of raster data, 13 EMAP field sample locations were considered where USGS DEM 10m were also available. A summary of vector and raster data used in this study is shown in Table 4.1.

Table 4.1 Summary of vector and raster data

<table>
<thead>
<tr>
<th>Data and Source</th>
<th>VBMP</th>
<th>USGS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vector (55 Samples)</td>
<td>Hydro44</td>
<td>NHD</td>
</tr>
<tr>
<td>Raster (13 Samples)</td>
<td>DTM 3m, DTM 10 m and DTM 30m</td>
<td>DEM 10m and DEM 30m</td>
</tr>
</tbody>
</table>

All data sets were projected, as required, to a common coordinate system of NAD-83, UTM Zone 17N. Data processing was conducted in ArcGIS 9.1 using 3D Analyst and Spatial Analyst tools.

4.1 VECTOR DATA PROCESSING

4.1.1 Hydro44 data

Stream data from VBMP source denoted as ‘Hydro44’ for the state of Virginia was obtained from the Center for Geospatial Information Technology (CGIT) at Virginia Tech. Hydro44 streams at 55 EMAP sample locations were identified and clipped from this data set. A suffix of ‘44’ was added to indicate this data throughout in this study. For example, stream name Big Creek derived from this data set is referred to as ‘Big Creek 44’.
4.1.2 NHD

NHD high-resolution data was considered in this study. A suffix of ‘NHD’ was added at the end of stream names to identify the streams of this data. For example, stream name Big Creek derived from this data set is referred to as ‘Big Creek NHD.’

4.2 RASTER DATA PROCESSING

4.2.1 DTM data

Line and point features were extracted from the DTM data sets and converted from .dgn format to shape file format and were projected to NAD-83, UTM Zone 17N coordinate system. These shapefiles were used to create a Triangular Irregular Network (TIN) surface model using the 3D analyst in ArcGIS 9.1. The TIN model was then converted to raster DEMs at three different resolutions including 3m, 10 m, and 30 m. Since the linear unit of the VBMP DTM data is in feet, the elevation units were converted to meters by multiplying the raster grids by 0.3048. An example of the process of converting DTM to TIN and finally to DEM is shown in Figure 4.1.

Figure 4.1 DTM data processing: TIN model was created from point and line features and converted to DEM model
4.2.2 DEM 10m data

The DEM 10m data was converted from Spatial Data Transfer Standard (SDTS) format into raster grid using Arc Toolbox in ArcGIS 9.1. The DEM 10 m was then re-sampled into 30m resolution using the nearest neighbor interpolation method in ArcGIS 9.1. This process created a new grid of 30m resolution.

Data processing: fill sinks, create flow direction and flow network

In order to derive vector stream networks from raster data sets, various watershed analyses such as fill sinks, flow direction and flow accumulation were performed on all the raster data sets including DTM 3m, DTM 10m, DTM 30m, DEM 10m and DEM 30m. This was done using tools in the Hydrology menu in the Spatial Analyst tool of ArcGIS 9.1. The flow accumulation grid is used to create a flow network grid using an appropriate threshold area. A detailed description is given in Appendix A. Finally, the hydrology menu ‘Stream to Feature...’ tool was used to create a vector feature for each flow network grid. This process resulted in creation of streams in various resolutions including 3m, 10m and 30m from VBMP and USGS data sets.

4.3 SUMMARY OF DATA PROCESSING

Vector data: Streams segments at 55 EMAP field sample locations were identified using Hydro44 and NHD sources. Altogether 110 stream segments (i.e., 55 each for Hydro44 and NHD) form the vector data set. A sample stream segment (Lick Creek) is shown in Figure 4.2.

Raster data: Altogether, 65 stream segments (i.e., 13 stream segments in five different resolutions) were created from raster data sets. Figure 4.3 shows the New River segment derived using raster data sources.
Figure 4.2 Stream segments from vector data source

Figure 4.3 Stream segments in various resolutions from raster data source
4.4 METHODS

4.4.1 Assumptions

The following assumptions have been made in defining the methods used in this study:

1. The stream network defined by Hydro44 data represents the best estimate of valley length because the Hydro44 data represents the best digital estimate of the stream geometry since it is developed from high-resolution aerial photographs.

2. For all sinuosity computations, valley lengths derived using Hydro44 data were used as the standard valley lengths.

3. The EMAP sample point, for which sinuosity, valley length, and stream length data are available, is located on the center of the stream.

As discussed in section 1, estimation of sinuosity requires values of valley length and reach length for various streams under consideration. For this purpose, the methods described in the EMAP survey report (Kaufmann et al., 1999) were adopted.

4.4.2 The EMAP Method of Reach Length Estimation

- First, the wetted channel width, denoted by X in Figure 4.4, at the point of interest in the stream is estimated by the field team.
Figure 4.4  EMAP Method of Estimating the total Reach Length: 20X from a sample point for upstream and 20X for downstream along the stream

• From the point of interest (i.e., sample point), a distance along the stream measuring 20X on the upstream side and 20X on the downstream defines the reach length (Figure 4.4). This means the reach length is taken as 40X. The sample locations are denoted at the midpoints. A minimum reach length is set at 150 meters.

EMAP data provided reach lengths for all 55-stream segments. The EMAP method was used to estimate the reach lengths for streams derived from all data sources in GIS.

4.4.3 GIS technique used to measure reach length

The Hydro44 stream segment was chosen as the reference data for establishing values of reach length. A stepwise procedure is used to estimate reach length using EMAP’s method:

a) The EMAP reach length values were increased by 10% to define a reference reach length for each stream using Hydro44 stream data. Since absolute length is not critical (the sinuosity being a ratio) the length was increased slightly to help ensure representative lengths for the raster-generated flow networks at 30m-resolutions.
b) The stream length was divided into two sections from the mid point. For example, for Walker Creek, a target reach length of 352 m is divided into an upstream section measuring 176 m and a downstream section of 176 m length from the sample point of the EMAP field data. The Trace tool feature of the Editor tool bar of ArcGIS 9.1 was used to measure these two sections, each having a length of 176 m. For this purpose, the mid point was snapped to the Hydro44 stream. Then the ‘trim’ feature was used with a length value of 176 m to trim upstream length from the midpoint. The same procedure was repeated for the downstream half of the stream segment. In this manner, the Hydro44 stream segment was trimmed to the required length of 352 m for representing the Walker Creek (Figure 4.5). This procedure was repeated for all 55-stream segments. Figure 4.5 shows use of the GIS features for application of this process for Walker Creek using Hydro44 data.

Figure 4.5 Reach Length measurements in ArcGIS 9.1

c) Fifty-five GIS shape files were generated by exporting the data of the trimmed stream segments. In these shape files, multiple nodes were merged into one in order to have a linear stream segment.
Finally, Hydro44 data was used as a reference reach length for defining the polygon to define the reach length for streams identified in NHD data and streams created in various raster resolutions. Polygons were digitized and used to clip the reach segments of all streams at the fifty-five sample locations. The length of these clipped reach segments were computed in GIS. An example of a reach length polygon is shown in Figure 4.6. Again, in these shape files, multiple nodes were merged into one in order to have a linear stream segment.

![Reach length polygon used to clip the stream segments](image)

**Figure 4.6 Reach length polygon used to clip the stream segments**

### 4.4.4 EMAP’s Definition of Valley Length

The definition of valley length was adopted from the EMAP survey report (Kaufmann et al., 1999). The valley length (Figure 4.7) is defined as a straight-line distance between the two reach ends (A and B).
4.4.5 GIS technique to measure valley length

In GIS, the valley length was digitized for all fifty-five stream segments using Hydro44 data. Again, the Hydro44 stream was considered as the reference stream for defining the valley and a straight line was digitized between the two reach ends of the Hydro44 stream to define the valley length (see Figure 4.7) for each stream. This means that each stream is considered to have same valley length as obtained by Hydro44 data.

4.5 SUMMARY OF ALL DATA PROCESSING AND METHODS USING GIS

Vector data

- Stream segments at 55 EMAP field sample locations were identified in Hydro44 data.
- The reach lengths of Hydro44 data were measured and clipped to appropriate lengths.
- For each Hydro44 clipped stream segments, polygons were digitized. These polygons were then used to clip NHD streams. The length of all clipped NHD stream segments were computed.
- Valley lengths were digitized and computed for 55 Hydro44 data using Hydro44 clipped stream segments as a reference length.
For 110 clipped stream segments (i.e., 55 each using Hydro44 and NHD sources), sinuosity values for each stream segment were derived.

**Raster data**

- Streams at a subset of 13 EMAP field sample locations were identified. The selection of these streams were based on the availability of USGS 10m DEM.
- The identified stream segments were then created in five different resolutions including DTM 3m, DTM 10m, DTM 30m, DEM 10m and DEM 30m from VBMP and USGS sources.
- Hydro44 polygons that were digitized in vector data were used to clip all stream segments.
- Lengths of clipped reach segments were computed and sinuosity values were derived for all these reach segments.

Examples of stream segments derived from vector and raster data sources are shown in Figures 4.8 – 4.11.
Figure 4.8 Stream segments from Vector data source

Figure 4.9 Stream segments from Vector data source

Figure 4.10 Stream segments from Raster data source

Figure 4.11 Stream segments from Raster data source
5. DATA ANALYSIS AND RESULTS

Fifty-five EMAP field sample locations were considered in Virginia. Streams at these locations were identified in Hydro44 and NHD vector data sets. In addition, 13 EMAP sample locations were considered where USGS DEM 10m and VBMP DTM raster data sets were available. In this chapter, data analysis and results are presented under two categories (a) Vector and (b) raster.

5.1 VECTOR DATA ANALYSIS

Reach length, valley length and sinuosity values were computed for all stream segments at 55 EMAP field sample locations using Hydro44 and NHD data sets and results are listed in Table B.1 in Appendix B. These tables also list valley length, reach length and sinuosity values as provided by EMAP field data.

5.1.1 Analysis of Stream Sinuosity

In order to compare the sinuosity values computed using Hydro44 and NHD data sets with EMAP field data, histograms were plotted to observe the frequency distribution and variations in sinuosity values (see Figure 5.1).
As can be observed in Figure 5.1, all three sets of sinuosity values show more or less the similar distribution pattern. Further, Hydro44 sinuosity values show a similar distribution when compared to EMAP data. However, NHD based sinuosity values show slightly less variation compared to EMAP and Hydro44 sinuosity data, which is less than 1.41.

In order to examine the differences in means and variances of sinuosity values, appropriate statistical tests were performed using SAS software.

5.1.2 Statistical Tests for means and variances

A two-sample t-test for means of EMAP and Hydro44 was performed using an alpha (α) value of 1%. The null and alternate hypotheses are described below:

Null hypothesis \( H_0: \mu_{\text{EMAP sinuosity}} = \mu_{\text{Hydro44 sinuosity}} \)

Alternate hypothesis \( H_a: \mu_{\text{EMAP sinuosity}} \neq \mu_{\text{Hydro44 sinuosity}} \)
This test assumes that the variances of two data sets (i.e., $\sigma^2_{\text{EMAP sinuosity}} = \sigma^2_{\text{Hydro44 sinuosity}}$) are equal. The t-test results are shown in Table 5.1.

Table 5.1 Results: t-test for Means of EMAP and Hydro44 sinuosity values using 55 samples

<table>
<thead>
<tr>
<th>Data</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Std. Error</th>
<th>t-Statistics</th>
<th>p- Value</th>
<th>$\alpha$ Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMAP</td>
<td>1.12</td>
<td>0.11</td>
<td>0.015</td>
<td>0.82</td>
<td>0.40</td>
<td>0.01</td>
</tr>
<tr>
<td>Hydro44</td>
<td>1.11</td>
<td>0.11</td>
<td>0.015</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Since the p-value is higher than $\alpha$ (0.01), the null hypothesis cannot be rejected. This means statistically there is not enough evidence to support that the means of sinuosity values computed using Hydro44 and EMAP field data are different.

It may be noted that the two sample t-test assumes that $\sigma^2_{\text{EMAP sinuosity}} = \sigma^2_{\text{Hydro44 sinuosity}}$. In order to verify this assumption, two-sample test for variances (i.e., an F-test) was carried out using an alpha level of 1%. An example of this test is:

Null hypothesis $H_0$: $\sigma^2_{\text{EMAP sinuosity}} = \sigma^2_{\text{Hydro44 sinuosity}}$

Alternate hypothesis $H_a$: $\sigma^2_{\text{EMAP sinuosity}} \neq \sigma^2_{\text{Hydro44 sinuosity}}$

Results are shown in Table 5.2. Again, the p-value is greater than $\alpha$ (0.01). This means there is not enough statistical evidence to reject the null hypothesis that the variances of Hydro44 and EMAP sinuosity values are the same.

Table 5.2 Results: F-test for Variances of EMAP and Hydro44 sinuosity values using 55 Samples

<table>
<thead>
<tr>
<th>Data</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Var.</th>
<th>F-Value</th>
<th>p- Value</th>
<th>$\alpha$ Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMAP</td>
<td>1.12</td>
<td>0.11</td>
<td>0.012</td>
<td>0.94</td>
<td>0.82</td>
<td>0.01</td>
</tr>
<tr>
<td>Hydro44</td>
<td>1.11</td>
<td>0.11</td>
<td>0.013</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Similarly, these statistical tests (i.e., t-test and F-test) are performed for EMAP and NHD- derived sinuosity data. The results are shown in Tables 5.3.
Table 5.3 Results: t-test for Means and F-test for Variances of EMAP and NHD sinuosity values using 55 samples

<table>
<thead>
<tr>
<th>Data</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Std. Error</th>
<th>Var.</th>
<th>t-test</th>
<th>F-test</th>
<th>α Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>t-Statistics</td>
<td>p-Value</td>
<td>F-Value</td>
</tr>
<tr>
<td>EMAP</td>
<td>1.12</td>
<td>0.11</td>
<td>0.015</td>
<td>0.012</td>
<td>1.97</td>
<td>0.051</td>
<td>1.26</td>
</tr>
<tr>
<td>NHD</td>
<td>1.08</td>
<td>0.09</td>
<td>0.013</td>
<td>0.009</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

All statistical tests presented above indicate that there is insufficient statistical evidence to support the hypothesis that means and variances of sinuosity values computed using NHD and Hydro44 data are different from the field data.

In order to examine the predictive power of EMAP field data and linear relationship between EMAP and Hydro44 and NHD data sets, linear regression and correlation analyses were performed.

5.1.3 Regression and Correlation Analyses

Since there is not enough statistical evidence to confirm that means and variances of EMAP data are different from Hydro44 and NHD data, linear regression analysis was performed to examine the predictive power of EMAP data. For this purpose, the sinuosity values were plotted in a scatter (x, y) plots. EMAP data was plotted along the x-axis as an independent variable because it is assumed to have less variation since it is a field data (see Figures 5.2 through 5.4). These figures also show a 45° slope line.
Figure 5.2  Plot of Hydro44 vs. EMAP sinuosity values (n-55), showing least-squares linear regression line

Figure 5.3  Plot of NHD vs. EMAP sinuosity values (n-55), showing least-squares linear regression line
Figures 5.2 and 5.3 indicate that the EMAP data typically underestimates the sinuosity values computed using NHD and Hydro44 sources. The Hydro44 vs. EMAP regression line explains only 27% of variation while for NHD vs. EMAP regression, only 10% of variation is explained by the regression line. This result implies that EMAP data may not be a good predictor of sinuosity values for Hydro44 and NHD data. However, the linear regression coefficient is relatively high (~71%) between NHD and Hydro44 sinuosity values. This is expected because both Hydro44 and NHD data are digital data. Hydro44 data was digitized from aerial photographs and NHD data set was developed from topographic maps and digital line graph (DLG) files. This also implies that both data sets have included similar hydrography details.

In addition, correlation analysis was carried out to observe the linear relationship between various sinuosity data sets (see Table 5.4). It can be seen that all correlation values are observed to be positive implying that the general trends of sinuosity values (i.e., EMAP field data and Hydro44 and NHD computed values) agree with each other. NHD and Hydro44 based sinuosity values showed a high degree of linear correlation.
(~84%) followed by Hydro44 and EMAP (52%) data of sinuosity. NHD based sinuosity values showed least value of correlation with EMAP field data.

Table 5.4 Sinuosity correlation

<table>
<thead>
<tr>
<th>Data</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydro44 vs. EMAP</td>
<td>0.522</td>
</tr>
<tr>
<td>NHD vs. EMAP</td>
<td>0.320</td>
</tr>
<tr>
<td>NHD vs. Hydro44</td>
<td>0.844</td>
</tr>
</tbody>
</table>

5.1.4 Analysis of Stream Sinuosity– By Stream Order

The fifty-five stream samples are categorized by stream orders. The samples include 13 streams of order zero, 17 streams of order 1, 15 streams of order 2 and 10 streams of order 3. Sinuosity values were analyzed using histograms to observe the variability based on stream orders (see Figures 5.5 through 5.8).
As can be observed in Figures 5.5 through 5.8, the spread in the range of the sinuosity values is more or less same except in case of streams of order one, where EMAP data seems to display the highest variations in the sinuosity values when compare to Hydro44 and NHD data.
In order to examine the differences in means and variances of sinuosity values, statistical tests for mean and variances, as discussed in section 5.1.2, were repeated using SAS software for all stream orders.

5.1.5 Statistical Tests for means and variances

First, mean values of various sinuosity values under various stream orders were compared. A two-sample t-test for means of EMAP and Hydro44 was performed using an alpha (α) value of 1%. Statistical tests for comparing the means (t-test) is described below:

Null hypothesis \( H_0: \mu_{\text{EMAP sinuosity-order0}} = \mu_{\text{Hydro44 sinuosity-order0}} \)

Alternate hypothesis \( H_a: \mu_{\text{EMAP sinuosity-order0}} \neq \mu_{\text{Hydro44 sinuosity-order0}} \)

It was assumed that the variances of two data sets (i.e., \( \sigma^2_{\text{EMAP sinuosity-order0}} = \sigma^2_{\text{Hydro44 sinuosity-order0}} \)) were equal. A two-sample t-test for means of EMAP and Hydro44 was carried out using SAS software using an alpha (α) values of 1%. Test results are shown in Table 5.5.

Table 5.5 Results: t-test for Means of EMAP and Hydro44 sinuosity values for streams of order 0 using 13 samples

<table>
<thead>
<tr>
<th>Data</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Std. Error</th>
<th>t- statistics</th>
<th>p- Value</th>
<th>α Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMAP</td>
<td>1.09</td>
<td>0.07</td>
<td>0.02</td>
<td>-0.86</td>
<td>0.39</td>
<td>0.01</td>
</tr>
<tr>
<td>Hydro44</td>
<td>1.12</td>
<td>0.09</td>
<td>0.03</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Since the p-value (39%) is higher than \( \alpha \) (0.01), the null hypothesis cannot be rejected. This means statistically there is not enough evidence to support the hypothesis that the means of sinuosity values computed using Hydro44 and EMAP field data are different.

Again, above test assumes that \( \sigma^2_{\text{EMAP sinuosity-order0}} = \sigma^2_{\text{Hydro44 sinuosity-order0}} \). In order to verify this assumption, two-sample test for variances (i.e., an F-test) was carried out using an alpha level of 1%. An example of this test is below:
Null hypothesis \( H_0: \sigma^2_{EMAP \sinuosity-order0} = \sigma^2_{Hydro44 \sinuosity-order0} \)

Alternate hypothesis \( H_a: \sigma^2_{EMAP \sinuosity-order0} \neq \sigma^2_{Hydro44 \sinuosity-order0} \)

Results are shown in Table 5.6. Again, the p-value is greater than \( \alpha \) (0.01). This means there is not enough statistical evidence to support that the variances of Hydro44 and EMAP sinuosity values are not the same.

Table 5.6 F-test for Variances of EMAP and Hydro44 sinuosity values for streams of order 0 using 13 samples

<table>
<thead>
<tr>
<th>Data</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Var.</th>
<th>F-Value</th>
<th>p-Value</th>
<th>( \alpha ) Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMAP</td>
<td>1.09</td>
<td>0.07</td>
<td>0.005</td>
<td>0.53</td>
<td>0.29</td>
<td>0.01</td>
</tr>
<tr>
<td>Hydro44</td>
<td>1.12</td>
<td>0.09</td>
<td>0.009</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Likewise, similar statistical tests were repeated for remaining sets of data for various stream orders. Tests results are shown in Tables 5.7 through 5.10.

Table 5.7 Results: t-test for Means and F-test for Variances of EMAP and NHD sinuosity values for streams of order 0 using 13 samples

<table>
<thead>
<tr>
<th>Data</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Std. Error</th>
<th>Var.</th>
<th>t-test</th>
<th>F-test</th>
<th>( \alpha ) Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMAP</td>
<td>1.09</td>
<td>0.07</td>
<td>0.01</td>
<td>0.005</td>
<td>-0.31</td>
<td>0.43</td>
<td>0.15</td>
</tr>
<tr>
<td>NHD</td>
<td>1.10</td>
<td>0.11</td>
<td>0.03</td>
<td>0.012</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.8 Results: t-test for Means and F-test for Variances of EMAP and Hydro44 and EMAP and NHD sinuosity values for streams of order 1 using 17 samples

<table>
<thead>
<tr>
<th>Data</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Std. Error</th>
<th>Var.</th>
<th>t-test</th>
<th>F-test</th>
<th>( \alpha ) Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMAP</td>
<td>1.13</td>
<td>0.11</td>
<td>0.02</td>
<td>0.013</td>
<td>2.24</td>
<td>4.15</td>
<td>0.01</td>
</tr>
<tr>
<td>Hydro44</td>
<td>1.06</td>
<td>0.05</td>
<td>0.01</td>
<td>0.003</td>
<td></td>
<td>15.74</td>
<td>0.01</td>
</tr>
<tr>
<td>EMAP</td>
<td>1.13</td>
<td>0.11</td>
<td>0.02</td>
<td>0.013</td>
<td>3.23</td>
<td>15.74</td>
<td>0.01</td>
</tr>
<tr>
<td>NHD</td>
<td>1.04</td>
<td>0.02</td>
<td>0.01</td>
<td>0.001</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 5.9 Results: t-test for Means and F-test for Variances of EMAP and Hydro44 and EMAP and NHD sinuosity values for streams of order 2 using 15 samples

<table>
<thead>
<tr>
<th>Data</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Std. Error</th>
<th>Var.</th>
<th>t-test</th>
<th>F-test</th>
<th>α Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>t-Statistics</td>
<td>p-Value</td>
<td>F-Value</td>
</tr>
<tr>
<td>EMAP</td>
<td>1.11</td>
<td>0.12</td>
<td>0.03</td>
<td>0.015</td>
<td>0.35</td>
<td>0.72</td>
<td>0.79</td>
</tr>
<tr>
<td>Hydro44</td>
<td>1.09</td>
<td>0.13</td>
<td>0.03</td>
<td>0.019</td>
<td>-0.16</td>
<td>0.87</td>
<td>0.73</td>
</tr>
<tr>
<td>EMAP</td>
<td>1.11</td>
<td>0.12</td>
<td>0.03</td>
<td>0.015</td>
<td>0.66</td>
<td>0.50</td>
<td>1.23</td>
</tr>
<tr>
<td>NHD</td>
<td>1.08</td>
<td>0.11</td>
<td>0.02</td>
<td>0.012</td>
<td>0.65</td>
<td>0.51</td>
<td>1.15</td>
</tr>
</tbody>
</table>

Table 5.10 Results: t-test for Means and F-test for Variances of EMAP and Hydro44 and EMAP and NHD sinuosity values for streams of order 3 using 10 samples

<table>
<thead>
<tr>
<th>Data</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Std. Error</th>
<th>Var.</th>
<th>t-test</th>
<th>F-test</th>
<th>α Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>t-Statistics</td>
<td>p-Value</td>
<td>F-Value</td>
</tr>
<tr>
<td>EMAP</td>
<td>1.19</td>
<td>0.10</td>
<td>0.03</td>
<td>0.012</td>
<td>-0.16</td>
<td>0.87</td>
<td>0.73</td>
</tr>
<tr>
<td>Hydro44</td>
<td>1.20</td>
<td>0.12</td>
<td>0.04</td>
<td>0.016</td>
<td>0.65</td>
<td>0.51</td>
<td>1.15</td>
</tr>
<tr>
<td>EMAP</td>
<td>1.19</td>
<td>0.10</td>
<td>0.03</td>
<td>0.012</td>
<td>0.65</td>
<td>0.51</td>
<td>1.15</td>
</tr>
<tr>
<td>NHD</td>
<td>1.16</td>
<td>0.10</td>
<td>0.03</td>
<td>0.010</td>
<td>0.65</td>
<td>0.51</td>
<td>1.15</td>
</tr>
</tbody>
</table>

The results of all statistical tests presented above indicate that there is insufficient statistical evidence to support the fact that means and variances of sinuosity values computed using NHD and Hydro44 data differ from field data except in case of stream order 1 (see Table 5.8). As can be seen in this table, p-values for both means and variances are smaller than alpha values, indicating that statistically there is enough evidence to support that the means and variances of sinuosity values of EMAP and Hydro44, and EMAP and NHD data are not same. This inference is consistent with the histograms shown in Figure 5.6. Further, these observations are only based on small numbers of data points ranging from 10 to 17. Larger sample sizes are expected to improve results.

In order to examine the linear relationship between sinuosity values of Hydro44, NHD and EMAP field data, correlation analysis was performed.
5.1.6 Correlation and Regression Analysis of Sinuosity- By Stream Order

Correlation analysis was performed to observe the linear correlation between Hydro44 and EMAP, NHD and EMAP, and NHD and Hydro44 sinuosity values for various stream orders. Table 5.11 lists the results.

Table 5.11 Sinuosity correlation of various data sets of streams of order 0, 1, 2 and 3

<table>
<thead>
<tr>
<th>Data set</th>
<th>Stream Order</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>(13 samples)</td>
</tr>
<tr>
<td>Hydro44 vs. EMAP</td>
<td>0.062</td>
</tr>
<tr>
<td>NHD vs. EMAP</td>
<td>0.039</td>
</tr>
<tr>
<td>NHD vs. Hydro44</td>
<td>0.940</td>
</tr>
</tbody>
</table>

As can be seen in Table 5.11, positive correlation between EMAP sinuosity data and NHD or Hydro44 sinuosity data was observed for stream orders 0, 2 & 3. For stream order one, low correlation was observed for all the data sets. For order 0, only NHD and Hydro44 data showed high correlation. Overall, improved positive correlation was observed for stream orders of two and three. This infers that the proposed EMAP method of estimating stream sinuosity in the state of Virginia using GIS technique is better suited for stream orders 2 & 3.

Sinuosity values of EMAP, Hydro44 and NHD data were also plotted in scatter plots for various stream orders (see Figures 5.9 through 5.20). These figures also show a regression line and a 45° slope line. The figures indicate that the EMAP sinuosity technique adopted into a GIS environment is better suited for orders 2 and 3 using digital data such as Hydro44 and NHD. Hydro44 and NHD data show consistency in sinuosity estimation for stream order 2 and 3.
Figure 5.9 Plot of Hydro44 vs. EMAP sinuosity values showing least-squares linear regression line for streams of order 0

Figure 5.10 Plot of NHD vs. EMAP sinuosity values showing least-squares linear regression line for streams of order 0
Figure 5.11 Plot of NHD vs. Hydro44 sinuosity values showing least-squares linear regression line for streams of order 0

Figure 5.12 Plot of Hydro44 vs. EMAP sinuosity values showing least-squares linear regression line for streams of order 1
Figure 5.13 Plot of NHD vs. EMAP sinuosity values showing least-squares linear regression line for streams of order 1

Figure 5.14 Plot of NHD vs. Hydro44 sinuosity values showing least-squares linear regression line for streams of order 1
Figure 5.15 Plot of Hydro44 vs. EMAP sinuosity values showing least-squares linear regression line for streams of order 2

Figure 5.16 Plot of NHD vs. EMAP sinuosity values showing least-squares linear regression line for streams of order 2
Figure 5.17 Plot of NHD vs. Hydro44 sinuosity values showing least-squares linear regression line for streams of order 2

Figure 5.18 Plot of Hydro44 vs. EMAP sinuosity values showing least-squares linear regression line for streams of order 3
Figure 5.19 Plot of NHD vs. EMAP sinuosity values showing least-squares linear regression line for streams of order 3

Figure 5.20 Plot of NHD vs. Hydro44 sinuosity values showing least-squares linear regression line for streams of order 3
Sample aerial photographs and DRG maps (Figures 5.21 through 5.24) are also examined in support of inferences made above. Figures 5.21 through 5.23 demonstrated that the digitized streams in orders 0 and 1 seem to follow a different course than the actual streams.

Figure 5.21 Comparison of streams using Hydro44 and NHD with the actual stream (Big Creek) shown in the Aerial photograph (left) and DRG map (right) for streams of order 0.

Figure 5.22 Comparison of streams using Hydro44 and NHD with the actual stream (Holloway Draft) shown in the Aerial photograph (left) and DRG map (right) for streams of order 1.
Figure 5.23 Comparison of streams using Hydro44 and NHD with the actual stream (Hunting Creek) shown in the Aerial photograph (left) and DRG map (right) for streams of order 2

Figure 5.24 Comparison of streams using Hydro44 and NHD with the actual stream (Burks Fork Creek) shown in the Aerial photograph (left) and DRG map (right) for streams of order 3
5.2 RASTER DATA ANALYSES

A total of 13 EMAP field sample locations were used to evaluate stream sinuosity values resulted from five different raster resolutions including DTM 3m, DTM 10m DTM 30m, DEM 10m and DEM 30m. Reach length and valley length values were computed and results are listed in Table C.1 in Appendix C. Sinuosity results are shown in Table 5.12.

Table 5.12 Results - Sinuosity values derived in various resolutions

<table>
<thead>
<tr>
<th>Stream Name</th>
<th>Stream Order</th>
<th>DTM 3m</th>
<th>DTM 10m</th>
<th>DTM 30m</th>
<th>DEM 10m</th>
<th>DEM 30m</th>
<th>EMAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stock Creek</td>
<td>1</td>
<td>1.160</td>
<td>1.099</td>
<td>1.195</td>
<td>1.122</td>
<td>1.007</td>
<td>1.049</td>
</tr>
<tr>
<td>Moore Creek</td>
<td>1</td>
<td>1.161</td>
<td>1.108</td>
<td>1.131</td>
<td>1.075</td>
<td>1.002</td>
<td>1.020</td>
</tr>
<tr>
<td>NNT Cub Run</td>
<td>1</td>
<td>1.050</td>
<td>1.026</td>
<td>1.013</td>
<td>1.094</td>
<td>1.065</td>
<td>1.043</td>
</tr>
<tr>
<td>Big Run</td>
<td>1</td>
<td>1.027</td>
<td>1.014</td>
<td>1.019</td>
<td>1.074</td>
<td>1.015</td>
<td>1.010</td>
</tr>
<tr>
<td>Peters Creek</td>
<td>1</td>
<td>1.051</td>
<td>1.050</td>
<td>1.058</td>
<td>1.036</td>
<td>1.000</td>
<td>1.169</td>
</tr>
<tr>
<td>North Fork Back Creek</td>
<td>2</td>
<td>1.012</td>
<td>1.010</td>
<td>1.027</td>
<td>1.085</td>
<td>1.034</td>
<td>1.014</td>
</tr>
<tr>
<td>Bearpen Branch</td>
<td>2</td>
<td>1.026</td>
<td>1.010</td>
<td>1.002</td>
<td>1.006</td>
<td>1.000</td>
<td>1.060</td>
</tr>
<tr>
<td>Little Snake Creek</td>
<td>2</td>
<td>1.069</td>
<td>1.058</td>
<td>1.010</td>
<td>1.004</td>
<td>1.010</td>
<td>1.076</td>
</tr>
<tr>
<td>Guess Fork</td>
<td>2</td>
<td>1.064</td>
<td>1.062</td>
<td>1.032</td>
<td>1.060</td>
<td>1.048</td>
<td>1.050</td>
</tr>
<tr>
<td>NNT New River</td>
<td>2</td>
<td>1.317</td>
<td>1.305</td>
<td>1.178</td>
<td>1.322</td>
<td>1.330</td>
<td>1.475</td>
</tr>
<tr>
<td>Carvin Creek</td>
<td>2</td>
<td>1.140</td>
<td>1.066</td>
<td>1.116</td>
<td>1.160</td>
<td>1.126</td>
<td>1.271</td>
</tr>
<tr>
<td>Jennings Creek</td>
<td>3</td>
<td>1.287</td>
<td>1.238</td>
<td>1.268</td>
<td>1.315</td>
<td>1.276</td>
<td>1.091</td>
</tr>
<tr>
<td>Hogue Creek</td>
<td>3</td>
<td>1.267</td>
<td>1.266</td>
<td>1.155</td>
<td>1.194</td>
<td>1.097</td>
<td>1.409</td>
</tr>
</tbody>
</table>

5.2.1 Effect of data resolutions on estimation of stream sinuosity using GIS

In order to compare the sinuosity values derived in various resolutions, histograms were plotted to observe the frequency distribution and spread of sinuosity values (see Figure 5.25).
As can be observed, all sinuosity values, derived in DTM and DEM resolutions, show a similar distribution pattern. However, EMAP based sinuosity values show higher variability. The maximum value is more than 1.45.

In order to examine the differences in means and variances of sinuosity values, statistical tests were carried out using SAS software.

5.2.2 Statistical Tests for means and variances

A two-sample t-test for means of EMAP and DTM 3m sinuosity values was performed using an alpha (α) value of 1%. The t-test results are shown in Table 5.13. The null and alternate hypotheses are described below:

Null hypothesis $H_0$: $\mu_{\text{EMAP sinuosity}} = \mu_{\text{DTM 3m sinuosity}}$

Alternate hypothesis $H_a$: $\mu_{\text{EMAP sinuosity}} \neq \mu_{\text{DTM 3m sinuosity}}$
Table 5.13 Results: t-test for Means of EMAP and DTM 3m sinuosity values

<table>
<thead>
<tr>
<th>N</th>
<th>Data</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Std. Error</th>
<th>t-statistics</th>
<th>p-value</th>
<th>α Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>EMAP</td>
<td>1.13</td>
<td>0.15</td>
<td>0.04</td>
<td>0.16</td>
<td>0.87</td>
<td>0.01</td>
</tr>
<tr>
<td>13</td>
<td>DTM 3m</td>
<td>1.12</td>
<td>0.10</td>
<td>0.02</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Since the p-value (0.87) is higher than α (0.01), null hypothesis cannot be rejected. This means statistically there is not enough evidence to support the hypothesis that the means of sinuosity values of EMAP and DTM 3m data are different. This test also assumes that the variances of two data sets are equal. A two-sample test for variances (F-test) was performed to verify this assumption. An example is given below:

Null hypothesis \( H_0: \sigma^2_{\text{EMAP sinuosity}} = \sigma^2_{\text{DTM 3m sinuosity}} \)

Alternate hypothesis \( H_a: \sigma^2_{\text{EMAP sinuosity}} \neq \sigma^2_{\text{DTM 3m sinuosity}} \)

The results are shown in Table 5.14 and p-value is greater than α (0.01). This means statistically there is not enough evidence to support that the variances of EMAP and DTM 3m sinuosity values are not the same.

Table 5.14 Results: F-test for Variances of EMAP and DTM 3m sinuosity values

<table>
<thead>
<tr>
<th>N</th>
<th>Data</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Variance</th>
<th>F Value</th>
<th>p-Value</th>
<th>α Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>EMAP</td>
<td>1.13</td>
<td>0.15</td>
<td>0.01</td>
<td>0.47</td>
<td>0.21</td>
<td>0.01</td>
</tr>
<tr>
<td>13</td>
<td>DTM 3m</td>
<td>1.12</td>
<td>0.10</td>
<td>0.02</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Similar tests were carried out for EMAP and other possible combinations of data resolutions for both means and variances for testing similar statistical hypotheses. Results are given in Table 5.15.
Table 5.15 Results: t-test for Means and F-test for Variances of EMAP and DTM 10m, EMAP and DTM 30m, EMAP and DEM 10m and EMAP and DEM 30m sinuosity values

<table>
<thead>
<tr>
<th>Data</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Std. Error</th>
<th>Var.</th>
<th>t-test</th>
<th>F-test</th>
<th>α Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>t- Statistics</td>
<td>p-Value</td>
<td>F- Value</td>
</tr>
<tr>
<td>EMAP</td>
<td>1.13</td>
<td>0.15</td>
<td>0.04</td>
<td>0.02</td>
<td>0.63</td>
<td>0.52</td>
<td>2.3</td>
</tr>
<tr>
<td>DTM 10m</td>
<td>1.10</td>
<td>0.10</td>
<td>0.02</td>
<td>0.01</td>
<td>0.83</td>
<td>0.41</td>
<td>3.1</td>
</tr>
<tr>
<td>EMAP</td>
<td>1.13</td>
<td>0.15</td>
<td>0.04</td>
<td>0.02</td>
<td>0.28</td>
<td>0.78</td>
<td>2.2</td>
</tr>
<tr>
<td>DTM 30m</td>
<td>1.09</td>
<td>0.08</td>
<td>0.02</td>
<td>0.01</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EMAP</td>
<td>1.13</td>
<td>0.15</td>
<td>0.04</td>
<td>0.02</td>
<td>1.10</td>
<td>0.28</td>
<td>1.9</td>
</tr>
<tr>
<td>DEM 30m</td>
<td>1.07</td>
<td>0.11</td>
<td>0.03</td>
<td>0.01</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The statistical results indicate that there is not enough evidence to reject that means and variances of sinuosity values computed using various resolutions including DTM 3m, DTM 10m DTM 30m, DEM 10m and DEM 30m data are statistically different than sinuosity values of EMAP data. In order to examine the linear relationship between sinuosity values derived in various data resolutions and EMAP field data, correlation analyses were repeated.

5.2.3 Correlation Analysis of Sinuosity derived in various Resolutions

Results of correlation analysis are shown in Table 5.16. In this table, correlation of Hydro44 and NHD data are also listed in order to compare with the correlations that resulted from various resolutions.
Table 5.16 Results: Sinuosity correlation values derived in various resolutions

<table>
<thead>
<tr>
<th>Sinuosity correlation</th>
<th>DTM 3m</th>
<th>DTM 10m</th>
<th>DTM 30m</th>
<th>DEM 10m</th>
<th>DEM 30m</th>
<th>Hydro44</th>
<th>NHD</th>
<th>EMAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>DTM 3m</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DTM 10m</td>
<td>0.971</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DTM 30m</td>
<td>0.897</td>
<td>0.805</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DEM 10m</td>
<td>0.890</td>
<td>0.864</td>
<td>0.830</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DEM 30m</td>
<td>0.797</td>
<td>0.794</td>
<td>0.657</td>
<td>0.939</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydro 44</td>
<td>0.825</td>
<td>0.806</td>
<td>0.616</td>
<td>0.831</td>
<td>0.833</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NHD</td>
<td>0.791</td>
<td>0.756</td>
<td>0.680</td>
<td>0.901</td>
<td>0.861</td>
<td>0.902</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>EMAP</td>
<td>0.698</td>
<td>0.753</td>
<td>0.425</td>
<td>0.627</td>
<td>0.621</td>
<td>0.888</td>
<td>0.729</td>
<td>1</td>
</tr>
</tbody>
</table>

All correlation values are positive. When comparing correlation values with EMAP data, DTM 10m resolution values yielded the highest correlation value of 75%. This was followed by DTM 3m resolutions. Also, DTM 10m resolution gave better correlation with EMAP data as compared to DEM 10m data. It may be also noted that the loss of correlation with EMAP values is significantly high from DTM 10m to DTM 30m resolution. However, in case of DEM data sets, sinuosity correlation values remains more or less the same from DEM 10m to DEM 30m (~62%).

Sinuosity values derived in various resolutions were also used in scatter plots to observe the spread of data. Again, forty-five degree and regression lines were used to examine the data (see Figures 5.26 through 5.30).
Figure 5.26 Plot of DTM 3m vs. EMAP sinuosity values showing least-squares linear regression line

Figure 5.27 Plot of DTM 10m vs. EMAP sinuosity values showing least-squares linear regression line
Figure 5.28 Plot of DTM 30m vs. EMAP sinuosity values showing least-squares linear regression line

Figure 5.29 Plot of DEM 10m vs. EMAP sinuosity values showing least-squares linear regression line
Figure 5.30 Plot of DEM 30m vs. EMAP sinuosity values showing least-squares linear regression line

The $R^2$ value in case of DTM 10m is highest as was shown by correlation values discussed earlier. Some inferences based on above analyses:

1) DTM 10m resolution gave the best estimate of sinuosity values when compared with EMAP data.

2) For a 30 m resolution, DEM derived sinuosity gave better results than DTM data when compared with EMAP field data.
6. FINDINGS AND SUMMARY

Fifty-five stream segments including 13 streams of order 0, 17 streams of order 1, 15 streams of order 2 and 10 streams of order 3 in Virginia were considered in an analysis of stream sinuosity using GIS. Stream data from various sources including VBMP and USGS were used to generate stream networks using GIS. Sinuosity definition technique from EMAP was used for computing sinuosity values for all streams. Field sinuosity data from EMAP were used as a reference data. A specific list of findings is presented below:

Sinuosity Computation Using GIS

1) Developed and Implemented a GIS technique for computing stream sinuosity using EMAP’s method and applied this technique for computing sinuosity for 55 streams in Virginia.

2) Found insufficient statistical evidence that computed sinuosity values using Hydro44 and NHD data are different from EMAP field data for all 55 streams.

3) Sinuosity values computed using Hydro44 and NHD increase with the increase in EMAP sinuosity (positive correlation) for all 55 streams.

4) EMAP data on sinuosity did not predict sinuosity values computed using Hydro44 (R² = 27%) and NHD (R² = 10%) sources well.

Effects of Stream Order on Stream Sinuosity

1) Found insufficient statistical evidence that computed sinuosity values for various stream orders are different from EMAP field data.

2) The EMAP technique of computing sinuosity in GIS using digital data such as Hydro44 (VBMP source) and NHD (USGS source 1:24,000) is better suited for stream orders 2 and 3.
Effects of Data Resolution on Stream Sinuosity

1) Found insufficient statistical evidence that computed sinuosity values for streams derived using various resolutions (i.e., DTM 3m, DTM 10m, DTM 30m, DEM 10m and DEM 30m) are different from EMAP field data.

2) Found positive correlation between sinuosity values for streams derived in all resolutions with EMAP field data. DTM 10m resolution data yielded best correlation value (75%) with EMAP field data.

Above results are based on data samples ranging from 10 to 55 data points and hence have a scope of improvement for a larger sample size. Also, the results presented are for streams in various watersheds within Virginia. This study should be repeated at various geographic locations for generalizing the results.
REFERENCES


Appendix A

Definition of Threshold area in defining the flow network in a raster grid

Threshold area defines the number of cells that are required to create a flow network grid. This process also discards the undesired cells. This way a vector stream networks derived from this flow network grid will avoid having very small segments of stream network. Therefore, this is a repetitive process until a desired flow network grid is created. An explanation of definition of the threshold area using flow accumulation grid used to create required stream networks for all raster resolutions follows:

An example of DTM data

- **Defining the threshold area for DTM 3m resolution grid: 3 X 3**
  
  Area of one cell = 9 m²
  
  Threshold area for defining stream network based on various trials = 7776 m²
  
  Number of cells = \( \frac{7776}{9} = 864 \) cells

- **Defining the threshold for DTM 10m resolution grid: 10 X 10**
  
  Area of one cell = 100 m²
  
  Threshold area for defining stream network based on various trials = 7776 m²
  
  Number of cells = \( \frac{7776}{100} = 77.76 \approx 77 \) cells

- **Defining the threshold for DTM 30m resolution: 30 X 30**
  
  Area of one cell = 900 m²
  
  Threshold area for defining stream network based on various trials = 7776 m²
  
  Number of cells = \( \frac{7776}{900} = 8.64 \approx 8 \) cells
Raster calculator example of creating a flow network grid of 3 X 3 meter resolution:

Raster calculator is used to create a flow network grid in 3m resolution using following command:

\[
\text{Streamgrid} = \text{setnull} ([\text{flowaccu}] < 864, 1) 
\]

where: \text{flowaccu} is the flow accumulation grid.

The outcome from above calculation is a new grid (i.e., Streamgrid). This new grid has all cells with more than 864 cells flowing into them, these are assigned the value 1, and NoData is assigned to all other cells. This process discards undesired cells.
### APPENDIX B

Table B.1 Vector Data Results - Reach Length, Valley Length and Sinuosity

<table>
<thead>
<tr>
<th>Name</th>
<th>Stream Order</th>
<th>Hydro44 Valley Length (m)</th>
<th>EMAP Valley Length (m)</th>
<th>Hydro44 Reach Length (m)</th>
<th>NHD Reach Length (m)</th>
<th>EMAP Reach Length (m)</th>
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Table B.1 Continued. Vector Data Results - Reach Length, Valley Length and Sinuosity

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Table B.1 Continued. Vector Data Results - Reach Length, Valley Length and Sinuosity

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APPENDIX C

Table C.1 Raster Data Results - Reach length and Valley length

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<th>DTM 30m Reach Length (m)</th>
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<th>EMAP Reach Length (m)</th>
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