Lower Chattooga River Before Tugalo Dam

By David S. Leigh, Shishir Rao, and Seth J. Wenger

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Conversion Factors

International System of Units to U.S. Customary Units

Multiply	**By**	**To obtain**
Length		
millimeters (mm)	0.0393701	Inches (in)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
Area		
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)

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EXECUTIVE SUMMARY

As the 2023 centennial anniversary of Tugalo Dam and Lake Tugalo approaches, interest is upwelling among conservation and recreation organizations for removal of the dam to restore the inundated lower 7 km of the iconic *Wild and Scenic* Chattooga River and the lower 3 km of the Tallulah River. Both the dam and the reservoir are owned and operated by Georgia Power Company. If dam removal project planning were to occur, channel restoration design would require knowledge of the channel morphology prior to its 1923 impoundment. Such knowledge would be critical for understanding channel adjustments to dam removal, as well as for informing project permitting, construction reservoir drawdown, sediment management plans, and other construction logistics. This report provides an assessment of the pre-1923 Chattooga River channel characteristics, targeting standard metrics of channel morphology (slope, width, depth, sinuosity, bed and bank composition), based on historical survey data, photographs, and maps, as well as modern morphometric models used as analogs for the inundated channel. Morphometric models rely on comparable watersheds of similar size in the region and the adjacent, upstream, free-flowing Section IV of the Chattooga River. Key pieces of information utilized include a channel survey conducted for the U.S. Geological Survey (USGS) in 1903, two oblique aerial photographs of the lowermost Chattooga River from 1922, and exceptionally high-resolution digital elevation models (DEMs) released by the USGS in spring 2022.

Two distinct river reaches emerged from these analyses, including a very steep reach (average slope = 0.015) beneath the upper 2 km of the lake and a much lower gradient reach (average slope = 0.0016) over the lower 5 km. We refer to these as the “knickpoint reach” and the “graded reach”, respectively, in reference to their inherent morphology resulting from long-term river channel evolution and adjustments to an ancient stream capture event that is thought to have occurred 5-23 million years ago during the Miocene epoch.

Prior to inundation, the steep knickpoint reach was a confined bedrock channel that had bankfull channel widths of 30-50 m, bankfull depths of 2.8-2.9 m, sinuosity of 1.0-1.2, and likely

contained class III, IV, and V cascades flowing over bedrock sills and boulders that were separated by gentler riffles, glides, and pools. The knickpoint reach probably looked much like the steep Five-Falls reach found in the lowest section of today's free-flowing Chattooga River channel, because the Five-Falls reach is essentially the upstream extension of this knickpoint reach. Therefore, evidence indicates that restoration of this reach would add two additional kilometers of world-class whitewater to the lower Chattooga River.

The gentler, graded reach was a mixed bedrock and alluvial channel that had bankfull channel widths of 50-70 m, bankfull depths of 2.8-2.9 m, sinuosity of 1.0 to 1.4. The greatest sinuosity was located in the middle portion of this reach, in an area where the gorge was widest and likely contained alluvial bottomlands with a wandering river channel. Alluvial channel beds with gravelly and cobbly riffles separated by sandy pools would have been more common in the widest section of this reach, whereas beveled bedrock shoals would have been more common in the uppermost and lowermost parts of this graded reach. Regional modern analogs for the graded reach include the Chattahoochee River between the Soque River and the Georgia Highway 384 bridge, the Tuckasegee River between Savannah Creek and Dillsboro, North Carolina, and the Pigeon River between Crabtree Creek and Dotson Branch, just west of Crabtree township in Haywood County, North Carolina. Restoration of this graded reach would provide 5 km of scenic Blue Ridge river with class I-II rapids likely well suited to wadable fly-fishing, paddling, floating, swimming, and aesthetic beauty within easy driving distance of Atlanta and Greenville.

If Tugalo Dam were to be removed, restoration of the lowest 7 km of the Chattooga River would provide a uniquely varied stretch of the river, with its steep, upper knickpoint reach (2 km) and the gentler, lower graded reach (5 km). Few rivers in the southeastern United States exhibit such variation within such a short distance. These exceptional physical characteristics and the reach's high recreational potential could make the restored reach an important travel destination and economic contributor to the region.

INTRODUCTION

The Tugalo Dam and Lake Tugalo (also known as Lake Tugaloo) have inundated the lower seven kilometers of the iconic *Wild and Scenic* Chattooga River and the mouth of the Tallulah River for an entire century (dam completion in 1923) in northeastern Georgia and northwestern South Carolina (Figure 1). Both the dam and the reservoir are owned and operated by Georgia Power Company. All dams have a finite life span, after which they must be either repaired, replaced, or removed; the best option for a given river depends on the services and disservices provided by the impounded versus the free-flowing river. Because the Chattooga is an important river for local and regional tourism, trout-fishing, and whitewater-paddling industries, the potential for those industries in the currently impounded reach is of particular interest. Thus, it is important to understand what the river might have looked like prior to the 1923 filling of the lake. In order to characterize the pre-dam river channel, historical maps, photographs, and survey data were examined, and morphometric modeling was conducted. Morphometric models are based on the adjacent modern river channel immediately upstream of the inundated reach (Section IV of the Chattooga River), as well as hydraulic geometry models from watersheds of similar size that also drain the Blue Ridge Mountains. The four basic metrics of any river channel form are the focus of this retrodiction/prediction, including: (1) gradient or slope; (2) cross-sectional width and depth; (3) bed and bank materials and forms (sediment size, bedrock, falls, riffles, pools, etc.); (4) planform (map view or sinuosity). These are discussed below and form an impression of what the lower 7 km of the Chattooga River looked like prior to 1923.

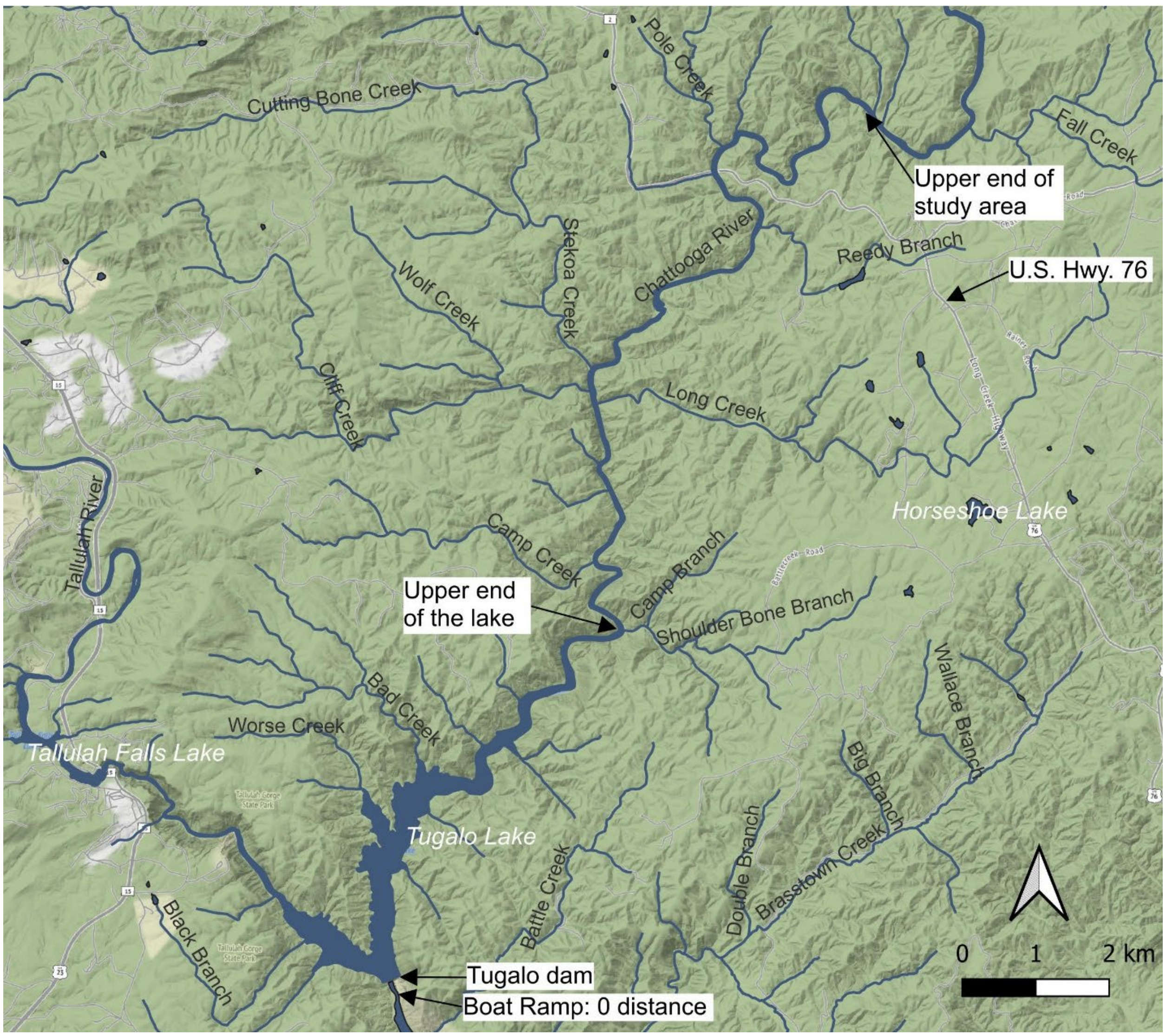

Figure 1. Map showing the location of the study area. Grey areas are built-up, yellow areas are farmlands, and green is forest. Map tiles by Stamen Design, under CC BY 3.0. Data by OpenStreetMap, under ODbL.

Physical Setting

When the Chattooga River was free-flowing to its confluence with the Tallulah River, the watershed upstream of its mouth was 723 km^2 with total relief of 1265 m. When Lake Tugalo was filled in 1923, the drainage area upstream of the free-flowing river was reduced to 701.9 km^2 with a 40 m loss in total relief down to 1225 m. The Chattooga River watershed is entirely within the Blue Ridge Mountains physiographic province in North Carolina, South Carolina, and Georgia. Mean annual precipitation in the watershed is 1880 mm (from PRISM data within USGS Streamstats watershed delineation tool at https://streamstats.usgs.gov/ss/), and about 90 percent of the watershed is covered by forests (National Land Cover Database, 2019).

In 1974, the federal government designated the Chattooga River as a *National Wild and Scenic River*, which is managed by the USDA Forest Service (https://www.rivers.gov/rivers/chattooga.php). It is recognized as one of the Southeast's premier whitewater rivers, owing largely to its steep gradient through a bedrock gorge in the lower reach. The steep gradient resulted from a stream piracy event when headwaters of the ancestral Tugaloo River (tributary to the Savannah River) captured the Chattooga and nearby Tallulah Rivers from their previous southwesterly flow direction into the Chattahoochee River system (Hayes, 1896; Johnson 1907a and 1907b; Acker and Hatcher, 1970). The deep canyon of the Tallulah Gorge and the gorge of the lower Chattooga River resulted from subsequent river incision, as an adjustment to the lower base level of the Tugaloo/Savannah River system following this stream piracy. The age of the stream capture is not well known, but it may have coincided with the most recent phase of tectonic uplift in the Blue Ridge that is thought to have occurred 5-23 million years ago during the Miocene epoch (Gallen, 2013; Hatcher and Prowell, 2019). Bedrock beneath the river and its tributaries consists primarily of the graywacke-schist and graywacke-schist-amphibolite members of the Neoproterozoic to early Cambrian Tallulah Falls Formation (Hatcher et al., 2000: https://ngmdb.usgs.gov/Info/dmt/docs/hatcher05.html), with lesser amounts of thin strata of the garnet-aluminous-schist member. The southwest-trending course of the main stem of the river generally parallels the strike of foliations and joints in the metamorphic rock (Hatcher et al., 2000; Brame and Hatcher, 2014). However, in its lowest reaches (between Cliff Creek and the upper end of Lake Tugalo), the river distinctly crosses the strike and has the steepest gradient of the entire main stem (Figures 1 and 2). This stretch includes the closely-spaced “Five Falls” of renowned class IV+ whitewater cascades (*Entrance, Corkscrew, Crack-In-The-Rock, Jawbone, and Sock-Em-Dog*).

This study focuses on the lower 21-km segment of the Chattooga River, including the bottom of Lake Tugalo, extending from 4 km upstream of the U.S. Highway 76 bridge and down to the base of the Tugalo Dam (Figures 1 and 2). Within this segment, the river drops 149.5 m in elevation from 376.3 meters above sea level (masl) to 226.8 masl making an average gradient of 0.007. Georgia Power Company considers the lake full at 271.73 masl. This segment includes all of whitewater Section IV and the terminal reach of whitewater Section III of the river (Figures 1 and 2) (https://www.americanwhitewater.org/content/River/view/river-detail/476/main; https://www.sherpaguides.com/georgia/mountains/blue_ridge/eastern/chattooga_river.html), and this free-flowing reach above Lake Tugalo is used as an analog for understanding the inundated lowest reach beneath the lake. This is one of the highest gradient portions of the main stem of the Chattooga River profile. This portion exhibits a convex longitudinal profile (Figure 2), which is characteristic of steep erosional knickzones and knickpoints adjusting to the lower base level imposed by the ancient stream capture. It contains many class III-IV-V whitewater cascades interspersed with class I-II rapids, riffles, glides, and pools. Most of the high-gradient cascades and rapids are bedrock reaches with rock sills and ledges, along with numerous potholes etched into the rock.

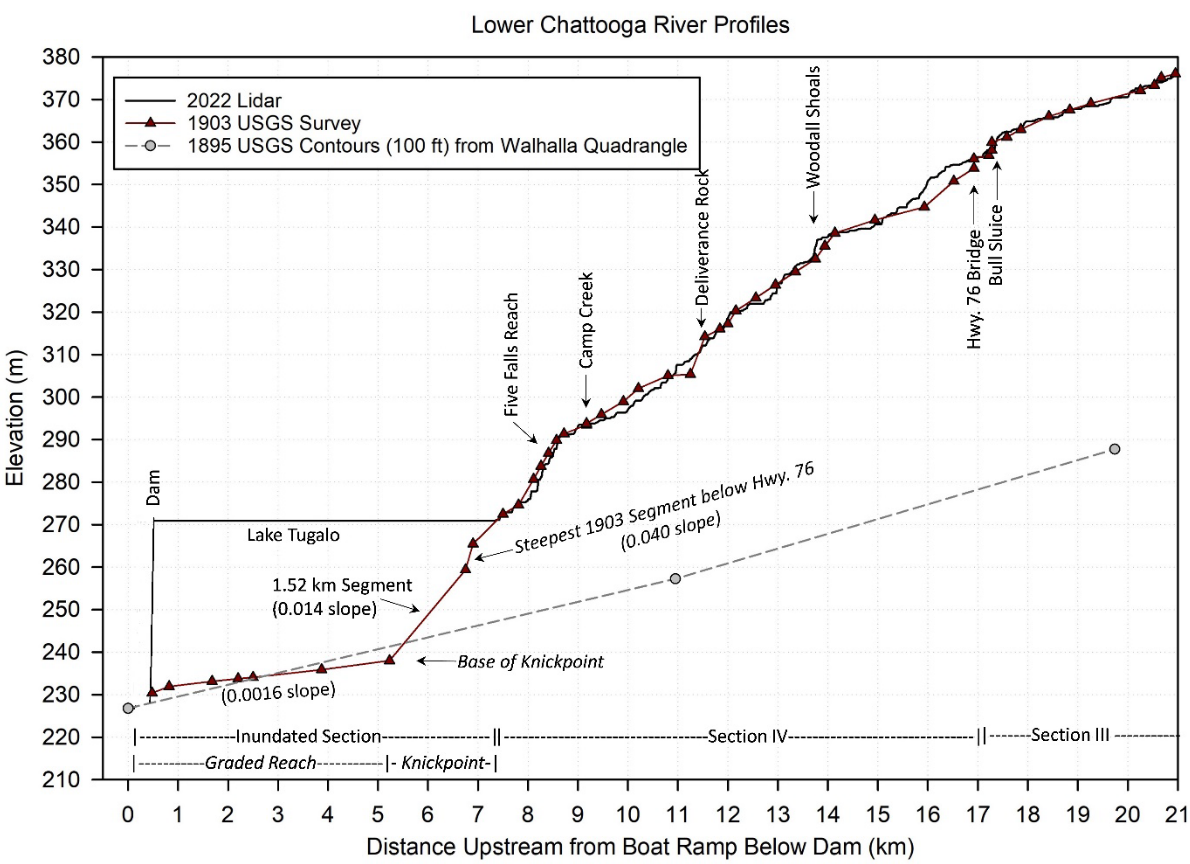

Figure 2. Longitudinal profiles of the Chattooga River comparing the 1895 and 1903 pre-dam surveys against the latest 2022 elevations from 1 m lidar grid cells. The zero distance is located at the concrete boat ramp at 0.5 km downstream of the top edge of the Tugalo Dam.

Much of the river bed material in Section IV consists of large boulders of rock-fall from adjacent slopes, as well as from abrasion and cavitation of the bedrock channel bed itself. The bedrock in the river channel retains its original strike and dip in many places, with angular slabs of the most resistant rocks jutting into the channel bed. The river is a classic example of a bedrock channel that is undergoing active erosion in response to ongoing knickpoint adjustments to the ancient stream capture event. Numerous tributaries along the studied reach supply coarse bed material of boulders, cobbles, and gravel, as well as fines of sand, silt, and clay. However, most of the fines remain in transport and move further down the river (and accumulate in Lake Tugalo), except for some limited accumulations of fines in pools and lateral sand bars. The river bed primarily consists of bedrock in the cascades and rapids, with boulders, cobbles and gravel in the intervening riffles, glides and pools.

METHODS

A variety of methods were used to reconstruct the channel morphology of the inundated pre-1923 channel. These included (1) historical sources, such as old photographs, maps, and survey data; (2) analogs based on digital elevation models (DEM) and morphometrics of the lower Chattooga River channel between Lake Tugalo and just above the U.S. Highway 76 bridge; and (3) hydraulic geometry models, which estimate channel dimensions based on contributing drainage area. Each of these methods are discussed below.

Historical Sources

Historical sources were limited, largely because Georgia Power Company was unwilling to share any archived pre-dam information on the lower Chattooga River. We contacted Tony Dodd of Georgia Power Company's Natural Resources Division on May 26, 2022 to inquire whether the company had any archived records of pre-dam surveys, photos, or other information that they could make available to us. He replied on June 6, saying that "the existence of the types of information you are seeking would be expected to be extremely rare and we are unable to provide access to archived material." Given his definitive response, we did not pursue further inquiries. Nonetheless, two excellent 1922 oblique aerial photographs of the dam site were found, looking upstream from the confluence of the Chattooga and Tallulah Rivers (Figures 3 and 4). These were posted on the Chattooga Conservancy's "Restore Chattooga Gorge" fundraiser website (https://chattoogariver.org/initiatives/restore-chattooga-gorge/). In addition, the Walhalla 1:125,000 U.S. Geological Survey (USGS) topographic maps were available on the "USGS Historical Topographic Map Explorer" website (https://livingatlas.arcgis.com/topoexplorer/index.html) for the years 1886, 1892, and 1896. However, these were of limited use, because little detail was available for the study reaches of the Chattooga River.

Pre-dam surveyed points of the river gradient were obtained from Hall and Hall's (1908) report, the "Second Report on the Water Powers of Georgia" (Appendix A). This includes a leveling survey conducted in 1903 by surveyors Thomas B. O'Hagan and Carroll Caldwell. Those data were originally reported in Hall and Hall's (1907) report, "Water Resources of Georgia" (p.73-74). Only the survey points that were designated as "water surface" were used in this study, excluding various reference points on rocks, trees, and bridges that were above the natural gradient of the river. The elevations of the original survey points were adjusted to the datum of the 2022 LiDAR (light detection and ranging) DEM obtained from the U.S. Geological Survey (USGS).

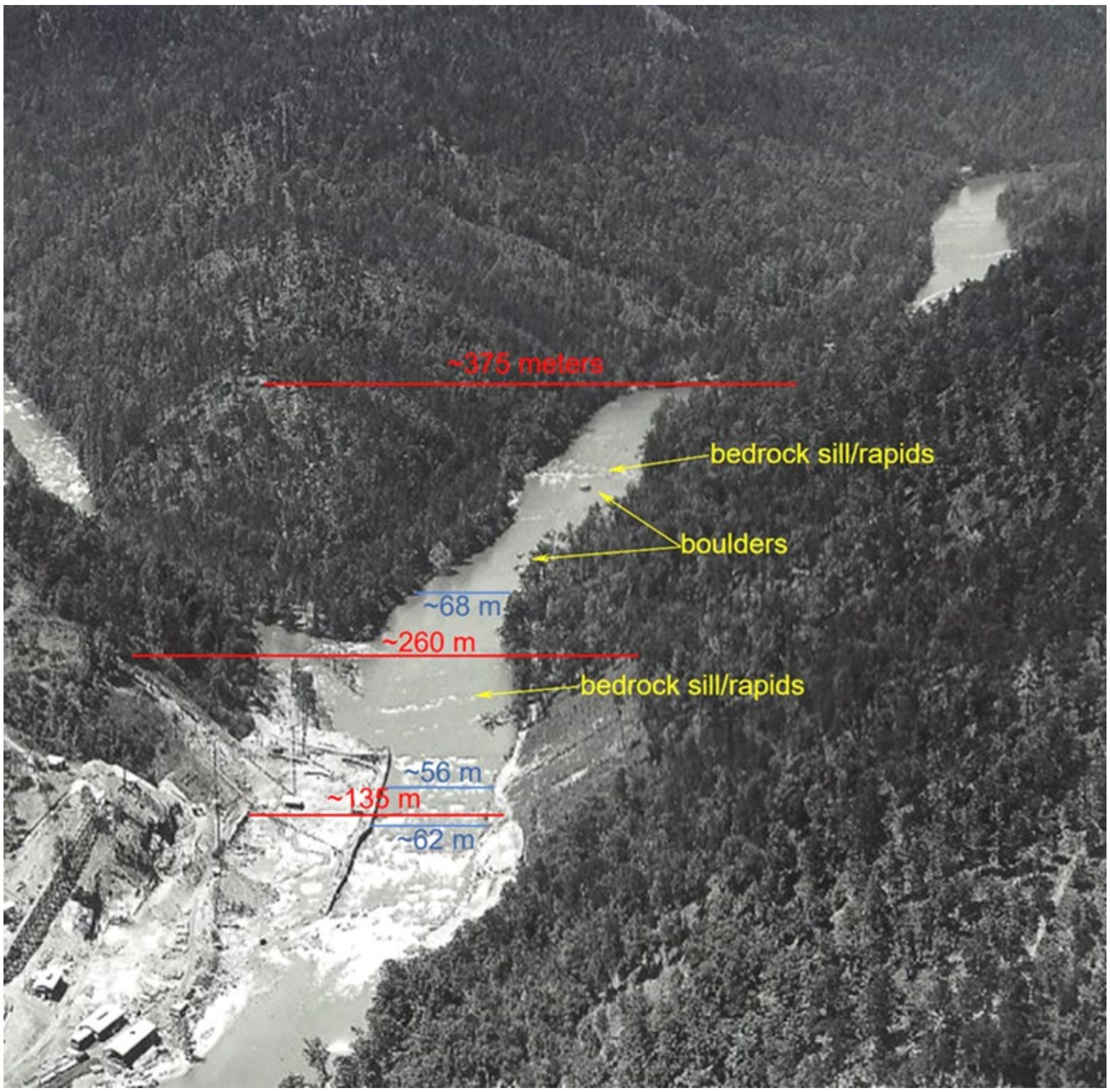

Figure 3. Oblique aerial photo of Tugalo Dam under construction in 1922 showing the confluence of the Tallulah River (left fork) and Chattooga River (right fork). Red lines and numbers indicate widths of distinctive topographic reference points measured from USGS topographic maps and LiDAR imagery, which were used as calibrations for the measured river channel widths in blue. Photo courtesy of Georgia Power Company as posted on the Chattooga Conservancy website (https://chattoogariver.org/initiatives/restore-chattooga-gorge/).

Figure 4. Oblique aerial photo of the mouth of the Chattooga River in 1922. Photo courtesy of Georgia Power Company as posted on the Chattooga Conservancy website (https://chattoogariver.org/initiatives/restore-chattooga-gorge/).

Digital Elevation Models (DEMs) and Morphometrics

A 14-km section of the lower Chattooga River from the upper end of Lake Tugalo (near the mouth of Opossum Creek) to a point about 4 km upstream of the U.S. Highway 76 bridge (Figures 1 and 2) was used as an analog for the pre-1923 channel that is now submerged beneath Lake Tugalo. Within this reach, the majority of measurements for this study were made from digital elevation models (DEMs) that were obtained from the U.S. Geological Survey's *The National Map download site* (TNM Download v2.0 at: https://apps.nationalmap.gov/downloader/), and examined and manipulated using ArcGIS Pro 2.9.0 (© by ESRI) and open-source software QGIS version 3.24.2. Measurements on the river channel and its immediate valley (i.e., channel gradient, channel width, gorge width) relied on DEMs that were created with the LiDAR (light detection and ranging) technique, which have 1-m horizontal resolution and centimeter-scale vertical resolution per pixel.

River gradient was measured directly from the 2022 lidar DEM as rise/run from a line trending down the middle of the river, which was manually smoothed from the Chattooga River course portrayed in the USGS *National Hydrography Dataset Plus* high resolution (NHDPlus HR) vector dataset. Smoothing was necessary because the original version cut corners, traversed large boulders, and failed to accurately represent the river path (particularly around tight bends). Bankfull river channel width was measured from the "curvature" transformation of LiDAR DEMs using ArcGIS Pro, which creates an image that easily distinguishes the planar water surface from the concave upward-sloping river banks and adjacent hillsides (Figure 5).

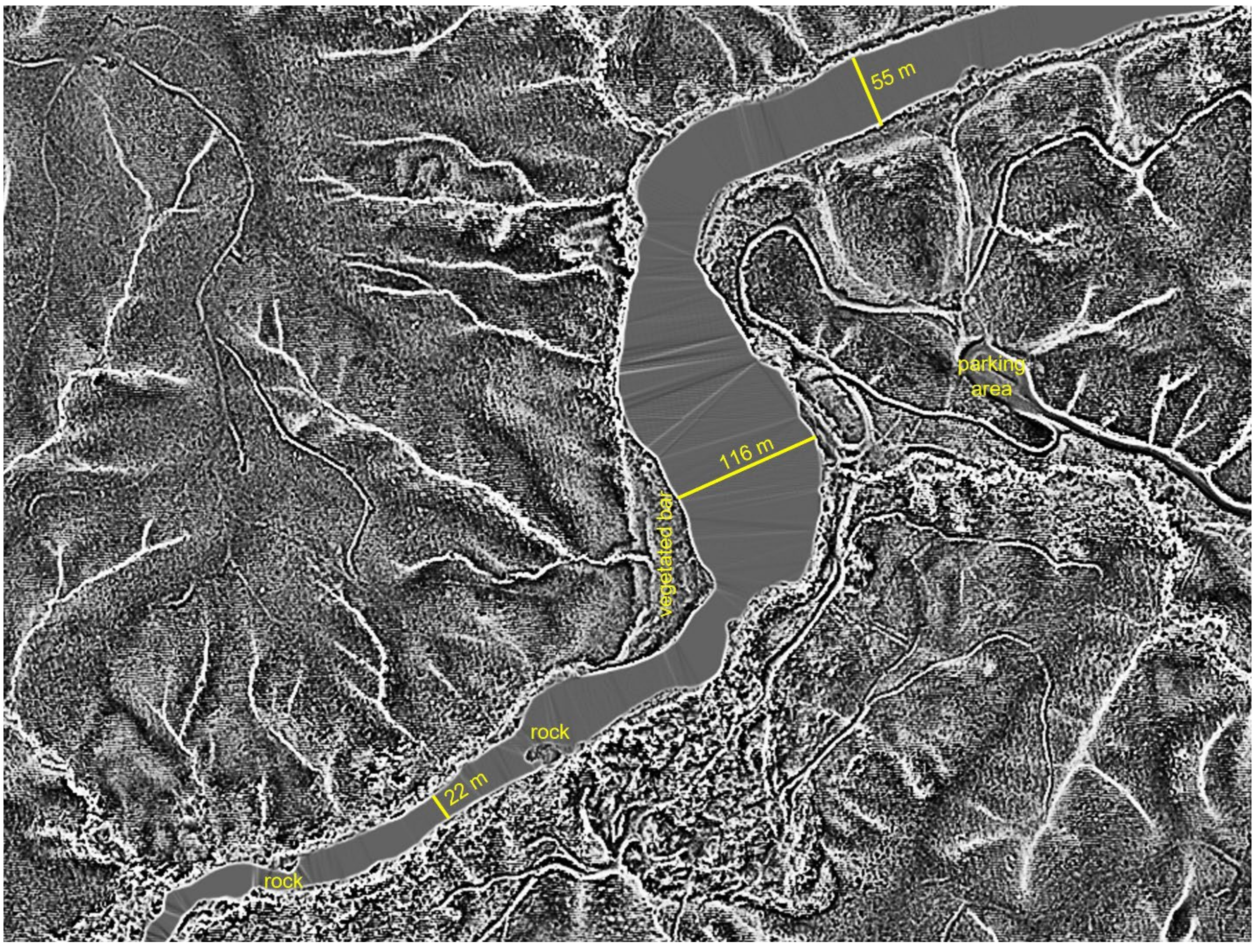

Figure 5. "Curvature" transformation of the 1 m horizontal resolution LiDAR DEM showing the large amount of variability in channel width around Woodall Shoals (widest spot) in the Chattooga River. White indicates the greatest amount of concavity and black indicates the greatest amount of convexity. Note that the white line on the edge of the channel marks the distinct concavity of the channel bank. Various bankfull width measurements are shown in meters (m), along with other features (rocks, vegetated bar, parking area).

Width of the bedrock gorge was used as a predictor of river channel width, because it was apparent that the river channel width did not behave in the typical fashion for alluvial channels, in which river width steadily increases in the downstream direction with increasing drainage area. Width of the bedrock gorge was measured from the DEMs at a height of 40 m above the channel bed. Measurement locations were limited to places that exhibited interfluve noses and planar hillslopes representing the narrowest pinch-points of the valley in between mouths of tributary stream valleys and concavities in the valley wall. Pronounced meander bends in the bedrock valley were avoided, because they likely represent some lateral migration and associated widening of the river channel. A height of 40 m was chosen for gorge width measurements, because that is the minimum height that would allow visibility of the valley walls on either side of Lake Tugalo. The 40 m height above the river bed and intersecting contours on the valley side slopes were determined with QGIS by interpolating a point's elevation every 10 m along the smoothed NHDPlus stream line, boosting the elevation of that point by 40 m in elevation, and inscribing a line perpendicular to the orientation of the stream line until it intersected hillslope contours on either side of the valley. The elevation and gradient of the stream line beneath Lake Tugalo was estimated by smoothing the 1903 USGS channel survey points (Appendix A) into a continuous line with a power function regression in the lower 5 km and a linear regression in the upper 2 km (Appendix B). River channel widths (bankfull widths) were measured directly beneath the valley-width measurements on the "curvature" transformed DEM image and used as the dependent variable in a linear regression model to estimate the channel widths that would have been present prior to the 1923 filling of Lake Tugalo.

Hydraulic Geometry Models

Hydraulic geometry models use linear regression power functions that predict channel dimensions (dependent variable) from drainage area (independent variable), based on measured stream and river channels (Leopold and Maddock, 1953). Bieger et al. (2015) demonstrated that regional hydraulic geometry models, which were calibrated to individual physiographic provinces in the United States, performed much better than general models. However, their model for the Blue Ridge Mountains was based on data of Harmon (2000), which did not include watersheds as large as that of the Chattooga River, so the existing model was augmented and modified to better suit this scale.

Hydraulic geometry data of Harmon (2000) for western North Carolina (n=14) are regionally appropriate for the Chattooga River (all sites are in the Southern Blue Ridge Mountains), but those data have an upper watershed size limit of 326 km^2 that falls short of the lower Chattooga River. Therefore, new hydraulic geometry regression models were created by adding four additional data points and extending the watershed size limit to 907 km^2 to capture the appropriate drainage area of the inundated lower Chattooga River. These additional points were obtained from nearby rivers in the Southern Blue Ridge Mountains province from USGS gaging stations that had sufficient field measurement data published to derive bankfull dimensions, including the Chattahoochee River near Leaf, Georgia (USGS 02331000), the Chattahoochee River near Cornelia, Georgia (USGS 02331600), the Pigeon River near Canton, North Carolina (USGS 3456991), and the Pigeon River near Hepco, North Carolina (USGS 3459500). All hydraulic geometry data and regression models are provided in Appendix C.

RESULTS

Gradient

Stream gradient is the single most important morphological variable of any stream or river channel, because it is so influential on the flow velocities and sediment transport capacities that shape overall channel form. Pre-1923 surveys of the Chattooga River gradient include an unspecified USGS survey to produce the 1886 Walhalla 1:125,000 Quadrangle, and a 1903 USGS survey specifically focused on the lower Chattooga River channel (Hall and Hall, 1907 and 1908). Only the contour lines for the Walhalla quadrangle were available for measuring the river gradient, and they were found to be very inaccurate when compared to the modern 2022 LiDAR elevations; in contrast, the 1903 survey data were found to be quite accurate and very comparable to the modern data (Figure 2). The 1903 survey clearly reveals a relatively low-gradient channel (0.0016 average slope) beneath the lower 5 km of the lake, versus a very steep gradient (0.015 average slope) beneath the remaining upper 2 km of the lake (Appendices A and B). Unfortunately, the critical transition point between these low- and high-gradient inundated portions of the river is uncertain, because there is a 1.52 km segment between the uppermost point of the low-gradient portion and the next point upstream, which is clearly within the steep reach (Figure 2). In fact, the steepest 1903 surveyed segment of the entire river below the U.S. Highway 76 bridge (slope of 0.040 within a 0.15 km segment) occurs beneath the uppermost portion of the lake (Figure 2). It is unusual that the 1903 surveyed points were 1.52 km apart in this transitional zone, because the average interval between all surveyed points below U.S. Highway 76 is 0.44 km (+/- 0.36 km std. dev.). However, the presence of the exceptionally steep segment (0.040 gradient) beneath the upper portion of the lake strongly indicates that class IV+ cascades probably existed in that segment, because even the most challenging series of class IV-V cascades in the “Five Falls” reach (Figure 2) have a 1903 average gradient of 0.020 in comparison. The overall 1.52 km long segment is very steep with a slope of 0.014, which also must have contained cascades, because the 1903 average overall slope for the entire whitewater Section IV reach is only 0.009, and only five reaches were surveyed in 1903 with slopes greater than 0.0105 over the entire span of Section IV (reaches with 0.015, 0.019, 0.030, 0.039, 0.020 slopes from Hwy. 76 down to the lake). One can only speculate about why the 1903 survey produced the unusually long 1.52 km segment, but a possible explanation is that the terrain was so steep, cascading, and difficult to traverse that they could not accurately survey any closer points.

The unusually steep segment of the 1903 survey from the bottom of the 1.52 km segment up to the top of the Five Falls reach (Figure 2) is befitting of the overall longitudinal morphology of the river, because this coincides with the knickpoint segment of steep channel gradients adjusting to lower base levels imposed by the ancient stream capture event. That is, knickpoint erosion typically migrates “headward” (in the upstream direction) from the point of capture as the channel adjusts its gradient to the new base level conditions (Figure 6) as a “graded” stream. The relatively low gradient from the dam upstream to the base of the 1.52 km segment is the new “graded” reach that has been eroded by the river as the knickpoint moved upstream through time. Indeed, the slope of the lower 5 km (0.0016) is very similar to the slope of the Tugaloo River below Yonah Dam (0.0015), confirming that the Chattooga River is graded to the main stem of the Tugaloo River. Thus, the base of the knickpoint at 2 km downstream

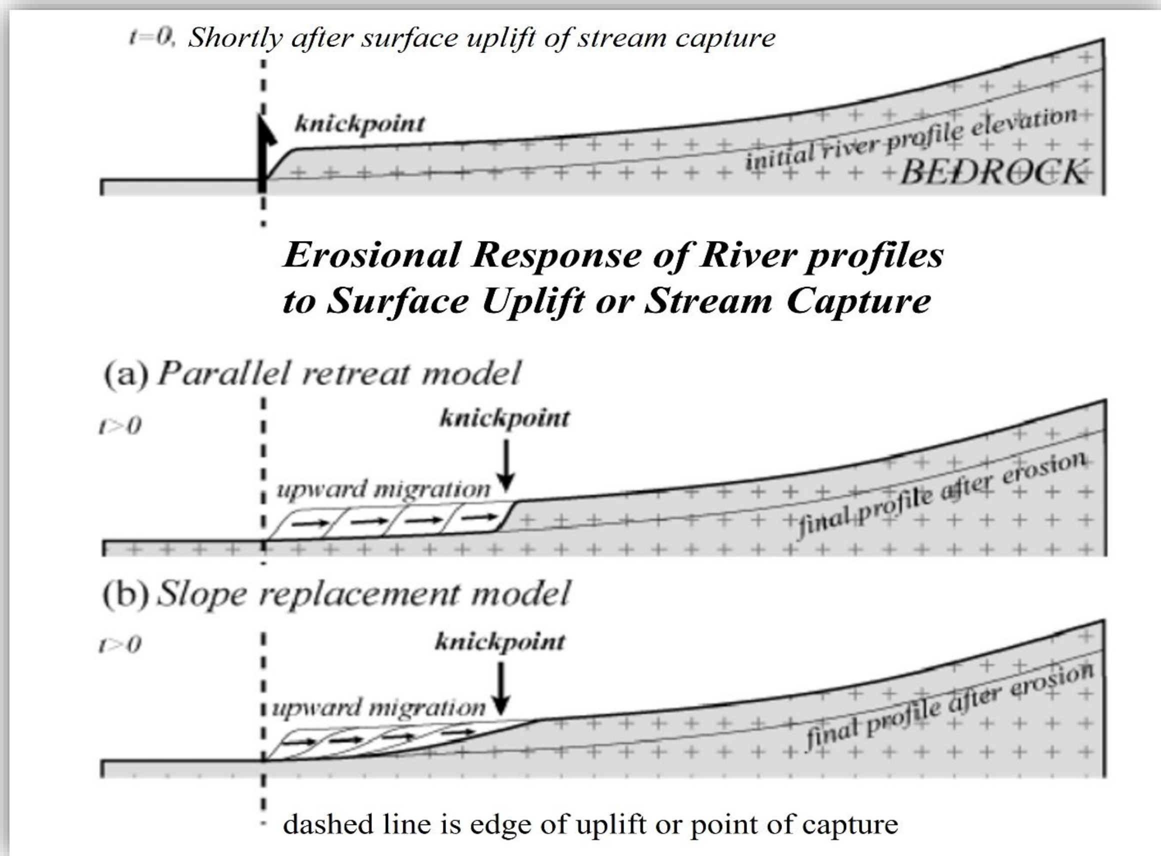

Figure 6. Schematic illustration of knickpoint migration along longitudinal river profiles. Surface uplift or stream capture generates a knickpoint that propagates upstream. Knickpoint retreat is represented by two end-members models: (a) parallel retreat, and (b) slope replacement. Modified after Gardner (1983), Seidl and Dietrich (1992).

from the upper end of the lake (Figure 2), marks significant transition from the steep upper reach to the gentle lower reach of the inundated channel. Despite the lack of survey points within the steep 1.52 km segment, the point at the base of that segment appears to be a good candidate for the true base of the knickpoint, because linear extrapolation of the points above (from the top of the Five Falls reach) confirms it as the base of the knickpoint. Assuming the stream capture occurred 5-6 million years ago (Miocene/Pliocene boundary), and the capture location was near the confluence of the Tallulah and Chattooga Rivers (Johnson, 1907b), knickpoint migration rate in the Chattooga River has been approximately 1 mm/year, which is squarely within realistic rates indicated by Whittakar and Boulton (2012).

Width

Channel widths for the now-inundated lower reaches of the Chattooga River were measured from the 1922 (pre-dam) oblique aerial photograph that offered the widest view of topographic reference points (Figure 3). Channel widths at the upper end of the inundated reach were estimated using modern channel widths measured immediately upstream of the lake with the ArcGIS curvature-transformed DEM images. Using distinctive topographic landmarks as key reference points for distance measurements (e.g. top edge of the dam, first prominent summit knob on the Tallulah-Chattooga divide, gorge sideslopes) indicates that the pre-1923 Chattooga River had a maximum channel width of about 60-70 m just upstream of its confluence with the Tallulah River (68 m measured in Figure 3). In addition, the 1922 photographs show that the river appears somewhat wider within bedrock shoals than it does in other sections, which is typical for the region. Immediately upstream of Lake Tugalo, in the reach between Camp Creek and the lake, the Chattooga River has an average measured bankfull width of 40.1 m (n=19, st. dev. = 12.0 m), and ranges from 21 to 63 m wide. The regional hydraulic geometry curve for the Southern Blue Ridge Mountains (Appendix C) predicts a channel width of 52.2 m at the upper end and 52.8 m at the river mouth. Thus, the hydraulic geometry model overestimates the channel width at the upper end of the lake where it is measured at 21-34 m wide in the lowest 1 km of the free-flowing channel; and it underestimates channel width at the downstream end of the lake where the photographic measurements indicate widths of 60-70 m.

The analog model relating bedrock gorge width to channel width from Section IV and the lowest part of Section III (Figure 7) shows a highly significant statistical relationship ($R^2 = 0.60$, $p < 0.0001$). Channel width within the Chattooga gorge is not simply a positive function of contributing drainage area, as assumed by standard hydraulic geometry relationships. In fact, the data show that the average width of the Chattooga River actually *decreases* slightly with downstream direction (Figure 8), opposite to what hydraulic geometry would predict. Thus, the bedrock gorge is exerting influence on the channel width, probably by constricting the channel in the more durable rocks that form the narrower gorges and by rock-fall boulders from the steep gorge slopes that impinge upon and constrict the river channel. At the upper end of the inundated reach beneath Lake Tugalo, the bedrock gorge begins a gradual widening in the

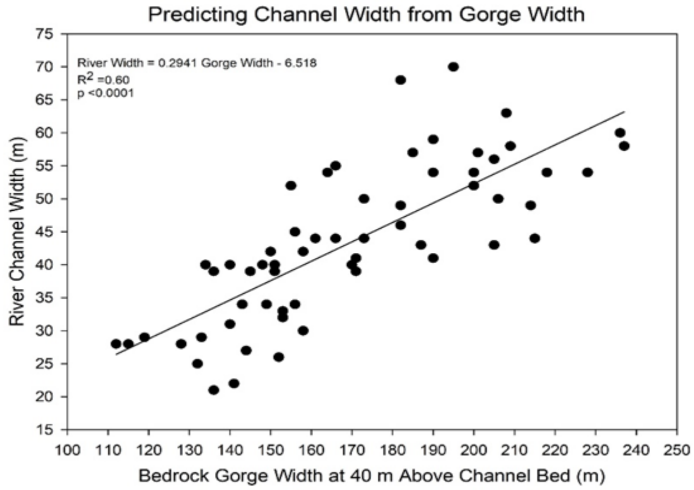

Figure 7. Bivariate plot of measured gorge width at 40 m above the channel bed versus measured river channel width.

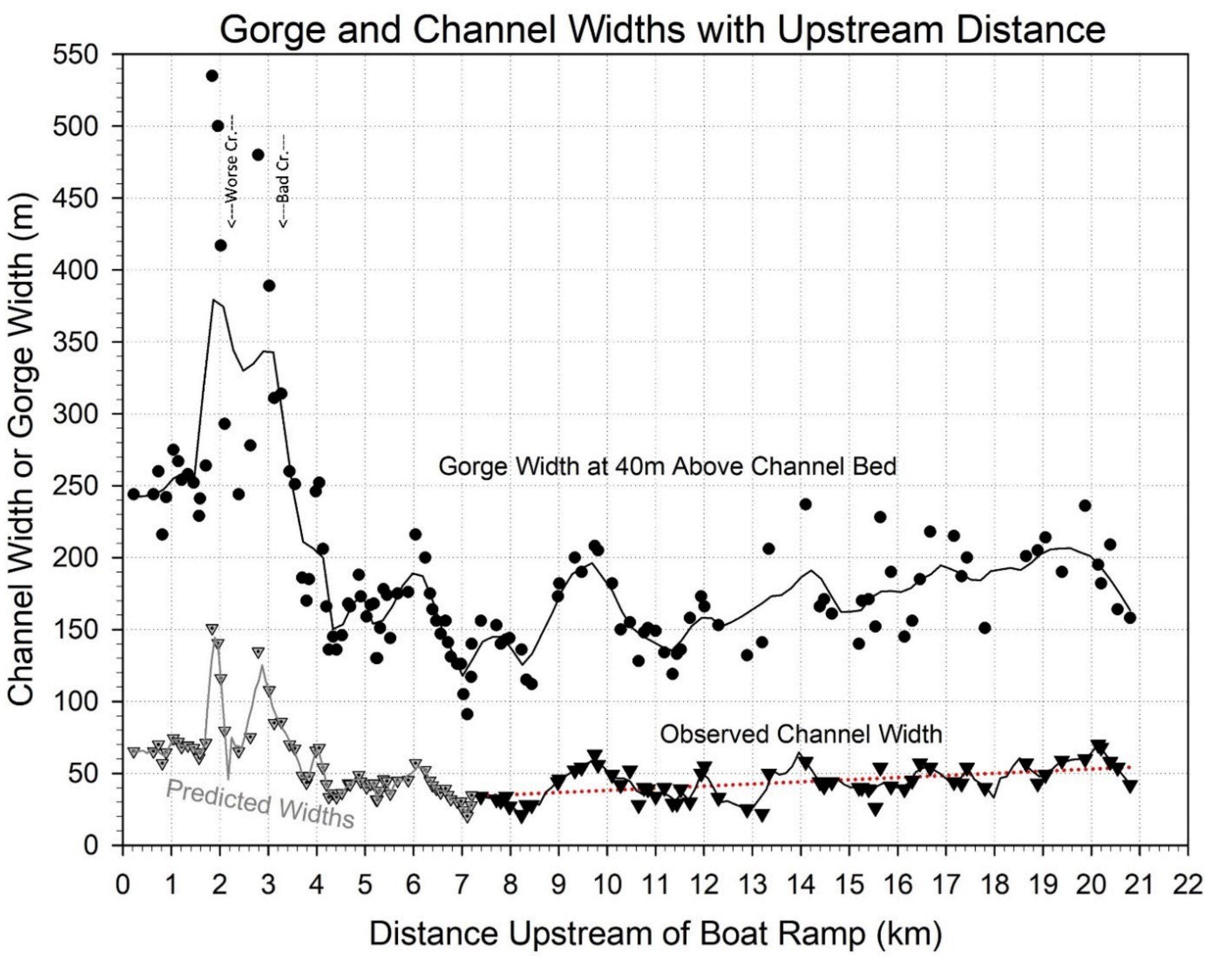

Figure 8. Plot of river channel width (bottom triangles) and gorge width (circles) at 40 m above the channel bed. A LOESS smoothing curve (trend line through points) was applied to each data set using a 0.075 sample interval and a first-order polynomial. The red dotted line is the linear regression showing that the average channel width actually decreases with distance downstream. The zero distance is located at the concrete boat ramp at 0.50 km downstream of the top edge of the Tugalo Dam at the southern end of the Tugaloo Campground next to the river. Therefore, subtract 0.5 km to derive distance above the dam.

downstream direction (Figure 8), and the gorge widths predict the channel widths near the mouth to be 60-70 m, which closely agrees with the 1922 photos.

The middle section of the present-day lake includes some wide fluctuations in the gorge widths that correspond to pronounced widening in the vicinity of the mouths of Worse Creek and Bad Creek (Figure 8), except that there is a long isthmus that causes a short stretch of narrowing immediately upstream of Worse Creek (Figures 1 and 8). Thus, there probably was some proportional narrowing and widening of the river channel as a function of changes in gorge width. In fact, the 1922 oblique aerial photograph illustrates some narrowing of the channel immediately upstream of a subtle constriction occurring where boulders have accumulated in the channel (Figures 3 and 4). The regression model of gorge widths (Figure 7) predicts that the channel might have been 100-150 m wide within the wide valleys in the vicinity of Worse Creek and Bad Creek mouths (Figure 8); however, those predictions probably are incorrect, because they are extrapolated well beyond the empirical observations, and in those areas of the wide gorge it is more likely that there was an alluvial channel, rather than a bedrock channel, which is where the 52-53 m wide channel width predicted by the hydraulic geometry is more likely. Unfortunately, no modern analogs exist for alluvial reaches of the channel in the Section IV reach upstream of the lake, but comparable size rivers in the region (Chattahoochee, Tuckasegee, Pigeon) commonly show narrower reaches of channels with alluvial beds versus and wider channels in the bedrock reaches (Table 1).

Table 1. Modern analogs for the lower 5 km of the pre-1923 Chattooga River inundated beneath Lake Tugalo.

River Reach	Drainage Area (km^2)	Gradient (m/m)	Modeled Bankfull Width (m)	Measured Bankfull Width in Alluvium (m)	Measured Bankfull Width in Shoals (m)	Modeled bankfull Depth (m)	Sinuosity (channel length / gorge length)
Pigeon River immediately below Crabtree Creek	712	0.0028	52	45-55	50-76	2.8	1.0-1.1
Tuckasegee River immediately below Savannah Creek	738	0.0018	53	50-60	60-80	2.9	1.0-1.1
Chattahoochee River between Soque River and GA Hwy. 384	815	0.0013	55	45-57	65-82	3.0	1.0-1.1

In summary, bedrock reaches of the river (in the narrow gorge sections) probably were about 30-50 m wide in the upper 2-3 km of the inundated reach and progressively widened in the downstream direction to 60-70 m wide near the confluence with the Tallulah River. Alluvial portions of the inundated reach (in the widest gorge sections) probably existed in relatively wide valleys immediately downstream of the mouths of Worse and Bad Creeks where the channel widths were more closely aligned with hydraulic geometry estimates of 52-53 m.

Depth

Channel depth is a difficult parameter to estimate, simply because it is so variable depending on the water discharge conditions and variations in channel slope. The hydraulic geometry model indicates that mean bankfull depth of the now-inundated channel would have been 2.8-2.9 m with little variation from the upper end of the present-day lake down to the lowest end. The 1922 photographs appear to have been taken at or near baseflow conditions, and they indicate that the river channel is exposing sills of bedrock transverse to the river as well as isolated boulders. Thus, an estimate of the baseflow depth for locations just above the mouth of the river is likely in the range of 0.2-1.0 m. It is reasonable to assume that similar depths would have existed upstream throughout the inundated reach, especially in bedrock shoal areas. However, it is probable that the widest portion of the gorge immediately downstream of the mouths of Worse and Bad Creeks would have flowed within an alluvial bottomland, which would have had variable depths according to riffles and pools, including deep scour pools within the most sinuous segments of the alluvial channel. In any case, the depth of the lower Chattooga River would not have differed greatly from similar-sized rivers in the region that occasionally are flowing on bedrock, such as the Chattahoochee, Tuckasegee, and Pigeon Rivers (Table 1). Those rivers are noted regional fly-fishing destinations, because of their wadable depths and high frequency of riffles and shoals. In summary, the average bankfull depth was probably around 2.8-2.9 m throughout the inundated reach and baseflow conditions had wadable depths of about 0.2-1.0 m.

Channel Bed and Banks

Given the steep slope conditions of the upper 2 km of the inundated knickpoint reach (Figure 2), it is reasonable to conclude that its morphology would be very similar to the steep Five Falls reach (Figure 9). That is, having a steep average gradient of about 0.015, a bankfull width of about 30-50 m, very steep (0.03-0.10) class IV and V cascades over bedrock separated by lower gradient segments with boulder-cobble riffles and glides. Rock-fall boulders would commonly occur within the reach as a result of the relatively narrow gorge, and “youthful” rock outcrops with potholes would be common. Fine sediment (sand and silt) would fill spaces

Figure 9. March 16, 2019 aerial image (from Google Earth) of the Five Falls reach of the Chattooga River immediately above Lake Tugalo. The channel beneath the uppermost 2 km of the lake, the knickpoint reach, probably resembled this prior to 1923.

between boulders on the bank. Stems of large wood (tree trunks) derived from debris flows and floods would clutter the banks in some areas.

In contrast, once below the knickpoint and into the lower 5 km of the inundated reach, the river channel would have a “gentler” appearance. The average gradient would be about 0.0016, the bankfull width would range from about 50 m wide at the upper end of the reach to 60-70 m wide just above the river’s mouth, and this reach would have scattered class I and II rapids over bedrock sills and gravels/cobbles within riffles. The main tributaries entering the inundated reach (Worse and Bad Creeks) were sufficiently large to supply ample amounts of alluvial sediment to the river to create riffles and bars of gravels and cobbles within alluvial reaches of the river (as opposed to bedrock reaches) facilitated by the wider gorge and wider valley near those stream mouths. In addition, an abundant supply of gravel and cobbles was likely provided to the lower 5 km of the river from the much steeper knickpoint section upstream. Thus, the lowest 5 km probably had characteristics more akin to an alluvial channel than within the bedrock reaches above it, including undulating channel bed morphology of riffles and pools. Scattered, large rock-fall boulders would still occur in the lowest 5 km (as illustrated in Figures 3 and 4), but they would be less frequent in the wider portions of the gorge, where alluvial channel bed material (gravel and cobble) would be more common. The widest portions of the gorge (300-550 m wide) occur immediately downstream of Worse and Bad Creeks, and these reaches probably would have contained alluvial bottomlands as a result of abundant, finer sediment contributions from upstream and tributaries feeding into a wider valley bottom. This is where one would expect the river to have had an entirely alluvial channel appearance with sand, gravel and cobbles on the bed, and with sandy and silty alluvium composing the river banks. Also, alluvial reaches tend to have slightly narrower channels than bedrock reaches and occasionally would have 1-2 m deep scour pools (swimming holes) along the outside (cutbank) of meander bends. In contrast, elsewhere in narrower reaches of the inundated gorge (the upper and lower ends of the graded reach), the former channel probably would have had some bedrock reaches as well as gravelly and cobbly shoals or riffles.

The best regional analog of the three rivers mentioned (Table 1) for the lower 5 km of the inundated Chattooga River is the Tuckasegee River between its confluence with Savannah Creek and Dillsboro, North Carolina next to the water treatment plant (Figures 10 and 11). This river reach shows a combination of both bedrock and alluvial stretches over a short distance. Here the river cuts through a small gorge on the southwestern flanks of Kings Mountain with a 60-80 m wide bedrock channel, and bedrock shoals reveal transverse beds of resistant rock outcrops; in addition, there is a short alluvial reach immediately downstream of the Savannah Creek confluence (Figure 10), which is only 50-60 m wide. This analogous reach of the Tuckasegee River drains a comparable 738 km^2 and it has a very similar gradient (0.0018) to the lower 5 km of the inundated Chattooga River (0.0016).

Figure 10. Aerial image (April 2022 from Google Earth) of the Tuckasegee River just below its confluence with Savannah Creek, and just upstream of Dillsboro, North Carolina near the water treatment plant (WTP). The stream gradient in this reach is 0.0018 and watershed area upstream is 738 km^2, which is very similar to the lower 5 km reach of the inundated Chattooga River. The alluvial reach just above the water treatment plant is narrower than most of the bedrock reach.

Figure 11. Ground view of the Tuckasegee River at the water treatment plant just upstream of Dillsboro, NC, looking downstream (photographed by David S. Leigh on 27 October 2022). This is a good analog of what the lowest 5 km of the Chattooga River probably looked like prior to 1923.

Planform

Most rivers in the Blue Ridge Mountains and upper Piedmont provinces have low sinuosity (<1.3), and much of the curvature is etched into the bedrock. The 1921 reprint of the 1896 Walhalla 1:125,000 quadrangle does not indicate any free meandering within the 7 km inundated reach, only bedrock meanders that are apparent even from the plan view of the lake. The sinuosity of the present centerline course of the lake is 1.12, and the sinuosity of the same reach on the Walhalla quadrangle is 1.08. The Walhalla quadrangle is not very accurate spatially, as it misplaces the river and gorge in many places; nonetheless, it gives no indication of free meandering that would commonly be associated with alluvial channels.

The 1922 oblique aerial photos looking northward from the dam construction site do show a slight eastward meander bend (Figures 3 and 4), and that bend appears to be about 0.4 to 0.5 km upstream of the confluence with the Tallulah River. This is too short of a distance from the dam for the bend to correspond to a bend in the bedrock gorge, so it probably does indicate minor free meandering of the river channel, or "wandering" at least in its lowest kilometer. Also, a small portion of floodplain surface (or a low terrace) is visible on the north side of the river bend in the 1922 photos, indicating ample alluvium for a wandering reach of the river. If the river is wandering in that lowest kilometer, where the gorge is relatively narrow and straight, then it also probably was wandering further upstream where the gorge is definitely wider immediately downstream of Worse and Bad Creeks. Thus, it is probable that there were some wandering segments of the river below the knickpoint, where sinuosity may have reached values of 1.3-1.4 within the wider portions of the alluvial bottomland. However, it still would not be considered a true "meandering river", as that designation requires sinuosity of at least 1.5.

CONCLUSION AND SUMMARY

The inundated river channel beneath Lake Tugalo would have had two distinctly different reaches prior to 1923, which we refer to as the *knickpoint reach* and the *graded reach.* These two sections are logical byproducts of long-term river channel adjustment following the ancient capture of the Chattooga River system into the Tugaloo system from its original Chattahoochee course. The likely morphologies of the two reaches are described below and summarized in Table 2 and Figure 12.

Table 2. Summary of pre-1923 channel morphology for the inundated 7 km or beneath Lake Tugalo.

Inundated Reach	Average Gradient (m/m)	Bankfull Width (m)	Bankfull Depth (m)	Baseflow Depths (m)	Planform or Sinuosity (not of the bedrock gorge)	Bed Material	Bank Material	Other
Upper 2 km "Knickpoint Reach"	0.015	30-50	2.8-2.9	0.2-1.0	1.0-1.2	bedrock, potholes, rock-fall boulders, bedrock sills & obstacles, large wood stems from debris flows & floods	rockfall boulders, bedrock, cobbles within matrix of fines (sand and silt); large wood stems from debris flows & floods	some very steep segments & ledges (0.03-0.10 slopes)bedrock class III-V whitewater, bedrock runs & pools; much like the "Five Falls" reach at the base of Chattooga whitewater Section IV
Lower 5 km "Graded Reach" (gently graded to Tugaloo River). *Two subtypes:* (1) bedrock channel in relatively narrow gorge at upper and lower ends; (2) alluvial channel in much wider gorge in middle parts downstream of mouths of Worse and Bad Creeks	0.0016	50-70 (52-53 meters wide in alluvial sections)	2.8-2.9	0.2-1.0	1.0-1.2 in narrow gorges; 1.3-1.4 in wider gorge of the middle part where alluvial channels existed	beveled bedrock with rock sills and sparse gravels-cobbles & few rock-fall boulders in narrow gorge parts; alluvial riffles & pools with cobbles-gravels-sand in middle parts of wider gorge	rockfall boulders, bedrock, cobbles within matrix of fines (sand and silt) in narrow gorge parts; alluvial fines of sand-silt in middle parts of wider gorge with meandering alluvial channels	beveled bedrock channel bed at upper and lower ends where gorge is narrow; wandering alluvial reaches in middle part with scour pools and gravel/cobble riffles; overall, classic relatively wide wadable fly fishing river with scattered class I-II rapids

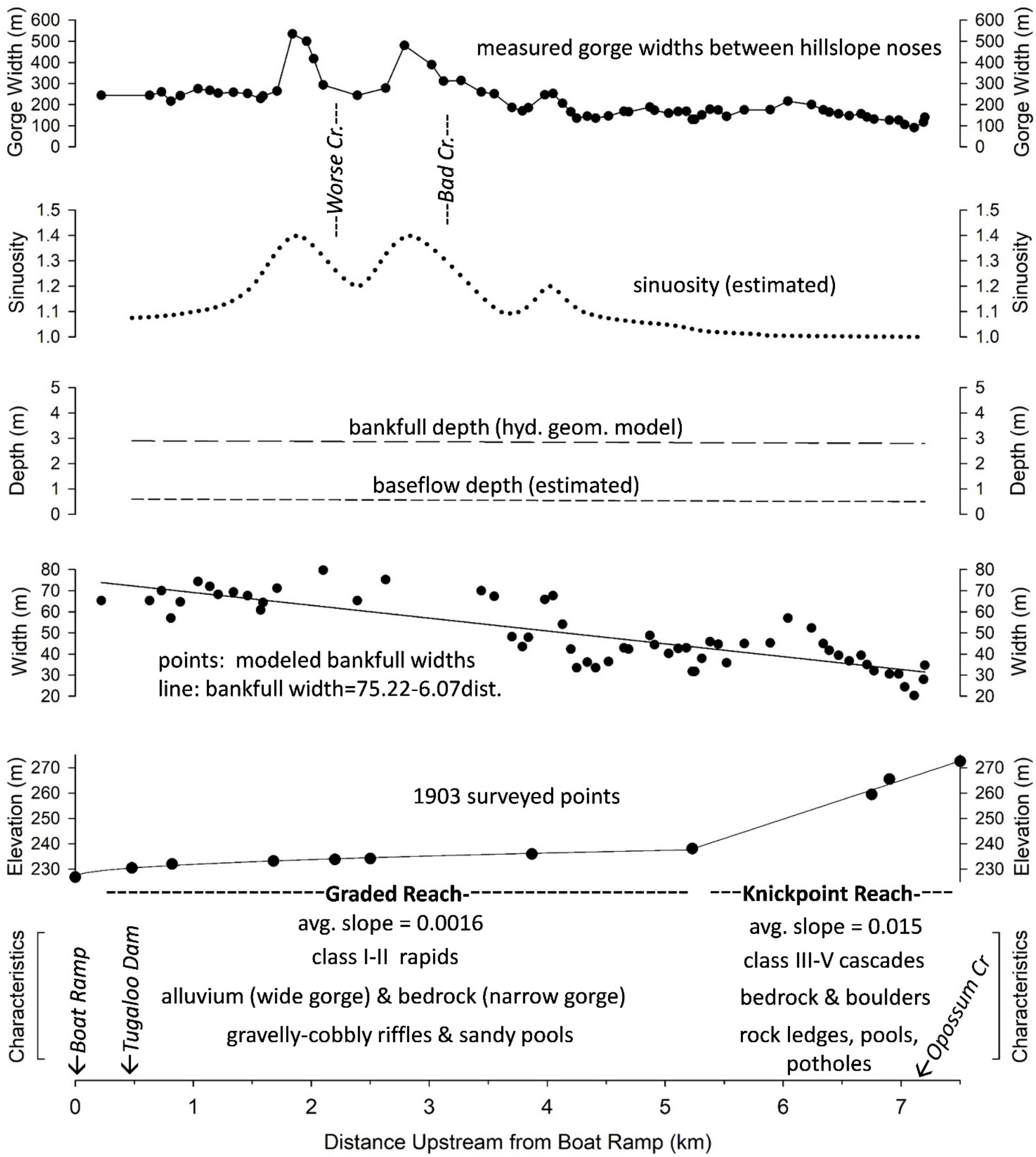

Figure 12. Graphic summary of Chattooga River morphology beneath Lake Tugalo. Gorge widths were measured from hillslope noses on either side of the valley at 40 m above the 1903 river channel. Sinuosity is an estimate for the channel in alluvial valleys, not sinuosity of the bedrock gorge. Bankfull depths were calculated from hydraulic geometry models (Appendix C). Channel widths are predicted from gorge widths (see Figure 7). The 1903 survey points are from Hall and Hall (1908) with distances adjusted to the boat ramp (zero point) and elevations adjusted to the 2022 LiDAR DEM.

Knickpoint Reach

The *knickpoint reach* (the uppermost 2 km) would have been an extension of the very steep knickpoint section of the river that currently contains the Five Falls whitewater reach between Camp Creek and the uppermost end of the lake (Figures 1 and 2). Indeed, the best modern analog is the Five Falls reach itself (Figures 2 and 9). The average slope in this 2 km inundated knickpoint reach is estimated at 0.015, but it would have included some very steep class IV-V ledges and small falls with 0.03-0.10 local gradients. The bankfull width was likely 30-50 m, bankfull depth was likely 2.8-2.9 m, and baseflow depths were much shallower at 0.2-1.0 m. Channel sinuosity (as distinct from bedrock gorge sinuosity) was likely close to 1 (straight channel) or just slightly higher (1.2). Bed material probably was mostly bedrock with sills and obstacles, along with large boulders due to rock-fall from adjacent hillslopes. Bank materials probably were coarse as well, with bedrock, rock-fall boulders, and cobbles integrated within a matrix of sand and silt, as well as abundant pieces of large wood stems from debris flows and floods. In short, the knickpoint reach would have been a stretch of world-class whitewater cascades much like that of the contemporary Five Falls reach.

Graded Reach

The *graded reach* (the lowest 5 km) had an order-of-magnitude lower gradient channel than the knickpoint reach. This "gentler" slope evolved as a graded channel that was adjusted to the slope of the Tugaloo River downstream. In fact, the average slope of 0.0016 in this 5 km reach is identical to the gradient of the Tugaloo River immediately below Yonah Dam (Tugaloo River gradient is not measurable any closer than that due to Lake Yonah). The channel characteristics would have been somewhat variable in this graded reach, depending on the amount of constriction by the bedrock gorge, which varies considerably in width through this reach, and whether the channel bed was alluvial or bedrock. It is likely that abundant alluvium was supplied to this graded reach from the much steeper knickpoint reach above, in addition to alluvium contributed from the moderately sized tributaries of Worse Creek and Bad Creek. The widest areas of the bedrock gorge immediately downstream of the mouths of Worse and Bad Creeks would have had the greatest potential for an alluvial channel, whereas the narrower gorge downstream and upstream may have had channels on bedrock. Indeed, bedrock sills are visible at the mouth of the Chattooga River on the 1922 photographs. Bankfull width probably was 50-70 m, appearing wider in bedrock reaches and narrower in alluvial reaches. Bankfull depth probably was pretty close to the 2.8-2.9 m value predicted by hydraulic geometry. Sinuosity probably was low in the narrower gorge reaches (1.0-1.2) and wandering (sinuosity of 1.3-1.4) in the alluvial reaches. Bed material probably was bedrock with thin patches of gravel and cobbles in the narrow gorge reaches, whereas alluvial cobbles, gravels, and sand occurred in the reaches of wider gorges. The alluvial reaches probably would have had gravelly-cobbly riffles and sandy scour pools integrated with a sinuous planform. Scattered rock-fall boulders would pepper the upper and lower ends of the inundated reaches where the narrower gorge width allowed boulders to roll into the channel from nearby hillslopes. In short, the graded reach would have been a fine wadable fly-fishing river with widely varied habitats owing to the mixture of bedrock and alluvial reaches throughout this lowest 5 km of the river.

Three nearby rivers in the Blue Ridge province provide good analogs for what the lowest 5 km of the Chattooga River must have looked like (Table 1). These include the Chattahoochee River between the mouth of the Soque River and Georgia Highway 384 just west of Cornelia, Georgia; the Tuckasegee River immediately downstream of the mouth of Savannah Creek and just upstream of Dillsboro, North Carolina; and the Pigeon River between Crabtree Creek and Dotson Branch, just west of Crabtree, North Carolina. All of these rivers drain similarly sized watersheds, have similar gradients, and they fluctuate from bedrock-floored channels to alluvial channels. Of these, the best analog appears to be the Tuckasegee River just upstream of Dillsboro (Figures 10 and 11; Table 1). The nearby Little Tennessee River is not included in this list, because it has a very low gradient that is not comparable to the Chattooga River, at least at the point where it drains a similarly sized watershed to the Chattooga River.

Benefits of River Channel Restoration

If Tugalo Dam were to be removed, then restoration of the lowest 7 km of the Chattooga River would provide a uniquely varied stretch of the river with its steep upper 2 km of the knickpoint reach and the gentler lower 5 km of the graded reach. Also, dam removal would enable additional benefits of restoration of the lowest 3 km of the Tallulah River. Few rivers in the southeastern United States exhibit such wide variation over such a short distance, and the river's restoration would significantly augment the beauty and recreational opportunities of northeastern Georgia and northwestern South Carolina. Given our focus on river channel restoration, our evaluation of benefits is limited to the potential of the restored channel to attract recreational boaters and other types of river-based recreation. Our evaluation does not consider the multiple additional cultural, ecological, and economic benefits that have been demonstrated elsewhere from removing dams and restoring natural river function. The knickpoint reach would provide 2 km of additional river channel for whitewater enthusiasts interested in new and exciting class IV-V cascades, whereas the graded reach would provide a gentler float over class I-II rapids as well as extensive opportunities for those interested in wadable rivers for fly fishing and swimming. In short, restoration of the inundated 7 km likely would provide an important travel destination and economic benefit to the region.

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APPENDIX A. Survey Points Collected on the Lower Chattooga River in 1903 for the USGS (from Hall & Hall, 1908, pp. 93-94).

SURVEY OF CHATTOOGA RIVER.

The elevations in the following list are based on an aluminum tablet, marked "1050 M. C.," at the Washington street entrance to the State capitol at Atlanta, the elevation of which is accepted as 1,049.546 feet above mean sea level. The initial point upon which these levels depend is a bench mark of primary levels of the Tugaloo and Savannah River survey at the mouth of Chattooga River. The elevations accord with the 1903 adjustment.

The leveling was done for the U. S. Geological Survey in 1903 by Thomas B. O'Hagan, levelman, under the direction of Carroll Caldwell, field assistant.

Elevations on Chattooga River from mouth of Chattooga River to Russell Bridge, Georgia. [a]

Distance	Description of points	Elevation above sea level
Miles		*Feet*
0.0	Tallulah and Chattooga rivers, 100 feet north of junction, point on rock	761.29
0.0	Tallulah and Chattooga rivers, white-oak tree 75 feet west of junction of, 25 feet north of Tallulah River, nail in root of oak tree	762.21
0.0	Tallulah and Chattooga rivers, water surface	754
0.2	Water surface	759
0.7	Mouth of stream, water surface	763
1.0	Worse Creek, mouth of, water surface	765
1.2	Water surface	766
1.9	Small stream on north edge of river, Spanish oak, nail in root of	776.27
1.9	Water surface	772
2.1	Water surface	775
2.6	North side of river, point on rock	788.63
3.0	Water surface	779
4.0	East side of river, point on rock	851.51
4.0	Water surface	849
4.1	Water surface	869
4.5	Mouth of creek, water surface	892
4.7	Water surface	899
4.9	East side of river, point on rock	918.27
4.9	Water surface	919
5.0	Water surface	929
5.1	Water surface	939
5.2	Water surface	949
5.3	Mouth of stream, head of shoals, water surface	954
5.6	Camp Creek, mouth of, water surface	961
5.6	Trail Ford, point on rock 20 feet east of river	967.50
5.6	Trail Ford, water surface	962
5.8	Water surface	969
6.1	Water surface	979
6.3	Water surface	989
6.7	Water surface	999
7.0	Water surface	1,000
7.2	Water surface	1,029
7.4	Cliff Creek, mouth of, water surface	1,035
7.4	Cliff Creek, 300 feet above, east side river, point on rock	1,045.26
7.5	Water surface	1,039
7.6	Chechero Creek, mouth of, water surface	1,049
7.8	Water surface	1,059
8.0	Water surface	1,069
8.2	Water surface	1,079
8.4	Water surface	1,089
8.5	Water surface	1,099
8.6	Water surface	1,109
9.0	Water surface	1,119
9.5	Water surface	1,129
9.8	Water surface	1,149
10.0	East side of river on edge of bank, point on rock	1,152.43
10.0	Water surface	1,159
10.0	Iron bridge, South Carolina side, iron bar under bridge, point on	1,168.95
10.0	Iron bridge, water surface	1,166.3
10.0	High water	1,177
10.5	Water surface	1,169
10.6	Mouth of creek, water surface	1,173

[a] Seven miles north of Russell, S. C.

Elevations on Chattooga River from mouth of Chattooga River to Russell Bridge, Georgia—Continued.

Distance	Description of points	Elevation above sea level
Miles		*Feet.*
10.6	Head of falls, water surface	1,179
10.8	Mouth of stream, water surface	1,183
11.0	Water surface	1,189
11.4	Water surface	1,199
11.7	Mouth of stream, water surface	1,204
12.0	Water surface	1,209
12.5	50 feet south of island, east side of river, 10 feet from bank, point on rock	1,217.86
12.7	Water surface	1,219
12.9	Water surface	1,223
13.0	Water surface	1,229
13.2	Mouth of stream, water surface	1,232
13.6	Water surface	1,239
13.8	South Carolina side of river, at large cliff, point on rock	1,245.53
14.0	Water surface	1,249
14.0	Mouth of Fall Creek, water surface	1,262
14.5	Water surface	1,268
14.7	Water surface	1,279
15.0	Water surface	1,289
15.7	Water surface	1,296
16.0	Water surface	1,299
16.6	Rich Creek, mouth of, water surface	1,308
16.8	Water surface	1,309
16.9	South Carolina side of river, point on rock	1,310.4
17.0	Water surface	1,319
17.4	Water surface	1,329
17.8	Sandy bottom, 1,000 feet below, east side of river, point on rock	1,332
18.0	Water surface	1,340
18.7	Water surface	1,359
18.7	East side of river, point on rock	1,366.45
18.9	Water surface	1,360
19.1	300 feet below falls, at bend in river, point on rock	1,376.19
19.2	Foot of falls, surface of water	1,375
19.0	Head of falls, water surface	1,381
19.7	Water surface	1,399
19.8	Rock Creek, mouth of, water surface	1,406
20.0	Sand ford, water surface	1,411
20.0	Sand ford, 75 feet north of, 15 feet east of river, nail in root of white oak tree	1,416.55
20.2	Water surface	1,419
20.6	Water surface	1,429
20.7	Dick Creek, mouth of, water surface	1,439
20.8	Water surface	1,449
21.0	East side of river, point on rock	1,452.91
21.2	Water surface	1,459
22.0	Water surface	1,469
22.1	Water surface	1,473
22.3	4 feet east of river, nail in root of pine tree	1,481.86
22.7	Water surface	1,479
23.0	Earl Ford, 100 feet below ford, east side of river, point on rock	1,486.74
23.0	Earl Ford, water surface	1,486
23.0	Warwoman Creek, mouth of, water surface	1,486
23.8	South side of river point on rock	1,494.13
23.8	Water surface	1,492
24.8	Water surface	1,499
25.2	West side of river, point on rock	1,510.51
25.2	Water surface	1,505
26.0	Horseback Ford, water surface	1,518
26.3	Water surface	1,519
26.4	Ford, 65 feet above, north side of river, nail in live stob (white-oak tree)	1,522.66
26.4	Water surface	1,521
26.8	Water surface	1,529
27.1	Water surface	1,339
27.9	Barlow stream, center of river, point on rock	1,547.26
28.0	Water surface	1,549
28.7	Long Bottom Ford, east side, nail in fork of sugar-maple tree	1,557.68
29.7	Small stream, mouth of river at, water surface	1,554
30.6	West fork, mouth of, water surface	1,563
30.6	Wooden bridge above Russell, S. C., southwest side of bridge, point on bolt	1,584.84
30.6	Bridge, water surface	1,564

Appendix B: Regression Models to Describe Gradients and Widths

Elevations of the 1903 Graded Reach from distance 0 to 5230 m:

Elevation (m) = 226.843 + 0.2013 (distance (m) $^{0.464}$)

$R^2 = 0.99$; $p < 0.0001$

Elevations of the 1903 Knickpoint Reach from distance 5230 to 7200 m:

Elevation (m) = 157.89 + 0.0153 distance (m)

$R^2 = 0.99$; $p < 0.01$

Bankfull width predicted from gorge width at 40 m height above 1903 channel bed:

Bankfull Width (m) = 0.2941 – 6.518 Gorge Width (m)

$R^2 = 0.60$; $p < 0.0001$

Bankfull width (line) predicted from distance upstream from 0 to 7.2 km:

Bankfull Width (m) = 75.216 – 6.074 Distance (km)

$R^2 = 0.68$; $p < 0.0001$

APPENDIX C: Hydraulic Geometry Data (C1)and Models (C2-C3)

C1: Harmon et al. (2000) data plus four new sites at 130 mi^2 and larger to create new models (below). English units are given to remain consistent with the original data set of Harmon et al. (2000).

Stream Name	USGS Gage #	Rosgen Type	Area (mi^2)	Qbkf (cfs)	Xsec Area (ft^2)	Bankfull Width (ft)	Bankfull Mean Depth (ft)	Return Interval (years)
East Fork Hickey Fork Creek	n/a	B3a	2.0	242	39.3	27.4	1.4	n/a
Cold Spring Creek	n/a	B4	5.0	352	74.4	42.9	1.7	n/a
Bee Tree	3450000	B3	5.5	231.5	56.0	32.1	1.7	1.9
Catheys Creek near Brevard	344000	B4c	11.7	470	94.2	38.0	2.5	1.7
Caldwell Fork	n/a	B	13.8	560	79.3	39.4	2.0	n/a
North Fork Swannanoa	344894205	C3	14.5	855.7	170.6	69.3	2.5	n/a
West Fork of the Pigeon	3455500	B3c	27.6	2433	277.9	80.6	3.4	1.1
Davidson River	3441000	B4c	40.4	1457	316.0	87.6	3.6	1.1
Cataloochee	3460000	B4c	46.9	1320	186.9	58.7	3.2	1.6
East Fork Pigeon River	3456500	B	51.5	3450	446.3	107.0	4.2	1.6
Mills River	3446000	C4	66.7	2263	333.0	74.3	4.5	1.9
French Broad at Rosman	3439000	E4	67.9	3226	544.9	82.4	6.6	1.3
Watauga River	3479000	B4c	92.1	3492	572.0	140.3	4.1	1.3
Big Laurel	3454000	B4	126.0	2763	406.0	110.8	3.7	1.6
Pigeon River near Canton	*3456991*	n.a.	130.0	7850	1430.0	175.0	8.2	1.9
Chattahoochee River near Leaf	*2331000*	n.a.	150.0	5290	1020.0	125.0	8.2	1.4
Chattahoochee River near Cornelia	*2331600*	n.a.	315.0	10100	2400.0	183.0	13.1	1.7
Pigeon River near Hepco	*3459500*	n.a.	350.0	9500	1400.0	180.0	7.8	1.7

C2: Harmon et al. (2000) power function regression equations for bankfull discharge and dimensions, where Q_{bkf} = bankfull discharge (cfs), A_w = watershed drainage area (mi^2), A_{bkf} = bankfull cross sectional area (ft^2), W_{bkf} = bankfull width(ft), and D_{bkf} = bankfull mean depth (ft).

Parameter	Power Function Equation	Coefficient of Determination R^2
Bankfull Discharge	$Q_{bkf} = 115.7A_w^{0.73}$	0.88
Bankfull Area	$A_{bkf} = 22.1A_w^{0.67}$	0.88
Bankfull Width	$W_{bkf} = 19.9A_w^{0.36}$	0.81
Bankfull Depth	$D_{bkf} = 1.1A_w^{0.31}$	0.79

C3: New power functions for this report using the four new sites from the Pigeon and Chattahoochee Rivers. Slopes of all models are significant at p values <0.0001.

Parameter	Power Function Equation	Coefficient of Determination R^2
Bankfull Discharge	$Q_{bkf} = 125.660A_w^{0.751}$	0.89
Bankfull Area	$A_{bkf} = 15.248A_w^{0.829}$	0.81
Bankfull Width	$W_{bkf} = 19.072A_w^{0.392}$	0.86
Bankfull Depth	$D_{bkf} = 0.684A_w^{0.465}$	0.78