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River Channel bifurcations resulting from partial avulsions are features of fluvial systems that remain poorly understood. The southeastern Piedmont of North Carolina is an area where large bifurcated rivers are uncommon, yet in an area near the foot of the Blue Ridge Escarpment several prominent contemporary examples exist. The initiation of these uncommon bifurcations and the subsequent persistence of split flow in these river reaches (Catawba, Linville, Yadkin Rivers and Wilson Creek) are yet to be fully understood. This study entailed GIS spatiotemporal analysis of planform morphologies, hydraulic geometry and geomorphic analysis of river bank sedimentation and channel narrowing in the losing branch of a prominent Catawba River bifurcation, that are believed to influence the long-term stability of bifurcated channel patterns, and allows for determining pre and post bifurcation states, morphostratigraphic surveys of channel bank deposits, the nature of sedimentation events contributing most to channel adjustments over the last 39 years. It is important to study and understand the evolution of river bifurcations and the processes of avulsion that produce them because of the significant implications of these events pertaining to infrastructure management (roads, bridges and dwellings), flood hazard assessment and zonation, land conservation, as well as riverine ecosystems.

MORPHOLOGICAL RESPONSE TO REDUCED DISCHARGE

ON A LOSING CATAWBA

RIVER BIFURCATE

by

Jennifer L. Reynolds

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Approved by

____Dr. Dan Royall____________
Committee Chair

To my children, each and every one of you has inspired or encouraged me along the way and for this I am forever grateful. Never give up on your dreams.

Give me silence, water, hope. Give me struggle, iron, volcanoes. Pablo Neruda

APPROVAL PAGE

This thesis written by Jennifer L. Reynolds has been approved by the following committee of the Faculty of The Graduate School at The University of North Carolina at Greensboro.

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Thanks to my mother who unconditionally encouraged me and supported me. Even though you are no longer with us, I promised you I would I would finish, so this one's for you.

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CHAPTER I

INTRODUCTION

Through adjustments to their hydraulic geometry and river pattern, channels respond to changes in regional physiography, hydrology and sediment load (Nanson and Knighton, 1996). A wide range of geometries and river patterns are found in nature, with single thread sinuous patterns commonly found in many areas. Even in such areas, local zones of multi-thread patterns may sometimes occur, introducing additional complexity to channel adjustment. A river bifurcation is a node where water in a single channel divides into two downstream branches or bifurcates (Kleinhans et al., 2013). "Bifurcations play a fundamental role in certain river systems, determining the downstream distribution of fluid and momentum, of sediment transfer and hence of channel change" (Miori, Hardy and Lane, 2012, p. 666).

Examples of divided flow around large vegetated islands, similar to anabranching channels, have persisted longer than historical records, suggesting that they exist in a state of quasi-equilibrium, having had sufficient time to have become fully adjusted to their flow regimes (Kleinhans et al., 2013). Under such circumstances, study of bifurcated reaches may not be particularly informative regarding how and at what pace adjustments to changing discharge have occurred. In some instances, however, the dates of bifurcation can be established, and both pre- and post-bifurcation states can be compared to determine the types and rates of change.

In newly (and historically recent) excavated bifurcates, channel width and depth change. In losing bifurcates, the same types of change can be determined. In this case however, channel widths and possibly also depths would tend to decrease due to loss of discharge and the likelihood of channel narrowing via sediment accretion onto banks and local bed aggradation. When bifurcation occurs the older channel loses water flow and may react by creating bank attached sediment flats called fluvial benches that reduce river width. The characteristics of such benches indicate the adjustment history of the river. The details of such changes are significant because the rates and magnitudes of channel narrowing via bank sediment accretion have been suggested as being critical determinants of bifurcation stability (Kleinhans et al., 2011; Sorrells and Royall, 2014).

Considering that increases in climatic variability, including the timing, frequency and magnitude of droughts and flooding, are predictions of global climate models under conditions of global warming, the differential loss and gain of water in river bifurcates might provide analogs for rivers experiencing multi-decadal drought and flood episodes.

This study addresses issues regarding the adjustment of river channels to the sudden onset of bifurcated flow, based on evidence from the upper Catawba River basin in North Carolina. The Catawba River field site is near the community of Greenlee (close to Marion, NC), where bifurcation of river flow occurred in November 1977, as a result of heavy and persistent flooding. This date, well within aerial photographic records (Sorrells and Royall, 2014), allows for mapping pre- and post-bifurcation channel planform morphologies and channel widths over several decades. Data from field-based morphostratigraphic surveys of channel bank accretionary deposits can be used to ascertain the nature of sedimentation events contributing most to channel adjustments in the losing bifurcate over the last 39 years.

The combination of mapping, morphostratigraphic and more limited streamflow gaging data will allow the testing of the major hypothesis of Kleinhans et al. (2011) that rapid channel narrowing in a losing bifurcate increases the longevity of bifurcated flow. To test the ideas of Kleinhans et al. (2011) for the Catawba River, three fundamental questions must be answered: 1) What is the nature, amount and timing of channel change in both bifurcates over the last 39 years, 2) What geomorphic processes have been most important in that change, and 3) What does this change indicate regarding the stability and future development of this and potentially other bifurcations on the upper Catawba and similar rivers elsewhere?

CHAPTER II

LITERATURE REVIEW

2.1 Bifurcations

Kleinhans et al. (2013, p.47) state that bifurcations, which they define as “a node where water in a single channel divides into two downstream branches” or the splitting of single thread channel flow into two threads or channels are considered by geomorphologists and sedimentologists as elements of the fluvial system that are under-studied and poorly understood. Large bifurcated river reaches are not common in Piedmont streams in the Southeast, yet in North Carolina, in one area near the foot of the Blue Ridge Escarpment there are several prominent examples that have remained for nearly 40 years (Sorrells & Royall, 2014). The initiation of these uncommon bifurcations and the subsequent persistence of split flow in river reaches such as the Catawba, Linville, Yadkin and Wilson Creek are yet to be fully understood.

It is difficult to attempt to classify bifurcations as they have many common properties or similar forms but also many different generating processes. Gaining a better understanding of bifurcations require the consideration of how form and process interact at different time and space scales (Kleinhans et al., 2013). The balance between deposition and erosion of fine sediments on the floodplain and in channels can affect the width of channels, bar pattern and flood morphology, all of which affect channel migration and avulsion probability (Kleinhans et al., 2013). Erosion and deposition are very important to the initial development of bifurcations and also play a key role in their evolution and persistence.

Although bifurcations can be initiated in various ways and for various reasons, such as mid-channel deposition (Leopold and Wolman, 1957), enlargement of a crevasse during overbank flooding (Smith et al., 1989; Slingerland and Smith, 1998), and log-jams (Phillips, 2012), the main trigger appears to be a flood or successive flooding. Flooding as a trigger for bifurcation makes sense because it involves high water and high rates of bed material transport. Sorrells & Royall (2014, p.34) reiterated that, "branching is typically initiated during overbank flooding by avulsion of the primary flow into other areas of the floodplain in which excision of a new channel is possible".

Kleinhans et al. (2013) believed aggradation of the main channel to be significant. They also point out four factors that are believed to be relevant once the bifurcation exists; 1. Whether the two flow paths are in sediment transporting equilibrium, 2. Gradient and bed composition of each channel, 3. How the water discharge and bed-material flux are distributed across the channel immediately upstream of the bifurcation, and 4. Whether sediment transport is mainly suspension or bedload? Kleinhans et al. (2013) reviewed the influences of sediment supply and spatial distribution, sorting and grain size on the longevity of bifurcations, and evolution of the bifurcates. They list upstream bend curvature, the migration of upstream sediment bars, channel bed armoring by coarse particles, and bank sediment cohesion as all potentially significant influences on bifurcation stability and morphology.

Kleinhans et al. (2011) found that upstream bifurcations persist longer when their downstream bifurcates are more adjustable in width and noted that the phenomenon of channel width adjustment is poorly understood and depends on rates of bank erosion, bench formation, and levee formation relative to the rate of channel filling. They point to a particular need for better information on the processes and sedimentary styles of channel narrowing.

Bifurcations are of interest to the scientific and engineering community because they are potentially unstable and affect billions of people (world-wide) who live in fluvial and deltaic plains, as well as on the coast (Small and Nicholls, 2003) where larger rivers sometimes exhibit such patterns. It is important to study and understand the evolution of river bifurcations and the processes of avulsion, the rapid wholesale or partial abandonment of channel courses and subsequent relocation of river channels that produce them because of the significant implications of these events pertaining to infrastructure management such as roads, bridges and dwellings, flood hazard assessment and zonation, land conservation, as well as riverine ecosystems.

2.2 Anabranching

Nanson and Knighton (1996, p. 231) defined anabranching rivers as "multiple channels separated by vegetated semi-permanent alluvial islands excised from existing floodplains or formed by within-channel or deltaic accretion that divide flows at discharges up to nearly bankfull". They felt that anabranching rivers are uncommon enough to suggest that they result from an "unusual set of flow and sediment-load conditions" (Nanson and Knighton, 1996, p. 231). Kleinhans et al. (2013) also compares bifurcations to “partial avulsions” that may stabilize, but more often will convert to full avulsions at some future date.

Nanson and Knighton (1996) recognized six main types of anabranching that are arranged roughly in order of increasing specific stream power, sediment load, bed and bank material size, vertical accretion rate, sinuosity, gradient and the ratio of island length to channel width, levees, vertical accretion rate and lateral migration rate. Nanson and Knighton’s (1996) anabranching types are significant to the bifurcation found on the Catawba site and Sorrells and Royall (2014) felt that the great environmental and morphological diversity encompassed by these forms complicates the comparison of branching patterns and processes.

Rivers that are characterized by anabranching over long distances are globally uncommon relative to single thread types. (Knighton, 1998; Burge, 2006; Huang and Nanson, 2007; Charlton, 2008). Anabranching rivers occupy a wide range of climatic, sedimentary and low to high energy environments, yet they are uncommon within the Appalachian Piedmont (Sorrells and Royall, 2014). Walter and Merritts (2008) felt that they were more common to this area in the past, at least for low-order drainages. Map (Google Inc., 2015) and aerial photographic analyses showed that branching channels actually were a minute proportion of total river distance relative to single-thread channels in this province; yet locations were identified where branching for short distances or bifurcated flow has persisted for at least the last several decades (Sorrells & Royall, 2014).

2.3 Benches

Benches represent distinct in-channel features that are often referred to by terms, such as berms, inner berms, shelves, inset floodplains, and incipient floodplains (Royall et al. 2010). Erskine and Livingstone (1999, p.446) defined benches as "depositional landforms which are essentially tabular, often vegetated, elongated, discontinuous, sometimes paired, usually bank-attached sediment bodies which occur at intermediate elevations between the river bed and the main valley flat". This definition was used to distinguish them from the floodplain which was in contrast to Kilpatrick and Barnes (1964) who first identified natural benches on the Piedmont Province of the southeastern United States, and others who regularly applied the term "bench" to features of the floodplain.

Vietz et al. (2004, p.1) for field interpretation purposes define a bench as "a bank-attached, planar and narrow, fine grained sediment deposit occurring at elevations between the river bed and the floodplain. They felt that nomenclature is important as is differentiating benches from other horizontal features such as the floodplain and bars Vietz et al. (2004). Erskine and Livingston (1999) felt that it was important to recognize that benches are not floodplains. Rather they are fragmentary or discontinuous, narrow (rarely approaching channel width) ephemeral landforms that temporarily store sediment and that multiple benches are present at most sites as well as finding that benches and floodplains coexist. Page and Nanson (1982) found that benches also alter the hydraulic characteristics of river channels and play a role in floodplain formation.

Vietz et al. (2004) found that numerous authors have attempted to classify benches according to relative elevation within or above the channel (i.e. 'low', 'medium' and 'high') which was first proposed by (Kilpatrick and Barnes 1964) and later adopted by numerous authors including (Woodyer 1968, Warner et al. 1975, Woodyer et al. 1979, Thoms and Sheldon 1996, Erskine and Livingstone 1999). In order to attempt to differentiate between the four main levels of benches found in their study Erskine and Livingstone (1999) used the stratigraphic terms (massive, cumulic and stratic) "stratic" or well-stratified sediments consisting of thinly bedded silts and sands; sediments composed of thick uniform beds were considered "massive" and sediments consisting of thick, finer grained and relatively organic-rich deposits found mostly on higher benches were termed "cumulic".

The Vietz et al. (2004) classification identifies six types of depositional benches: concave benches, point benches, lateral benches, marginal benches, tributary confluence benches, and lee benches, depending on relative locations within the channel. Point benches are usually the result of fine suspended load material over predominant bedload material and tend to visibly grade from coarse to fine material or a fining upwards sequence (Woodyer et al. 1979). Tributary or confluence benches usually form at a confluence and are the result of increased sediment supply, and mismatched floods (Changxing et al. 1999). Lee benches or feature benches can form in slackwater or dead-water zones due to rocks, vegetation, large woody debris or vegetation (Vietz et al. 2004). Concave benches are generally crescent shape and form as a result of deposition upstream of the meander apex on the concave bank (Nanson and Page, 1983). Marginal benches are the result of back-water effects from either a natural or man-made weir (Changxing et al., 1999). Lateral benches commonly occur in straight reaches and are sediment deposits occurring in flow expansion zones resulting from erosion (Woodyer et al., 1979)

Erskine (1996) felt benches represented a recovery type mode from severe bank erosion by catastrophic floods associated with periods of high flood frequency. Warner relates benches to multi-decadal drought and flood cycles; Royall et al. (2010) relying heavily on Kilpatrick and Barnes (1964) discusses the occurrence of benches on southeastern rivers and the possible environmental links for them. They felt bench formation may be tied to a balance of erosion and deposition at specific flow stages like the mean annual discharge or the canonical 1-to-2 year "bankfull" flood of the eastern U.S. They also felt that there were a number of other potential influences on bench formation and morphology such as "local reach characteristics, and the specifics of watershed land use histories impacting sediment availability, sediment textures, and large woody debris inputs" (Royall et al., 2010, p. 463). Sorrells and Royall (2014) used benches to look at channel narrowing on a losing branch, and attempt to relate bench flood frequencies with changing discharge bifurcation trends.

CHAPTER III

RESEARCH OBJECTIVES

Kleinhans et al. (2011) theory of bifurcation stability, such that rapid narrowing of the losing branch stabilizes a bifurcation, has been derived from world rivers where anabranching patterns are of much greater extent. Do those theories apply to highly localized instances of branching in the southern Piedmont? Sorrells and Royall (2014) work under this premise, and mentioned, but did not further explore, that maybe there are other explanations for Piedmont rivers. For example, maybe there just isn't enough sediment mobilized by moderate floods to plug up a bifurcate entrance in Piedmont streams? Also, the watershed hydrogeomorphology, and valley geomorphology (orientation, gradient, and valley width constraints) of the Yadkin River site are different from other branching rivers in the Piedmont, such as the Catawba River so the same explanations for bifurcation and its persistence may not apply (Sorrells and Royall, 2014).

This research is designed to test whether or not the hypothesis of Kleinhans et al. (2011) is a viable explanation for the maintenance of bifurcated flow on the Catawba River for the past thirty-nine years. This requires data on how much and how fast losing channels have narrowed vis-à-vis fluvial bench construction. (i.e., if it has been very slow, then Kleinhans et al. (2011) are possibly contradicted in some rivers).

There is also a lot that is not known about the bench construction process itself that is relevant to both the bifurcation node stability issue, and the general ability of channels that may be experiencing flow losses (due to avulsion, or by analogy, drought) to adjust to lessened flows in such a way as to maintain surface water flow and aquatic habitat. What type of events are constructing benches; higher frequency, moderate or lower frequency, higher magnitude flooding events? How do these sizes compare to the likely bifurcation event flood size?

CHAPTER IV

STUDY AREA DESCRIPTION

4.1 Catawba River Basin

The Greenlee study site is on the upper Catawba River near Greenlee, NC, upstream of Marion (Fig. 1) in McDowell County. The Catawba River flows approximately 315 km from its headwater streams in the Blue Ridge Belt of the Southern Appalachian Highlands of western North Carolina to the Atlantic Ocean. It flows east-north-east through escarpment topography for approximately 145 km before heading almost due south for 362 km where it ultimately becomes the Wateree River in the state of South Carolina (FEMA, 2006). The basin covers approximately 8,650 km^2 and is the eighth largest river system in the state containing over 4,896 km of streams (NCSU, 2014).

The upper portion of the basin is mostly undeveloped and lacking large urban centers but in the lower portion the land use shifts from forest and agricultural to more urban as it enters the large metropolitan area surrounding Charlotte. Urban and built-up categorization comprises roughly twenty-three percent of the entire basin which is a thirty-five percent increase since 1982 (FEMA, 2006). Despite the urban growth the basin has approximately forty-five percent forestland (both private and federal forests) and sixteen percent of the land area use is considered Agricultural (FEMA, 2006)

The Catawba River travels along the northern edge of the city of Marion, one of two municipalities located within McDowell County before emptying into Lake James. The main stem of the Catawba River contains what is often referred to as the Catawba Chain Lakes or a series of reservoirs that are formed by seven hydroelectric dams. The reservoirs or lakes begin with Lake James which is ~18.4 river km downstream from the Greenlee study site. Although this portion of the basin contains dams, the study site in the upper portion of the basin is not affected by any significant impoundments.

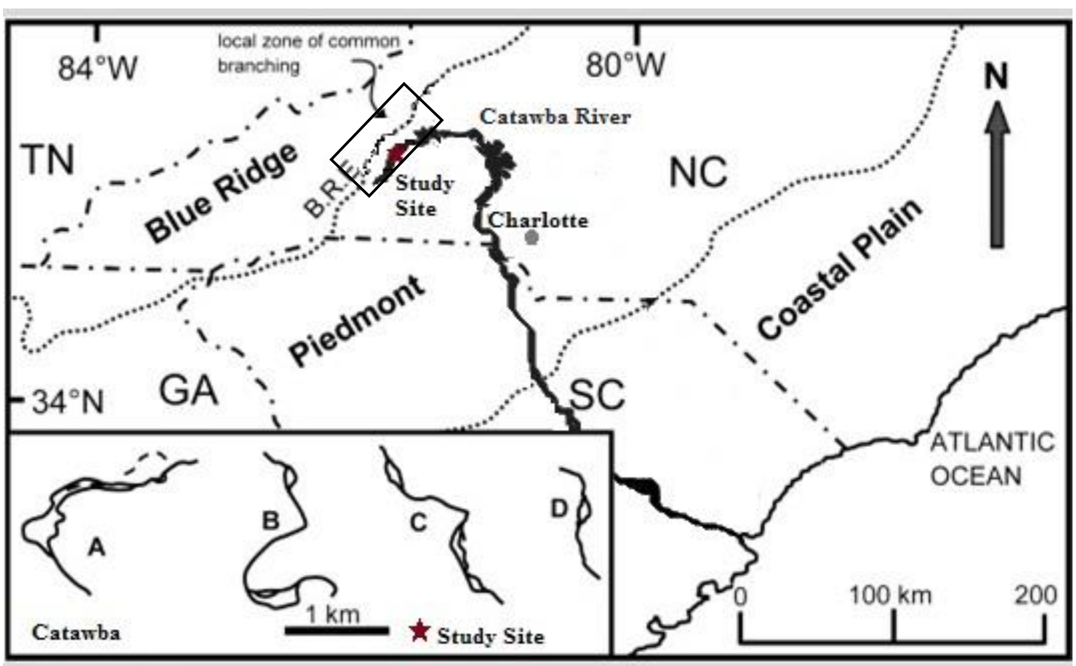

Figure 1. Study Site in Relation to Major Physiographic Provinces of North Carolina. *BRE stands for the Blue Ridge Escarpment, the base of which coincides with the Blue Ridge/Piedmont boundary on the map. The small rectangle incorporating the study site encloses an area within which examples of branching are common. The inset box shows the patterns of some branched rivers: (A) Catawba River, (B) Wilson Creek, (C) Linville River, and (D) Yadkin River. This figure is adapted from Sorrells and Royall (2014) and used with permission from D. Royall.*

The Greenlee study site is on the headwaters of the Catawba River near the base of the Blue Ridge Escarpment (*Fig. 1*) an 800 km southeast facing zone of steeplands that separate the Blue Ridge Mountains from the western lower relief Piedmont physiographic province (Sorrells & Royall, 2014). Here the escarpment coincides with the inactive Brevard Fault Zone, the geologic zone that separates the Blue Ridge geologic belt from the western flank of the migmatitic Inner Piedmont. The dominant rock types of the Inner Piedmont where the Catawba River flows includes quartzofeldspathic gneiss, amphibolite, quartzite and pelitic schist with lesser amounts of amphibole gneiss, calc-silicate, and ultramafic rocks (Bream, 2002).

The area consists of strongly sloping or steep uplands that contains tributaries that flow southeasterly from the slopes of the Blue Ridge Mountains. These steep uplands open into wide, nearly level or gently sloping flood plains. The flat floodplains along the corridor formed by the Catawba River are generally the only or most accessible land for development in McDowell County. This accessibility issue has allowed for some encroachment on the flood plains of residential and industrial development.

The soil system found in this region is categorized a broad basin, river terraces and floodplain system which although prone to flooding can be conducive to bottomland agriculture, which has been common in this area. The NRCS Soil Survey (1995) identified taxonomic classification of the dominant soils as Uf or Udifluvents. This report stated “Udifluvents consist of areas where the natural soil has been altered by excavation or covered by fill material during sand and gravel mining” (NCRS, 1995, p.92). Evidence of historical gravel mining in this immediate area would also render this classification of Udifluvents (Corp. of Engineers, 1971; Stamey, 1989)

Total annual precipitation near Greenlee, NC is roughly 1,422 mm (NRCS, 2015). Tropical storms and contrasting air masses allow for increased cyclonic and frontal activity which can produce significant rainfall in this area. Numerous hurricanes have tracked through the region and some have been associated with widespread flooding.

The area has experienced many flooding events associated with precursor storms or the set-up of antecedent soil moisture having reached field capacity, then a subsequent meteorological event occurring (Henry, 1916; Corp. of Engineers, 1971; Bailey, 1975; Neary & Swift, 1987; Miller, 1989; Stamey, 1989; La Penta, 1992; Gamble, 1997; Phillips, 2002; Witt, 2005). The well documented flooding event of 1916 left the Catawba River Valley devastated. Practically all growing crops were destroyed along with four bridges that were completely washed away; the Greenlee and Garden City bridges were left standing, but damaged (*Fig. 2*).

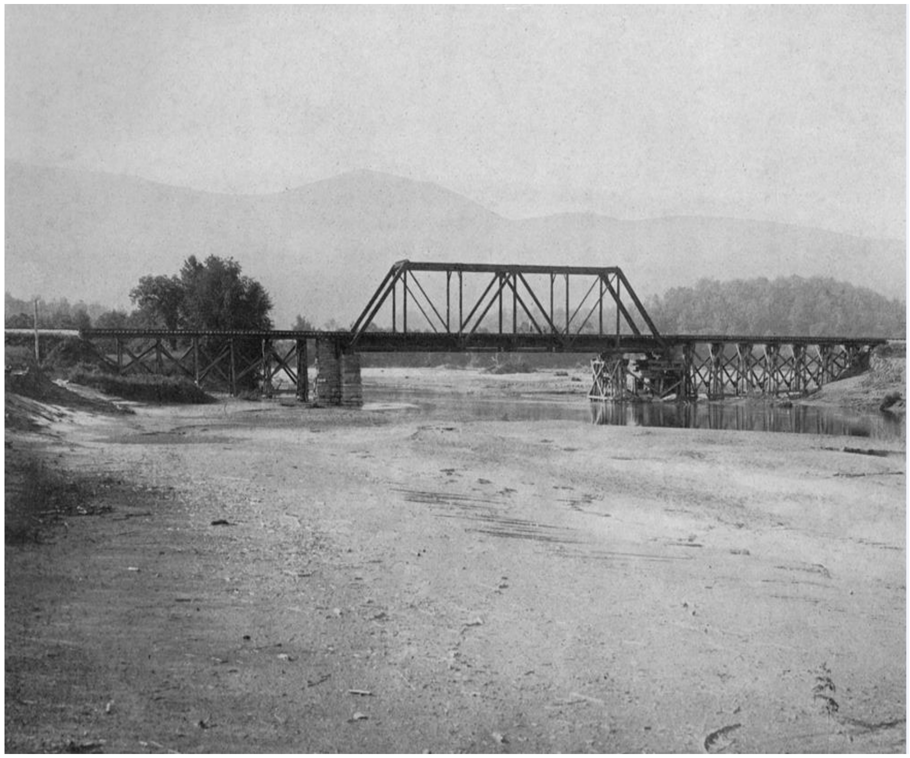

Figure 2. Greenlee Railroad Bridge. *One of two bridges left standing but damaged after the 1916 flood event that left the Catawba River Valley in a state of devastation. D.H. Ramsey Library, Special Collections, University of North Carolina at Asheville. Toto.lib UNCA 1916 Flooding*

This flooding event is said to be far greater and more destructive than any known flood of this area (Corp. of Engineers, 1971). The November, 1977 flood event that initiated the bifurcation was also an event that occurred when the soils were already saturated as September and October precipitation were 177% of normal and the wettest on record for these two months. Intense convection allowed for substantial rainfall and subsequent flooding (Neary & Swift, 1987; Witt, 2004).

Anthropogenic influences such as mining also may have either altered or amplified the effects of these meteorological events and could possibly play a role in the development of the 1977 bifurcation. The Army Corp of Engineers report (1971) detailed the floodplain between Greenlee Road and the Southern Railroad as being used as a borrow area (borrow pit) which describes an area where material has been mined/dredged and used for other purposes. According to the 1971 report this had lowered the ground level and allowed for diverted flow of the Catawba River during high stages that wash out Greenlee Road on the east side of the bridge (Corp of Engineers, 1971).

4.2 Study Site

This site was chosen after contemporary and historical aerial photography analysis led to the identification of a bifurcated reach, which is uncommon in the southeastern Piedmont. Preliminary examination identified during a brief survey, a point bench and two lateral benches, one of which was actually a compound bench with two levels.

The Greenlee study site focuses on the northwesterly losing branch of a prominent Catawba River bifurcation that was created during the November, 1977 flooding event (Neary and Swift, 1987; Witt, 2005). This distinctive river adjustment is the bifurcated flow around the large (0.1 km^2) stable, vegetated island (*Fig. 3 and DEM Fig. 4*). The bifurcation node is located at (35° 39' 45" N, 082° 06' 16" W). The stable island is currently 1.4 km in length. The study site is situated in USGS Hydrologic Unit Code 0305010, the closest gage being USGS 02137727 Catawba River near Pleasant Garden, NC, which has over thirty years of historical data and will be utilized for flood frequency analyses.

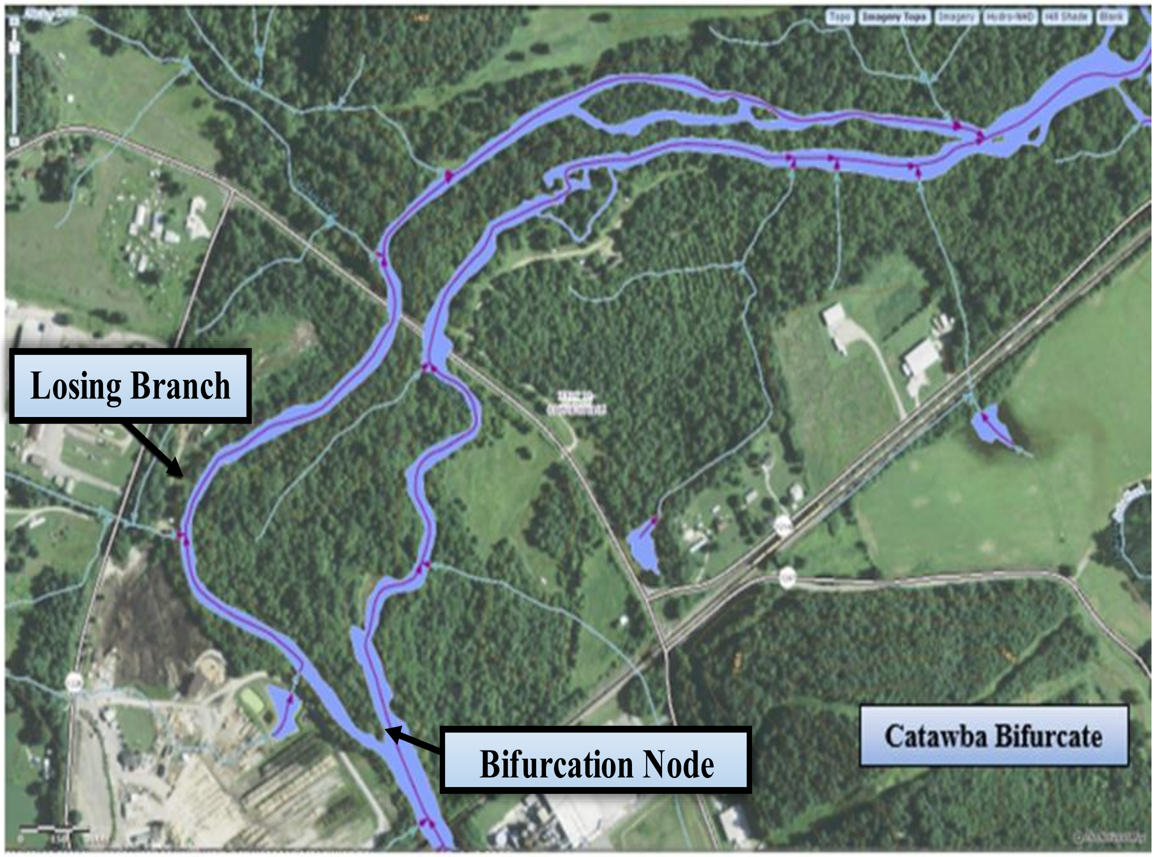

Figure 3. Stable Island –Bifurcation Catawba River. *Losing Branch and flow direction labeled. National Map Viewer* *https://viewer.nationalmap.gov/viewer/*

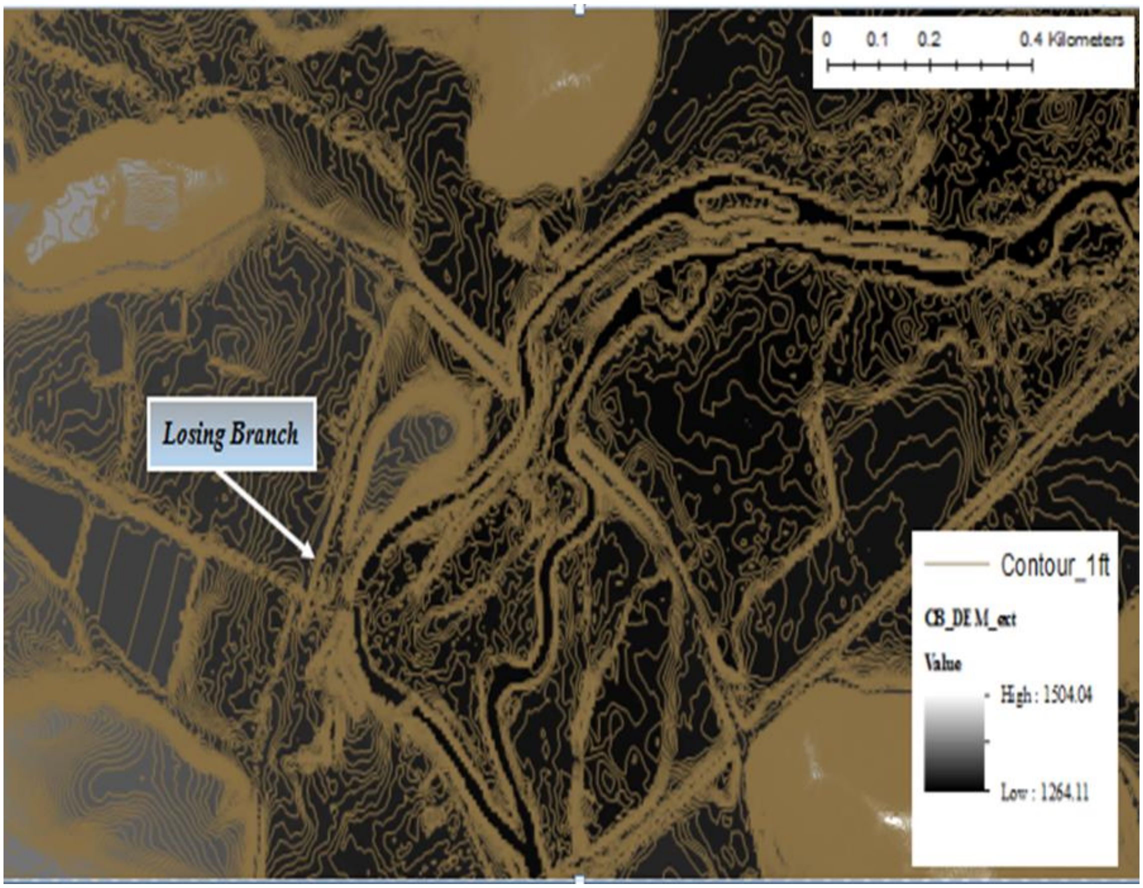

Figure 4. Greenlee Site DEM. *DEM source: North Carolina Floodplain Mapping Program website http://www.ncfloodmaps.com*

CHAPTER V

METHODOLOGY

For the Greenlee site three major research efforts were required: 1. The mapping of pre- and post-1977 channel centerlines and widths on both bifurcates at as high a spatial resolution as remote sensing data will allow, 2. Field mapping, measurement, and stratigraphic description and analysis of all identified benches on the losing bifurcate, and 3. The analysis of pre- and post-bifurcation hydraulic geometry.

5.1 Geospatial/Spatiotemporal Analysis

Historical aerial photographs have been recognized as the ideal platform for examining historical planform change (Gurnell, 1994). Imagery for the period of 1947-2014 allowed for the examination of geomorphic conditions and channel morphology over time. Aerial Images and DEM's were downloaded courtesy of U.S. Geological survey archives using Earth Explorer found at http://earthexplorer.usgs.gov. Spatiotemporal analysis was performed using ENVI (Exelis Visual Information Solutions, 2010) software's various workflows. Further edge-enhancement was necessary for the older images and the use of various filters allowed for a more accurate image analysis. Some of the various ENVI processes that were utilized for enhancement were convolution filters such as high-pass, in order to sharpen the edges, and low-pass, to smooth out the various images. ENVI's Sobel and Laplaccian filters were also used for edge enhancement as well.

Georeferencing the Raster data allowed the images to be viewed, queried and analyzed with other geographical data. ENVI's Image to Image Registration Workflow was used for georeferencing or registering some of the various aerial photographs using three to six tie points minimum that were positioned at fixed features obtained from the 2010 high resolution orthoimagery base image (0.5 ft.) that was also visible in the other images.

Geospatial analysis was performed utilizing various methods in ESRI's ArcMap 10.2.2. (2015). The ArcMap registration workflow was also used for georeferencing. ESRI's Map Image layer which consists of 0.3m resolution imagery was used for ground control/tie point selection. At a minimum, three to five ground control points were chosen from clearly distinguishable, fixed features. Contemporary high resolution orthoimagery (2010, 2014) allowed for more ground control/tie points to be utilized. Greenlee Rd. and the Southern railroad bridge are considered hard points, features with sharp corners or edges with no fuzzy attributes, so they were able to be used as accurate points around the immediate channel. Having hard points surrounding the bifurcation assisted with the warping process in this suboptimal rural setting. These points were scrutinized, especially on the older images to ensure a level of accuracy. Due to the low amount of points that were able to be chosen, a 1st Order Polynomial or Affine transformation was performed.

The georeferenced images were then mosaicked and extracted by mask using the Spatial Analyst tool to utilize only the relevant study areas. Extraction also improved the contrast in the images and DEM. Shapefiles were constructed for each corresponding aerial image in order to digitize centerlines. Digitized centerlines were then created using shapefile polyline features and the polyline editing tool was used to draw out channel centerlines over each corresponding image. Sorrells and Royall (2014) digitized channel centerlines for the branched reach of the nearby Yadkin River using a series of georeferenced aerial photographs, and overlaid them to determine channel motion through time. A similar analysis was completed in the current Catawba River study using GIS overlays of georeferenced aerial photographs from years 1947, 1955, 1964, 1975, 1978, 1986, 1993, 1998, 2010, and 2014 with digitized centerlines.

The GIS overlays of georeferenced aerial photographs with digitized centerlines allowed for visual interpretation and tracking the history of the river channel locations and widths through time. Temporal and spatial aerial photography analysis also assisted with examining vegetation stature which is to be used as supporting evidence to indicate when benches might have formed, and thus when they were possibly colonized by woody vegetation.

Latitude and longitude coordinates of the various bench locations were collected during field surveys using a Delorme Earthmate portable GPS and then used to produce an accurate bench map shapefile in ArcMap. The bench map was then overlaid or projected with the various centerlines to examine spatiotemporal channel shifts and channel migration trends.

5.2 Field Surveys

Field survey required numerous site visits which took place during the spring and summer of 2015-2016. Some of the benches were unable to be easily accessed, so a kayak was used to survey the losing branch. Survey of the Greenlee site included cataloging coordinates of all possible post bifurcation benches of the left branch (losing bifurcate) utilizing a Delorme Earthmate PN hand-held GPS. Post bifurcation benches were taken as those at elevations lower than eighty percent of the height of the low channel bank described in 1971 by the McDowell County flood survey (Corp. of Engineers, 1971) averaging about 2.1 m above bed.

All identified examples of post-bifurcation in-channel benches in the losing bifurcate were mapped and measured in the field and later using GIS technology. Meter tape and level were used to survey and describe the bench morphological attributes - length, width and elevation (height above channel bed) of benches. These measurements allowed for important various calculations in regards to the amount of channel narrowing they contribute over channel distance, as well as volumes of sediment, and the stage of water needed to cover (and thus create) them.

A 0.5-1-meter soil pit was excavated on each bench surface and sediment stratigraphy was described (texture, color, organic matter if obvious) and photographed with a scale in order to further describe and document stratigraphy and descriptions of textural layering in the lab (Erskine and Livingstone, 1999; Erskine et al., 2012). Observation and documentation of vegetation type and stature on fluvial benches was also conducted. Descriptions of obvious former bank positions by tree-lines was documented, this aided in determining approximate stability and age of benches.

5.3 Hydrologic and Flood Frequency Analysis

Discharge in both branches was measured to determine the flow division ratio between them. The flow division ratio is one method by which to estimate discharge in the two branches, based on the gage data. Meter tape and digital water velocity meter were used to measure differences in discharge in the two bifurcates. The two bifurcate discharges were added to get the total discharge at the site; then subtracting the total from the current gage (USGS 02137727 Catawba River near Pleasant Garden) reading gave the percent contribution of flow from any downstream tributaries.

USGS PeakFQ version 7.1 was used to assemble flood frequency curves and recurrence intervals necessary for analysis. This software was provided courtesy of the U.S. Geological Survey http://water.usgs.gov/software/PeakFQ/. PeakFQ was chosen as it implements both the Bulletin 17B and Expected Moments Algorithm (EMA) procedures for flood-frequency analysis of streamflow records. The output also includes estimates of the parameters of the Log-Pearson Type III frequency distribution, including the logarithmic mean, standard deviation, skew, and mean square error of the skew. The output graph includes the fitted frequency curve, systematic peaks, low outliers, censored peaks, interval peaks, historic peaks, thresholds, and confidence limits.

Extensive data encompassing seventy years, dating back to 1940 (pre-bifurcation) was available from a decommissioned gage (USGS 02138000 Catawba River near Marion, NC). Flood frequency analysis was carried out for this gage utilizing peak flows. The decommissioned gage data was useful for determining the bankfull discharge for the pre-bifurcation period. While the newer data derived from the gage (USGS

02137727) Catawba River near Pleasant Garden was more appropriate for determining the discharges over the period of bench formation (post-1977).

There are several different approaches possible for analyzing the flood records and bench processes. The most direct method for estimating the recurrence intervals for bench inundation at the Greenlee site was to make field observations during flood stages, and document the time that a bench went under water during a flood, then subsequently verify what the particular discharge was at Pleasant Garden at time of inundation. Then the recurrence interval was obtained from the gage flood frequency analysis curve.

Frequency magnitude curves from the gage, plus field knowledge of flow amounts, and bench-full flood stages were then used to estimate the frequency of bench-topping flows. It can then be assumed that if most benches are just inundated by the same recurrence interval of a flood that is considered bankfull at the gage, the channel has equilibrated to the new flow.

The logistics and timing of high flow events limited the amount of observations that were possible at the field site. Most of the channel is only easily accessible by kayak, as there is deep water portions and thick vegetation that prevents access to many of the banks and benches. Flooding events would only allow access to Bench 10 and possible observations of others in the immediate area, but it would have been too dangerous to navigate the channel by boat or foot during any significant stages.

Strandline observation of Bench 10 following a flooding event on 3 October, 2015 was used for analysis. The problem with this data was that it was only available for the bench nearest the Greenlee Rd. bridge and it is necessary to have observations for a large number of benches to be able to make judgment about the whole channel.

5.4 Hydraulic Geometry Analysis

Without the needed bench inundation field observations, it was necessary to perform hydraulic analysis. Assuming if actual measured channel widths are close to predicted values, then a new equilibrium will have been achieved. The standard hydraulic geometry equations are:

$$W = aQ^x$$

$$D = bQ^y$$

Where W is bankfull channel width, D is bankfull channel depth, a and b are empirical coefficients accounting for the influence of multiple environmental variables such as sediment grain size and bank vegetation, Q is bankfull water discharge, and x and y are empirically derived exponents describing the rates of growth of width and depth as functions of Q.

In order to perform hydraulic analysis, three steps were carried out:

1. The hydraulic geometry equation's coefficients were calculated based on the prebifurcation channel size information, and the estimates gained through field observations described above (*Hydrologic and Flood Frequency Analysis*) for determining what bankfull discharge should have been at the Greenlee site for the

pre-1977 period. This calculation requires the establishment of exponent values, thus,

2. It was assumed that the exponents of the hydraulic geometry equations were the same as those calculated from Harman (2000) regional curves for the rural Blue Ridge of North Carolina, requiring the translation of drainage area (from regional curves) to bankfull discharge. I chose the Blue Ridge instead of the Piedmont curves because Weaver et al (year) classify the upper Catawba as having Blue Ridge style hydrologic regime. The exponents are: x = 0.48, and y = 0.4. These exponents are similar to the Piedmont values of x = 0.51 and y = 0.41, and both sets come very close to the averages given for a large number of humid climate rivers (Knighton, 1998).
3. With the two hydraulic geometry equations established for channel width and depth, bench height above bed can be substituted for depth in the depth equation, which is solved for the corresponding discharge. This discharge is placed into the width equation to calculate what the bankfull channel width should be. Actual (measured) channel width is subtracted from the predicted width, with large negative differences indicating lack of post-bifurcation bank accretion and width adjustment.

CHAPTER VI

RESULTS

6.1 Geospatial/Spatiotemporal Analysis

Georeferenced aerial images of the Greenlee site proved to be an invaluable resource which allowed for spatiotemporal interpretation of change such as channel migration, land use or modifications to the floodplain for the period of 1947 through 2014. Overlaying the digitized centerlines allowed for inspection of channel shifts or trends. By superimposing the digitized centerlines for the period of 1947 through 2014 a shift became evident. A slight lateral shift is shown in the pre-bifurcation main channel centerlines (pre-1977). The lateral shift can be detected immediately upstream of the incipient avulsion zone. The channel shows a lateral migration towards the far right bank in 1955, then the 1964 and 1975 centerlines appear to make a leftward lateral migration away from the eventual node area (*Fig. 5*). The 1955 lateral far right shift may be exaggerated by registration error or a centerline digitizing error, due to poor image resolution. With the earlier images, other than 1947, the resolution was less than ideal and made ground control points and warping less accurate.

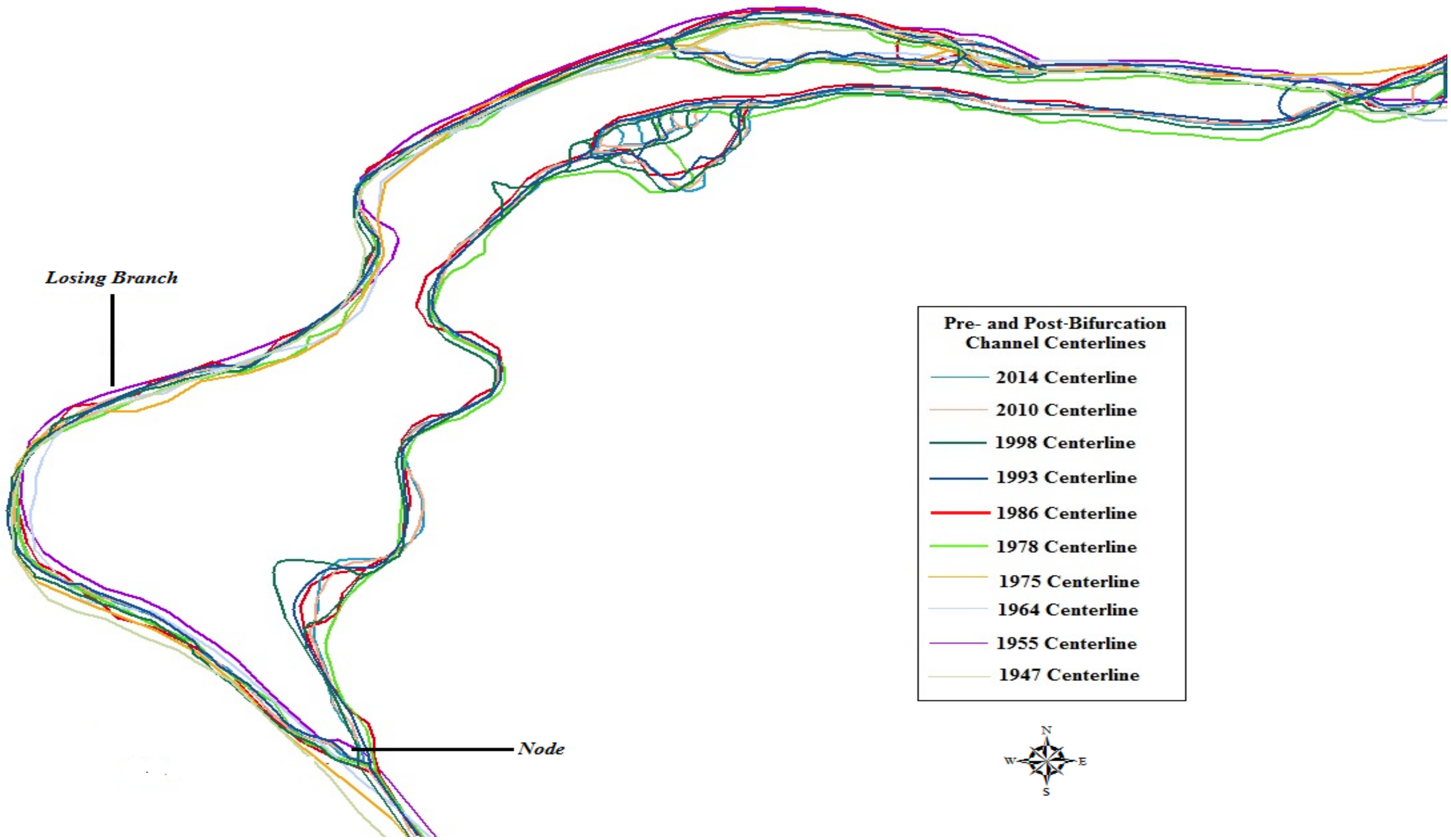

Figure 5. Digitized Centerlines 1947 Through 2014. *Channel migration is detected in the main channel pre-bifurcation (pre-1977), immediately upstream of the incipient avulsion zone. Scale 1:5000.*

The channel centerlines in the new (post-bifurcation) exhibited areas that generally followed a course through the anthropogenically altered areas on the floodplain caused by historic mining. The Army Corp. of Engineers (1971) Flood Plain Information Report for McDowell County identified the floodplain between Greenlee Rd and the Southern Railroad as being used as a borrow area. Examination of early aerial photography also showed that the dredged or lowered areas on the right bank of the main channel (due to mining), near the eventual bifurcation node, is the area where the incipient avulsion occurred. Given the spatial coincidence, it is probable that the river once avulsed, generally followed the course of the lowered or dredged areas, just like a channel will follow a relict swale or abandoned channel *(Fig. 6 & Fig. 7)*.

The downstream portions of both branches have experienced rapid lateral channel migration with evident decadal shifts in some areas. The new branch appears to have experienced more prominent channel shifting over the years *(Fig. 8)*. Contemporary channel positions have remained relatively stable. Overlaying the centerlines for 2010 and 2014 demonstrated little to no shifting other than slight migration in the downstream portion of both branches. This could just be due to the fact that the period of examination is too short to make any valid assumptions in regards to stability.

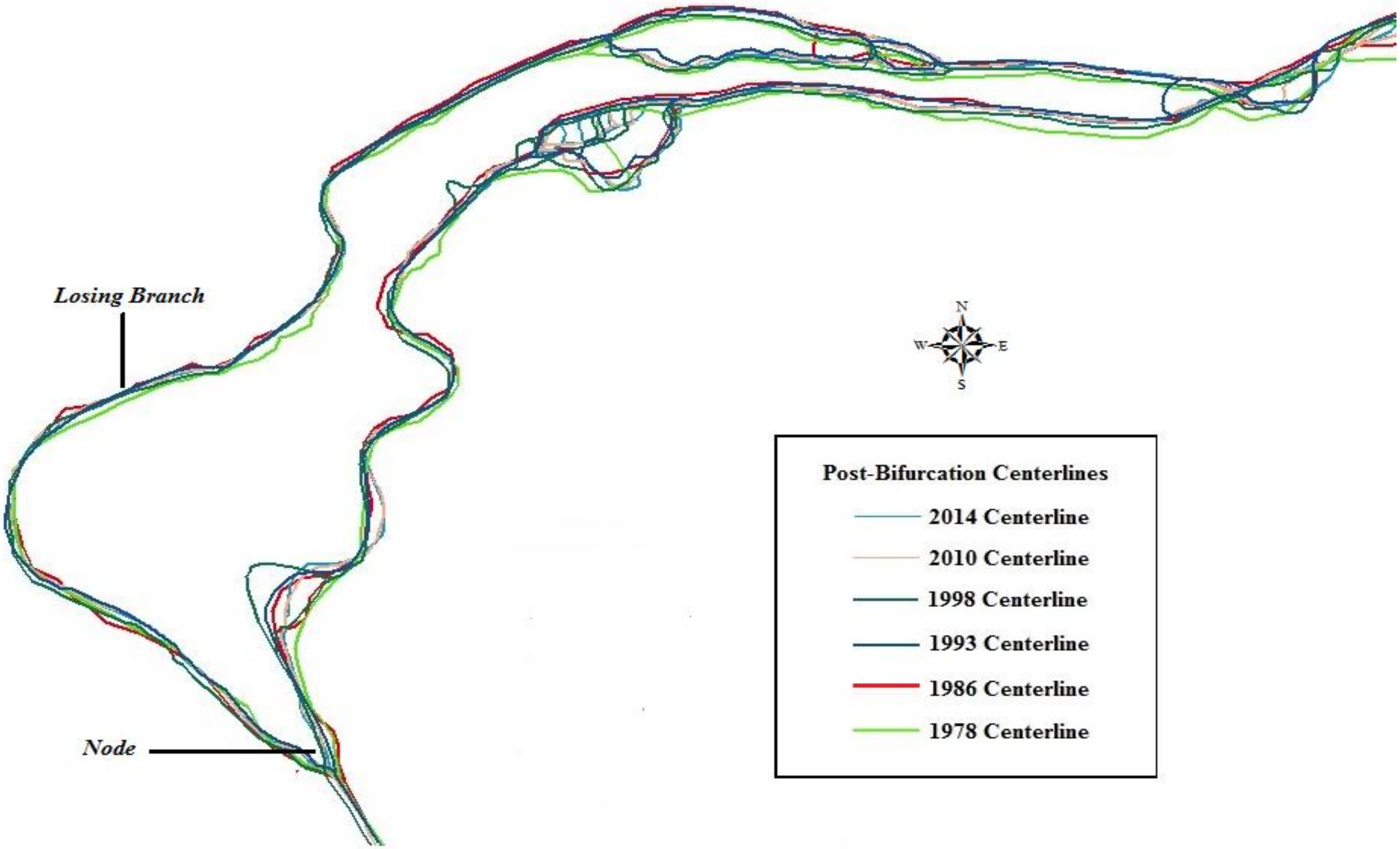

Figure 6. Post-Bifurcation Centerlines (1978-2014). *Scale 1:5000*

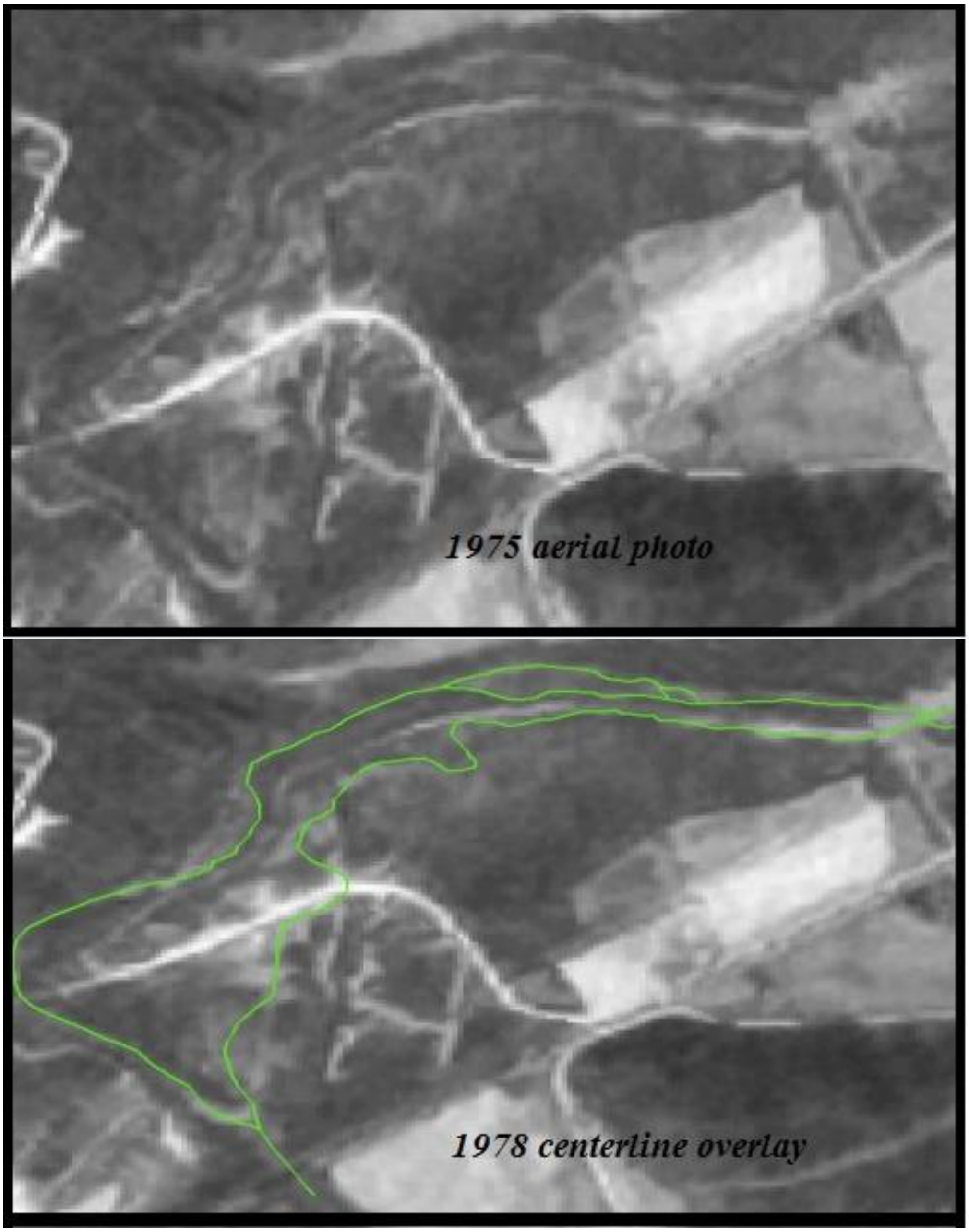

Figure 7. 1975 Aerial Image with 1978 Channel Centerline Overlay*. These images show it is probable that the river once avulsed, generally followed the course of the lowered or dredged areas, just like a channel will follow a relict swale or abandoned channel.*

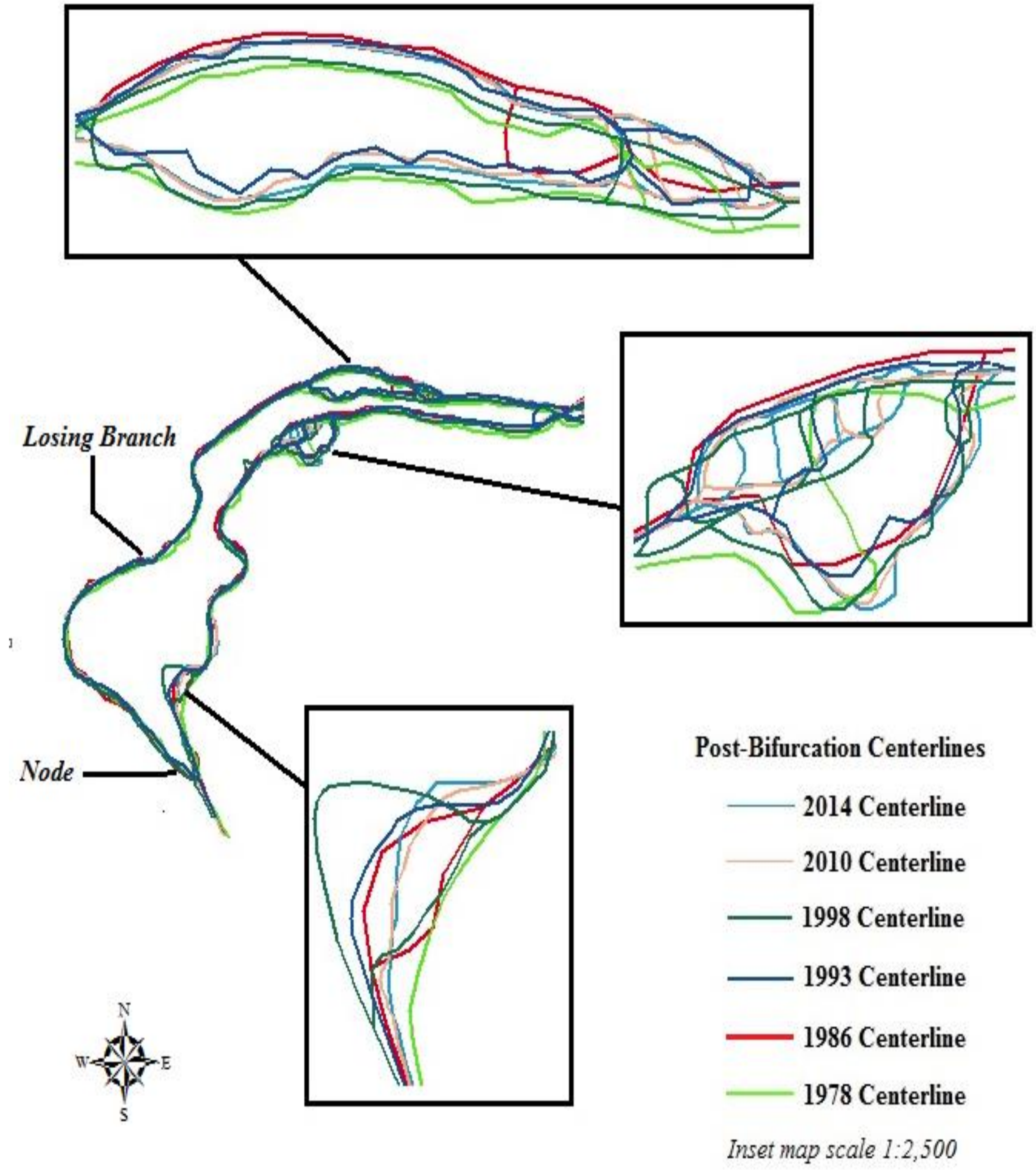

Figure 8. Predominant Shifting of the Post-Bifurcation Channel (1978-2014). Most shifting occurred downstream on the losing branch and above the node as well as downstream on the new branch.

6.2 Field Surveys

Nineteen benches were identified, described, and mapped on the study reach *(Fig. 9)*. The majority of the study reach exhibited discontinuous benches. The benches did not appear to be randomly situated; some spatial patterning was identified.

Parallel or lateral benches generally alternated from the right bank to the left bank and were typically situated in the straighter sections of the channel. The parallel benches are believed to be the direct result of the channel's attempts to narrow its width. This narrowing could be in response to the post-bifurcation apportionment of water flow to the losing-branch. During field survey and current metering, a surplus flow was noted on the new branch. Current metering allowed for the calculation of a split flow ratio of Q =54 cfs/184 cfs (Q=losing/new, 23/77%), with the new (right) branch receiving ~77% of the main channel flow. The water flow was diminished in the losing branch, due to only ~23% of the total discharge from the main channel now entering the losing branch post-bifurcation.

Benches one and two were directly situated downstream of the node on the losing branch. Their position immediately downstream of the node could be due to the angle of the channel entrance. The channel entrance is angled such that it can become less efficient at transferring water and sediment, due to a localized reduction in flow velocity. This reduction in flow velocity is often experienced at the node allowing the channel to aggrade and thereby causing alluvial bench construction through lateral accretion (Burge, 2006).

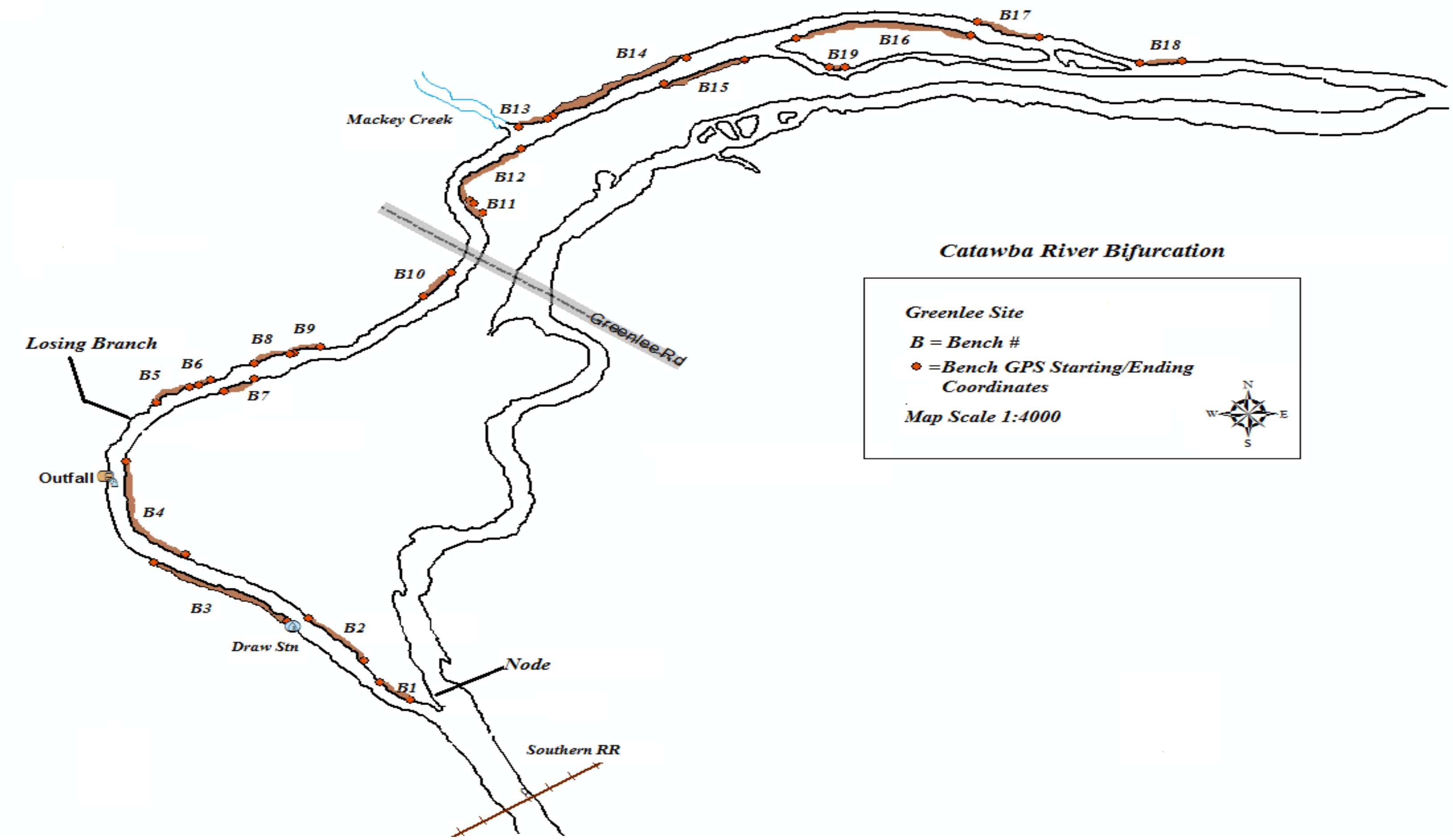

Figure 9. Catawba River Bifurcation Bench Map. *The GPS starting and ending latitude and longitude coordinates of all identified benches were collected during field survey and projected using ESRI's ArcMap. This allowed for the creation of an accurate bench and channel map.*

Five of the nineteen benches (benches four, eleven, twelve, sixteen, and nineteen) were present in the convex or inner bank portions of the losing branch where deposition occurs at point bars and could be classified as point benches. Bench thirteen is classified a tributary confluence bench. It is situated downstream of the confluence with Mackey Creek and is most likely created from the sediment supply of the tributary, but no sediment yields from this tributary were calculated.

Bench five, six and seven could possibly be classified lee or feature benches as they are situated in an area of deep still water with a large presence of woody debris. Bench five, six and seven may even be classified as marginal benches. The presence of still water and large woody debris could allow for reverse flow upstream creating this type of bench (Changxing et al. 1999). Bench three may possibly be a concave bench, but other than its position there has been no other evidence to support this classification. These particular bench types may not necessarily be any indication of diminished flow, but the flow loss has most likely made it easier to form benches of all types. Rather the longer, larger benches may be a better indication of flow loss.

Analysis of bench architecture and stratigraphy of the upper 0.5 m *(Table 1)* of bench sediment revealed that 62.5% or 10 of the 16 benches surveyed at the Greenlee site exhibited a well-stratified sand-rich sediment that is characteristic of coarse stratic and stratic benches (Erskine and Livingstone, 1999), and the remaining 37.5%, or 6 out of the 16 benches surveyed, (benches 6, 8,13,16,17and 18) were visually massive (Royall et al., 2010) or lacking any visible stratification.

Table 1. Bench Measurements

Bench #	*Width (m)*	*Ch. Width (m)*	*Hgt. Abv. Bed (m)*	*Length (m)*	*Stratigraphy Type*	*A Horizon*
B1	*2.50*	*11.90*	*1.71*	*31.06*	*No Stratigraphy*	*No*
B2	*4.63*	*13.70*	*1.94*	*58.16*	*Stratic*	*No*
B3	*5.00*	*16.10*	*2.50*	*123.00*	*Coarse Stratic*	*No*
B4	*3.00*	*11.50*	*2.09*	*114.00*	*Stratic*	*Yes*
B5	*3.00*	*12.20*	*2.12*	*38.10*	*No Stratigraphy*	*No*
B6	*4.00*	*14.80*	*1.69*	*11.00*	*Massive*	*No*
B7	*1.50*	*15.50*	*1.68*	*28.00*	*Coarse Stratic*	*No*
B8	*2.50*	*15.60*	*1.77*	*30.57*	*Massive*	*No*
B9 (L)	*0.49*	*14.00*	*0.52*	*23.60*		*No*
B9 (U)	*1.46*	*14.00*	*0.76*	*23.60*	*Coarse Stratic*	*Yes*
B10	*4.20*	*15.20*	*1.56*	*33.70*	*Coarse Stratic*	*No*
B 11	*2.42*	*13.80*	*0.50*	*11.70*		
B11	*3.40*	*13.80*	*1.68*	*11.70*	*Coarse Stratic*	
B12 (L)	*2.00*	*13.40*	*1.00*	*82.00*	*Coarse Stratic*	*No*
B12 (U)	*3.65*	*13.40*	*2.10*	*82.00*		
B13	*3.00*	*17.25*	*1.18*	*24.80*	*Massive*	*No*
B14	*12.50*	*12.30*	*1.51*	*121.00*	*Coarse Stratic*	*No*
B15	*1.50*	*21.43*	*1.60*	*68.00*	*Coarse Stratic*	*No*
B16 (L)	*2.00*	*13.60*	*1.09*	*139.00*	*Massive*	*No*
B16 (U)	*2.70*	*13.60*	*0.68*	*139.00*		*Yes*
B17	*4.50*	*10.70*	*1.00*	*52.14*	*Massive*	*No*
B18	*4.50*	*13.20*	*No Data*	*33.63*	*Massive*	*No*
B19	*3.50*	*11.34*	*1.40*	*11.90*	*No Stratigraphy*	*No*

Table 2. Greenlee Site Bench Statistics

Stat. Measure	*Width*	*Length*	*Hgt. Abv. Bed*	*Channel Width*
Mean	*3.39*	*54.49*	*1.50*	*14.08*
Median	*3.00*	*33.70*	*1.58*	*13.70*
Mode	*3.00*	*#N/A*	*1.68*	*#N/A*
Stand. error	*0.48*	*9.53*	*0.11*	*0.57*
Standard Dev.	*2.31*	*41.56*	*0.51*	*2.51*
Sample Var.	*5.33*	*1727.21*	*0.26*	*6.28*
Kurtosis	*11.30*	*-0.47*	*-0.45*	*2.97*
Skewness	*2.88*	*0.94*	*-0.16*	*1.36*
Range	*12.01*	*128.00*	*1.98*	*10.73*
Minimum	*0.49*	*11.00*	*0.52*	*10.70*
Maximum	*12.50*	*139.00*	*2.50*	*21.43*
Sum	*77.95*	*1035.36*	*32.92*	*267.52*
Count	*23.00*	*19.00*	*22.00*	*19.00*
Con. Lvl. (95%)	*1.00*	*20.03*	*0.23*	*1.21*

The mean width of all identified benches is 3.39 m. Bench 14 was exceptionally wide at 12.50m, but may possibly be a much older former meander, as this same feature is present in the 1955 image. The mean bench length is approximately 54.49 m, the average elevation above the bed surface is 1.50 m *(Table 2)* and the mean channel width is 14.08. Compound benches or those with two distinct topographical features were present at four locations. The transition between the two features was rounded and not steep. Most of the bench treads were flat, but some were sloping towards the channel. Average width of benches represents 19% of the pre-bifurcation channel width.

Benches 9 *(Fig. 10)* and 10 consisted of coarse sands and silts of alternating layers ranging from 8cm to 20cm thick. There was a general absence of any pedogenetic features or soil development that might indicate a great age for benches, although a possible incipient A horizon was present in benches 4, 9 *(Fig. 11*), and 16. Organics were also identified at Bench 11. At 20.32 cm in depth from the bench surface a 15.24 cm layer of coarse sand with organics was identified. At the bottom layer of the pit, 52.70 cm in depth from the bench surface, a 2.54 cm thick of organic rich sediment was also exhibited. Bench 13, a tributary bench displayed 15.24 cm of gleyed sediment. There was a gravel or cobble basal layer present in the majority of the low bench stratigraphic profiles that were fully exposed to channel bed level.

Figure 10. Bench 9, Losing Branch.

Figure 11. Bench 9 Stratigraphy.

Large woody debris was present along the entire reach of the losing branch. An increased accumulation of large woody debris was evident in the channel section where benches 5, 6, and 7 were situated. This area of the losing branch contains deep still water (1.15-1.83m). Remnants of a possible large log jam, evidence of a previous high flow event, was also present on top of the node and in the channel parallel to the right bank immediately downstream of the node *(Fig. 12)*. This large woody debris (remnants of a possible log jam) is also present in the 2010 aerial image and has since grown larger, as evidenced during the May, 2016 field survey.

Figure 12. Remnants of a Possible Log Jam. *The presence of large woody debris pile-up immediately downstream of the node, on right bank of losing channel indicating previous high flow event. Photo taken during field survey May 25, 2016*

Observations of the current vegetation statures reveal bench vegetation to be mostly herbaceous riparian cover consisting of grasses, grass-like plants and forbs with little woody vegetation of any kind, showing that many of the benches may have youthful ages. Thirty-two percent of the identified benches on the losing branch exhibited the presence of trees that are common to riverine ecosystems or riparian zones (Caldwell, 1999) such as Box elder *(Acer negundo)*, River Birch (*Betula nigra)* and Sycamore (*Platanus occidentalis) (Table 3)*.

The larger, established trees were found to be growing directly on benches 1, 2, 3, 4, 9, and 12 *(Table 3)*. For the trees that were found growing directly on the benches the range of tree stature is from 6-70 cm in diameter and the average diameter is 26 cm *(Table 4)*. There appears to be a spatial pattern to the presence of vegetation on the benches. It is possible that this indicates early formation of benches first near the node, and that the benches further downstream may have been created later. These larger trees are exhibited mainly on higher benches. Benches one, two, three and twelve had varying tree species growing directly on the bench that appeared to be larger, possibly older trees and these benches have elevations ranging from 1.71m to 2.50m above bed *(Table 1)*. It is possible that the benches with an absence of any tree species were unable to allow seedling establishment, due to high flood variability and frequent scour (Royall et al., 2010). It remains possible that those benches absent of established trees might not be relatively youthful, as assumed.

Table 3. Greenlee Site - Bench Tree Statures

Species	***Growth Rate***	***Diameter (cm)***	***Bench #***
Box elder *(Acer negundo)*	*Fast*	*30*	*1*
		6	*1*
		13	*1*
		19	*1*
		16	*1*
		35	*1*
		11	*2*
		13	*2*
		16	*2*
		20	*3*
		50	*4*
		20	*12*
River Birch *(Betula nigra)*	*Slow-Medium*	*8*	*1*
		10	*9*
		60	*12*
Sycamore *(Platanus occidentalis)*	*Fast-Rapid*	*70*	*12*
Eastern hophornbeam *(Ostrya virginiana)*	*Fast*	*40*	*12*

Table 4. Bench Tree Stature Statistics (cm)

Statistical Measure	***Value***
Mean	*26*
Standard Error	*5*
Median	*19*
Mode	*16*
Standard Deviation	*19*
Sample Variance	*363*
Kurtosis	*1*
Skewness	*1*
Range	*64*
Minimum	*6*
Maximum	*70*
Sum	*438*
Count	*17*
2nd Largest	*60*
2nd Smallest	*6*
Confidence Level (95.0%)	*10*

All of the identified benches, except bench fourteen were backed by an older, established line of varying tree species. The presence of these trees benches and the existence of the established line of very large trees on what was the original bank may be evidence that most of these benches finished the majority of their formation possibly decades earlier, shortly after bifurcation. The very large trees were set back from the current bank edge, which indicates the former pre-bifurcation bank. The distance between these trees and the current bank edge represents bank accretion via bench formation presumably since 1977 *(Fig. 13).*

Figure 13. Bench 9, Line of Older, Established Trees. *Note the large trees set back from the current bank edge, which indicate the former pre-bifurcation bank. The distance between these trees and the current bank edge represents bank accretion via bench formation since 1977.*

The alluvial bottom can be considered ideal growing conditions for all of these species. According to *Silvics of North America*, *Volume 2,* tree species such as the box elder can have growth rates up to 2.5 cm (d.b.h) a year (Burns and Honkala, 1990). This would approximate the age of the box elder exhibited on these benches at a range of ~2.4 years to 20 years old. The river birch which have a slow to medium growth rate, present on bench 12, could possibly be older than the bifurcation itself. According to Burns and Honkala (1990), a 58-year-old *Betula nigra* (River Birch) is commonly measured at 58 to 76 cm (23 to 30 in) in d.b.h. and 15.2 to 19.8 m (50 to 65 ft.) tall. The River Birch present on bench 12 was ~60 cm in diameter, at a minimum growth rate it is conceivable that it could have established itself at approximately ~39 years ago or later. This is evidence that bench 12 might have become established either immediately after avulsion or existed as a pre-bifurcation bench. Tree coring would have further constrained the minimum age for bench establishment, however access was not such that tree coring was permitted.

6.3 Hydrologic and Flood Frequency Analysis

Post-bifurcation bankfull discharges and recurrence intervals *(Table 5)* were computed for the Greenlee site using conventional procedures utilizing Log-Pearson Type III distributions of peak annual discharge *(Fig.14)* (USGS, 1982).

Table 5. Flood Frequency

recurrence (years)	Q (cfs)	Q_5 (cfs)	Q_{95} (cfs)
1000	41,196	72,593	27,840
500	35,695	60,858	24,636
200	29,090	47,346	20,678
100	24,564	38,503	17,878
50	20,414	30,736	15,232
25	16,612	23,954	12,724
20	15,458	21,966	11,943
10	12,067	16,348	9,581
5	8,935	11,508	7,278
3.333	7,191	8,996	5,923
2.5	5,972	7,335	4,933
2	5,018	6,099	4,129
1.667	4,216	5,104	3,433
1.429	3,498	4,246	2,797
1.250	2,811	3,450	2,183
1.111	2,074	2,612	1,530
1.053	1,612	2,088	1,133
1.020	1,214	1,629	804
1.010	1,004	1,383	638

***Q & Recurrence Interval** – Catawba Bifurcation USGS 02137727 Catawba River near Pleasant Garden, NC Gage (PeakFQ)*

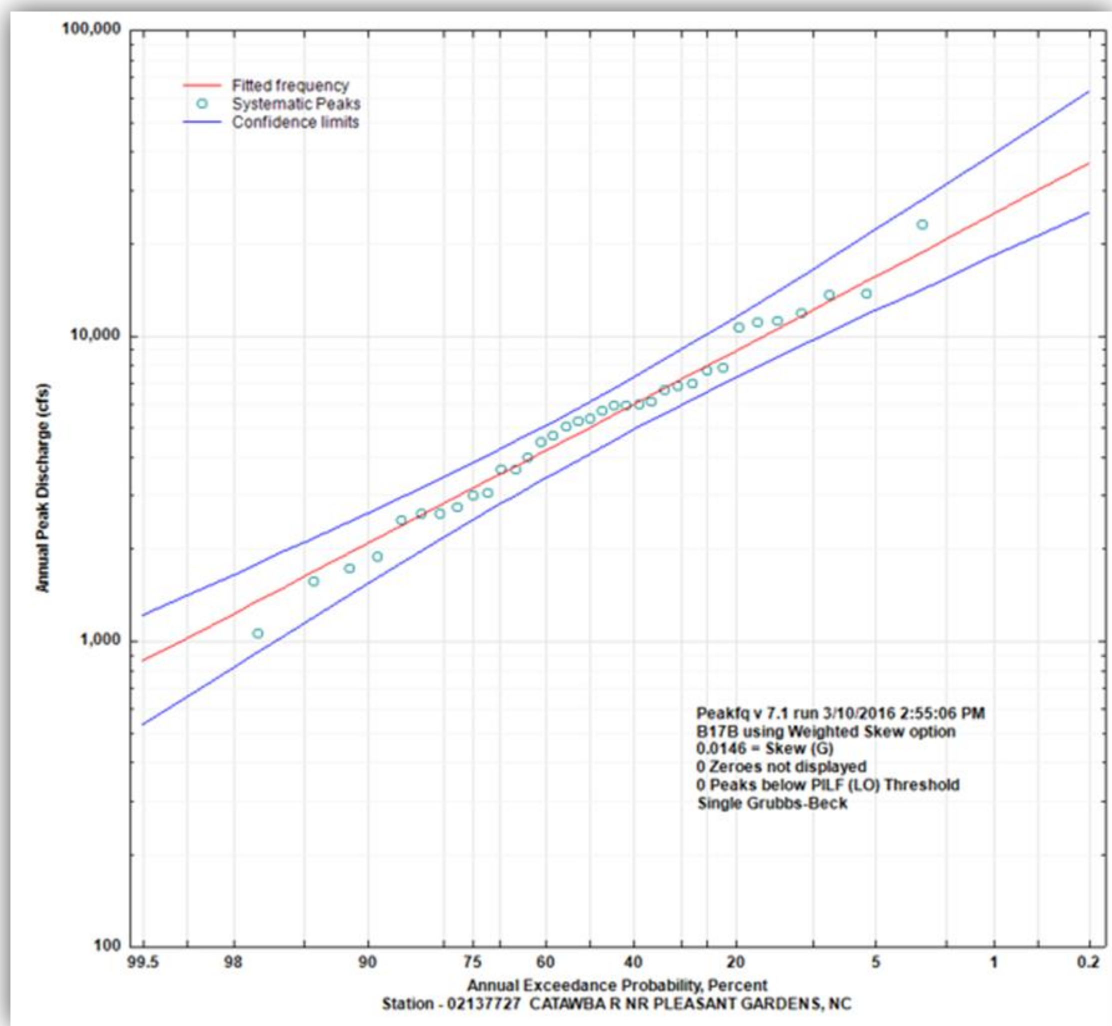

Figure 14. Flood Frequency Curve, Log Pearson Type III Parameters.

The discharge corresponding to the canonical bankfull 1.5-year flood is 3650 cfs and a stage of 7.45ft. However, flood reports from the older Marion gage further downstream (172 mi^2) state that the bankfull flood is 7000 cfs, with a recurrence interval of 1.65 years. Flood estimation equations from Weaver et al. (2009) demonstrate that bankfull flood discharge scales almost perfectly with drainage area for the upper Catawba

River. Being that the drainage area for the ungaged Greenlee site is 65.4% (112 mi^2) that of USGS 02138000 Catawba River near Marion (126 mi^2) the adjusted value of the 1.65 -year flood at Greenlee would be 4,758 cfs for total Q_b from both branches.

Meter tape and current meter allowed for discharge to be calculated for the left (losing) and (new) right branch. The losing branch had a discharge of 54 cfs and the right branch discharge was measured at 185 cfs, therefore a 23/77% apportioned flow in favor of the new branch was determined. The flow bifurcation ratio for this site calculated the losing branch apportionment at 23% of total flow, so therefore the Q_b of the losing branch is estimated to be 1,053 cfs, assuming that the flow split ratio does not vary with discharge.

Bench stratigraphy data and flood frequency analysis suggest the size of floods during which benches experience net growth (and more sediment is stored). Since a flood must usually top a bench to deposit on it, the frequency of benchfull flow determined from flood observations and gaging data was quantified, and considered the lower limit on frequency for bench growth.

The logistics and timing of high flow events prevented many field observations, but one such event was able to be witnessed on 4 October, 2015 (*Fig. 15)*. Flood observations relative to benches was able to be conducted through examination of strandlines immediately following flooding. Bench-topping flows were determined based on strandlines and flattened vegetation left on top of benches, or on banks if stages were lower. This observation made it possible to estimate the probable frequencies using the gage data.

Figure 15. High Flow Event. *3 October, 2015 observed the day after 4 October, 2015. Bench 10 - strandlines and sand evidence of benchfull Q or partial inundation.*

At 3:30 pm (EST), 4 October, 2015 bench 10 exhibited evidence of inundation. Strandlines and sand deposited across the top surface of the bench were measured to be an average of 0.41 m in width. At this time the gage at Pleasant Gardens was showing a Q of 1160 cfs and a stage of 4.11 ft. The drainage area adjusted flow for the site as demonstrated above (88.7% by drainage area) would be 1029 cfs. Meaning that the losing branch is estimated to have been carrying 237 cfs. At this flow, Bench 10's elevation was 0.17 m above the water surface.

At 5:15 pm (EST) on 3, October, 2015, the day of the flooding event, the Pleasant Garden gage was showing peak flow at 5000 cfs and a stage of 8.72ft. The drainage area adjusted value for the site would be 4435 cfs with the losing branch experiencing flows of 1020 cfs. This flow would have partially or completely inundated bench 10 and possibly inundated other low benches. It was not ideal conditions on this day to use a kayak to survey the river, in order to view the other benches. Several observations would be necessary to render judgement in regards to the entire channel. Without the needed bench inundation field observations, it was necessary to perform hydraulic analysis.

6.4 Hydraulic Geometry Analysis

Assuming that benches represent incipient floodplains adjusted to lower flows in the losing branch, hydraulic geometry equations were used to estimate what current channel widths should be if it is assumed that depths, estimated using bench height above bed, are adjusted to bankfull flows. In order to carry out hydraulic geometry analysis three steps were taken to derive the needed hydraulic equations for width and depth: the determinations of benchfull Q, coefficients and exponents and those steps were outlined in the Hydraulic Geometry Methods section.

The results of the hydraulic analysis are as follows *(Table 6)* containing data from the 14 (of the total 19 mapped) benches on sections of the reach that did not contain any sub-branches. Such sub-branching cannot be accounted for with the hydraulic data available. The average value of *a* was 1.05 with a range of a minimum at 0.83 to a maximum at 1.42. The average value for *b* was 0.28 with a range of a minimum at 0.21 to a maximum at 0.31. These are not much different than those derived from Doll et al. (2002) and Harman's (2000) regional curves. The average current channel width was 14.38m while the average predicted channel width was 12.15m. The average difference between the predicted vs. the current channel width was -2.23m, disregarding the lowest bench at compound bench sites. The average of the absolute values of deviations is 4.56 m (also disregarding the compound lower bench) 64% (9/14) of the channel widths were under-predicted, while 36% (5/14) of the channel widths were over-predicted.

Table 6. Hydraulic Geometry

Bench #	***a***	***b***	***Q_b***	***Predicted Channel Width (ft.)***	***Predicted - Current Ch. W (ft.)***
B1	*0.83*	*0.27*	*1885.25.*	*30.86*	*-8.18*
B2	*1.05*	*0.31*	*1925.47*	*39.68*	*-5.26*
B3	*1.21*	*0.31*	*3629.80*	*61.93*	*9.11*
B4	*0.83*	*0.21*	*6468.57*	*56.16*	*18.43*
B5	*0.87*	*0.24*	*4505.40*	*49.49*	*9.46*
B6	*1.08*	*0.27*	*1830.75*	*39.73*	*-8.83*
B7	*0.98*	*0.27*	*1803.79*	*35.67*	*-15.18*
B8	*1.04*	*0.30*	*1694.72*	*36.86*	*-14.33*
B9(U)	*0.89*	*0.31*	*184.96*	*10.87*	*-35.06*
B10	*1.11*	*0.29*	*1287.96*	*34.63*	*-15.24*
B11(U)	*0.99*	*0.27*	*1803.79*	*36.09*	*-9.19*
B12(U)	*0.98*	*0.27*	*3151.37*	*46.76*	*2.80*
13	*1.39*	*0.27*	*745.12*	*33.35*	*-36.53*
14	*1.42*	*0.27*	*1381.52*	*45.78*	*5.43*

Total bankfull discharge (Q) for combined branches =4578 (exponents x=0.48 y=0.4 derived from regional curves)

There appears to be no spatial patterning to the benches that were over or under predicted. Channel widths were under predicted at benches 3, 4, 5, 12 and 14. It is evident through field observations and hydraulic analysis that the channel has narrowed through bench formation. This analysis demonstrated that the channel has sufficiently narrowed to meet the expectation that narrowing should occur, but still does have some narrowing to achieve 100% of the predicted width. This demonstrated that 64% of the channel's widths still need to reach or exceed their predicted widths. The greatest difference was exhibited in benches 9, and 13. For bench 13, the predicted channel width to the current channel width is showing at -36.53 ft. or -11.13m.

Using the measurement-based estimate of bankfull discharge in the losing channel, the regional curves of Doll et al (2002) and Harmon (2000) can be used to calculate channel dimensions as well *(Table 7)*. The predicted minus observed values for channel width in the losing bifurcate are most minimized by using the Piedmont-based regional curves of Doll et al. (2002). The average differences are smaller for the Piedmont width regional curve estimates than they are for those based on reconstructed hydraulic geometry, and thus might be interpreted to indicate better adjustment. They are also derived from data representing essentially modern physiography and land use. However, the use of regional curve equations is not as analytically rigorous as the hydraulic reconstruction. There are no points in the plots of Doll et al. (2002) from the upper Catawba, a river that is not firmly in the Piedmont or Blue Ridge provinces, but straddles them.

Collectively, this information will illustrate how the Catawba losing branch has responded to reduced flow and how quickly, and thus whether or not the Kleinhans et al (2011) hypothesis is sufficient for explaining bifurcation stability in the upper Catawba

Table 7. Hydraulic Analysis Results Regional Curve Comparison

Bench #	Reconstructed Pred. W - Obs. W (m)	Reconstructed Deviation as % Pred. W	Blue Ridge Reg. Curve Pred W - obs W (m)	Blue Ridge reg. Curve Deviation as % of Predicted W	Blue Ridge Reg. Curve Pred D-Obs D (m)	Blue Ridge Reg. Curve Deviation as % pred. D	Blue Ridge Reg. Curve XSA pred - obs. (m2)	Blue Ridge Reg. Curve XSA pred - obs. (% of pred)	Piedmont Reg Curve Pred W - Obser W (m)	Piedmont Reg Curve Deviation as % Pred. W	Piedmont Reg Curve Pred D - Obser D (m)	Piedmont Reg. Curve Deviation as % Pred. D	Piedmont reg. Curve XSA pred - obs. (m2)	Piedmont Reg. Curve XSA pred - obs. (% of pred)
B1	-2.49	-26.50	5.31	30.86	-0.87	-103.97	-4.65	-29.63	3.58	23.13	-0.39	-29.37	-0.12	-0.58
B2	-1.60	-13.26	3.51	20.40	-1.10	-131.40	-10.88	-69.32	1.78	11.51	-0.62	-46.77	-6.35	-31.37
B3	2.78	14.70	1.11	6.46	-1.66	-198.20	-24.56	-156.42	-0.62	-4.00	-1.18	-89.14	-20.03	-98.94
B4	5.62	32.81	5.71	33.18	-1.26	-150.49	-8.46	-53.85	3.98	25.72	-0.78	-58.88	-3.92	-19.36
B5	2.88	19.11	5.01	29.12	-1.28	-152.87	-10.17	-64.77	3.28	21.20	-0.80	-60.39	-5.63	-27.84
B6	-2.69	-22.22	2.41	14.01	-0.85	-101.58	-9.32	-59.34	0.68	4.40	-0.37	-27.86	-4.78	-23.62
B7	-4.63	-42.56	1.71	9.94	-0.84	-100.39	-10.35	-65.89	-0.02	-0.12	-0.36	-27.10	-5.81	-28.71
B8	-9.35	-149.42	1.61	9.36	-0.26	-31.21	-1.46	-9.32	-0.12	-0.77	0.22	16.78	3.07	15.18
B9 (U)	-10.69	-322.44	3.21	18.66	0.08	9.35	5.06	32.22	1.48	9.57	0.56	42.50	9.60	47.41
B10	-4.65	-44.01	2.01	11.69	-0.72	-86.08	-8.02	-51.06	0.28	1.82	-0.24	-18.02	-3.48	-17.20
B11 (U)	-2.80	-25.45	3.41	19.82	-0.84	-100.39	-7.49	-47.70	1.68	10.86	-0.36	-27.10	-2.95	-14.59
B12 (U)	0.85	5.99	3.81	22.14	-1.26	-150.49	-12.45	-79.27	2.08	13.44	-0.78	-58.89	-7.91	-39.09
B13	-11.13	-109.49	-4.09	-23.75	-0.34	-40.70	-9.43	-60.06	-5.82	-37.58	0.14	10.76	-4.89	-24.18
B14	1.65	11.85	4.91	28.53	-0.67	-80.11	-2.88	-18.32	3.18	20.55	-0.19	-14.24	1.66	8.20
Avg	-2.59	-47.92	2.83	16.46	-0.85	-101.32	-8.22	-52.34	1.10	7.12	-0.37	-27.70	-3.68	-18.19
Avg of ABSVal		59.99		19.85		102.66		56.94		13.19		37.70		28.30

CHAPTER VII

DISCUSSION

Phillips (2012, p. 18) states that "geomorphic phenomena tend to be governed or influenced" by two sets of controls, such as universal and local factors. Knowledge of these factors are critical to the understanding, prediction, and management of channel shifts. Spatiotemporal analysis of the Greenlee site, coupled with field studies and historical land use information allowed for these possible factors to be revealed and examined in order to gain a better understanding of the channel shift or avulsion that occurred at this site.

Through visual interpretations of earlier aerial photographs, especially 1955 through 1975 images, local factors became evident. These local factors, such as floodplain mining, demonstrated evidence that the bifurcation could be a direct result of human modification to this immediate floodplain *(Fig. 16).* There is no absolute proof that was gained from this study or at this time to state that the avulsion would not have occurred in the absence of mining. The 1955 aerial image clearly shows the area where the right bank has been lowered by mining operations; further evidence that the 1977 avulsion and subsequent bifurcation may have been anthropogenically induced *(Fig. 17).*

***Figure 16. Bank Destruction, 1955 Image**. Red arrow points to possible bank destruction caused by gravel and sand mining (dotted box). It is apparent that mining has increased in this particular area since 1947 (earliest available image). This area is the future site of the initial 1977 avulsion; so this appears to be evidence of the set-up for avulsion and subsequent bifurcated flow.*

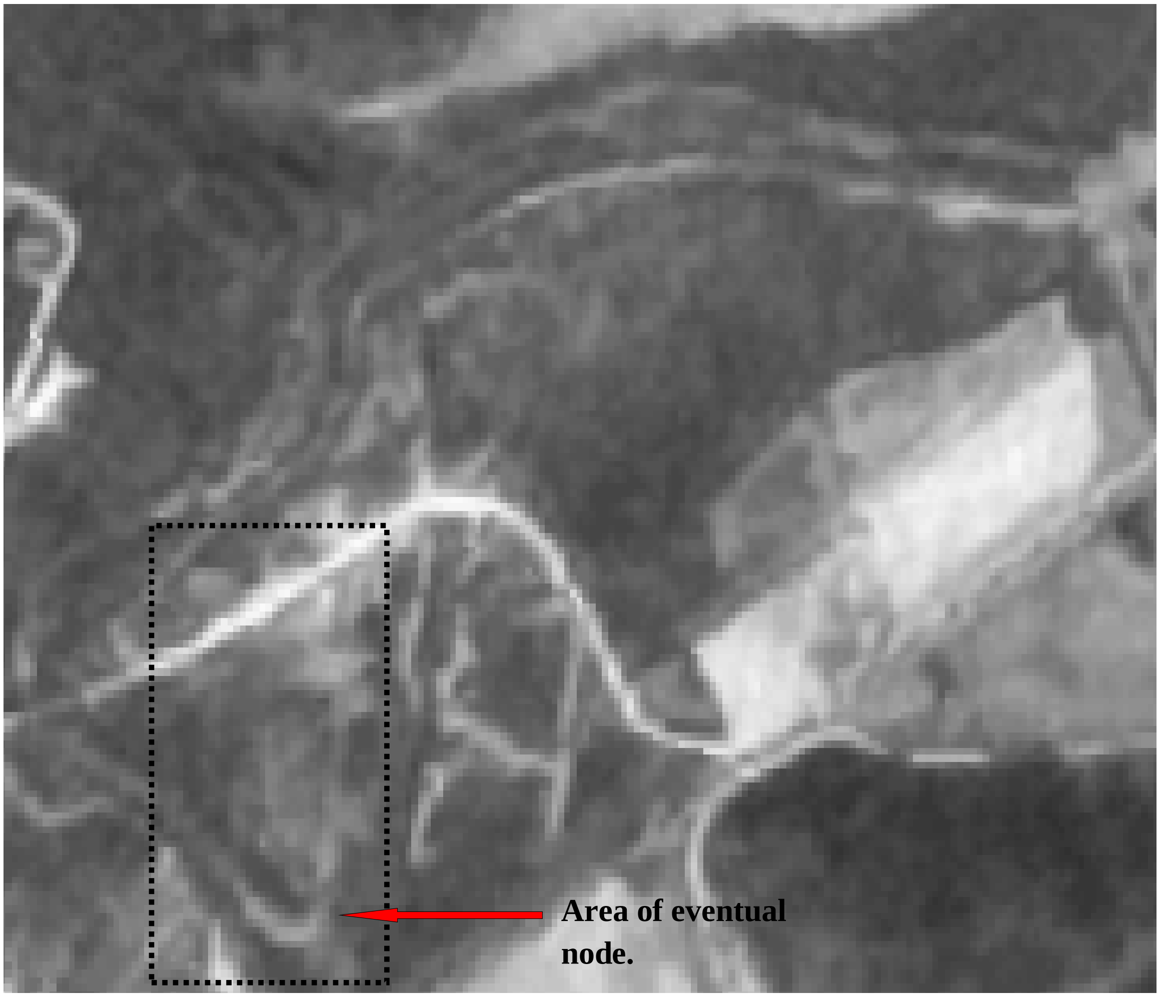

***Figure 17. Mining Zones, 1975 Image**. The arrow points out the area of the eventual 1977 bifurcation node. The photo also exhibits flood plain modification caused from historic gravel and sand mining that will generally set the course for the right, new channel post-bifurcation.*

Evidence of mining and borrow pits were also observed during field surveys. Historical anecdotes speak of floodplain mining of sand necessary after the 1916 flood event. The Army Corp. of Engineers 1971 report also specifically references a lowering of this area of the floodplain (borrow area) due to mining (1971).

This bifurcation follows the general set-up and trigger framework like most avulsions (Phillips, 2012). For the Greenlee site, mining would be the set-up or factor that most likely caused a local point of weakness for a levee breach (possible bank destruction caused by gravel and sand mining) and the November, 1977 flood event could be considered the trigger. This site also has a history of over-bank flows, such as the large floods of 1916, 1940, and 1977, which Phillips (2010) found to be significant in regards to avulsions.

It is possible that the bifurcation could have happened in the absence of floodplain mining, as avulsions have been known to occur during flooding (Phillips. 2012). This study area has a long history of repeated flooding events which has been known to trigger avulsions. Floods, some catastrophic, have been documented on this area of the Catawba River, such years are 1901,1916, 1940, 1949, 1977, 1994, 1998, 2004 (Henry, 1916; Corp. of Engineers, 1971; Bailey, 1975; Neary & Swift, 1987; Miller, 1989; Stamey, 1989; La Penta, 1992; Gamble, 1997).

Field surveys and recent aerial photographs revealed remnants of a possible large log-jam in the node area and immediately downstream of the node. Phillips (2012) found that occurrences of log-jams can influence avulsions. This could also have happened during the 1977 flood event. This area, within what Sorrells and Royall (2014) referred to as the zone of common branching, contains many bifurcated reaches along the Yadkin, Wilson and Linville Rivers- why are all of these reaches bifurcating? Sorrells and Royall (2014, p. 43) felt that bifurcations occur “more likely at landscape positions along major gradient reductions where longitudinal connectivity is diminished and lateral connectivity enhanced". Mining impacts represent a different explanation, or perhaps an additional influencing factor, at least for the Catawba.

How and why have benches been created in the losing branch? Field survey showed evidence of bench growth along ~68%, 0.98km of the total reach length. Morphostratigraphic survey showed that the benches were almost equally split amongst stratic and massive characteristics. Fifty-six percent of the identified benches were classified stratic or coarse stratic, so the bench stratigraphy contains some evidence of the formative events, such as slow accretion of benches by moderate flood events. While the 44% massive benches may be indicating bench formation in a small number of much larger events, such as the bifurcation event of 1977 that had a 21.0-year recurrence interval.

The stratic benches may have formed from bankfull flow. Moderate events of moderate frequency are responsible for the most work, especially in humid climate rivers. Wolman and Miller (1960) demonstrated that the largest amount of sediment transport occurs at those flows which occur on average once or twice a year. This has come to mean the dominant discharge or bankfull which corresponds to the highest rates of work done. Both of these characterizations could be morphogenetically significant at this site, as there has been frequent moderate magnitude events, as well as lower frequency, higher magnitude events; thus allowing for both of these bench classifications to be exhibited. Periods of drought can also allow for bench growth (Royall, 2010), but for this study this information was not examined.

It is possible that you might interpret changes in bench formation rates by looking at changes that might occur in stratigraphy. For example, if the lower portion of a bench is massive, and it grades upwards into a stratic style, it is more likely to have started growing quickly in a few large events, and then slowed down with stratic accumulation. That can't be proven with certainty though it is something to consider, but complete stratigraphical profiles would be necessary to make these judgements.

The channel seems to generally fit into the Kleinhans et al. (2011) theory as it appears that channel narrowing occurred relatively rapidly following bifurcation, at least in some areas. According to Kleinhans et al. (2011), rapid channel narrowing is required to maintain deep, fast, flows. The mean percent of channel narrowing was ~ 19% which seems to be significant, but Kleinhans et al. (2011) never stated exactly how much narrowing was necessary; although hydraulic adjustment to some flow regime or dominant discharge (such as the bankfull discharge used herein) may be interpreted as implicit in his hypothesis.

It would be useful to determine which if any benches existed in the pre-bifurcation state of this branch. Once identified, these branches would need to be excluded for a more accurate calculation of the mean percentage of channel narrowing. Bench 14 may be a pre-bifurcation bench; its much larger width ~12.50m means that it is not a characteristic width of the bench sample and may need to be eliminated as an outlier. Once bench 14 was removed from the calculation the mean percent of channel narrowing increased slightly to 20%.

Table 2 did show tree diameters and species growing on various benches (1,2,3,4,9 and 12) that would be characteristic of or evidence of these benches having completed most of their formation decades earlier

According to hydraulic calculations based on the geometry of the prebifurcation channel, channel narrowing has been insufficient at most bench sites to exactly contain the 1.65-year bankfull flow considered by many geomorphologists to be the dominant channel forming discharge in eastern rivers (Dunne and Leopold, 1978; Knighton, 1998), thus morphogenetically significant. This was ascertained through the channel narrowing ratio derived from the average rate of bench growth, assuming bench creation began immediately after bifurcation. Also, 36% of the channel widths narrowed as predicted, even exceeded the expectations. The average difference between the predicted vs. the current channel width was -2.35m.

It is possible that the amount of narrowing necessary could be ascertained by a few simple calculations of critical shear stress (based on bed grain size) and actual shear stress (based on depth and slope) to see whether benchfull flows are more than capable of transporting the sediment sizes in the bed; they will be, but if there is a large amount of excess shear stress available relative to sediment size in the bed (mostly sand probably), then scouring and depth maintenance should be good enough.

The channel appears to be relatively stable as the channel centerlines in the last decade, 1993 through 2014 centerlines show little mobility in the study reach. This is again most likely due to the formation of benches after bifurcation, but the lack of channel migration could be also due in part to the increased vegetation density post-bifurcation found on the stable island, benches, and channel banks of the losing branch. Tal et al. (2003, p. 3) found that vegetation decreased channel mobility and essentially the channel "becomes "pinned" in to a well-defined fairway that is substantially narrower than the original width". This decrease in channel mobility leads to the assumption that new bench creation in the losing branch would not be due to channel shifting, and must be due to a channel contraction response to loss of flow.

Vegetation density was assumed after visual inspection of the aerial photographs post-bifurcation. Further studies would need to be conducted in order to verify or quantify vegetation density for the Greenlee study site. There could possibly be registration errors present that are hindering analysis of the channel centerlines. The images used to digitize the centerlines were historical aerial photographs of sub-optimal resolution and this can cause errors during the registration process.

The flow on the losing branch is now only ~twenty-three percent of the flow of the right branch or new channel, yet the channel is able to stay open even with this diminished flow. Kleinhans et al. (2011) felt that the rapid channel narrowing was necessary to maintain deep, fast flows, yet this channel has many areas of deep, still water; is it possible that the tributaries such as Mackey Creek are maintaining sufficient enough flow to keep this branch open?

There are some problems when attempting to explain the dynamics at this site due to anthropogenic disturbances or human induced modifications to the floodplain and the channel itself that have historically occurred and may still be occurring today. Currently, it appears that the gravel operations have ceased in the losing channel, but other operations such as a plywood manufacturer that is adjacent to the Greenlee site has an NDPES permit (NC0087076) to discharge into the surface waters through an outfall station (NCDENR, 2013). In the downstream vicinity of the outfall the channel contains deep still water, unlike the shallower, faster moving water found further downstream and the channel bed contains much more stationary sediment in this area.

The original floodplain contains mining debris, boulder and cobble berms, as well as regions of the island adjacent to the channel bearing evidence of huge cuts in the floodplain. Areas of the island near the channel on the losing branch consist of a hummocky irregular surface where it is assumed that machinery has pushed around soil and mining spoils during past operations and the building of the new Greenlee Rd. bridge in 1977. Slackwater areas are currently distributed across the immediate floodplain that are caused by borrow pits.

Whether or not these disturbances currently play a part or have played a role in the continued persistence of this bifurcation is not known. Further studies of this site would be necessary to make any judgements. Currently, there is no definitive evidence that these operations or their legacies may have or currently play a significant role in the morphogenesis of the bifurcation, the growth of benches or the dynamics of this channel.

Aerial photography of the Greenlee site proved to be an invaluable resource for historical analysis of channel morphology and human modification of the floodplain. The aerial photographs that were readily available for this site provided a spatially complete, temporally continuous record dating back to the 1940’s, yet there were disadvantages. The analysis of the available historical aerial images had limitations due to the lack of assigned spatial coordinates and poor image contrast, quality, and low resolution that is common of some of these older images. Visual interpretation was impeded by the low resolution and interfered with accuracy when digitizing the channel centerlines and allowed for possible error in all tasks that were necessary to carry out a thorough examination. Human error could have also led to inaccurate registration of images that are lacking spatial coordinates. Visual interpretation of aerial images is subjective and may not always be the most accurate or efficient means of analysis, but for this study it was the most effective approach for the historical and contemporary data that was available.

Hydraulic geometry was used to calculate what the current channel widths should be, but this required assumptions about the values of hydraulic equation exponents, the stationarity of bankfull flow frequency over time, and the primacy of bankfull flow as the dominant channel-forming discharge. Although such assumptions are justifiable on the basis of much prior work, and were necessary given the absence of long-term direct monitoring data on-site, their potential limitations should also be recognized.

CHAPTER VIII

CONCLUSIONS

Through geospatial analysis, hydraulic geometry and morphostratigraphic survey it is clear in regards to the evolution of the losing branch system that benches have formed after bifurcation and these were the direct result of the channels innate attempt to narrow and not channel migration which has slowed to an almost standstill as predicted and demonstrated through examination of the channel centerlines. The amount of narrowing demonstrated through hydraulic geometry calculations shows that the channel has generally not narrowed as much as predicted, and still has some narrowing to complete.

More information is necessary to further test Kleinhan's hypothesis in regards to channel narrowing at the Catawba River Greenlee site. Full stratigraphic profiles and empirical data on sediment yield and transport would assist with bench studies allowing for the examination of bench sediment storage accumulated since bifurcation. This data is important for assessing future remobilizations of sediment under conditions of changing flow bifurcation ratio, and more generally understanding the reach-scale sediment budget for this river and a possible indication of how available sediment is to create benches or perhaps plug up a bifurcate. More direct observations and measurements of discharge for both branches during a high flow event would test the true validity of the flow ratio that was calculated for the Greenlee site. Tree coring would assist with bench stability studies and age determinations. Studying other bifurcated reaches in this area may also help explain why bifurcations are relatively common in this area of the southeastern Piedmont.

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