Abstract

Recent work has suggested that parts of the Appalachian Mountains were uplifted during the Neogene, based on stream knickpoint analysis (Gallen et al., 2013; Miller et al., 2013). Analysis of the symmetry of valleys has the potential to indicate tectonic activity by determining migration trends of channels. Tectonic quiescence promotes lateral migration of stream bends. This creates asymmetrical bend valleys with shallow point bars and steep cut banks. Uplift promotes downcutting over lateral migration, producing symmetrical stream valleys. Using LIDAR data and ArcMap software, I quantified the symmetry of stream valleys in the Blue Ridge Mountains of western North Carolina. I calculated the symmetry of valleys by dividing the right valley slope by the left valley slope to form ratios ranging from 0 to 1, with 1 indicative of a symmetrical valley. Where the right slope exceeded the left slope, I inverted the ratio to avoid numbers greater than 1. I measured slope ratios across the Broad, Cullasaja, French Broad, Linville, New, Pigeon, Toe, and Tuckasegee Rivers. To separate similar symmetry values between areas of gentle and steep topography, I multiplied the symmetry value by the average of the right and left slopes. The resultant values were then combined with a knickpoint propagation model to project areas of equilibrating streams and relict topography. Active landscapes were projected across most of the Blue Ridge Mountains in North Carolina, excluding the French Broad river valley, which was either unaffected by Neogene activity or equilibrated in the distant past. These conclusions agree with hypothesized locations of active landscapes, in addition to projecting new potential locations of rejuvenation.

Introduction

The morphology of rivers, particularly river profiles, exerts control over topography in landscapes undergoing erosion (Kirby and Whipple, 2012). Workers have implemented numerous methods to detect active landscapes undergoing response to uplift, many of which involve analyzing river profiles. Typical channels respond to increased uplift rates by steepening longitudinal profile gradients, which results in the creation and upstream propagation of knickpoints (Whipple and Tucker, 1999). Knickpoint analysis is commonly employed to locate equilibrating streams, and may also be used to estimate changes in relief (Gallen et al., 2013; Miller et al., 2013). Areas containing knickpoints may be located using the normalized steepness calculation $S = k_{sn}A^{-\theta ref}$, which can highlight channel slopes that exceed the expected steepness for their given drainage areas (Wobus et al., 2006).

Knickpoints commonly occur within a range of elevations, with the highest knickpoints representing the upstream-propagating front. Active equilibration occurs downstream of the knickpoint front, and uplifted relict landscape lies upstream of the highest set of knickpoints. A celerity model for knickpoint propagation has been proposed which depends upon erodability (C), drainage area (A), and a discharge proxy (p): dx/dt = CA^P (Crosby and Whipple, 2006). The propagating front also forms the boundary between uplifted relict landscape and areas of active incision (Gallen et al., 2013), the latter of which this study sought to locate.

Unlike the broad valleys of laterally migrating rivers, incised valleys often host steep, symmetrical walls that exhibit downcutting. Such downcutting is a result of ongoing equilibration to uplift, and areas with incised valleys often contain knickpoints throughout their reaches. Downstream of the incised area, already equilibrated valleys gradually begin to meander and broaden. The longitudinal anatomy of an equilibrating stream is illustrated in Figure 1. The study used the calculated symmetry of valleys to digitally locate potential areas of incision. Valley symmetry was then applied to the aforementioned knickpoint propagation model to estimate locations that may be responding to Neogene uplift.

Study Area

The investigation focused on North Carolina's Blue Ridge Mountains, as shown in Figure 2. Eight rivers evenly distributed across the field area were included in the study. Small streams were avoided, and instead I focused upon well-established channels. The French Broad River was chosen for its extent, which reaches from Transylvania County northward into Tennessee. The Cullasaja River had been previously investigated by Gallen et al. (2013) and was selected for its extensive documentation that greatly aided in interpretations. As it had already been hypothesized as an active landscape, I used its valley morphology sequences to project additional locations of potentially active landscapes. The Linville and Broad Rivers were chosen for their location along the Blue Ridge Escarpment. The New, Pigeon, Toe, and Tuckasegee Rivers were selected for their high sinuosity, a potential indicator of relict topography. The New River was not

included in the distribution and scatter plot of corrected symmetry due to its potential

fractures, but was nonetheless a channel of interest.

It should be noted that rivers flowing through the mountains of North Carolina are not

isolated; to the contrary, they are often chosen as prime locations for homes and roads.

The French Broad River flows through heavily populated areas, and the Pigeon River

valley hosts an interstate near the North Carolina – Tennessee border. Another common

occurrence is the construction of dams and lakes, which affect multiple rivers in the area

(namely, the Pigeon and Tuckasegee Rivers). Anthropogenic interference has likely

hindered the accuracy of the project's data to some extent, as have natural features such

as unaccounted for mass-wasting events. Future expansions of the study would ideally

focus on low-population areas with minimal human development and slope failure.

Methods

I obtained 20-foot resolution LIDAR data for the project from the North Carolina

Department of Transportation. The DEM files were obtained individually for each

county and seamlessly mosaicked in ArcMap. I filled the resultant raster to remove any

sinks, and used it to create flow direction and flow accumulation rasters. I used the flow

direction and flow accumulation files in conjunction with ArcMap's cost path tool to

create rasters of stream and river channels, which I then converted to polylines. Using a

transect tool available online (Ferreira 2014), I created perpendicular transects across the

channel polylines at the midpoints of all line segments (Figure 3). The transects extended

100 meters from the channel in both directions, and I removed transects that intersected

the channel multiple times (a frequent occurrence in very low-radius meanders). I

recorded elevations at each transect's vertices and midpoint, and used them to calculate

slopes for each side of the valley using the following equations:

$$m_{RIGHT} = \frac{Z_{RIGHT} - Z_{MIDDLE}}{100} \quad \& \quad m_{LEFT} = \frac{Z_{LEFT} - Z_{MIDDLE}}{100}$$

I determined the symmetry (S) of each transect by dividing the right slope by the left

slope. In instances where the right slope exceeded the left slope and S>1, the ratio was

inverted. The end result was a number between 0 and 1 that still reflected deviation from

absolute symmetry, where S=1.

$$S = \frac{m_{RIGHT}}{m_{LEFT}} = \left(\frac{Z_{RIGHT} - Z_{MIDDLE}}{100}\right)\left(\frac{100}{Z_{LEFT} - Z_{MIDDLE}}\right) = \frac{Z_{RIGHT} - Z_{MIDDLE}}{Z_{LEFT} - Z_{MIDDLE}}$$

The resultant S-value calculated valley symmetry but was unable to distinguish between

symmetrical valleys in broad floodplains and those in narrow, V-shaped valleys (Figure

4). To facilitate the detection of high-symmetry, high-slope areas, I multiplied the

symmetry value by the average of the two slopes. The formula resulted in high values for

areas of potential incision, and low values for broad, flat floodplains. I designated these

values as "corrected symmetry," and used them for all interpretations and figures.

$$S_C = \left(\frac{Z_{RIGHT} - Z_{MIDDLE}}{Z_{LEFT} - Z_{MIDDLE}}\right)\left(\frac{Z_{RIGHT} + Z_{LEFT}}{2} - Z_{MIDDLE}\right)$$

I performed the above calculations in Microsoft Excel for each stream and used the XY

coordinates of the transect midpoints to plot the corrected symmetry values. I then

placed the corrected symmetry values onto a single basemap for analysis (Figure 5).

Results

Corrected symmetry values exhibited wide variations and often changed dramatically along rivers (compare Figures 6 and 7 of the Linville River). Few rivers hosted high corrected symmetry values, as evidenced in Figure 8. The majority of valleys were asymmetrical and contained gentle slopes, which implies that incision is a comparatively rare event in the study area. I plotted corrected symmetry values against elevation and found no linear trend between the two. It should be noted that maximum corrected symmetry values are located at intermediate elevations, somewhere between 460-1040 meters (Figure 9). This could be attributed to the model of equilibrating streams linking equilibrated areas to relict topography, as discussed in Figure 1.

Extended areas of incision were uncommon occurrences, but nevertheless appeared in expected patterns. The Cullasaja River adhered closely to the model of equilibrating streams, as illustrated in Figure 10. At high elevations, relict topography appeared with low-to-medium corrected symmetry values. Such values indicate moderate incision with varying degrees of symmetry, which vary intermediately throughout the stretch of river. At intermediate elevations the river becomes markedly more incised, suggesting that the area is undergoing downcutting and equilibration. The DEM also shows that the surrounding topography becomes considerably more rugged, which could be further illustrated with a map of local relief. Corrected symmetry past the area of incision drops below previous values, which indicates a greater level of lateral migration and equilibrium than before. The downstream pattern of medium S_C → high S_C → low S_C

exhibited by the Cullasaja River was employed to decipher corrected symmetry patterns throughout the field area and indicate areas of active landscape (Figure 5).

Conclusions

The study concludes that most of the Blue Ridge Mountains of North Carolina are responding to the Neogene uplift proposed by Gallen et al. and Miller et al. The sequence of medium S_C → high S_C → low S_C values seen on the Cullasaja was visible throughout the region, leading us to conclude that similar areas of relict topography and equilibrating landscapes are distributed about western North Carolina. The southwestern area of the study hosting the Cullasaja, Pigeon, and Tuckasegee Rivers appears to contain active topography, as evidenced by its streams. The French Broad River valley to the east appears to have not been affected by Neogene activity due to a lack of incision throughout its reaches. It is possible that if the river was indeed influenced by Neogene uplift, it equilibrated long ago and that evidence of uplift has been eradicated. Further east, the Toe River shows evidence of extremely sinuous relict topography flowing into areas of deep incision. Its valley and the surrounding area are likely active landscapes responding to the Neogene activity. The nearby Broad and Linville Rivers also exhibit downcutting, but that is likely a result of stream capture. To the north, the forks of the New River both host meandering valleys (possible relict topography) that grade into incised areas. It is conceivable that the incision is a result of fracturing in the area; however, the basin was still hypothesized to host uplift in keeping with the observed S_C sequence. The prevalence of such sequences throughout the study area indicates that the Neogene event affected a large, yet discontinuous portion of Appalachia. While the

study gave me valuable insight to the fluvial morphology of the Blue Ridge, it also raised

a great number of questions. As interest in this region grows, many more questions will

indubitably rise from this ancient, active landscape.
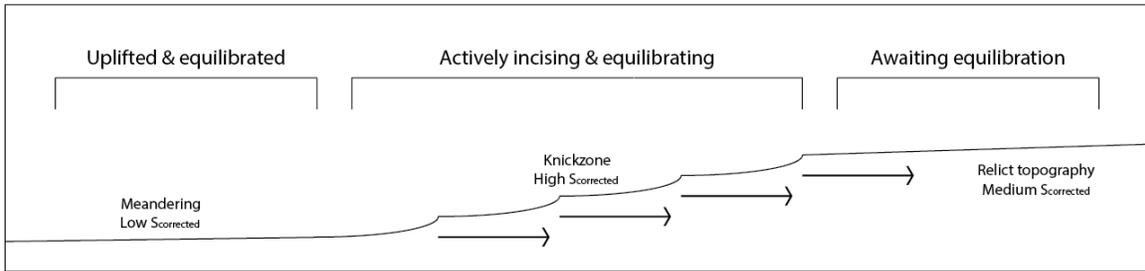
Figure 1. I used the above model to characterize active landscapes. Streams flowing through uplifted areas undergo equilibration, which is often marked by knickpoints and high-energy flow. Such areas also host vertically incising streams, while already-equilibrated stream segments at lower elevations exhibit broad, asymmetrical valleys. Uplifted areas are higher elevations that have not yet been affected by upstream knickpoint propagation host relict topography and low-to-moderate corrected symmetry.
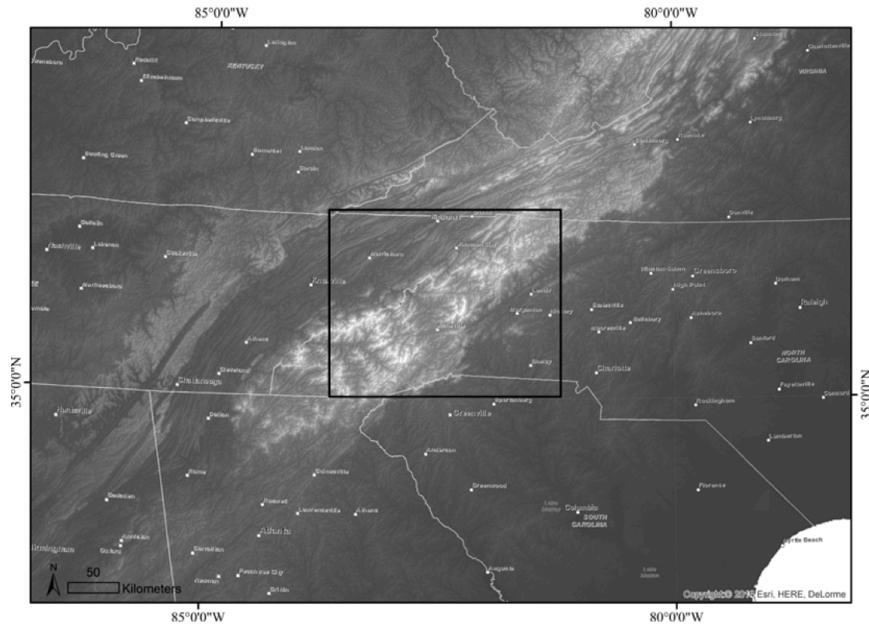
Figure 2. The study covered the western area of North Carolina using 6 meter resolution LIDAR, available online from the North Carolina Department of Transportation. Data were downloaded on a county-by-county basis and seamlessly mosaicked in ArcMap.
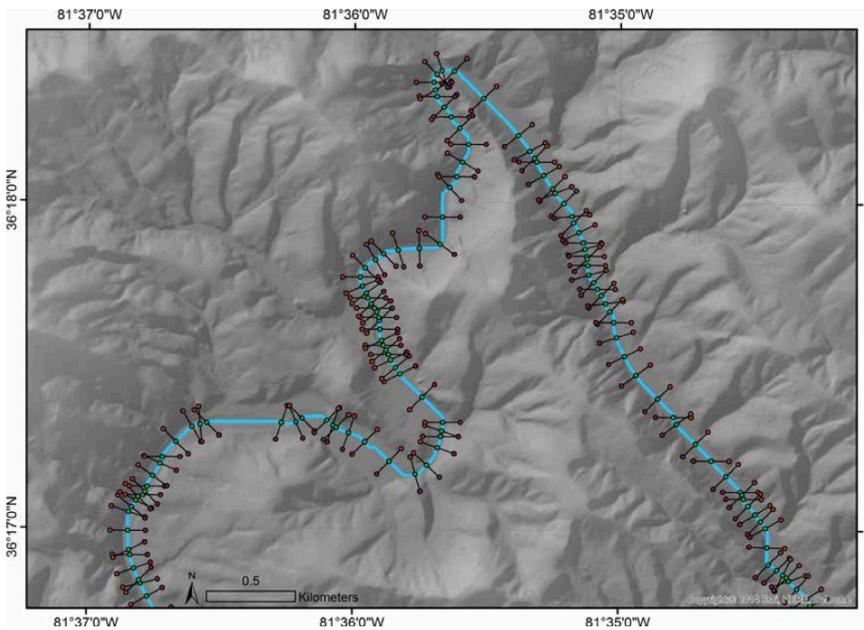
Figure 3. I located channels of interest using a USGS streams and rivers shapefile and created representative polylines using the cost path tool, available in ArcMap. I used a transect tool to create 200-meter long transects, the midpoints and vertices of which were used to quantify the profile of the valley being measured.
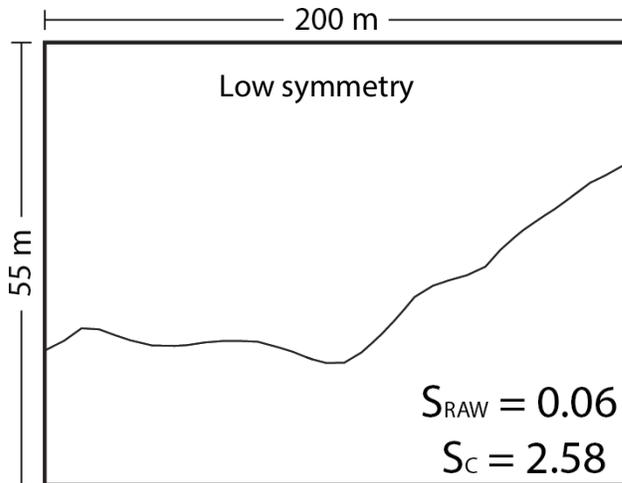
Figure 4a. This cross-section exhibits low raw symmetry and moderate average slope. It appears to be laterally migrating, as evidenced by the steep cut bank and gently sloping point bar. The low raw symmetry and moderate average slope produce a low corrected symmetry value.
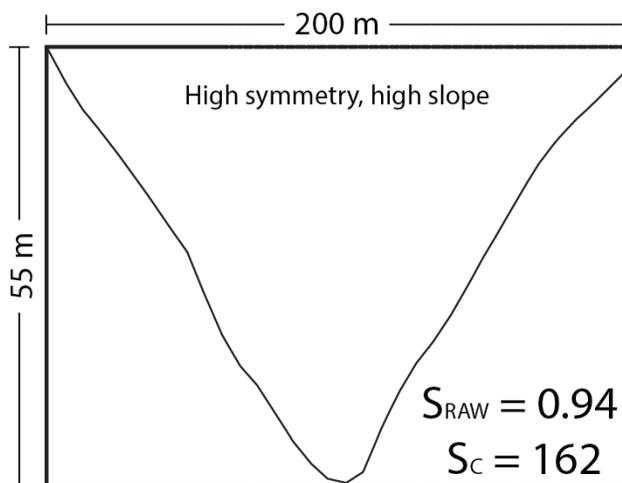
Figure 4b. This cross-section shows very high raw symmetry and high average slope. It appears to be vertically incising, with little to no lateral migration. The high raw symmetry and high average slope produce a high corrected symmetry value.
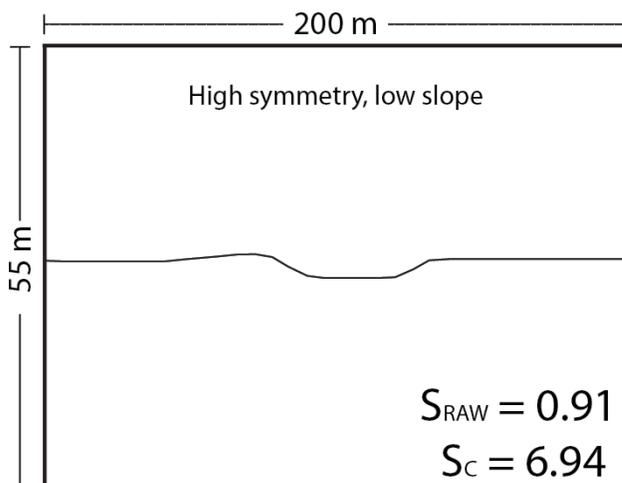
Figure 4c. This cross section exhibits high raw symmetry, which is misleading given the broad flood plain in which the channel flows. The low average slope corrects for the high raw symmetry and results in a low corrected symmetry measurement.
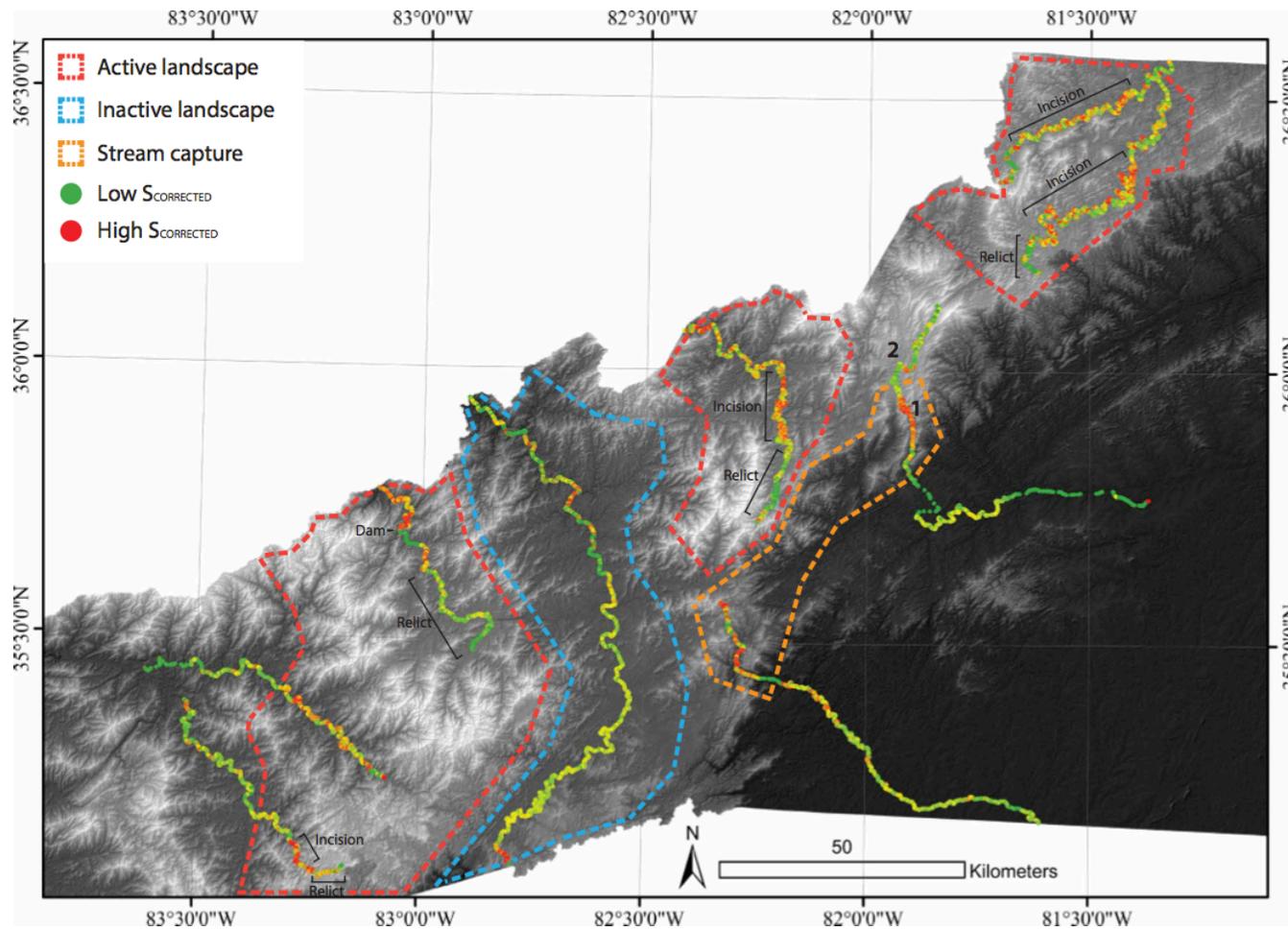
Figure 5. Illustrated above are corrected symmetry values and their interpretations. Inactive landscapes are hypothesized to be in states of equilibrium, as implied by their asymmetrical channel valleys. Active landscapes contain both incising channels and areas of relict topography, which have yet to achieve equilibrium through knickpoint propagation. Areas that experienced stream capture featured incised valleys, but were not included in the above projections of active landscape locations.
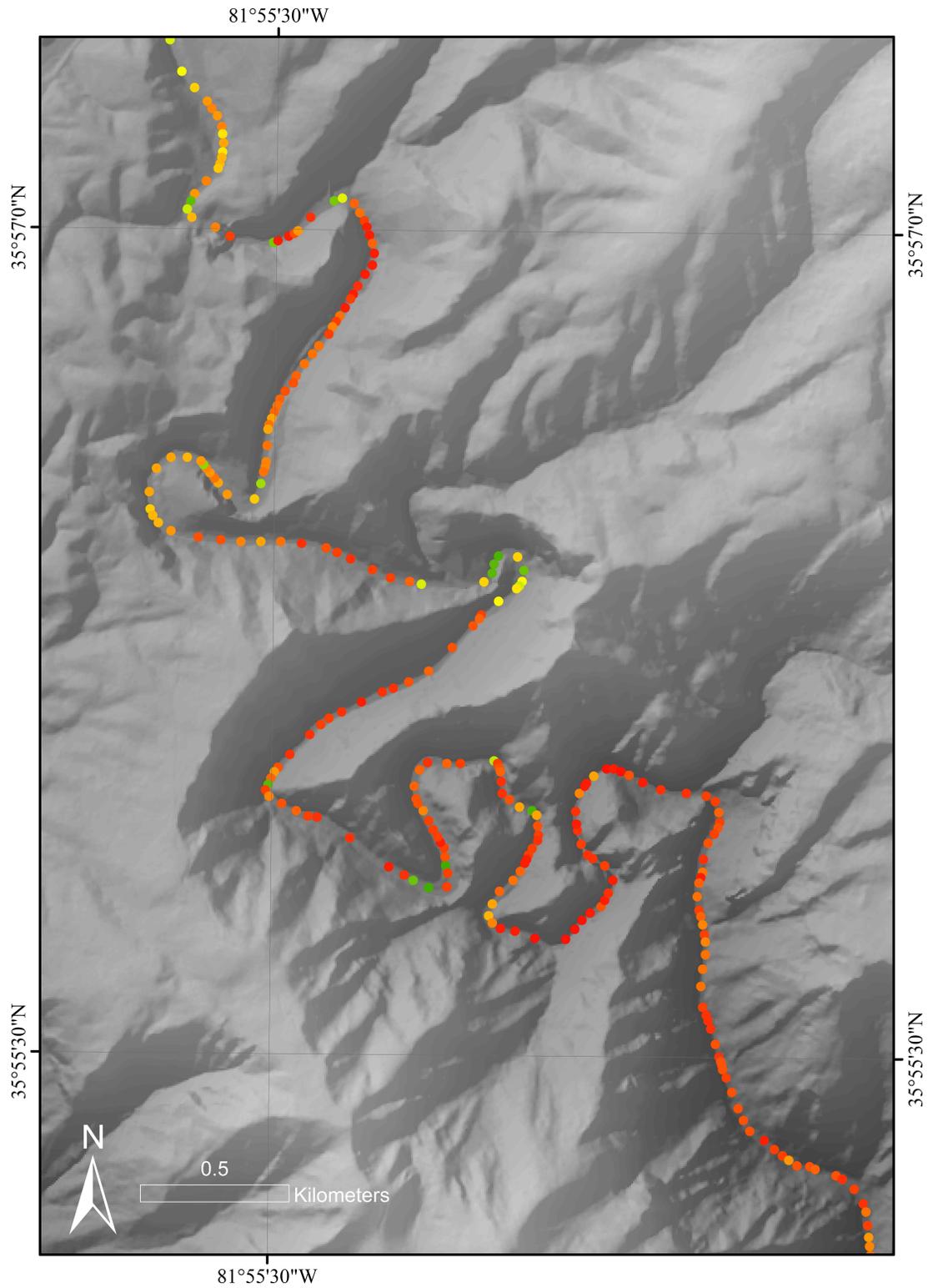
Figure 6. The figure above shows Linville Gorge in Burke County, NC. Valleys in the area exhibit exceptionally high corrected symmetry values, which reflect the minimal lateral migration that has occurred in the area. This deep incision is a result of proposed stream capture.
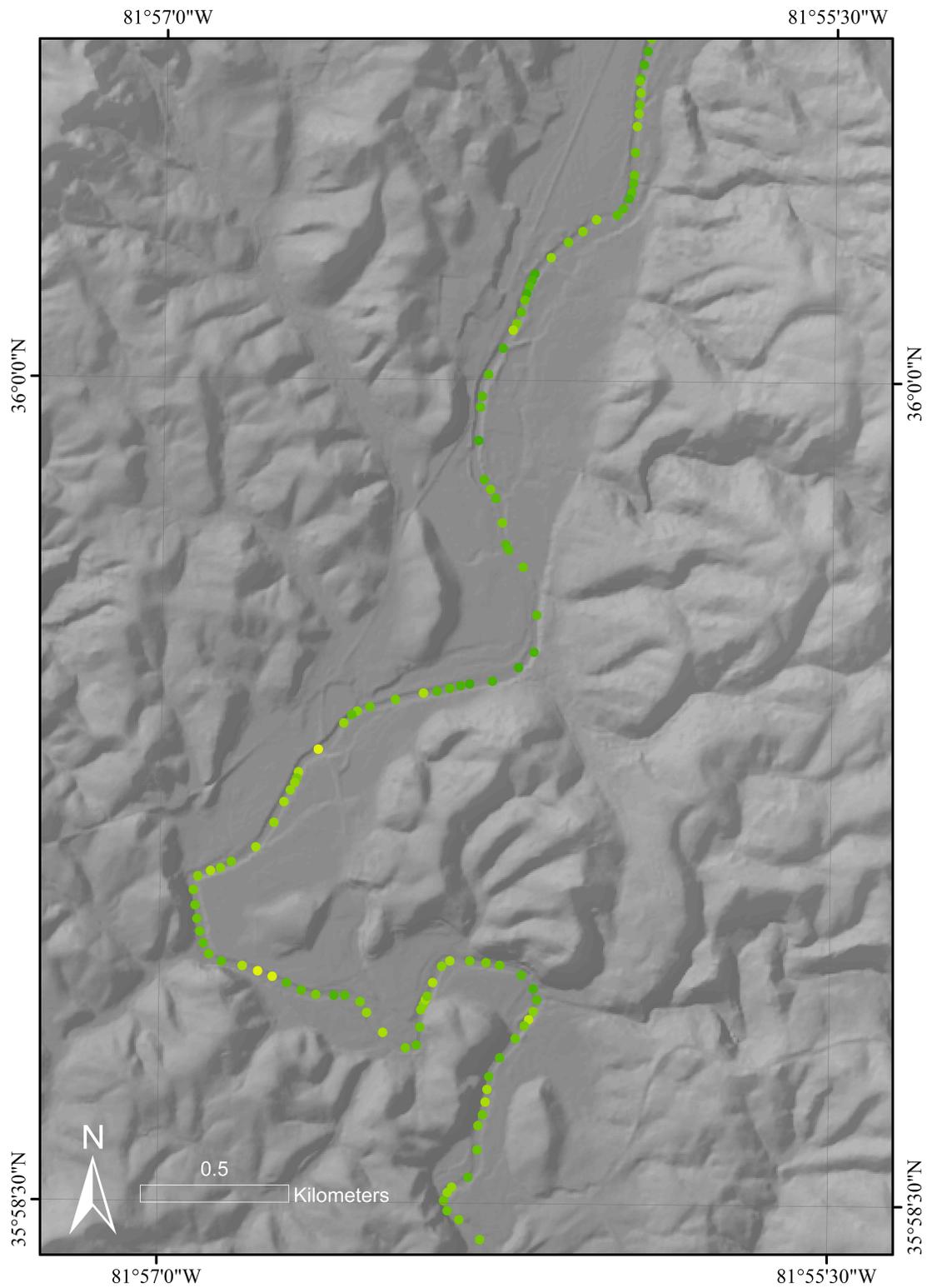
Figure 7. The figure above shows an area upstream of Linville Gorge. The channel flows through a broad floodplain and appears to not be actively incising or awaiting incision, as implied by its consistently low corrected symmetry values. The wide, flat valley is probably a result of lateral migration, high sedimentation, or a combination of the two.
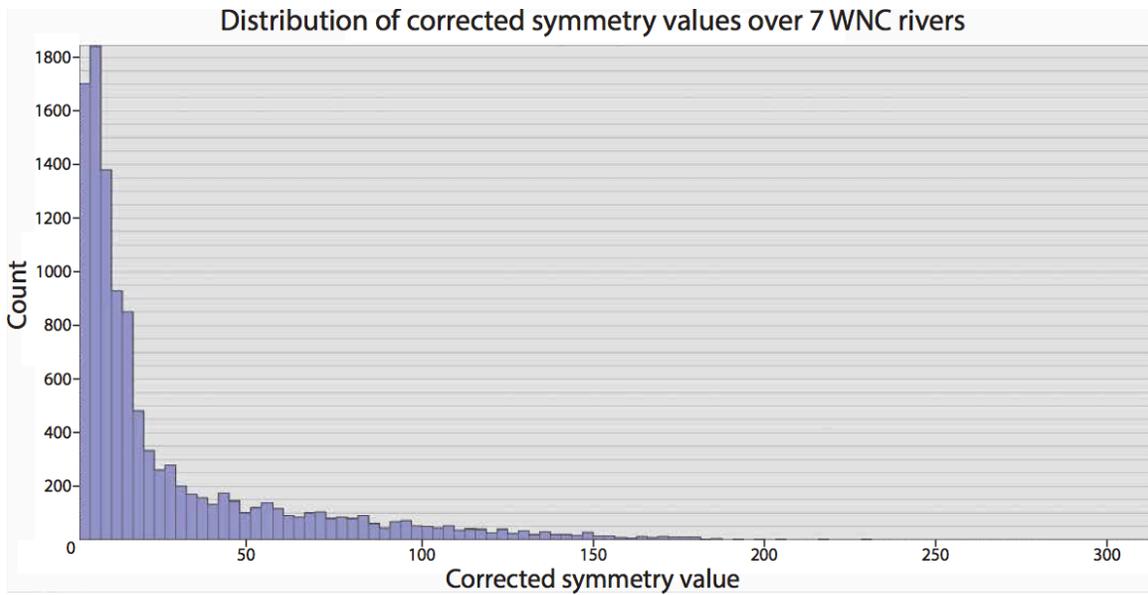
Figure 8. The distribution of corrected symmetry values was heavily skewed, indicating that instances of highly symmetrical and steep-sloping valleys were uncommon. Instead, the majority of streams flow through broad valleys and experience lateral migration.
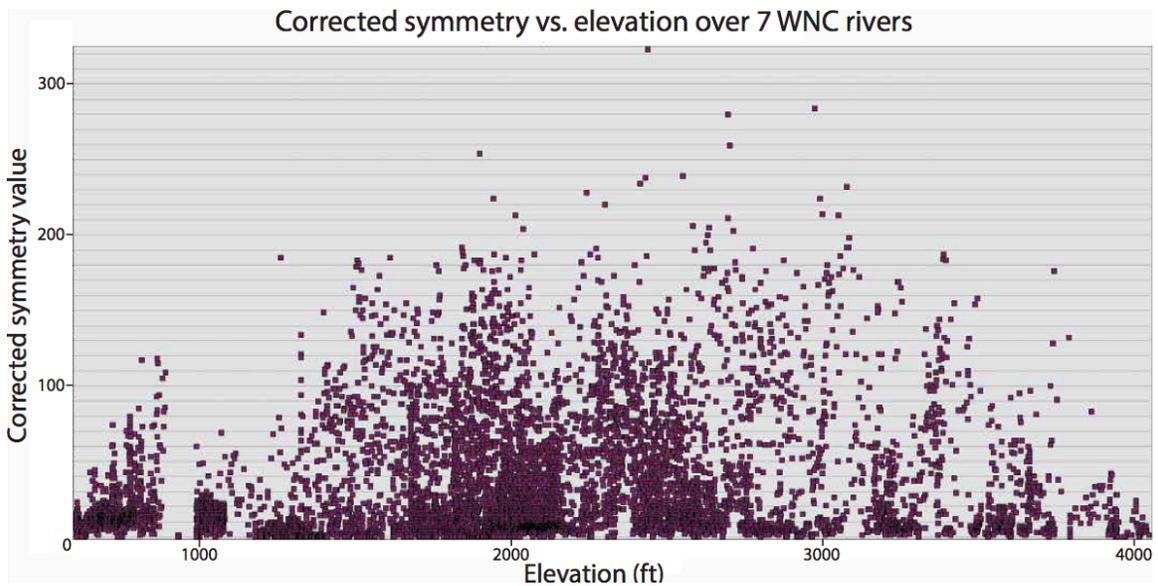
Figure 9. I did not find a linear correlation between altitude and corrected symmetry; however, maximum corrected symmetry values clustered between 1500-3400 feet, indicating that streams which experience minimal lateral migration are located at intermediate elevations.
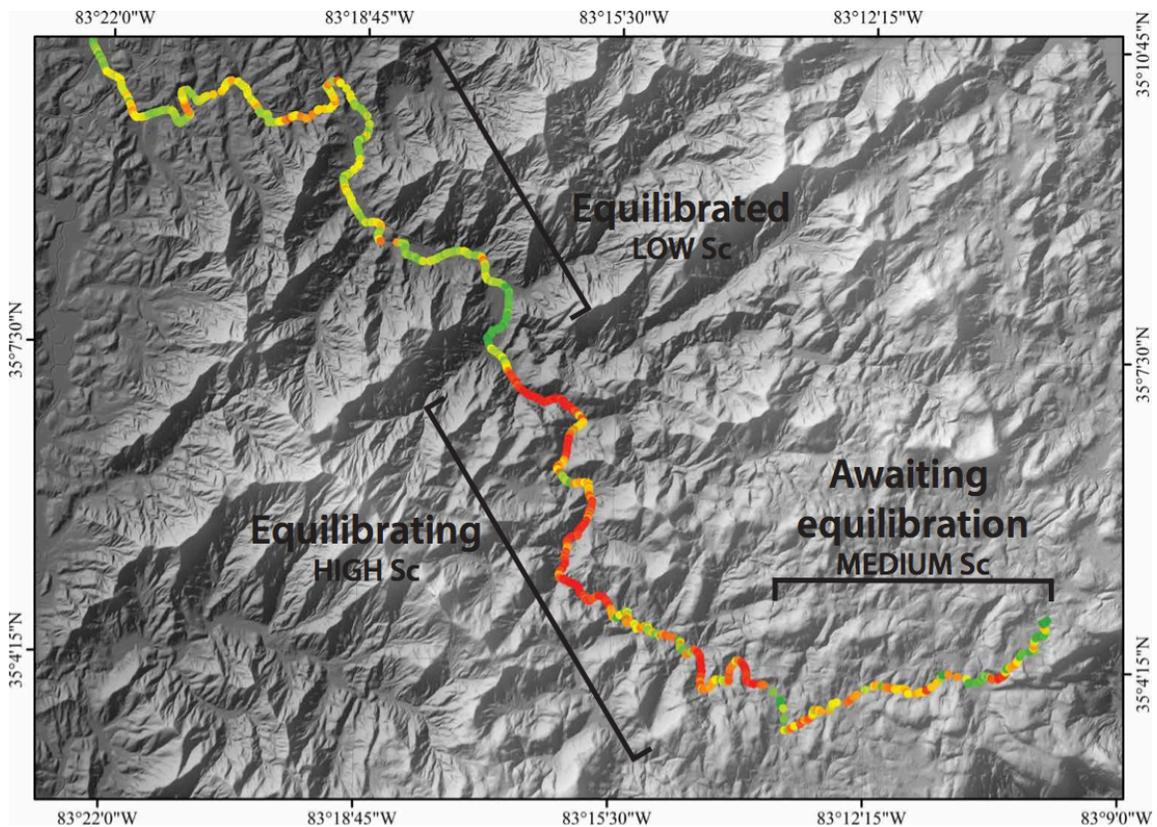
Figure 10. I applied the model described in Figure 8 to the Cullasaja River in Macon County, which had been previously investigated by Gallen et al. in 2013. Uplifted relict topography was marked by moderate corrected symmetry values. Areas undergoing equilibration hosted valleys with high corrected symmetry values. At lower elevations, already-equilibrated streams experienced lateral migration, as indicated by low corrected symmetry values. This sequence of valley forms was used as an analogue for the entire field area. Valleys exhibiting similar patterns were projected as active landscapes.

References Cited

Crosby, B.T., and Whipple, K.X., 2006, Knickpoint initiation and distribution within fluvial networks: 236 waterfalls in the Waipaoa River, North Island, New Zealand: Geomorphology, v. 82, no. 1–2, p. 16–38.

Ferreira, Mateus, 2014. Transect tool for ArcGIS 10.1 available online at http://gis4geomorphology.com/stream-transects-partial/

Gallen, S.F., Wegmann, K.W., Bohnenstiehl, D.R., 2013. Miocene rejuvenation of topographic relief in the southern Appalachians. GSA Today 23, 4–10.

Miller, S., Sak, P., Kirby, E., & Bierman, P. Neogene rejuvenation of central Appalachian topography: Evidence for differential rock uplift from stream profiles and erosion rates. *Earth and Planetary Science Letters*, , 1-12.

Ritter, D. F., Kochel, R. C., & Miller, J. R. (2011). *Process geomorphology* (5th ed.). Long Grove, Ill.: Waveland Press.

Whipple, K.X., Tucker, G.E., 1999. Dynamics of the stream-power river incision model: implications for height limits of mountain ranges, landscape response timescales, and research needs. J. Geophys. Res. 104, 17661–17674.

Wobus, C., Whipple, K.X., Kirby, E., Snyder, N., Johnson, J., Spyropolou, K., Crosby, B., Sheehan, D., 2006a. Tectonics from topography: procedures, promise, and pitfalls. In: Willett, S.D., Hovius, N., Brandon, M.T., Fisher, D.M. (Eds.), Tectonics, Climate, and Landscape Evolution. Geological Society of America Special Paper, vol. 398, pp. 55e74.

Appendix : Creating maps of corrected symmetry

First download the tools and elevation models necessary to calculate the symmetry of stream valleys. I used LIDAR files available from the North Carolina Department of Transportation at https://connect.ncdot.gov/resources/gis/pages/cont-elev_v2.aspx. I also employed a free transect tool available at http://gis4geomorphology.com/stream-transects-partial. This tutorial will assume the user is employing the above transect tool.

Use DEM file to create fill, flow direction, and flow accumulation rasters. These layer files will be used to calculate locations of streams, which will form the basis of the analysis. The fill raster will eliminate sinks and imperfections, which could impede the creation of stream paths. Depending on the quality of the DEM raster being used, multiple fills may be required to adequately smooth the terrain and remove sinks. The flow direction raster determines which directions water will flow, and will be used in calculating the flow accumulation raster. The flow accumulation raster illustrates the drainage area of any given point, which is useful for locating channels.

Now I will create the stream path to be analyzed. First, locate the headwaters of the channel of interest. Once a starting location is pinpointed, create a shapefile by opening the project's folder and clicking File>>New>>Shapefile. Ensure that the shapefile has the same projection as the basemap- if the two are different projections, compatibility issues may arise. Once the shapefile is added, right-click the shapefile and navigate to Editor>>Start editing. Use the tool to add a point where the channel path should start, then save the work and stop editing. Next, navigate to ArcToolbox>>Spatial Analyst

Tools>>Distance>>Cost Path. Use the following parameters as inputs to create a stream

path raster:

-Input raster = shapefile

-Destination field = Id

-Cost distance raster = flow accumulation raster

-Cost backlink raster = flow direction raster

-Path type = EACH_CELL

The process of creating a cost path raster may take several minutes depending on the

channel length, DEM quality, and available processing power. Once the raster is done, it

must be converted to a polyline feature that is compatible with the tool. To create a

polyline, navigate to ArcToolbox>>Conversion Tools>>From Raster>>Raster to Polyline

and use the following parameters:

-Input raster = cost path raster

-Field = do not change

-Background value = ZERO

-Minimum dangle length = 0

-Simplify polylines = yes

Now that a stream path polyline is available, it is time to create transects for analyzing

the valley slopes. To do so, navigate to ArcToolbox>>Transect Tool and select "create

transects at vertices." The approximate intervals method, while promising a more consistent transect distribution, is prone to errors. Next, choose an appropriate length for the transects. I used transects that extended 100 meters from the stream on both sides, but varying topography may call for different transect parameters. Run the tool.

A fraction of the transects will be incomplete, and will not extend across both sides of the channel. To erase the incomplete transects, find those with different lengths than the complete transects and erase them by following the instructions below:

-Right click the transect layer and navigate to the attribute table

-Right-click the field heading for which you want to make a calculation and click Calculate Geometry.

-Click the geometric property you want to calculate. In this case, it is length.

-Confirm the choice and append the calculations.

-Sort the lengths and note which lengths correspond to incomplete transects. Begin editing the layer, and delete the incomplete transects. Save the edits, but do not yet stop editing.

Once the incomplete transects have been eliminated, delete the start and end transects. They can cause problems when separating the sides of the stream. There may also be transects that cross the stream twice. They must be eliminated, or unwanted datapoints will be created later in the process. To eliminate double-crossing transects, simply navigate down the stream's length and delete any transects that cross the path multiple

times. Stop editing and save. Problematic transects are common in particularly low-radius meanders, but may also be found in straight areas thanks to the nature of the transect tool. It is absolutely essential to remove all transects that cross the stream twice, or future work will be for naught.

Now it is time to create the datapoints that will serve as the sample areas for the symmetry values. The datapoints will be assigned elevations and used to calculate symmetry. To plot the points, follow the instructions below. The first step generates the transect endpoints (Z1 and Z3) and the second generates the transect midpoints (Z2).

-Run Data Management Tools>>Features>>Feature Vertices to Points

-Input features = transects

-Point type = BOTH ENDS

-Run Geoprocessing>>Intersect

-Input features = stream polyline, transects

-JoinAttributes = ALL

-Output type = POINT

The transect endpoints must be separated into right-side and left-side sets. To do so, create a buffer that encompasses all transects on the right side. It will be used to select all right-side endpoints as well as their inverse selection, the left-side endpoints.

-Run Analysis Tools>>Proximity>>Buffer

-Input features = polyline

-Distance

-Linear unit = distance greater than transect length

-Side type = right

-End type = flat

-Dissolve type = none

-Run Selection>>Select by Location

-Selection method = select features from

-Target layers = transect vertices

-Source layer = right side buffer

-Spatial selection method = are completely within the source layer feature

-Extract vertices for each side

-Right-click layer containing highlighted transect vertices>>data>>export data

-Output feature class = shapefile

To obtain vertices for the left side, go to the attribute table of all vertices and reverse selection, then repeat the data export process. You should now have sets of right-side and left-side points, the lengths of which must be the same. The lengths of the sets also must equal the length of the midpoint set. If any of the lengths are different, it is

probably due to an incomplete transect or a double-crossing transect. If all lengths coincide, proceed to the next step.

I must convert the midpoint set to a file type that can accept elevation and location data. The step below converts it from a multipart file type into a singlepart file type, similar to the left-side and right-side datasets:

-Turn intersect point file from multipart file type into singlepart file type

-Use data management>>multipart to singlepart

-Input = intersects

I now have three point files which represent the endpoints and midpoints of the transects. I just need to give them elevation data, and they will be ready for analysis. Once that's done, I'll add XY (location) data to the midpoint set and use that information to plot the calculated symmetry. The two following steps append elevation data to all three point files and location data to the midpoint file.

-Run Spatial Analyst>>Extraction>>Extract Values to Points

-Input point features = point file

-Input raster = DEM

-Repeat for all three point files

-Run Data Management>>Features>>Add XY Coordinates

-Input features = midpoint set file

Now I need to associate the individual points with each other. Since points lie on the same transect, I can use the join feature to apply the transect FID to each point. Later, I will use the ID to associate all the points from different files. To append transect IDs:

-Right-click point layer>>Joins and Relates>>Join

-Join data from another layer based on spatial location

-Layer to join = transect polyline layer

-You are joining: lines to points

-Each point will be given all attributes of the line that is closest...

-Save as = rightjoin.shp ,leftjoin.shp , midjoin.shp

At this point, all work in ArcMap is complete. The files must be exported as databases, also known as .dbf or dBASE tables, and analyzed in a spreadsheet program. Repeat the process below for all three point files.

-Attribute table>>Table Options>>Export

-Export = All records

-Output table = y1.dbf , y2.dbf ,y3.dbf

-Save as type = dBASE Table

Open the files in the spreadsheet program of your choice. Microsoft Excel or OpenOffice Calc will both perform the necessary calculations.

-Order y1,y2,y3 sheets by ascending FID_2.

-Copy y1, y2, and y3 RASTERVALUE (elevation) columns into a new working spreadsheet and ensure that they are in adjacent columns.

-Create new column titled "raw" in the working spreadsheet with the equation =ABS((y1-y2)/(y3-y2)). This will render the raw symmetry information. Some still exceed 1, which is easily fixed.

-Create new column titled "fixed" in the working spreadsheet and use the IF() function to ignore values less than 1 and invert values greater than 1. The final product should have no values greater than 1.

-Create a new column in the working spreadsheet that subtracts the middle elevation (y2) from the average surrounding elevation ((y1+y3)/2). Use the formula (y1+y3)/2-y2. This is the "multiplier." Multiply the "fixed" values by this number in a new column to obtain the corrected symmetry.

-Open a final spreadsheet and paste XY data from mid-transect points into the first two columns. Use POINT_X and POINT_Y data, not the start/stop information. In the third

column, paste the "fixed" values. In the fourth column, paste the "multiplier." In the

fifth column, paste the corrected symmetry.

-Save the spreadsheet as a .dbf file.

-Open up ArcMap, then go to File>>Add Data>>Add XY Data

-Set the corrected symmetry column as the Z value, and adjust symbology to reflect

values.