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Prior research has been carried out to determine the relationships between flows cited as important to channel form and the morphology of step-like features bordering streams known as alluvial benches. However little effort has been undertaken to understand such relationships along anabranching river reaches, where relative flow volumes are divided and potentially more variable. Thus, the influence of the anabranching planform on the characteristics of alluvial benches is currently not well understood. In this study, low alluvial benches inset within the larger valley flat were surveyed along a two-branch anabranching reach of the Yadkin River at Patterson, North Carolina and related to calculated bench-full discharges and their recurrence intervals via flow apportionment for each branch. The results were compared with historical discharge and recurrence interval data, and used to infer potential pathways for anabranch adjustment to changing flows. It was determined that most of the lowest benches present in both channels of the anabranch exist in equilibrium with their current respective bankfull discharges and represent incipient floodplains, and also that bench creation via lateral accretion is the primary method for channel dimension adjustment within this reach as bench heights in both channel branches are similar to historical values for the single-channel state. It was also determined that the majority of the benches studied are within close proximity of the point of initial bifurcation, suggesting that anabranching exerts some control on bench location.

HYDROGEOMORPHOLOGY OF ALLUVIAL BENCHES IN AN ANABRANCHING REACH OF THE UPPER YADKIN RIVER, NORTH CAROLINA

by

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APPROVAL PAGE

This thesis 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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CHAPTER I

INTRODUCTION

The primary purpose of this study is to establish a better understanding of the genetic controls, forms, and hydrological significance of in-channel benches in an anabranching reach of the upper Yadkin River. Kilpatrick and Barnes (1964) investigated the relationship of bench heights to discharge events in a variety of locations in the Piedmont region, including the Upper Yadkin River at Patterson in North Carolina, but an adequate explanation of the time frame in which benches are created and destroyed remains elusive. In-channel alluvial benches are sediment bodies that are generally attached to the banks of stream channels below the level of the broader valley flat, and are typically discontinuous and often vegetated (Erskine & Livingstone, 1999). These benches are formed by the deposition of alluvium in locations of reduced water velocities associated with certain physical features of stream channels, such as the banks of straight reaches, the inside of bends, and the slack-water area downstream of a sharp bend's point bar (Erskine & Livingstone, 1999). Climate trends and their associated discharge changes, and changes in the availability of channel sediment may influence the number and elevations of in-channel benches in some locations (Erskine & Livingstone, 1999; Warner, 1987; Royall *et al*. 2010). The dominant valley flat is typically associated with the hydrological floodplain that is formed by the bankfull event, which floods the area with an empirically derived recurrence interval of every 1 to 2 years (Dunne & Leopold, 1978; Leopold1994) in the eastern U.S. However, streams in the eastern United States are commonly incised relative to the major valley flat, so lower in-channel benches are frequently seen as being incipient flood plains forming within the high banks of the incised channel (Warner, 1987). However, benches are by nature spatially discontinuous, and there are benches that do not seem to be associated with any particular flood stage and therefore these benches could have many different origins (Royall *et al*, 2010). Additionally, if these benches are associated with a single incipient floodplain, then all benches within the same stream should have developed similar morphometries and stratigraphies as they converge on equilibrium in response to the current climatic regime and sediment inputs.

Field observations for streams in the Piedmont region of the United States commonly document the presence of one or more inset bench levels below the top of the main valley flat (Kilpatrick & Barnes, 1964). While one of these benches may represent the incipient floodplain, the ultimate function of the remaining benches has not yet been adequately explained. These benches may ultimately be incorporated into the incipient floodplain bench, but this would cause the internal morphology of the floodplain bench to vary in accordance with the dominant formative processes at work in that particular reach of the stream. An alternative theory suggests that these benches may be ephemeral or perennial features that reflect certain discharge levels, such as the mean annual discharge or recent flood levels (Hupp & Osterkamp, 1985; Royall *et al*, 2010).

Benches along a single stream will often display contrasting stratigraphies and compositions, which are suggestive of dissimilar genetic pathways and thus also varying process linkages, including but not limited to those of floodplains. In some cases, entire bench forms could be related to an isolated genetic event, such as the passage of a sediment wave or even a single large (much larger than bankfull) flood event. Indirect effects, such as large inputs of woody debris from ice storms or increased beaver activity are also possible influences.

Observations indicate a need to better understand the genesis of flood-bench features that may be erroneously interpreted by river managers and restorationists as equilibrium floodplains. These in fact may be either evolving incipient floodplains in at least temporary disequilibrium, or simply features that reflect relatively recent changes in the fluvial systems (Royall *et al*., 2010). This is a problem for stream managers attempting to use the morphological attributes of streams to assess their current dynamic states for purposes of restoration design or stabilization. In addition, a better understanding of benches will add to the general understanding of bank reconstruction processes, and the occurrence of historical contingency with respect to modern morphologies.

Most studies to-date have emphasized potential linkages between benches, hydroclimatological regimes, and past or current discharge/sediment load imbalances (Kilpatrick & Barnes, 1964; Warner, 1987; Hupp & Osterkamp, 1985; Royall *et al,* 2010; Schumm, 2005). However, such controls can be mediated in different ways by relative adjustments in the four principle components of reach-scale channel form: cross-section form (shape and size), bed configuration, channel slope, and planform shape (Knighton, 1998; Phillips, 2007). The channel slope and bed configuration of the upper Yadkin River at Patterson are constrained by bedrock control, leaving cross-section form and planform dimension as the primary factors in reach adjustment. The study reach has developed in-channel alluvial benches paired with an anabranching planform. The goals of this study are:

1. To evaluate the influence of anabranching on the characteristics of in-channel benches at this site,
2. To determine the relationship between current bench-full flows and other flow stages cited as important to channel form, i.e., the bankfull stage and mean annual discharge,
3. To compare the characteristics of current benches to those reported by Kilpatrick and Barnes (1964) for the same site 50 years earlier in order to constrain rates of change.

CHAPTER II

LITERATURE REVIEW

Alluvial Benches

Erskine and Livingstone (1999) define benches as being spatially disconnected, flat, attenuated, and generally bank-attached bodies of alluvium deposits that can be found below the level of the valley flat. In-channel benches, those below the general elevation of the valley flat, are constructed by the deposition of sediment transported by streams during moderate, i.e. bankfull, flood events (Erskine & Livingstone, 1999). The internal structure of in-channel benches can be varied, such as single benches that are purely depositional features built solely through vertical accretion of sediments to multiple bench structures which are nested against each other and can possess a variety of core structures (Royall *et al*, 2010). The lowest in-channel benches are ultimately ephemeral in nature and serve only as temporary storage of sediment, though in-channel benches situated higher above the water surface will presumably store sediment for longer periods of time than lower benches which are destroyed and created more frequently (Erskine & Livingstone, 1999).

Climate may play a pivotal role in the creation and destruction of in-channel benches. Erskine and Livingstone (1999) found that catastrophic floods during decades characterized as being flood-dominated were primarily responsible for the destruction of in-channel benches. Warner (1995) stated that the mean annual floods found in New

South Wales are often twice the magnitude of floods with the same recurrence interval during drought-dominated regimes. The primary reaction of channels to flood-dominated regimes is a shift from sediment storage in benches due to common bank erosion into bed aggradation and the filling in of pools while simultaneously moving sediment downstream or out of the flood-dominated system (Warner, 1987). During drought-dominated regimes, the lower discharge values allow for the steady creation of bench structures, and the resulting narrowing of the channel creates velocity increases towards the center of the channel that helps to increase the channel depth (Warner, 1987). The creation and destruction of in-channel benches at Warner's (1987) Australian sites are thought to be responses to major regime shifts in discharge, in the form of adjustments within the channel and on the floodplain itself; however, the speed of this response can vary greatly based on the type of sediment being stored within the stream channel and in mixed-load channels complete adjustment to new discharge levels present in flood dominated regimes may never be made manifest (Warner, 1995).

In-channel benches can superficially resemble the incised channel with abandoned terraces and inset flood plain described in the Simon model (1989), which presents a generalized sequence of how streams reach a new equilibrium state via physical readjustments of stream dimensions and structures after some form of perturbation. Such disturbances can include channelization, removal of vegetative cover, and increase in runoff; all of which can be found in urban reaches of streams (Doll *et* al, 2002).

Little effort has been made to empirically relate the stratigraphy of in-channel benches to their physical origins. Erskine and Livingstone (1999) used the descriptive classes' *stratic, massive,* and *cumulic* to attempt to differentiate between the four main levels of benches found in their study. Stratic benches contain stratified layers of silts and sands, massive being "multiple, thick, uniform beds ranging from cobble and pebble gravels to sands and silty sands" (Erskine & Livingstone, 1999). Many of the sediment types described in their classes were commonly found in multiple levels of benches and being common in lower bench levels closer to the baseflow stream surface, with the best stratification presenting in the mid-level benches, while the cumulic type was common in the benches closer to the higher and larger apparent flood plain and composed uniform, finer grain sediments with apparent organic influence (Erskine & Livingstone, 1999). Royall *et al* (2010) noted the higher bench levels contained fewer flood couplets and are much less stratified than lower levels.

While there has been relatively little effort to explain the rate of construction of in-channel benches, many view lower benches as being potentially linked to drought-prone hydroclimatic phases in which lower discharge values and smaller flood events can redistribute bedload sediment laterally (Erskine and Livingstone, 1999; Royall *et al*, 2010), although many of these benches appear to exist at heights that exceed the mean annual discharge of the streams during a drought prone stage. Thus, the more frequently explored rates of construction of lower in-channel benches are still questionable. The sites studied by Erskine and Livingstone (1999) in Australia are much more climatically extreme, and hydrologically variable than those found in the Piedmont region of North

Carolina, so the formation of Piedmont in-channel benches may not follow the same modes of genesis as those suggested by the Australian research.

Anabranching Streams

An anabranching river is "a system of multiple channels characterized by vegetated or otherwise stable alluvial islands that divide flows at discharges up to nearly bankfull" (Nanson and Knighton, 1996). Anabranching streams are uncommon, and particularly so in the southern Piedmont, although it has been suggested that anabranching in Piedmont streams has been more common in the past (Walter and Merritts, 2008). The division of flow between branches permits only fractions of the streams' discharge to run through each channel, influencing the dominant major control on bench creation and morphology. Nanson and Knighton (1996) describe anabranching channels primarily based on stream power, but further characterize these types based on fluvial morphology, sedimentology, and processes. Under the Nanson and Knighton classification system, the Yadkin River at Patterson would be classified as a Type 6 channel. Type 6 channels are characterized as being gravel-dominated and stable rivers, having typically small drainage areas that respond rapidly to rainfall events (Nanson and Knighton, 1996). Channel stability is insured by boulder deposits intermixed with finer alluvium and bound by roots; finer deposits of alluvium are often protected from stream power due to lag-cobble surfaces or fallen macro-organic debris (Nanson and Knighton, 1996).

Anabranching channels often do not persist either temporally or spatially, and it is possible that very specific conditions may control the process (Nanson and Knighton, 1996). Multiple factors commonly operate simultaneously in order to create anabranching channels. These factors are stable, erosionally resistant banks, a highly variable flood-prone flow regime, and the presence of some form of flow displacement from the channel onto the flood plain. Erosionally resistant banks limit the rate at which the channel can adjust to variances in flow and sediment load, and also limits the rate at which the channel migrates (Nanson and Knighton, 1996). When this factor operates in concert with highly variable flood flows, it creates the preconditions for the avulsion of the flow out of the dominant (west) branch and onto the flood plain (Nanson and Knighton, 1996).

Miller (1991) described the pool-riffle structure of the primary channel of a Type 6 anabranching channel in Indiana as being alternating concave-up and convex-up, with the convex-up portions being dominated by coarse alluvium with grain diameters less than 20cm, and the largest material exceeding 60cm. The channel banks and bench deposits in these streams are typically dominated by finer alluvium, with a tendency towards fining upwards (Miller, 1991). Upstream reaches of auxiliary channels in Type 6 anabranching channels are typically reduced in channel depths, due to the deposition of material caused by reduced flow velocities (Miller, 1991). The remainder of the auxiliary channel may be dry or have limited flow during low flow periods (Miller, 1991).

CHAPTER III

STUDY AREA DESCRIPTION

The study area is the Yadkin River at Patterson, NC, which is located in Caldwell County. It possesses a permanent real-time USGS streamflow gage site, which has been active since 1939, and thus possesses a long-term daily streamflow data set. As an area with benches, this study area was first documented by Kilpatrick and Barnes (1964) who observed numerous in-channel benches. Kilpatrick and Barnes labeled this study area as Site #15 in their study (1964). Numerous benches are also observed at this location currently, and each is inset below one or more higher benches, the highest of which extends across the entire valley and was interpreted as a terrace by Kilpatrick and Barnes (1964). The Yadkin River principally flows through the central Piedmont section of North Carolina, which is underlain by a wide variety of rock types, but principally schists and amphibolites, mafic and felsic gneisses, and intrusive bodies (Royall *et al*, 2010). The Yadkin River at Patterson additionally flows through a narrow band of clastic metasedimentary and metavolcanic rock in the mountain physiographic region (Figure 1).

The Upper Yadkin at Patterson is a fully alluvial river flowing through a wide floodplain, which cuts down to shallow bedrock locally within channels. The bedrock serves as a control on reach slope, thus forcing the river to adjust primarily through planform shape and cross-sectional area; i.e., via sinuosity changes and anabranching and through vertical and lateral accretion and erosion of channel banks.

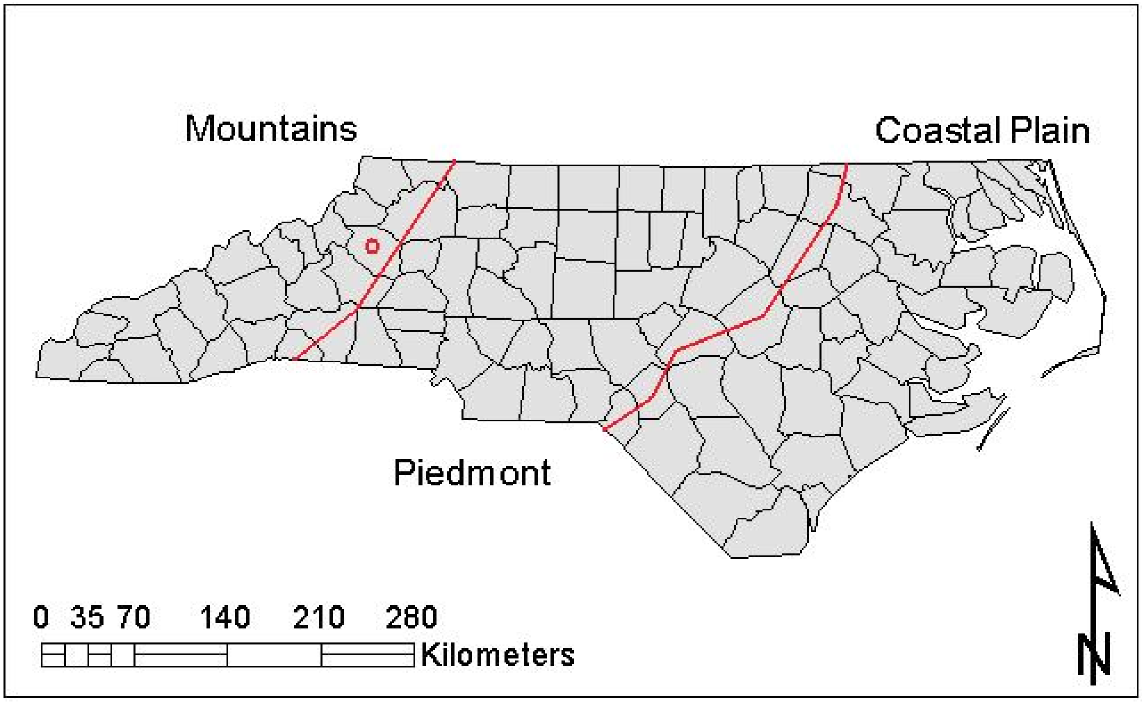


Figure 1: Location of the study area in relation to the major physiographic provinces in North Carolina.

This section of the Upper Yadkin displays a pattern of alternating concave-up and convex-up reaches, corresponding to pool and riffle structure. The average annual precipitation for this Piedmont area of North Carolina is a generally evenly (annually) distributed 114 to 127 cm. The drainage area for this site is 74.59 km^2, with a mean annual discharge of 1.39 m^3/s (Figure 2), and a mean annual flood of 53.49 m^3/s. This would have a recurrence interval between 3.68 and 3.88 years.

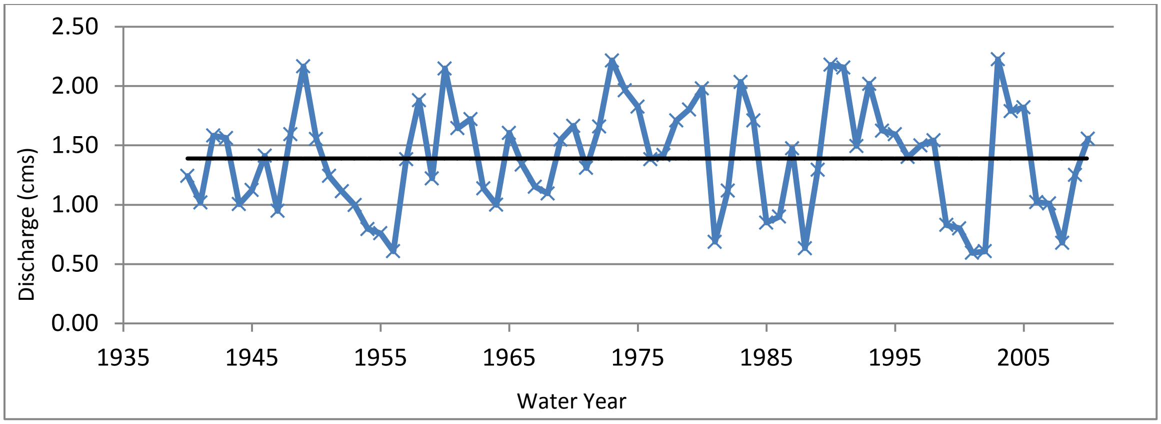


Figure 2: Mean Annual Discharge and Yearly Average Discharge (data obtained from USGS)

Figure 3: Yadkin River at Patterson, located in Caldwell County, North Carolina.

Bench Stratigraphy

Excavations of in-channel alluvial benches at one site, which was designated as "Site II", reveal variations in stratigraphy with height above channel, and that bench levels, at least at this site, represent discrete units that are structurally distinct from adjacent levels. The pit in the lowest bench exposed alternating layers of sands and a silt and sand mixture. These layers are approximately 6 to 7.5 centimeters in thickness with abrupt boundaries. Localized deposits of organic material were common in all layers. Layer thickness decreased with increasing depth, until reaching consolidated sands with gleyed material within (Figure 4). Accretion was vertical at the top of the bench but trended towards oblique as the pit neared the river, suggesting that both vertical and lateral accretion are important in bench formation at this locale.

The second level bench at Site 2 was not well stratified, although it did possess an abrupt transition from a sandy-silt layer to a silty-sand layer. The third level bench at Site 2 was composed primarily of a consolidated silt and sand mix with little to no stratification. It thus appears to be a result of a slack water deposit under high flow conditions. These findings correlate well with previous findings that higher benches are most likely to be massive or weakly stratified (Erskine & Livingstone; 1996; Royall *et al*, 2010). No particles larger than coarse sand were encountered during excavation on any of the pits. As a result of these excavations, it was determined that benches along this reach of the Yadkin are being actively created via accretion processes.

Figure 4: Pit Excavation of the lowest bench level at Site 2.

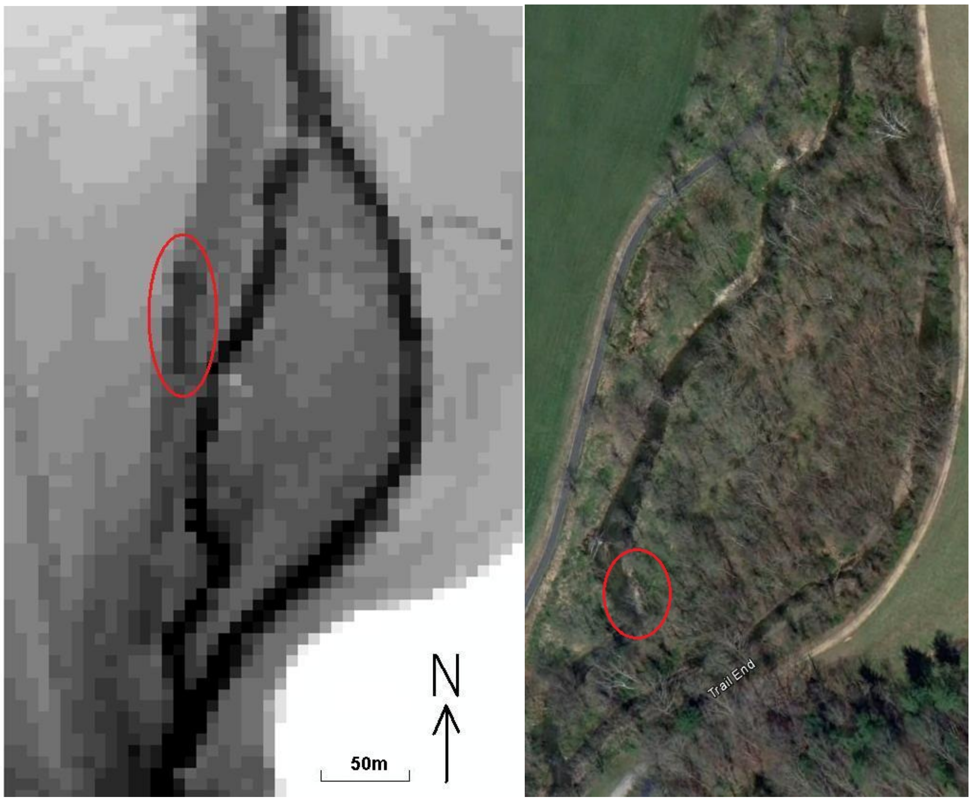


Figure 5: Digital Elevation Model (DEM) of the Yadkin River at Patterson (left), marshy area circled. Relict channel positions are visible west of the dominant (west) branch. Satellite photo of the Yadkin River at Patterson (right), with Site 2 circled.

While the channel location in this reach of the Yadkin at Patterson has been relatively stable over the past 20 years, the terrain adjacent to the dominant (west) branch has morphological features which pertain to historic channel position. The digital elevation model (DEM) in Figure 5 shows the current channel position and flood plain, as well as a marshy area immediately adjacent to the dominant (west) branch. This marshy area is an abandoned stream channel (slough) from previous anabranching or possible from a time prior to anabranching in which all flow was through this floodplain portion. The DEM shows that the island is low enough in elevation to be flooded by the Yadkin River during large flow events. The alluvium within the channel itself is dominated by gravels and cobbles, with few boulders. Stage response to precipitation events is rapid. These factors, combined with the small drainage area above the site, allow the site to be classified as a Type 6 anabranching stream under the Nanson and Knighton classification system (1996).

CHAPTER IV

METHODOLOGY

All in-channel alluvial benches were mapped between the discharge gage and the upstream bifurcation of flow into the two branches. Benches were measured for both length and average width, and a cross-sectional survey for each bench was done focusing solely on that portion of the cross section below and up to the top of bench. Channel roughness data were obtained during this period as well, for determining Manning's n.

The cross-sectional data were used in conjunction with the roughness and elevation data to calculate bankfull discharges for each cross-section. Discharges can be indirectly estimated for flows at sites without gages, and to estimate discharges at specific stages by using the Manning Equation after obtaining cross-sections, roughness values and channel gradient (Gordon *et al*, 2006). The original Manning Equation for average velocity estimation is:

$$V = \frac{1}{n} R^{.66} S^{.5}$$

where V is velocity in meters per second (m^3/s), n is Manning's coefficient for channel bed roughness, A is the cross-sectional area in square meters (m^2), R is the hydraulic radius in meters (m), and S is the (dimensionless) slope or gradient (Gordon *et al*, 2006). R is calculated by dividing the cross-sectional area under study by its wetted perimeter.

Finally, discharge, or Q is calculated by multiplying the product of the Manning equation (velocity) by the cross-sectional area being studied. I used a roughness coefficient (Manning’s n) of 0.04 and a field measured average gradient of 0.004421. Manning's n was selected after consulting a chart of Manning's N values, based on criteria which most closely approximated the conditions at the study site (Gordon *et al*, 2006), this being a mountain stream by virtue of its location within the Mountain physiographic region, as shown in figures in multiple publications (Kilpatrick & Barnes, 1964; Royall *et al*, 2010; Harman *et al*, 2000) and in Figure 2. This site has no vegetation in the channel, with a streambed composed primarily of gravel, cobbles, and few boulders. In order to apportion the total discharge measured at the gage into individual contributing discharges from each of the upstream branch, I calculated a flow division ratio based on the bankfull discharge calculated by the Manning equation for each channel as estimated from the heights of the most prominent benches. When one of the resulting discharges is divided by the sum of both discharges (*Qtotal*), this creates the ratio of flow required in order to match the flow data and resulting recurrence intervals from the USGS gage.

These individual ratios in decimal format sum to 1, which is representative of the total discharge observable at the gage. Transforming the individual discharges calculated using the Manning equation requires dividing the discharge calculated at a single bench level by the proportion of the total ratio estimated for that branch, which creates a total discharge which would be equal to the total discharge observable in both branches of the river during that flow event. This ratio was used to transform benchfull flows calculated for the first level benches at all cross-section sites, as well as terraces 2, 3, and 4 when possible. These flows were matched up against an Annual Maximum Series (AMS) created using all available maximum daily values from the USGS stream gage at the site to determine recurrence intervals for each benchfull flow. These data were then compared to historical data from the Kilpatrick and Barnes (1964) study.

CHAPTER V

RESULTS & DISCUSSION

Bench Occurrence and Morphology

There are five In-channel benches locations in each of the two anabranched channel, plus one location at the gage below the anabranch confluence for a total of 11 in-channel alluvial bench sites surveyed (Figs. 6 and 7-19). All benches were accompanied by at least one single higher bench and two locations (Site I and II; Figs. 6-9) exhibited more, although only the lowest inset benches, which are the principal feature of interest in this research, were surveyed at most sites.

The dominant (west) branch (west branch) contains the two largest benches studied, sites 4 and 6, both of which are located on the outer channel bank (as opposed to the island-side) (Fig. 6). Sites IV and VI also have largest widths surveyed (Table 1). The remaining two smaller benches are located on the island side, alternating sides with the larger benches and indicating an earlier period of lower sinuosity in the upper portion of the branch. Sites III through VI on the dominant (west) branch are located within 120 meters downstream of the channel bifurcation; the fifth being located 242 meters downstream. In-channel alluvial benches located along the dominant (west) branch are consistently paired with an opposing sheer channel wall, and are depositional features forming at the insides of channel bends (i.e., point bar locations), with the exception of Site II, which presents as a concave bench.

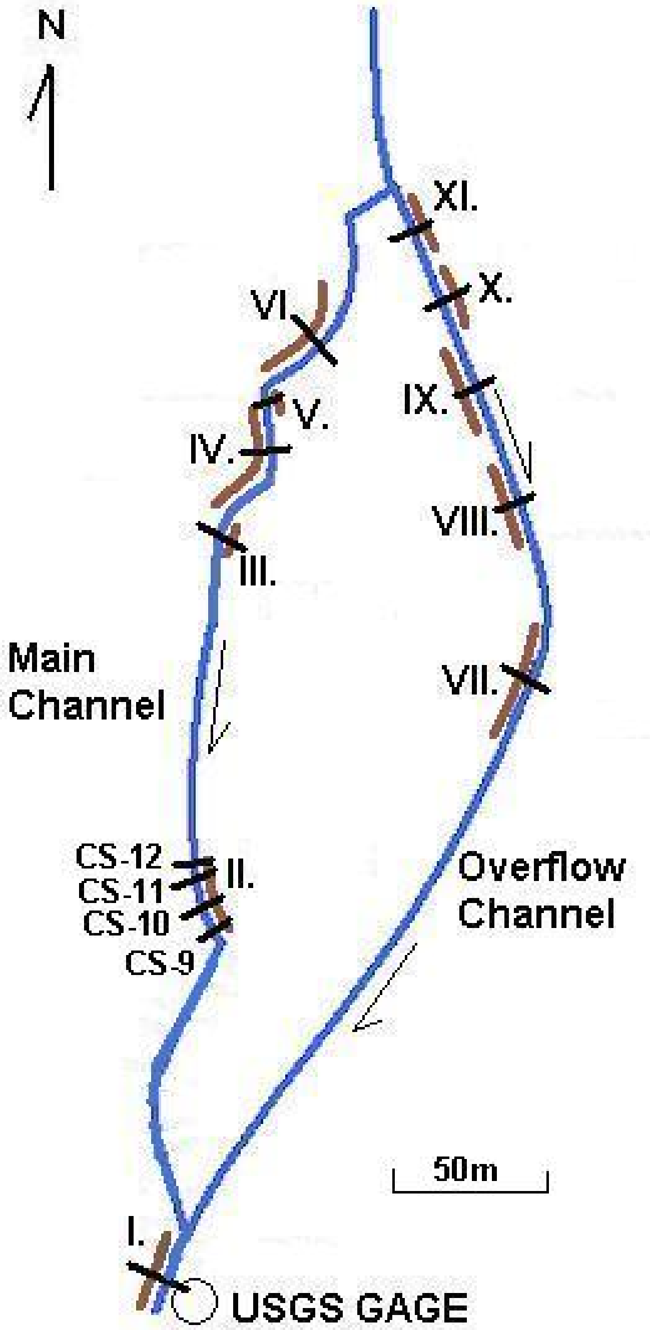


Figure 6: Relative position of all cross-section sites studied. Individual cross-section sites are labeled from I to IX. Site II has multiple cross-sections, which are sub-labeled as CS-9 through CS-12.

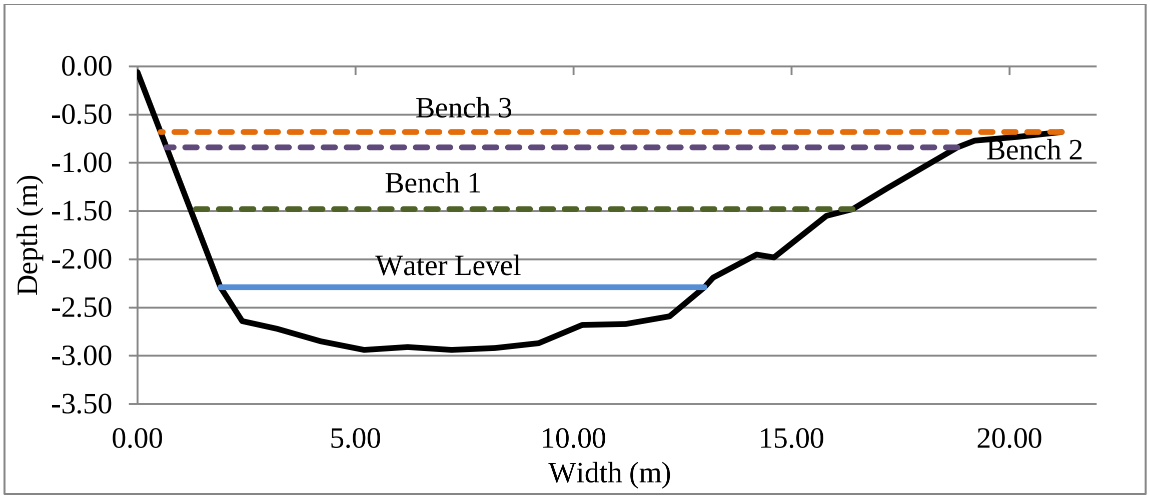


Figure 7: Site I Cross-section (above) and image (below). Dashed lines indicate the stage height of a benchfull flow matching that of the associated bench.

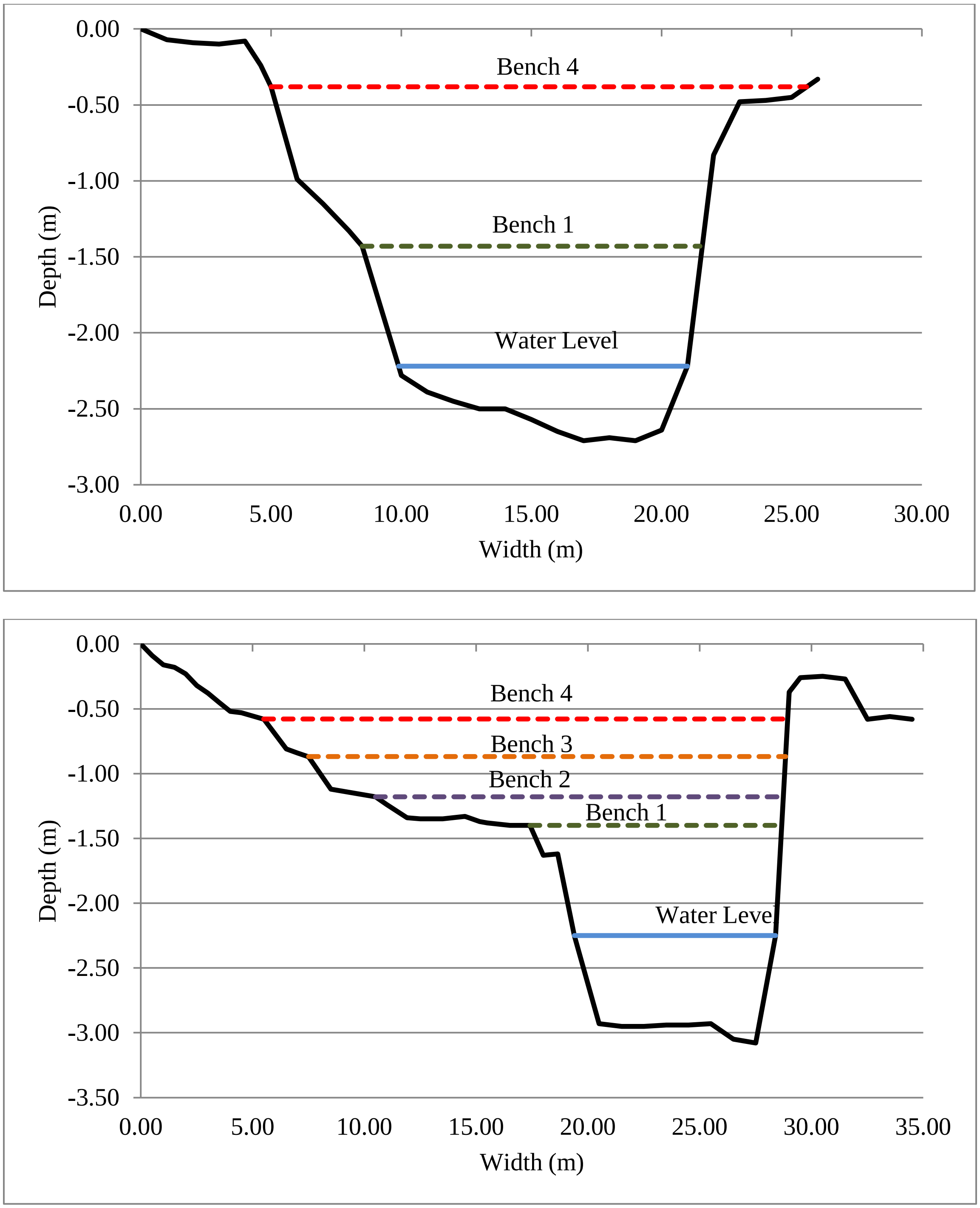
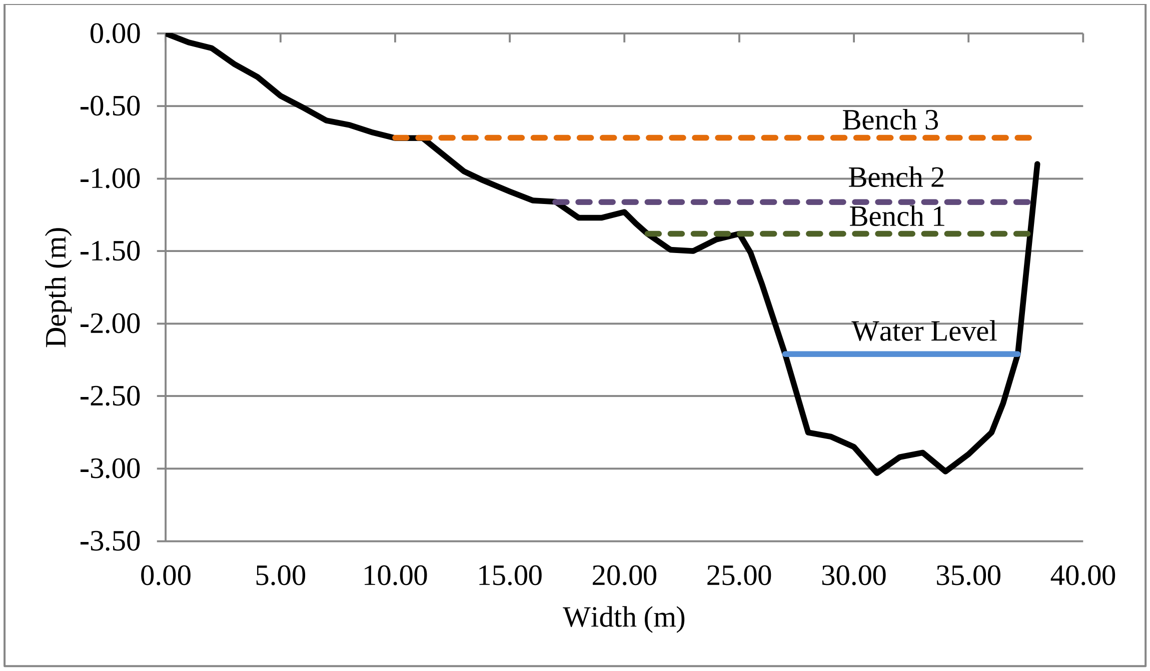


Figure 8: Cross Sections for Site II: CS-9(above) and CS-10 (below). Benches heights equal to benches 2 & 3 at CS-9 were not observed. Dashed lines indicate the stage height of a benchfull flow matching that of the associated bench.



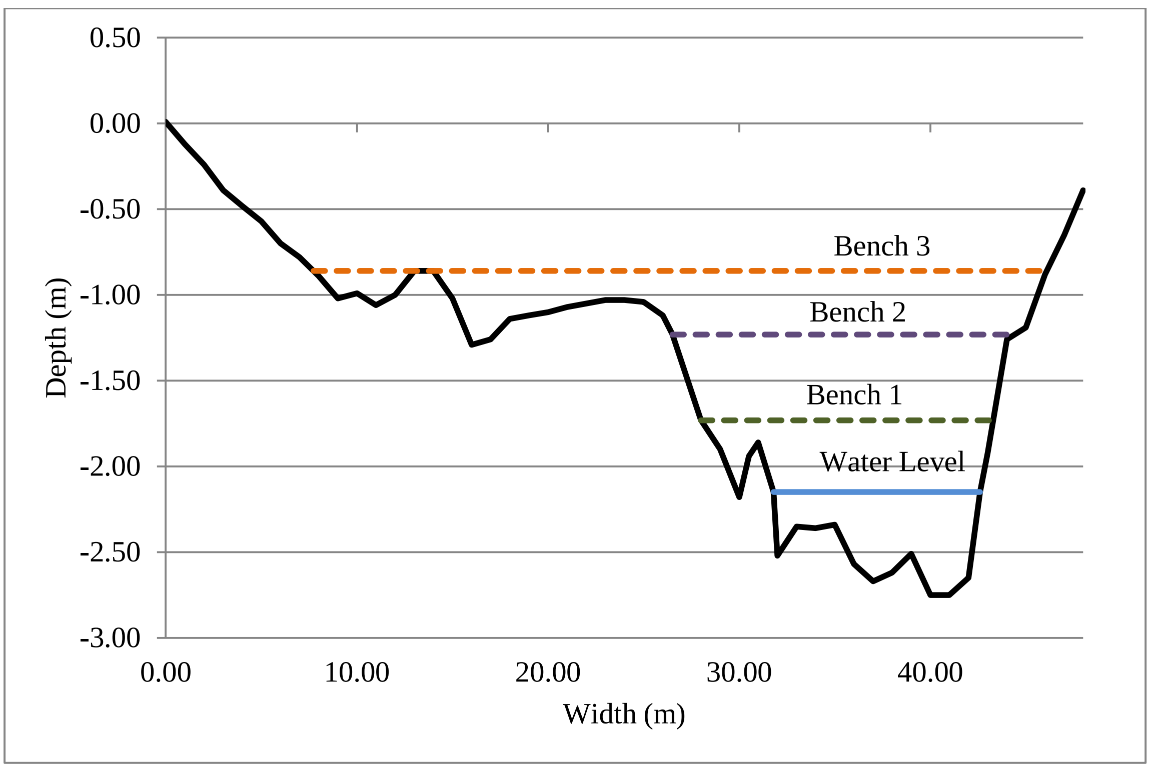


Figure 9: Cross Sections for Site II: CS-11 (above) and CS-12 (below). Dashed lines indicate the stage height of a benchfull flow matching that of the associated bench.

Figure 10: Image of Site II.

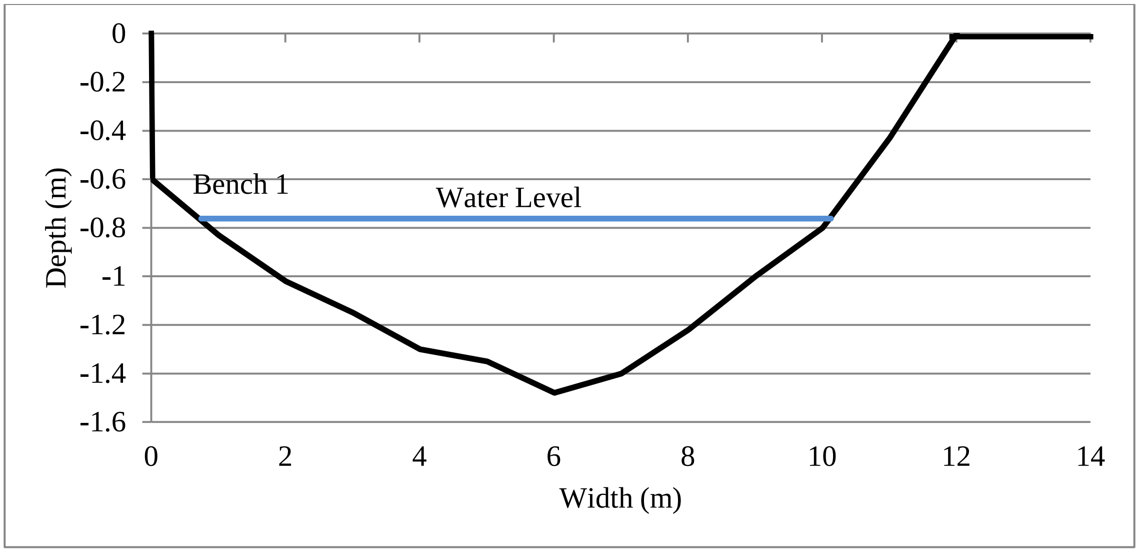


Figure 11: Site 3 Cross-section (above) and image (below).

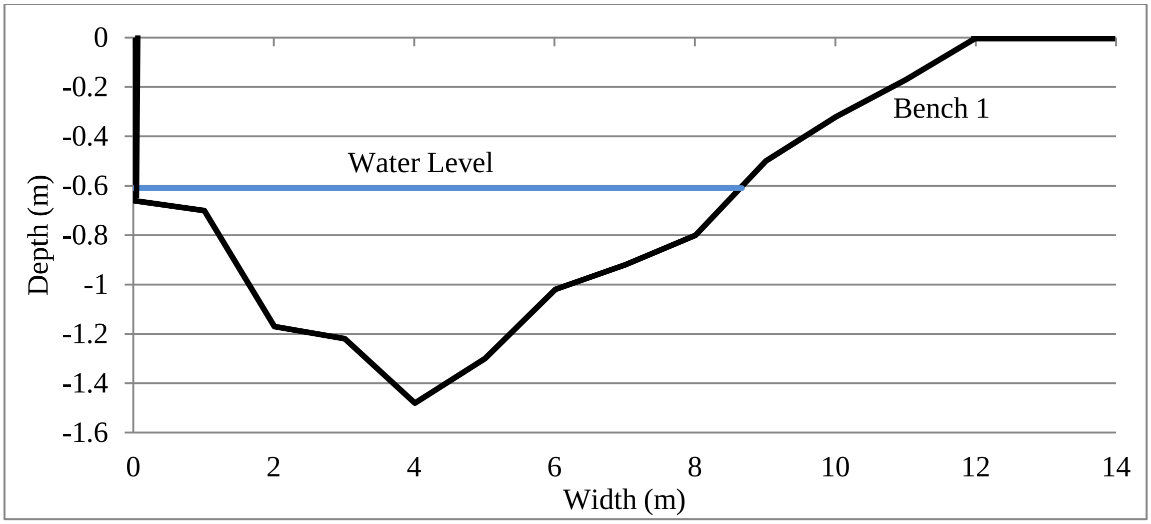


Figure 12: Site 4 Cross-section (above) and image (below).

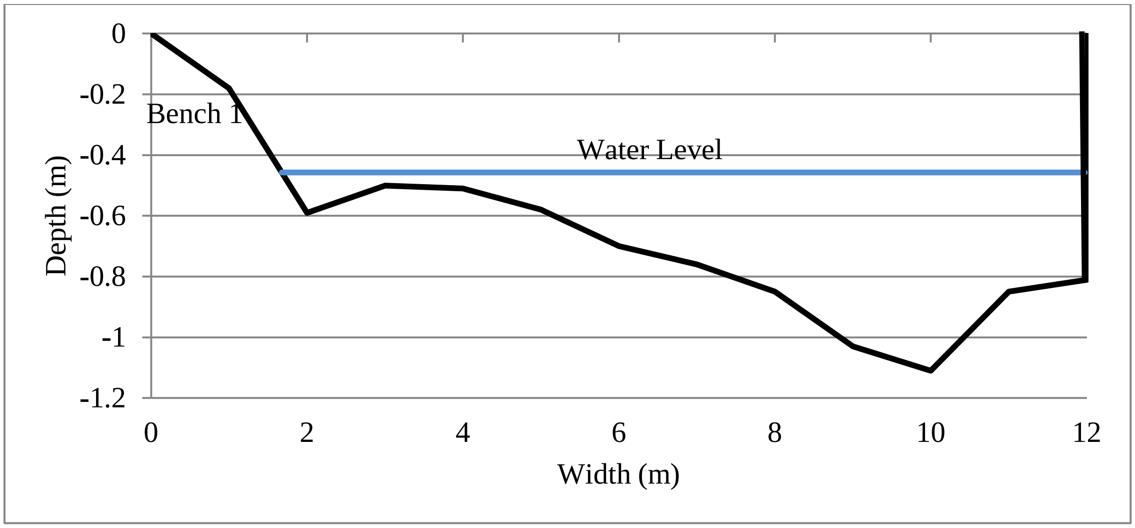


Figure 13: Site 5 Cross-section (above) and image (below).

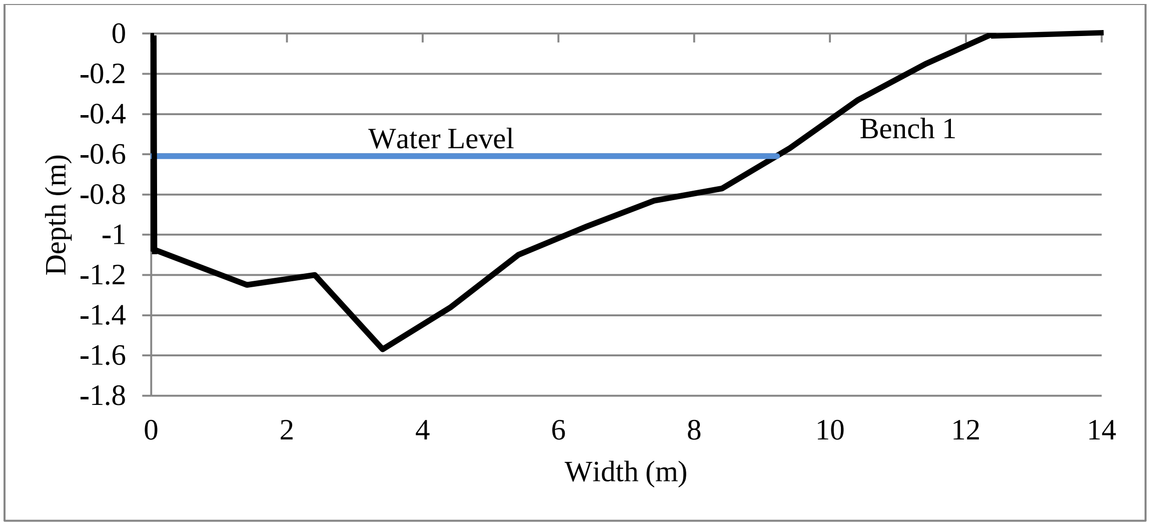


Figure 14: Site 6 Cross-section (above) and image (below).

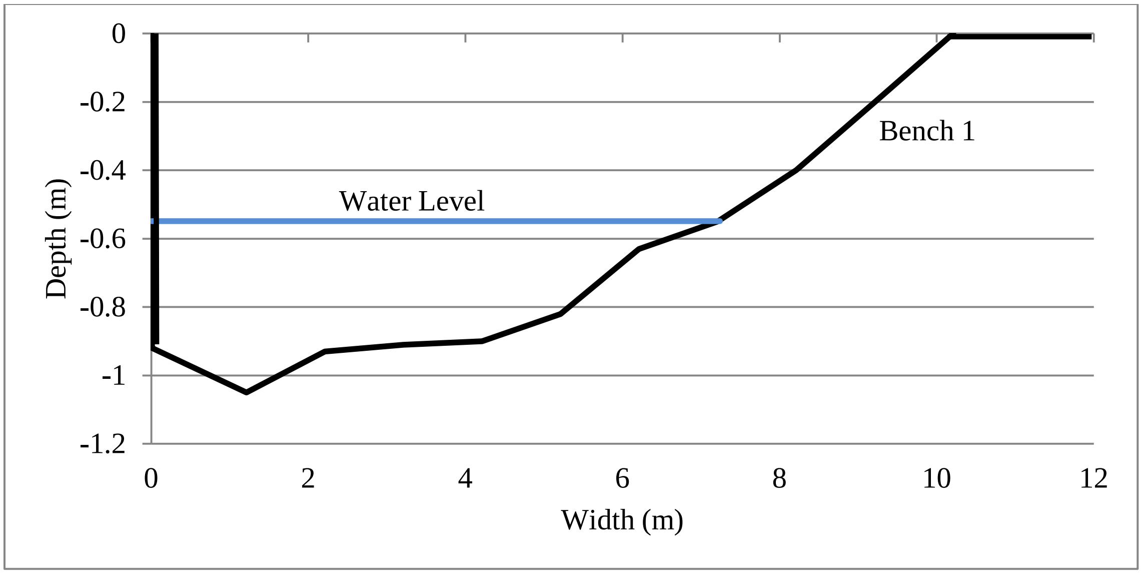


Figure 15: Site 7 Cross-section (above) and image (below).

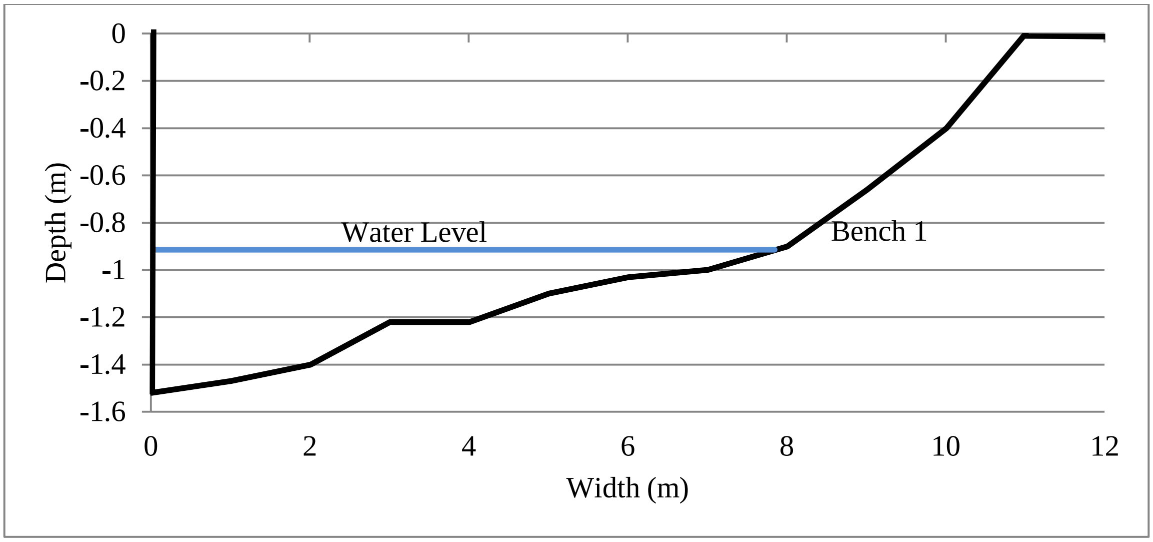


Figure 16: Site 8 Cross-section (above) and image (below).

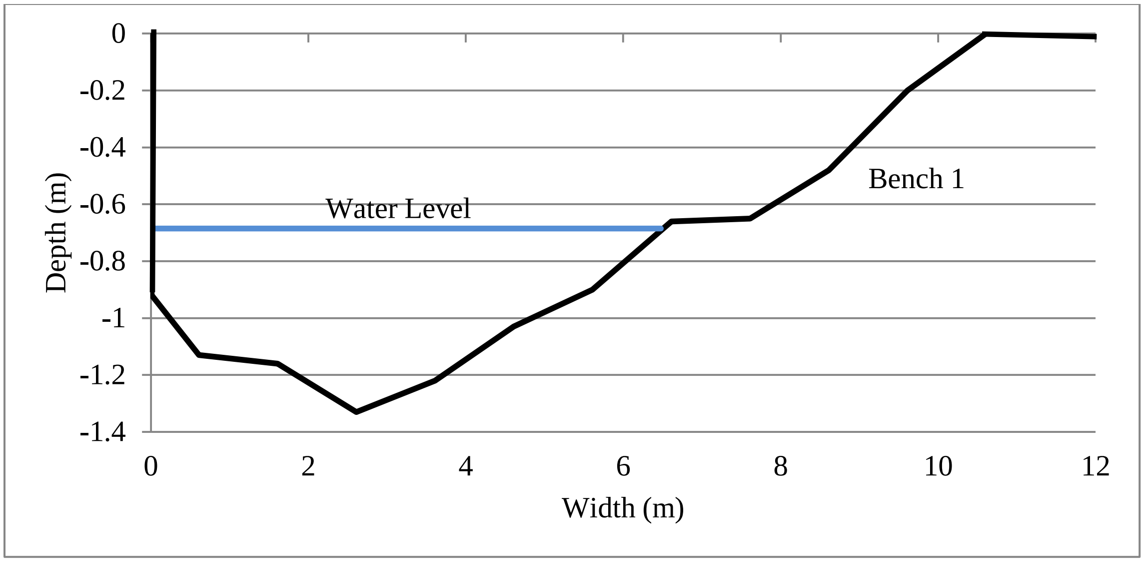


Figure 17: Site 9 Cross-section (above) and image (below).

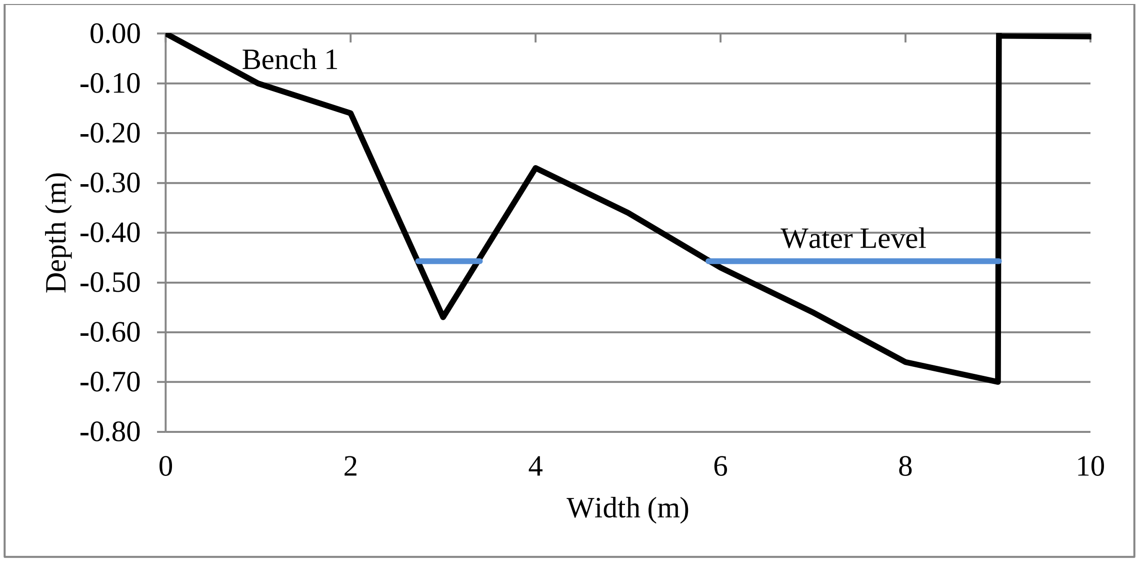


Figure 18: Site 10 Cross-section (above) and image (below).

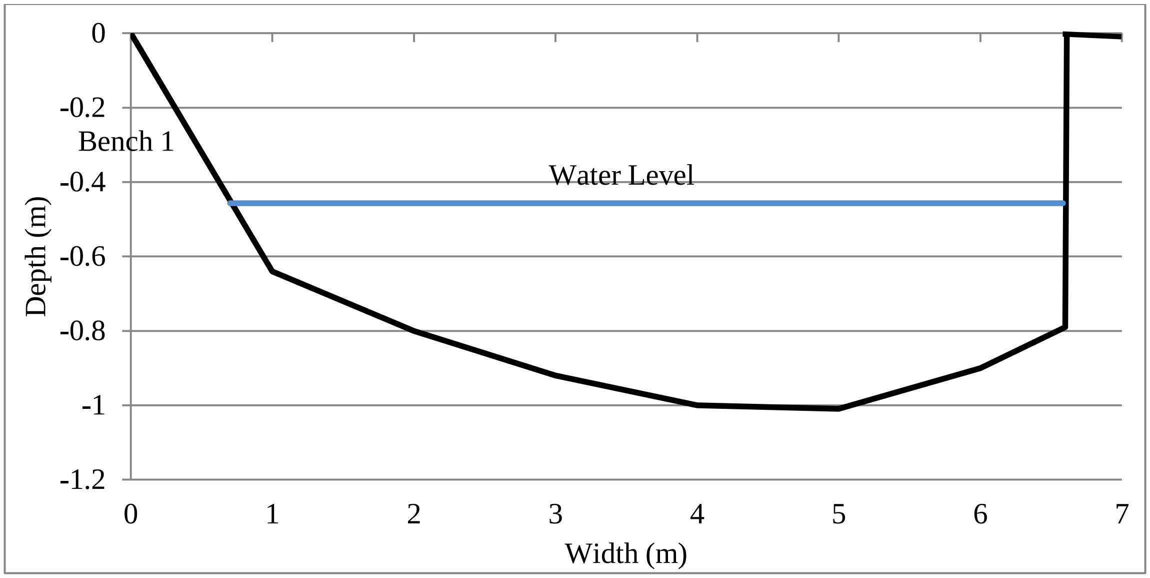


Figure 19: Site 11 Cross-section (above) and image (below).

Table 1: Measurements for benches at each surveyed site. Dimensions are only for the lowest bench observed. The lowest bench at Site 2 is the same feature across all cross-sections; the bench height used is an average of four observed bench heights from all sub-cross-sections.

	Length (m)	Width (m)	Area (m^2)	Height (m)	
Site 1	36.00	0.85	30.60	1.00	
West Branch	Length (m)	Width (m)	Area (m^2)	Height (m)	Total Area (m^2)
Site 2	36.00	1.00	36.00	1.27	176.75
Site 3	18.00	1.50	27.00	1.10	
Site 4	26.50	1.90	50.35	1.10	
Site 5	8.00	1.50	12.00	0.70	
Site 6	25.70	2.00	51.40	1.00	
Average	**22.84**	**1.58**	**35.35**	**1.12**	
East Branch	Length (m)	Width (m)	Area (m^2)	Height (m)	Total Area (m^2)
Site 7	22.50	1.25	28.13	0.90	139.13
Site 8	22.30	1.50	33.45	1.20	
Site 9	25.40	1.38	35.05	1.00	
Site 10	22.50	1.00	22.50	0.50	
Site 11	20.00	1.00	20.00	0.80	
Average	**22.54**	**1.23**	**27.83**	**0.88**	

Average height above bed for low benches along the main (West) channel is 1.12 meters, which is almost identical to that found for the lowest bench by Kilpatrick and Barnes (1964) of 1.1 meters. Older channel walls backing in-channel alluvial benches frequently show scour signs. Pool & Riffle structures are common in the dominant (west) branch, with some rapids being initiated by exposed bedrock and propagated by large cobbles, indicating the presence of structural control on the locations of both rapids and riffles.

The rapids in both the main (West) anabranch channel and the overflow anabranch channel (to the East) contain bedrock outcrops with strike coincident with the SW-NE trend of regional bedrock structure. One rapid and four paired pool and riffle structures were observed in the main anabranch channel. Average water depth in riffle structures is shallow at 0.37 m during winter base-flow conditions of 0.85 m^3/s. The two largest pool and riffle structures are located in the same 120m downstream distance from the bifurcation as Sites 3 through 6, with Site 6 located in the first riffle structure downstream of the bifurcation, and Sites 3 and 4 located in the second pool-riffle structure. These pools can have depths of 1.52 meters during winter base-flow conditions.

The overflow channel contains sites 7 through 11 (Fig. 6). Sites 10 and 11 are located on the outer channel bank side, and sites 7 through 9 are located on the island side. Sites 7 through 9 are also the largest benches located in the overflow channel, having lengths that are nearly the same as the channel average but with higher than average widths. Height above bed for low benches in the overflow (East) channel ranges from 0.5 – 1.2 m, and thus is generally lower than that documented for low benches by Kilpatrick and Barnes (1964) of 1.1 m and the similar value found for the dominant (west) branch. In-channel alluvial benches in the overflow channel exist primarily in reaches of the channel that are straighter than those of the dominant (west) branch. The overflow channel is approximately 386 meters long, and all five benches surveyed were located within the first 200 meters downstream of the channel bifurcation. Pool & riffle structures occur somewhat more frequently in the overflow channel than in the dominant (west) branch, with six paired pool & riffle structures, and one rapid observed. Pool and riffle structures and bedrock outcrops become more dominant downstream of the same 200 meter mark where in-channel alluvial bench formation terminates, which coincides with increased channel gradient from that point to the outflow point back into single, primary channel. Pool & riffle structures are shallower in the overflow channel, with depths of 0.35 meters and 0.17 meters respectively during winter base-flow conditions.

Current & Historic Benchfull Flood Frequencies

A single bench site was chosen from each channel branch to serve as being representative of the low bench benchfull stage for that channel in order to calculate the flow bifurcation ratio, as calculations for the discharge for each bench would only meet a fraction of the total discharge recorded by the gage downstream, due to the total flow being divided between the two channels. Site 4 was chosen as representative for the dominant (west) branch, and Site 11 was chosen as being representative for the overflow channel, these being the benches on each channel having the best all-around bench expression as probable bankfull flow benches. Benches at these sites are in upstream reaches, where it is more likely that benches are genetically related to anabranch processes, and have prominent and simple morphologies with easily defined edges and heights. Site 4 is at a point bar location, where maximum elevations are widely considered the best indicators of bankfull stage (Dunne and Leopold, 1978). Site 11, although not a classic point bar location, exists at the inner bend of the channel bifurcation which would have accreted laterally in response to the right-hand bend in flow direction into the west channel similar to a point bar. A flow bifurcation ratio based on estimated benchfull discharge was calculated for both channels at 66/34 in favor of flow being directed into the dominant (west) branch. This flow division is also close to that calculated using averages of all calculations of benchfull flows derived from each branch.

Kilpatrick and Barnes (1964) determined recurrence intervals and discharges based on their own field surveys, and these compare favorably with the findings of this study. Kilpatrick and Barnes found that the lowest bench, which they describe as predominant and the floodplain equivalent, had an average benchfull discharge of approximately 32.56 cubic meters per second (m^3/s) with a matching recurrence interval of 1.8 years (Table 2). These values are similar to those calculated for benches in the anabranching reach today which have a benchfull recurrence interval averaging about 1.5 years. These values also coincide with the commonly cited recurrence interval for bankfull flows in eastern U.S. streams of 1-2 years (Dunne & Leopold, 1978), indicating the likelihood that all low benches in the current survey represent incipient floodplain fragments as opposed to morphologically similar but lower channel shelves (Hupp & Osterkamp, 1985) associated with the mean annual discharge, or other lower flow (Figure 20). The next higher bench, which then may be rightfully acknowledged as a terrace, also matches well with Kilpatrick and Barnes (1964) data, with an average discharge of 44.73 m^3/s and a recurrence interval of 3.2 years.

However, these studies' numbers vary greatly for the higher third and fourth level benches, which are also terraces, with Kilpatrick and Barnes (1964) reporting an average discharge greater than 141 m^3/s for their second highest bench and this study having a discharge of approximately 93 m^3/s for Bench 4.

Table 2: Top; Kilpatrick & Barnes Benchfull flows and Recurrence Intervals (1964). Bottom; Study Benchfull Discharges, Ratio Discharges, and Recurrence Intervals. All discharges in m³/s.

	Bench 1	Ratio	RI	Bench 2	Ratio	RI	Bench 3	Ratio	RI	Bench 4	Ratio	RI
Kilpatrick & Barnes	32.56	N/A	1.80	44.73	N/A	3.20	147.23	N/A	13.7	308.61	N/A	90.0
SITE 1	26.48	N/A	1.59	54.87	N/A	3.88	60.52	N/A	4.11			
WEST BRANCH												
SITE 2												
cs9	21.30	32.27	1.89							61.82	93.67	7.77
cs10	20.25	30.69	1.84	27.52	41.70	2.91	41.33	62.62	4.11	57.90	87.73	6.36
cs11	24.27	36.78	2.26	30.83	46.71	3.50	52.83	80.05	5.00			
cs12	11.60	17.57	1.25	28.85	43.71	3.33	38.45	58.26	3.88			
SITE 3	19.82	30.04	1.79									
SITE 4	13.87	21.02	1.32									
SITE 5	9.80	14.84	1.14									
SITE 6	16.07	24.34	1.52									
EAST BRANCH												
SITE 7	8.63	25.38	1.55									
SITE 8	7.89	23.22	1.49	17.09	50.27	3.50						
SITE 9	8.35	24.56	1.55									
SITE 10	2.93	8.62	1.03									
SITE 11	6.99	20.56	1.32									

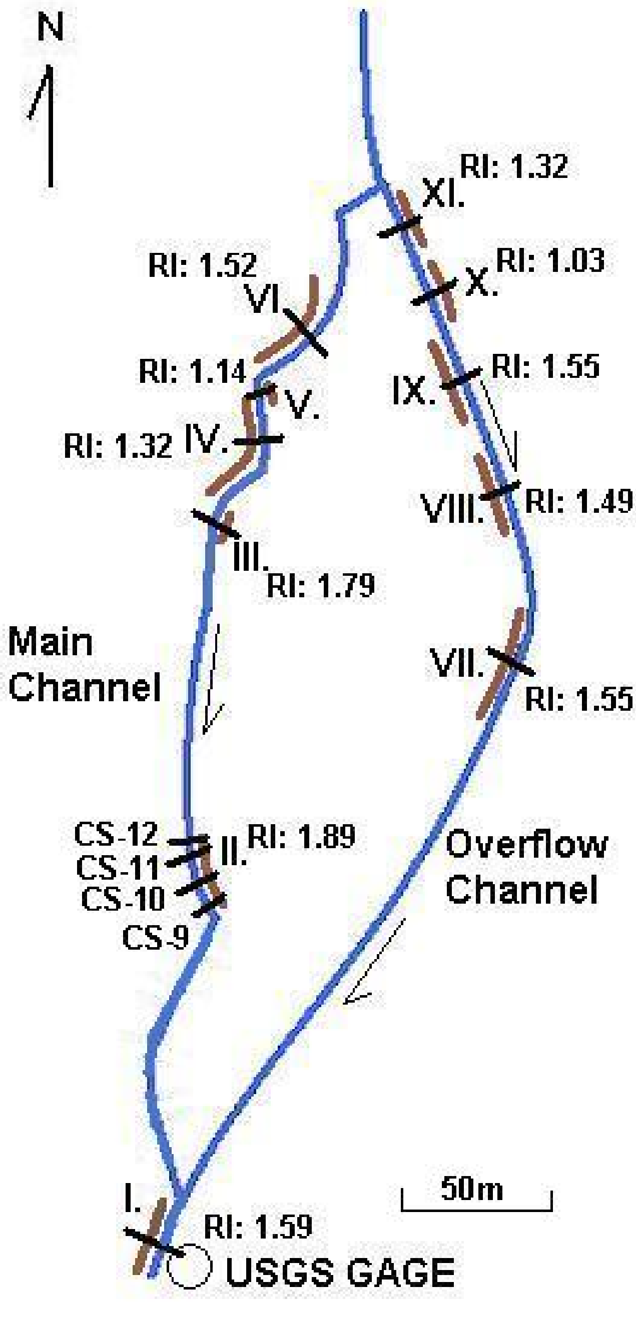


Figure 20: Relative position of all cross-section sites studied. Individual cross-section sites are labeled from I to IX. Site II has multiple cross-sections, which are sub-labeled as CS-9 through CS-12. Recurrence Intervals for each site are labeled as RI.

The most logical explanation for this difference is that the third and fourth level benches observed in the current study are not the third and fourth benches observed by Kilpatrick and Barnes. This is because this study used the third and fourth benches observed on the mid-channel island, upstream of the gage, and these benches may be representative of smaller discharges which shape bench formation on the island itself and not the larger benches found on adjacent apparent flood plain, which would have larger recurrence intervals. Kilpatrick and Barnes standard methodology involved performing cross-sectional surveys both up and downstream of the gage, so it is equally likely that the third and fourth level benches observed by them may be found in the bench features downstream of the gage, in the apparent flood plain. In either case, the third and fourth level benches observed by this study correspond to medium term flow events with recurrence intervals of less than a decade.

Influence of Anabranching and Bedrock on Bench Placement

It is possible and perhaps probable that anabranching at this site has influenced the initial position of in-channel alluvial benches. The flow division at the head of the island initially causes a localized reduction in flow velocity in the older branch, and that branch aggrades as a response. Initial benches are likely to be constructed symmetrically (i.e., on outer banks) on both channels as channels erode the island head and experience less flow deflection by it through time (Burge, 2006). This would cause bench construction in the formerly over-widened outside banks of reaches immediately downstream of the bifurcation. As time progresses, new benches would likely be created on alternate sides as a response to the side-to-side motion and natural helical flow of water in both channels, and local variability in resistance of channel banks to erosion associated with textures and root protection. At this site, the side-to-side alternation of in-channel alluvial benches is dampened by structural controls, such as the presence of bedrock that inhibit bench formation. On the dominant (west) branch, benches are constructed primarily in point bar locations. This is in part due to the influence of the island-side channel walls at Site 6, which are composed of buried cobble deposits held in place by root wads, which initiates a series of channel bends (Fig. 21). In the east branch, the benches are primarily located on the straighter reaches rather than in point bar locations. The creation of benches in straight reaches is a mechanism by which the channel attempts to narrow its width in response to reduced discharges. Bedrock controls channel gradients at the head of the west branch and the foot of the east branch, which may in turn affect where bifurcation is initiated and which sides grow as a result.

Bench Morphology, Benchfull Flows and Anabranching

The interpretation of bench data relative to river dynamics over time is dependent upon the flow status of the two anabranches at the time of the Kilpatrick and Barnes survey, and how these original surveys were conducted. The two possible scenarios are;

1.) Only one branch was present or active in 1964, and/or both branches are active, but one channel was carrying such small discharge that its contribution to total flow recorded at the downstream gage was minimal; Kilpatrick and Barnes surveyed into the most active branch, and

2.) Both branches active and flowing at the current flow division; Kilpatrick and Barnes choose to survey only downstream of the gage.

Figure 21: Site 6 on the Dominant (west) branch, downstream direction. Note the buried cobble deposits and root wads in the left bank, and root wads in the right bank downstream of the bench

Under Scenario #1, the assumption is that the current east branch was the only active channel in 1964, based on the location of the stream channel shown in the USGS quadrangle for Lenoir, NC (Figure 22). The map also shows a relict channel of some kind which may have been active, but Scenario #1 requires that this channel be either inactive or carrying minimal flow as opposed to the primary channel during this time period. This necessitates a large flow event to initiate bifurcation on the scale measured in this study.

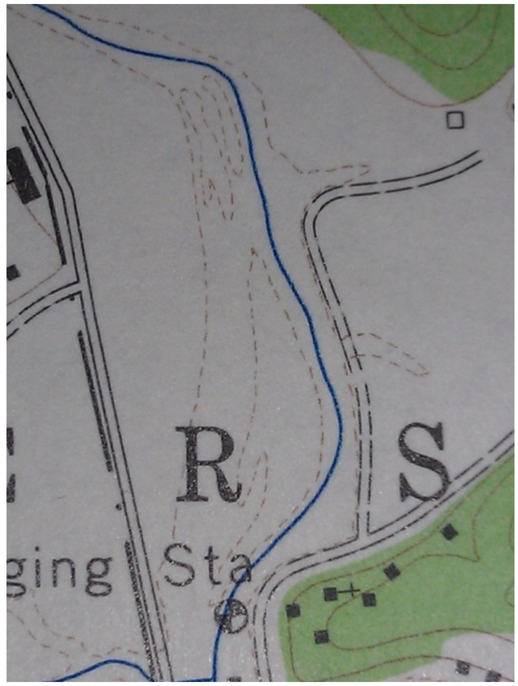


Figure 22: 1:24000 Topographic Map of the Yadkin River at Patterson, from the Lenoir, NC, Quadrangle. CI: 40 ft. (USGS, 1956).

Post-bifurcation, the reduction in discharge in the east branch would have resulted in bench growth as the channel adjusted to the new flow regime by reducing its overall dimensions.

Bench heights for the first level benches observed in the current east branch average to 0.88 meters, as compared to the 1.13 meter average bench height observed by Kilpatrick and Barnes (1964). This, combined with a lack of higher backing benches that indicate prior adjustment to higher flow regimes, indicates that some of the post-bifurcation adjustment was made through channel bed aggradation. The current benchfull width for the lowest bench at Site 1, which is downstream of the anabranch junction, is approximately 15.4 meters, while the average benchfull width for the east branch is 9.09

meters. This indicates that the channel also adjusted its dimensions via lateral accretion after the event which initiated channel bifurcation (post-bifurcation), which accounts for a greater proportion of the channel's adjustment than bed aggradation. Under Scenario 1, the lower bench heights and channel widths observed in the east branch therefore reflect the adjustment of the current east branch receiving only a fraction of the bankfull discharge observed at the gage.

In the west branch, the average bench height is 1.12 meters, which is approximately equal to those found by Kilpatrick and Barnes. The average benchfull width for lowest benches present at all of the sites on the west branch is 12.83 meters, in comparison to the benchfull width of 15.4 meters at Site 1. Scenario 1 assumes that the current dominant (west) branch, or west branch, was shallow or non-existent prior to the bifurcation event. During the event which caused the initial bifurcation, part of the single-channel flow avulsed to a position near the west branch's current location and, under these channel conditions, the west branch would have initially incised relative to the valley flat. This data indicates that after this branch had formed by incision, it became laterally active, migrating within the lower (presumably previously occupied) swale area west of the island, produce a bankfull bench on convex channel bends. It is also possible that the channel adjusted the cross-sectional area at bankfull discharges via vertical accretion, as well as lateral on the benches, since both processes may contribute to point bar formation; and that the bedrock in the channel bed at the head of the west branch ultimately served as a control for channel depth which initiated changes in flow direction downstream. The locations of the point bars on the west branch indicate that the channel has been shifting towards the island side cutbanks, which would make lateral accretion the primary, though not sole, means of channel adjustment in the west branch. The discharges for both branches, adjusted by ratio to a total discharge, approximate the benchfull values for the lowest bench found by Kilpatrick in Barnes in 1964. Operating under the assumption that Kilpatrick and Barnes surveyed upstream of the gage when the east branch was the only channel, this would indicate, given that total discharge values have changed little over that time period, that both branches have adjusted since then (a time span of 50 years or less) to be in equilibrium with the canonical bankfull flow.

Under Scenario 2, both the west and east branches were active and operating under discharge proportions similar to those observed currently, during the time at which Kilpatrick and Barnes surveyed this site. In this case, Kilpatrick and Barnes would have probably surveyed solely downstream of the gage given the ease of doing so relative to dealing with divided flow upstream. The bench heights being approximately equal between the west branch and those reported by Kilpatrick and Barnes would again indicate that the primary mechanism for channel response to flow reduction is lateral accretion in this section of the Yadkin River. However, Scenario 2 is unlikely as the benches observed in this study would as a result be at least 50 years old, and they lack any older vegetation to indicate that their age is in that range. In addition, Kilpatrick and Barnes make no mention of having to deviate from their field method of surveying equal distances up and downstream of gages, a practice which allows gage data to be better tied to survey data given the shorter distance involved.

CHAPTER VI

CONCLUSIONS

The final results of this study are as follows; 1.) Most of the benches on both branches occur within close proximity to the initial point of bifurcation. This indicates that the anabranching nature of this site has likely impacted the locations of in-channel alluvial benches. 2.) The recurrence intervals calculated for the first and second level benches are in accordance with those detailed by Kilpatrick and Barnes in 1964, and almost all match the 1-2 year recurrence interval usually associated with bankfull stage in the eastern U.S.; thus most current benches on both branches are best classified as incipient (or perhaps even stabilized in the east branch) floodplains. 3.) The average bench heights observed are similar to those given by Kilpatrick and Barnes (1964), despite the status of the reach upstream of the gage (one branch or two in 1964) being an unknown during that time period. With Scenario 1 (one channel only) being the most likely of the two, this would seem to indicate that lateral accretion is the primary mechanism for channel adjustment to flow reduction in this section of the Yadkin River.

Other explanations are possible for the variances between the discharges and recurrence intervals reported by this study and those of Kilpatrick and Barnes. First, this study used a static calculation for gradient based on an average of field measurements, while Kilpatrick and Barnes used separate gradients for each bench level. This may provide a minor adjustment to the result of the discharge calculation used in this study. Second, this study calculated discharge based on the Manning equation, while Kilpatrick and Barnes used a discharge rating curve. The rating curve used by Kilpatrick and Barnes may over report discharge based on cross-sectional area, while the Manning equation may under report discharge. Third, the roughness coefficient used in this study was derived from a chart for expediency. While this roughness coefficient closely approximates the conditions observed in the field at this site, a better figure would have been generated by following the procedure for a Wolman Pebble count for each individual cross-section site, and calibrating this by accounting for bed topography and vegetation in the channel margin which would be in the water during higher discharges. This would also ultimately impact the discharge calculated at each cross-section, and for each bench level. Fourth, the choice of the benches used to form the ratio for flow apportionment is crucial factor in this study. If two different sites were chosen as being representative for benchfull flow in both the main and east branches, a different flow ratio could have been calculated. The ratio calculated for this study was 66/34 in favor of the main branch. The most extreme ratio favoring the west branch indicated by the data would be 89/11, while the most extreme ratio in favor of the east branch would be 53/47. If this study used an average of calculated bankfull discharges for both branches in forming the ratio, that resulting ratio would have been 71/29 in the favor of the west branch. In all of these cases, the recurrence intervals for both channels would require adjustment and may no longer match against the low bench recurrence intervals noted by Kilpatrick and Barnes. Fifth, Kilpatrick and Barnes were working with a flow data set reaching from late 1939 to at best 1962, while the AMS used for this study was calculated using data from 1939 to January, 2012. That period between 1939 and 1962 was drought dominated, and as a result their AMS or PDS (Partial Duration Series) overestimated the recurrence interval of large flow events relative to estimates using the entire period of record. Finally, if the Yadkin at Patterson was indeed anabranching upstream of the USGS gage during their survey, Kilpatrick and Barnes may not have surveyed the upstream reach at all, and instead relied solely on data provided by the downstream reach. If this last possibility is indeed the case, then attempting to compare benchfull flows for the third and fourth level benches may be an inherently flawed study. In any of these cases, it is very difficult to make a definitive statement about what exactly is causing these discrepancies, as Kilpatrick and Barnes original field notes and materials are not currently available for further scientific use.

A sensitivity analysis was performed to determine if adjustments to branch discharges are significant by using values for gradient that are within the variation observed within these channels, while modifying the ratio used to apportion branch flow. The ratios used for this analysis were the original ratio; a ratio constructed using the average of discharges for each branch, and the ratios that most heavily favor discharge for each branch. Altering the gradient used does not significantly alter the recurrence intervals for the lowest bench level found at each site and all recurrence intervals remained in the acceptable range of 1 to 2 years for the bankfull event. Altering the gradient ultimately does not appear to be useful for calibrating the data used in this study, and may not be appropriate due to the limitations inherent in the Manning equation.

Modifying the ratio to reflect a proportion that uses either the average or favors the west branch also does not alter the results of this study. The ratio that favors flow into the east branch does revise the recurrence intervals for both branches upwards, and significantly increases the recurrence interval in the west branch. While a flow apportionment ratio which favors discharge into the east branch is not supported by the data for the benchfull flows used in this study, it may be a more realistic interpretation under higher flow events where the influence of channel bedform on local stage height is of less importance. Any further study at this site should seek to verify if the flow ratios used at all bench level are representative of actual high flows.

There are multiple avenues for improving the results of this study in the future. The discharges and recurrence intervals calculated for this study may be calibrated by mapping the location and extent of benches, at all other (higher) levels around the mid-channel island. These benches can then by surveyed by stadia and abney level in order to create more data points for the analysis. Observing and directly measuring the discharges on both branches during a single flow event would provide insight into the accuracy of the ratio calculated by this study to apportion flow between the two branches. This study focused primarily on the portion of the study site above the stream gage; further cross-sections undertaken on the reaches below the gage can be used to compare with the gage data without the need for modifying the data using a ratio, and can also be used to determine if the discharges and resultant recurrence intervals for all benches downstream of the gage match the Kilpatrick and Barnes data, and whether much change has occurred in benches downstream since their survey.

While dating bench structures is problematic, establishing the minimum ages of these benches would be useful for determining the temporal stability of the channel. Minimum bench ages can be established by using tree ring data. Older trees growing on a bench structure can be cored and have the resulting dates averaged, while younger saplings may simply be cut down in the field. The excavation and dating of anthropogenic debris could also be used to establish minimum bench age. Soil probe analysis on all benches and in selected areas immediately adjacent to the channel could also be used to establish minimum ages, and to propose a model for the evolution of the channel's planform and location over time. Detailed stratigraphic studies of all benches could help determine whether the hypothesis of lateral accretion dominance in bench construction is correct.

Surveying at regular intervals across both channels and the mid-channel island to the approximate height of the fourth bench in the flood plain to the west of the channel would result in data suitable for use in the HEC-RAS model, which could then be used to estimate the areal extent of flooding during large discharge events. This model could be calibrated using field monitoring of the Yadkin River during a large flow event by measuring the simultaneous discharges of both anabranches during the same event by using field markers and by using the stage height identified at the gage.

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